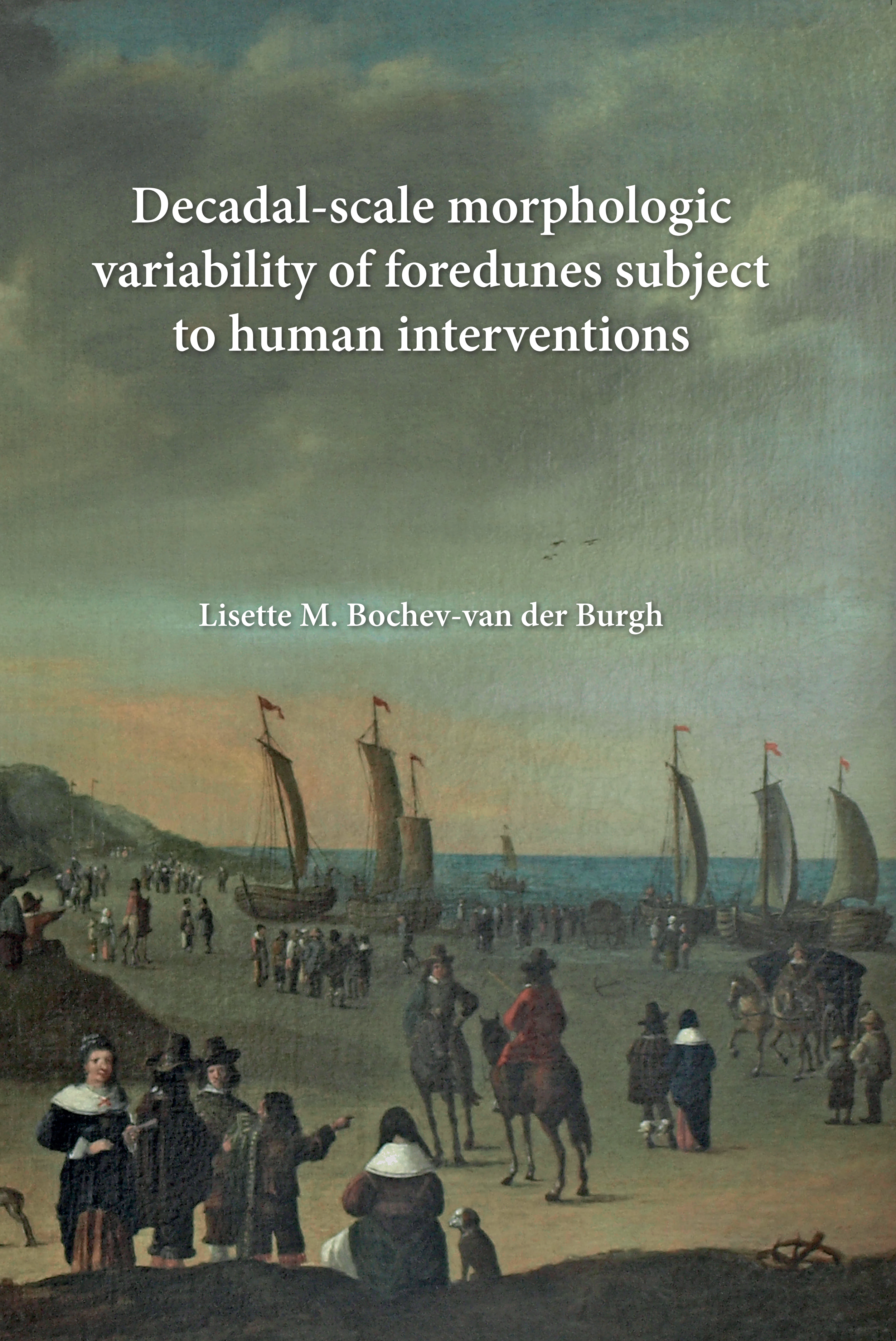

Decadal-scale morphologic variability of foredunes subject to human interventions

Lisette M. Bochev-van der Burgh

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DECADAL-SCALE MORPHOLOGIC VARIABILITY OF FOREDUNES SUBJECT TO HUMAN INTERVENTIONS

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. H. Brinksma,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen op
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door

Lisette Marije Bochev-van der Burgh
geboren op 5 mei 1978
te Hoorn

Dit proefschrift is goedgekeurd door de promotor prof. dr. S.J.M.H. Hulscher
en de assistent promotor dr. K.M. Wijnberg

Contents

Dankwoord

"Wie een omelet wil bakken, moet eieren breken"

Deze spreuk, die ruim 5 jaar geleden door een thans nog onbekend persoon op het bord van mijn kamer op de UT werd geschreven, geeft het proces van een proefschrift schrijven mijns inziens goed weer. Het continu bij- en herschrijven van documenten, waarbij soms veel werk en onderzoek wordt 'weggegooid', totdat uiteindelijk de omelet - het proefschrift - gereed is. Er zijn een aantal personen die ik wil bedanken voor hun bijdrage aan mijn omelet.

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Christus, in Wie al de schatten der wijsheid en kennis verborgen zijn (*1 Kol 2:3*).

Samenvatting

Voorduinen, de eerste duinenrij vanaf het strand bekeken, vervullen een belangrijke functie in het bieden van veiligheid tegen overstromingen vanuit zee. Door klimaat gerelateerde factoren als zeespiegelstijging en een toename in extreme storm condities zal deze functie onder steeds grotere druk komen te staan.

Aangezien duinen geen starre, statische landschapselementen zijn, maar hun vorm èn positie in de tijd verandert, heeft deze verandering directe gevolgen voor het veiligheidsniveau dat door de voorduinen wordt geboden. Het is hierbij belangrijk om te vermelden dat duinen die een rol spelen in het bieden van veiligheid meestal door de mens beheerd worden, om een minimaal veiligheidsniveau te garanderen. Het huidige kustbeleid (de 3^e kustnota, Ministerie van V&W (2000)) stelt dat het niet alleen van belang is dat de duinen de veiligheid 'nu' waarborgen, maar dat ze dat ook doen op een periode van 50 tot 200 jaar.

Het blijkt dat er op een tijdschaal van decennia tot eeuwen nauwelijks inzicht is in de verandering van de vorm en de positie van (beheerde) kustduinen. Het eerste doel van deze studie was daarom om de verandering van de vorm van beheerde duinen gedurende een periode van ongeveer 50 jaar te analyseren. Op deze tijdschaal zijn er meetgegevens beschikbaar uit het zogenaamde Jarkus-bestand (Jaarlijkse kustmetingen), die de jaarlijkse kustdwarse ontwikkeling van de duinen laat zien.

Met behulp van dit data-bestand is er allereerst gekeken naar de ruimtelijke en temporele variabiliteit van de zwaar beheerde duinen langs de Hollandse kust, tussen Den-Helder en Scheveningen. Aangezien de hoeveelheid data aanzienlijk is, meer dan 400 duinprofiel-lokaties waarbij elke lokatie metingen van de afgelopen 45 jaar bevat, is er voor gekozen om een data-reductie techniek toe te passen om de ontwikkeling van de duinen te analyseren. Deze data-reductie techniek staat bekend als EOF (Empirische Orthogonale Functie) analyse. Aangezien de interesse vooral uitgaat naar de vorm-verandering van het duin, zijn de profielen zodanig verschoven dat hun 'nulpunt' overeenkomt met de duinvoet-positie, die is vastgelegd op +3 m NAP. De duinvoet markeert de overgang van strand naar duin en is meestal zichtbaar als een scherpe hellingsknik tussen het vlakke strand en het steile duin. Daarnaast zijn ook de landwaartse en zeewaartse verplaatsingen van de duinvoet bekeken, omdat die meer inzicht verschaffen in erosieve of aanzandende perioden. De analyse van de duinprofielen laat zien dat hoewel de duinen zeer zwaar beheerd zijn geweest en het beheer vooral tot doel had het duin vast te leggen, de duinen toch variabel zijn geweest in de tijd (kustdwars) en ruimte (kustlangs). De meeste variatie in de vorm van het voorduin is geconcentreerd in het lagere gedeelte van de zeewaartse helling, rond de duinvoet. Tevens laat de analyse een opmerkelijke verandering in duinvorm zien een aantal jaren nadat de 3^e kustnota was ingevoerd. Rond 1996 krijgen veel duinprofielen een meer concave ('holle') vorm, terwijl de profielen voor 1996 dat niet laten zien.

Vervolgens is in meer detail gekeken naar de rol van verschillende beheersmaatregelen op de variabiliteit van de voorduinen. Hiertoe zijn twee gebieden geselecteerd langs de Hollandse kust, te weten een voorduingebied tussen Bergen en Castricum en tussen Noordwijk en Scheveningen. Interviews met duinbeheerders zijn gehouden om meer inzicht te krijgen in de rol van het beheer op de voorduinvorm. Daarnaast zijn diverse beheersdocumenten geraadpleegd. Uit deze studie kwam naar voren dat maatregelen vóór 1990 voornamelijk reactief van aard waren. Dat wil zeggen dat maatregelen uitgevoerd werden nadat erosie was opgetreden. Na 1990 werden maatregelen vooral proactief van aard. Dat houdt in dat er een buffer wordt aangebracht om erosie van het bestaande duin te voorkomen. Deze buffer bestaat uit zandsuppleties. Vanwege de schaalvergroting van de beheersmaatregelen, zand wordt van elders naar de onderwateroever of het strand gebracht en beïnvloedt zodanig de sedimentbalans van het onderwateroever-strand-duin systeem, heeft dit geleid tot een kustlangs consistente verandering in voorduinvorm.

In deze studie kon een link gelegd worden naar het hiërarchische duinlandschapsmodel van Bakker et al. (1979). De kern van dit model is dat maatregelen hiërarchisch geordend kunnen worden naar gelang het effect dat ze hebben op het duin. Beplantingen en zandschermen (maatregelen die vooral voor 1990 werden uitgevoerd) worden laag in de hiërarchie geplaatst, omdat gedacht wordt dat hun effect op het duinlandschap kleiner is dan maatregelen die een hoge hiërarchische positie innemen, bijvoorbeeld maatregelen die het substraat veranderen, waartoe ook suppleties behoren.

Echter, deze bevindingen gelden voor de Hollandse kust en tevens zijn twee ‘variabelen’ tegelijkertijd bekeken, namelijk het type maatregel (beplantingen, zandschermen, suppleties) en de manier waarop de maatregel uitgevoerd wordt (reactief of proactief). Er kan dus niet worden gezegd of het de type maatregel is die belangrijker is in het beïnvloeden van de voorduinmorfologie, of de uitvoeringsmethode. Om hier uitsluitsel over te kunnen geven, is de analyse verplaatst naar het Waddeneiland Schiermonnikoog. Eind jaren vijftig van de vorige eeuw is op Schiermonnikoog getracht een zogenaamde stuifdijk te initiëren om een doorbraak van het eiland tijdens extreme stormen te voorkomen. De groei van de stuifdijk is op gang gebracht door op grote schaal stuifschermen te plaatsen en helmgras te planten. Dit deel van Schiermonnikoog, wat tot die tijd uit een kale strandvlakte bestond, veranderde in de loop der tijd in een duingebied waarachter een reeds bestaande kwelder flink kon uitbreiden.

De Schiermonnikoog casus is dermate interessant, aangezien maatregelen die laag in de hiërarchie geplaatst waren nu op een proactieve manier werden ingezet. Wat bleek, het westelijk deel van de stuifdijk groeide uit tot een volwaardig voorduin, terwijl het oostelijke deel van de stuifdijk op diverse lokaties doorbroken werd tijdens stormvloeden. Uit deze casus kunnen belangrijke lessen worden geleerd. Allereerst, het is niet zo zeer het type maatregel dat van invloed is op de voorduinmorfologie, maar de *manier* waarop de maatregel wordt ingezet. Op een tijdschaal van jaren tot decennia hebben proactieve interventiemethoden een grotere invloed op voorduinmorfologie dan reactieve interventiemethoden. Ten tweede, een maatregel zal alleen echt succesvol kunnen zijn als het ‘past’ binnen de randvoorwaarden en beginvoorwaarden (initiële condities) van het systeem waarbinnen de maatregel wordt uitgevoerd. Als de kust van Schiermonnikoog zwaar erosief was, dan had deze maatregel niet geresulteerd in de groei van een stuifdijk. Echter, de zandaanvoer was zodanig hoog, dat hier een ‘duin’ kon opstuiven. Tevens, het doel was om langs een grotere kustlangse afstand een stuifdijk te laten ontstaan. De stuifdijk bleef langs een bepaald traject wel bestaan, maar verder naar het oosten toe brak de stuifdijk herhaaldelijk door. Dit resulteerde echter niet in de gevreesde doorbraak van het eiland. Sterker nog, de reeds aanwezige kwelder ten zuiden van de stuifdijk kon enorm uitbreiden. Dit illustreert dat als we iets willen zeggen over het effect van een maatregel, we inzicht moeten hebben in het gedrag van het totale sediment-delende systeem, waarbinnen zand wordt herverdeeld. Met andere woorden, we hebben inzicht nodig in het gedrag van het systeem op een hoger schaalniveau dan het systeem waarin we eigenlijk geïnteresseerd zijn (in dit geval de voorduinen).

Tot dusver is er gekeken naar het gedrag van de voorduinen in het verleden. Wat kunnen we nu met die inzichten naar de toekomst toe? Dit brengt ons naar het tweede doel van deze studie, namelijk het ontwikkelen van een kader om de verkregen inzichten te vertalen naar lange-termijn projecties aangaande voorduinmorfologie. In principe is de staat van het voorduin over 50 jaar te voorspellen als we complete kennis hebben over factoren zoals kolonisatie van vegetatie, veranderingen in strandbreedte, morfologische veranderingen aan het strand (bijvoorbeeld veranderingen in de helling), vochtgehalte van het strand (wat inhoudt dat we moeten voorspellen wanneer het de komende 50 jaar zal regenen) en ook hydrodynamische condities tijdens extreme weersomstandigheden die resulteren in duinerosie. Dit is helaas onmogelijk. Wat er nu meestal gebeurt bij het ontwikkelen van lange-termijn voorspellende modellen, is dat de parameters die van belang worden geacht in de ontwikkeling van het systeem worden geschematiseerd of geparameteriseerd om een uitspraak te kunnen doen op de tijdschaal waarin men geïnteresseerd is. Dit houdt meestal in dat er gemiddelde waarden voor bepaalde parameters worden gebruikt. Deze procedure wordt opschaling genoemd. Opschaling houdt in dat er informatie (zoals extreme parameterwaarden) verloren gaat op een grotere schaal. In termen van duinmorfologie houdt dit verlies van informatie meestal in dat het duin wordt weergegeven als een blok met een bepaald volume, in plaats van een echte duinvorm. Dit volume kan veranderen onder bepaalde beheersscenario's.

Aangezien de vorm van het duin, dus de ruimtelijke verdeling van een volume, juist belangrijk is voor de lange-termijn veiligheid, is dit verlies aan vorminformatie niet wenselijk. Als we er nu van uitgaan dat een lange-termijn model in staat is om een voorspelling te maken aangaande het duinvolume over 50 jaar gegeven een bepaald beheersscenario, en we zouden dat volume kunnen omzetten in een realistische duinvorm, dan kunnen we een uitspraak doen over de veiligheid van het duin over 50 jaar. Met veiligheid is het echter zo dat niet alleen de veiligheid *over* 50 jaar belangrijk is, maar ook de veiligheid *gedurende* deze 50 jaar. We willen dus eigenlijk iets kunnen zeggen over het morfologische gedrag van het voorduin onder een bepaald beheersscenario gedurende een bepaalde periode.

Allereerst merken we op dat als het voornaamste doel het waarborgen van de veiligheid is, er hoe dan ook een proactieve interventiemethode ingezet moet worden. Met reactieve methoden zit er namelijk altijd een tijdsvertraging tussen het optreden van een bepaalde (extreme) conditie en de uit te voeren maatregel, wat in het kader van de veiligheid niet wenselijk is. In Nederland bestaan de huidige proactieve maatregelen uit suppleties. Ten tweede zoeken we wat morfologisch gedrag van beheerde duinen betreft naar analogiën in natuurlijke duinsystemen. Dit biedt mogelijkheden naar projecties toe, want er bestaan diverse conceptuele modellen over het morfologische gedrag van natuurlijke duinen. De duinontwikkeling na de grootschalige suppleties bijvoorbeeld, vertoont overeenkomsten met een natuurlijk uitbreidend kustsysteem, waarbij de duinmorfologie verandert als de kustlijn een bepaalde snelheid van zeewaartse verplaatsing bereikt (dit is het model van Pye (1990)). Ten derde blijkt dat verschillende factoren belangrijk zijn in het ontwerp van een interventiestrategie. Deze factoren zijn de fysieke grenzen van het sediment-delend systeem, de bronlokatie van het buffer materiaal, de kustdwarse positie waar de buffer wordt aangebracht (vooroever, strand, duin), de frequentie waarmee de buffer wordt uitgevoerd en de hoeveelheid materiaal die wordt aangebracht en tenslotte de dispersie (verspreiding door wind en water) van de buffer. Deze factoren bepalen op welk schaalniveau een maatregel zal ingrijpen in het hïerarchisch geordend sediment-delend systeem en zodoende geven deze factoren een indicatie voor de verwachte levensduur van een maatregel en daarmee dus ook voor de periode dat veiligheid gegarandeerd kan worden. Een belangrijke bevinding is bijvoorbeeld dat in het kader van de veiligheid het meer wenselijk is om een suppletie wat vaker uit te voeren met een wat hogere frequentie (een ‘high frequency-low magnitude’ maatregel), dan eenmalig een mega-suppletie (een ‘low frequency-high magnitude’ maatregel).

Summary

Foredunes, the first row of dunes when viewed from the beach, fulfill an important task when it comes to protecting the hinterland against flooding from the sea. Due to climate related factors such as rising sea levels and an increase in extreme storm conditions, this task is under increasing pressure.

As dunes are not static landscape features, but their form and position change through time, the level of safety they provide also changes through time. It is important to note that dunes that are essential in protecting the hinterland against flooding are mostly managed by man to secure a minimal level of safety. The present Coastal Policy (3^e Kustnota, Ministerie van V&W (2000)) states that dunes should not only offer protection today, but also continue to do so in the coming 50 to 200 years.

It appears that at a time period of decades to centuries, there is hardly any understanding on the form and position of coastal dunes that are subject to interventions. Therefore, the first objective of this study was to analyze the changes in shape of these dunes over a time period of approximately 50 years. For this time period, data is available from the so-called Jarkus-database (yearly coastal measurements), that show the yearly cross-shore development of the dunes.

By using these measurements, we have first studied the spatial and temporal variability of foredunes that were subject to high intervention intensity along the coast between Den Helder and Scheveningen. As the amount of data is substantial, i.e more than 400 dune profiling locations containing data over the past 45 years, the choice was made to use a data reduction technique to analyze the evolution of the dunes. This data reduction technique is known as EOF (Empirical Orthogonal Function) analysis. Since we were mainly interested in the changes in shape of the dunes, the profiles were shifted in such a way that their origin corresponds with the dunefoot position, which has been set at +3 m NOD (NAP). The dunefoot marks the transition from beach to dune, which is visible as a sharp incline in slope between the flat beach and the steep dune. In addition, the landward and seaward movements of the dunefoot were analyzed, since these movements provide insight into periods of erosion and accretion. The dune profile analysis showed that even though the dunes had been heavily managed with the main focus on maintaining their position, the dunes have changed through time (cross-shore) and space (alongshore). Most variations in the shape of the foredune were concentrated in the lower part of the seaward facing slope, that is around the dunefoot. At the same time, the analysis showed a remarkable change in the shape of the dune in the years following the implementation of the Third Coastal Policy. From 1996 onwards, many foredunes showed a more concave (hollow) shape not seen in profiles before 1996.

After this,the role of the different intervention measures on the morphologic variability of the foredunes was investigated in more detail. Two separate areas along the Central Netherlands'

coast were selected, namely the foredune area between Bergen and Castricum and between Noordwijk and Scheveningen. Various interviews with dune managers were carried out to acquire a better understanding on the role of intervention measures on the shape of the foredunes. Besides interviews, various management documents were consulted. This study showed that measures *before* 1990 were mostly undertaken as a reaction to erosion. *After* 1990, the measures became more and more proactive, meaning that a buffer was placed as to prevent erosion. This buffer consists of sand nourishments. Since the material needed for this intervention was brought from far outside the shoreface-beach-dune system, the sediment balance of the shoreface-beach-dune system was positively affected by this measure. This increase in scale of the intervention method led to a consistent longshore change in foredune morphology.

In this study, a link could be made with the hierarchical dune-landscape model of Bakker et al. (1979). This model states that measures can be ordered hierarchically according to the effect they have on dune morphology. Vegetation plantings and sand fences (measures mostly used before 1990) are placed at a low level in the hierarchy, since these measures are believed to have less impact on the dune landscape than measures that are placed higher up in the hierarchy, such as measures that alter the substrate of the dunes (including nourishments). However, this model is based on the situation along the Dutch coast, but also two 'variables' (method and measure) were studied at the same time. Therefore, it was not possible to determine whether the intervention method is more important in affecting the decadal-scale morphologic variability of the foredunes, or rather the intervention measure.

To find a solution for this, the analysis was shifted to the Wadden Sea island of Schiermonnikoog. At the end of the 1950s, the growth of an artificial foredune was stimulated to prevent the island from breaching during storm surges. The initiation of the foredune was realized through erecting sand fences and vegetation plantings. Due to the development of the artificially initiated foredune, a large part of a beach plain was cut off from direct influence of the North Sea. This greatly stimulated the growth of a salt marsh that was already present south of the beach plain. This case is interesting to study, since measures that were placed at a low level in the hierarchy of Bakker et al. (1979) were now used in a proactive way. This proactive use of sand fences and vegetation plantings resulted in the western part of the study area in the development of a foredune, while the artificially initiated foredune along the eastern part of the study area breached several times during storm floods.

Some lessons can be learned from this case study. First of all, it is not so much the type of measure that is carried out which has an effect on foredune morphology at a yearly to decadal timescale, but rather the intervention method, being proactive or reactive. This has consequences for the hierarchical position of intervention measures: According to the way the measure is applied, reactive or proactive, the position of a measure in the hierarchy can change. Second of all, for a measure to have success, it should fit within the initial and boundary conditions of the system in which the measure is carried out. This can be illustrated as follows. If the coast of Schiermonnikoog had been extremely prone to erosion, the measures would not have resulted in the growth of a foredune. Apparently, the supply of sand was already sufficient enough for a dune to be able to develop. Furthermore, the aim was to initiate an artificial foredune along a certain coastal stretch. Along some part of this stretch a foredune indeed developed, but further to the east the dune repeatedly breached. This breaching however, did not result in the dreaded split of the island. On the contrary, an already existing salt marsh could expand substantially. Therefore, insight into the entire sediment-sharing system is needed to explain why changes in one part of the system lead to changes in another part of the system. In other words, we need to have an understanding on the behavior of the system on a larger scale than that of what we are mostly interested in, in this case the foredunes.

So far we have looked at the behavior of foredunes in the past, but what about the future behavior of the foredunes? This brings us to the second aim of this study, to develop a frame of reference to transform the insights obtained from the first objective into decadal-scale projections of foredunes subject to intervention measures. In principle, we can predict foredune morphology 50 years from now provided we have full knowledge (i.e. complete time series) on factors such as vegetation establishment and colonization, changes in beach width, morphological developments of the beach, moisture content of the beach and hydrodynamical conditions during storm events which result in dune erosion. Of course, this is impossible. As a result, in developing models which simulate long-term coastal developments, the parameters which are considered to be important in the evolution of the system are schematized or parameterized at the scale of interest. This usually involves spatial and temporal averaging of the processes for which mathematical equations have been formulated. This procedure is known as upscaling. Upscaling implies a loss of information, such as extreme parameter values. In terms of dune morphology, the dune is schematized as a layer with a certain volume, instead of a true dune shape. The volume of the dune layer can change under changing intervention scenarios.

Especially in the scope of long-term safety, where the spatial distribution of sediment is important, this loss of shape information is not desirable. If we assume that a long-term model is capable of forecasting a dune volume 50 years from now under a certain intervention scenario, and we would be able to transform this volume into a realistic dune shape, we can use this dune morphology to compute the future safety level of the dunes. However, safety 50 years from now does not only include safety *over* 50 years, but also *during* this 50-year time span. Hence, we actually want to gain insight into the morphologic behavior of the foredunes for the next 50 years, under (a) specific intervention scenario(s).

First of all, if the main aim is to guarantee safety we need to use a proactive intervention method. Using reactive methods, there will always be a time delay between the onset of an extreme condition (e.g. a storm surge) and the measure to be undertaken, which from a safety perspective is not desirable. In the Netherlands, proactive interventions consist of nourishments. Second of all, foredunes subject to interventions are dynamic, they are not static features. This gives a clue towards projections, since various conceptual models exist regarding the morphologic behavior of natural dunes. The foredune development after the large scale nourishment projects exhibits similarities with a naturally prograding coastal system, where foredune morphology changes after a critical rate of shoreline movement is exceeded (this is the model of Pye (1990)). Third of all, different factors need to be considered in designing an intervention strategy. These factors are the physical boundaries of the sediment-sharing system, the source area of the buffer material, the cross-shore location where the material is deposited, the frequency at which the intervention is undertaken, the buffer volume and the dispersion through wind and water of the buffer. Together, these factors affect the scale level at which the measure will intervene with the hierarchically ordered sediment-sharing system and as such, these factors give an indication of the expected life span of an intervention and hence, of the time period that a minimum safety level can be guaranteed. For example, one of the findings is that from a safety perspective it is better to undertake nourishments as a high frequency-low magnitude type of intervention (often a little bit) than as a low frequency-high magnitude type of intervention (only once a mega-nourishment).

Chapter 1

Introduction

"...You see it all below the level of the water, soppy, hideous, and artificial, and because it exists against nature, nobody can exist there except at a frightful expense, which is very well for the natives who may be thankful to live on any terms, but disagreeable for foreigners, who do not like to pay twice as much as elsewhere for being half as comfortable..."

Matthew Arnold, English writer, in Amsterdam, 1859

1.1 Motivation: Long-term safety of a dune protected coast

In low-lying coastal areas with sandy shores, coastal dunes often offer society protection against flooding from the sea. Sea level rise and an expected increase in more frequent and more intense storm conditions and – in the case of Northwestern Europe – post glacial subsidence of the North Sea basin, will exert greater pressure on the coastal dunes in the (near) future. Therefore, these developments result in an urgent need to gain insight into the future level of protection provided by the coastal dunes.

Therefore, to anticipate unwanted future developments, sustainable coastal zone management not only requires insight into the current strength of the foredunes, but also how this strength might evolve over time spans of 50 to 200 years (Jorissen et al. (2000); Rijkswaterstaat (2002); Ministeries van VROM, LNV, VenW and EZ (2004); Carter (1991)).

1.2 Safety assessment of coastal dunes as flood protection

1.2.1 Assessment of current dune safety

To assess the safety provided by dunes, dune erosion models are used. The essence of dune erosion models is to compute dune erosion volumes and the landward recession distance, often referred to as erosion point, of the dune under predefined normative storm surge conditions (see Figure 1.1).

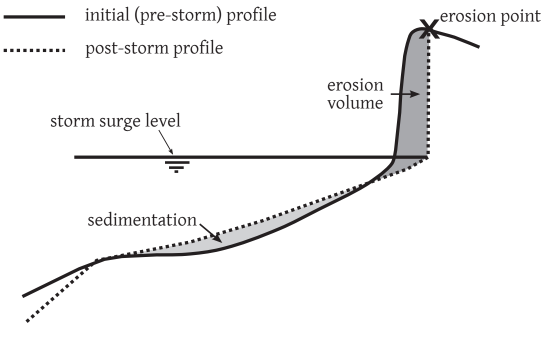

Figure 1.1: Graphic representation of erosion volume and erosion point.

Subsequently, an assessment is made regarding the strength of the remaining dune against amongst others mass failure, wave overtopping and wind erosion. Different types of dune erosion models exist, ranging from process-based models (e.g. Larson et al. (2004); Van Rijn (2009); Roelvink et al. (2009)) to more behavior-oriented, equilibrium type of models (Vellinga (1986); Van de Graaff (1986)).

Several factors affect the erosion volumes and landward recession distance of the dunes, which can be classified in two categories. The first category includes the factors that determine the load on the dune, that is the hydrodynamics and storm characteristics, such as the water level during storm surge, the wave period, storm surge duration, occurrence of squall oscillations and gust bumps (Van de Graaff (1986); Van Gent et al. (2006); Van Gent et al. (2007)). The second category involves the factors that determine the strength of the water defense itself. These factors are the cross-shore geometry of the dune just before the storm surge, the sediment the dune is composed of (which is reflected in the grain size), and the presence of vegetation.

1.2.2 Assessment of future dune safety

To assess the future safety of the dunes, we need to have insight into both (changes in) future loads and (changes in) the future strength of the defense. Studies which aim at forecasting future safety of the dunes usually focus on the role of the 'wet' part of the coastal system, i.e. the expected changes in sea level, hydrodynamics and storm climatology, rather than to consider the changes in the water defenses (e.g. Van de Graaff (1986); Steetzel and Wang (2003); Larson et al. (2004); Van Gent et al. (2006); Van Gent et al. (2007); Van Thiel de Vries et al. (2007); Van Rijn (2009); Roelvink et al. (2009)).

At present, long-term safety forecasting involves running a dune erosion model with an unchanged beach and dune configuration, but with a higher mean sea level (Rijkswaterstaat (2002)). The dashed line in Figure 1.2 shows how the erosion line – longshore connected erosion points – is predicted to shift landward according to this approach.

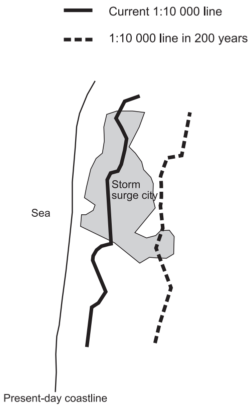

Figure 1.2: Present and expected future position of erosion lines for a fictional sea-side village for an extreme storm event with a 1:10 000 probability of occurrence.

However, several theoretical, empirical and experimental studies have shown that the cross-shore geometry or morphology of the water defenses (e.g. beach slope and dune height) is a critical erosion parameter as well (Carter et al. (1990); Hughes and Chiu (1981); Van de Graaff (1986)). In addition, a recent study by Van Thiel de Vries (2009) showed that longshore differences in foredune height also affect erosion volumes and recession distances. Figure 1.3 shows how erosion volumes and recession distances (indicated as dune retreat) change with varying seaward facing dune slopes and varying dune crest heights using both an equilibrium type of model (DUROS; Vellinga (1983)) and a process-oriented model (XBeach; Roelvink et al. (2009)).

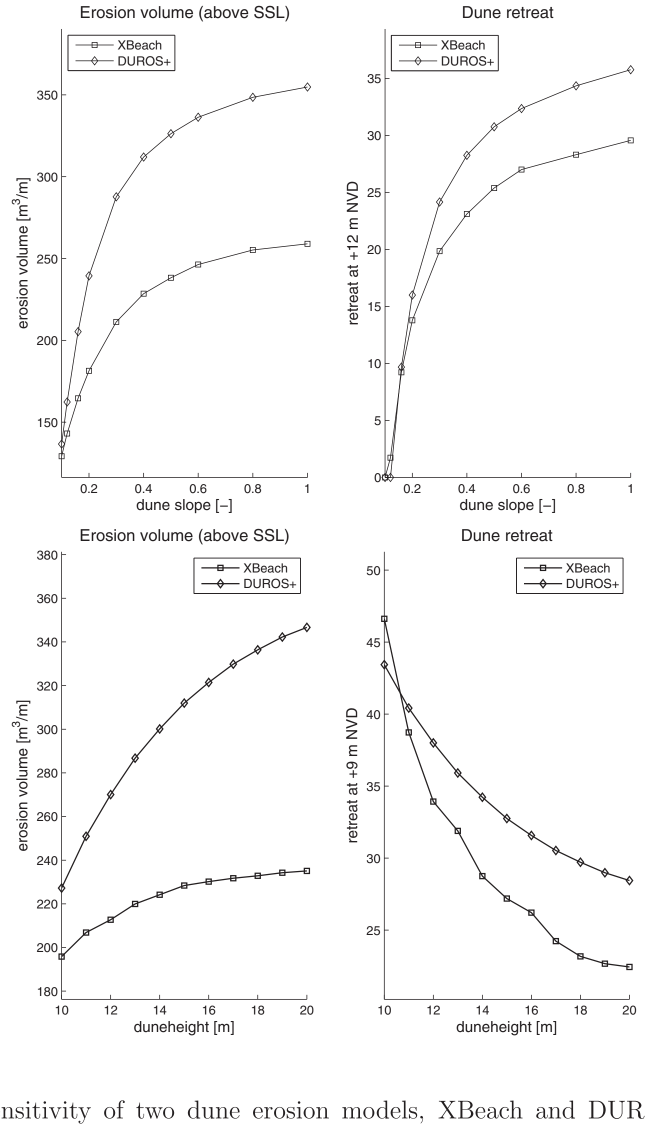

Figure 1.3: Sensitivity of two dune erosion models, XBeach and DUROS, to varying seaward facing dune slopes and dune crest heights.

Therefore, to know whether dunes are also safe flood protections in the future, that is 50 to 200 years from now, we need to know how the cross-shore geometry of the dunes develops over such long time spans. Of course, over this time period, other important dune characteristics as grain size and vegetation might change as well. However, since the cross-shore geometry is the resultant of, amongst others, grain size and vegetation (Hesp (1988)), and since we might expect observable changes in cross-shore geometry over this long time period, we chose to limit ourselves to considering the cross-shore geometry only.

In this study, focus is on the evolution of the cross-shore geometry of *foredunes*. Foredunes are “continuous or semi-continuous ridges of sand, normally well vegetated, which lie parallel to, and to the rear of, most beaches exposed to onshore wind energy” (Pye (1983)). Foredunes are in the front-line of wave attack during storm surges and therefore their role in providing safety is of utmost importance.

1.3 Long-term evolution of the cross-shore geometry of foredunes

The previous Section illustrated the importance of the cross-shore shape of the foredunes in safety assessments. To know whether foredunes are also safe flood protections in the future (50 to 200 years), we need to gain insight into foredune evolution over this long time period.

Theoretical considerations on the evolution of foredunes include two approaches: A mathematical model approach and a conceptual model approach. These two model categories will be discussed in this Section.

Mathematical models

Various mathematical models have been developed to simulate large-scale coastal behavior. These large-scale mathematical models are often known as behavior-oriented models or semi-empirical models. Since they are designed to forecast large-scale phenomena, they are not based on the elementary physical processes that are used in process-based models (De Vriend (1991)). In stead, these models make projections on the behavior of the coastal system by computing equilibrium states under certain hydrodynamical conditions. Much use is made of data for calibration (Steetzel et al. (2004); De Vriend et al. (1993)). Often, empirical relationships between system variables are established.

In behavior-oriented models, cross-shore morphology is simplified, for instance as a set of layers that represents a certain sediment volume (e.g. Steetzel and de Vroeg (1999)) (see Figure 1.4). Hence, these models do not provide insight into the shape of the coastal profile. The dune is represented as a source/sink term (Steetzel and de Vroeg (1999); Steetzel and Wang (2003)) and/or has a fixed geometry in time (Cowell et al. (1995)).

This simplification can be understood from the purpose for which those long-term models were developed. These models are usually used to simulate overall trends in coastal evolution under ‘average’ conditions, rather than to investigate the occurrence of critical conditions such as breaching of the dunes, in which the morphology of the foredunes is important.

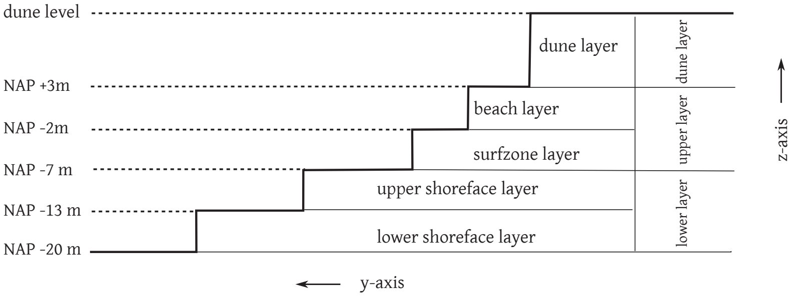

Figure 1.4: PONTOS model schematization. NAP is the Netherlands' Ordnance Datum, which corresponds approximately to mean sea level.

Conceptual models

The conceptual models on foredune behavior at a decadal to century time scale mainly provide insights into changes in sediment budget (volume changes) of the foredune, rather than to provide insight into the changes in the shape of the foredunes.

For example, Psuty (1988) relates foredune development to changes in the beach sediment budget, where maximum foredune development (largest foredune sediment budget) occurs at a slightly negative to stable shoreline position. Psuty (1988) considers the components of the beach-dune system to have their own sediment budget and each component reacts in 'short' time periods to differences in the budgets. As a result, the beach widens and narrows independently of the dune. Based on the idea of separate sediment budgets of the beach and the dune, the dunes might maintain a positive sediment budget (and even increase their budget) during periods of coastal erosion. In this case, since the total beach-dune budget is negative, the entire profile might shift in a landward direction. The situation of a total negative beach-dune budget might lead to a diminishing of the dune while the system migrates inland.

Arens (1994) classifies foredunes to be either progressive, stable or regressive based on their long-term development (without a precise specification of long-term). Progressive foredunes, which expand in a seaward direction, only exist when the dune sediment budget is strongly positive. Multiple foredune ridges might develop, but a seaward widening and heightening of the existing foredunes is also possible (see also Pye (1990)). Stable foredunes, which remain in place, with only slight sedimentation either around the dunefoot, dune crest or at the leeward side of the dune, occur in situations where the dune sediment budget is zero to slightly positive. Regressive foredunes occur in situations where more sediment is transported from the foredunes either in a landward or seaward direction than is being supplied to the dunes. In this case, the dune might migrate land inward while retaining its dimensions, or the dune might become more narrow (indicating erosion at the seaward side) while remaining in place, or the dune might migrate land inward and thereby becoming more narrow and showing an increase in height. This last situation is also recognized by Klijn (1981) and Psuty (2004) who mention that the highest dunes occur along eroding coasts.

According to Pye (1990), the highest foredunes occur in situations where the rate of sand supply to the shore by marine processes is balanced by the rate of aeolian transfer from the beach to the dune. When all sand is trapped by vegetation, the dune heightens, with no net change in shoreline position through time. In case of situations where the rate of sand supply from the beach to the dunes is somewhat higher than the supply of sand to the beach by marine processes, the beach is lowered and the shoreline slowly retreats in a landward direction, causing damage to vegetation and thereby re-mobilizing the dune and enhancing the formation of blowouts and transgressive parabolic dunes.

Summarizing, the models discussed above describe changes in sediment budgets, thus they do not provide explicit information on the shape of the foredune on the time period of interest from a long-term safety perspective. These models neither consider the role of human interventions in affecting the long-term evolution of foredunes.

1.4 Role of human interventions in long-term foredune evolution

Up to now, observations on the long-term evolution of foredunes have mainly focused on natural foredunes, free from human interventions (Miot da Silva and Hesp (2010)); McLean and Shen (2006); Short and Hesp (1982)). However, in studying the long-term evolution of foredunes which fulfill a safety function, we should acknowledge that these dunes are usually managed to a certain degree (Nordstrom and Arens (1998)). Especially in low-lying countries like the Netherlands and Belgium and parts of the United Kingdom, where the potential consequences of a flooding disaster are large (e.g. Jorissen et al. (2000); Pye et al. (2007)), dunes have become highly managed landforms for centuries (Klijn (1981); Arens and Wiersma (1990); Schoorl (1973); Pye and Neal (1994); Nordstrom (1994)). Hence, we might expect a combination of natural processes and human interventions to leave a mark on the shape of the foredune.

In this thesis, focus is on foredunes which primarily serve a safety function and have been managed accordingly to maintain this function. As a result, the interventions discussed in this thesis concern those interventions which are directly aimed at maintaining the safety function of the foredune. Interventions such as harbor moles and dikes might indirectly affect foredune morphology e.g. through altering longshore sediment supply patterns, but since these interventions do not directly aim at maintaining the safety function of the dunes, these are not considered in the present study.

1.5 The issue of scale in long-term projections of foredune morphology

As discussed in Section 1.3, knowledge on the long-term evolution of foredunes is about volumes, and not about shapes. This does not mean however, that no knowledge at all exists concerning the morphologic behavior of foredunes. At small scales, that is those temporal and spatial scales at which the physics of aeolian sediment transport are studied (e.g. Bagnold (1941)), quantitative knowledge does exist on the relation between sand transport and dune development (Saye et al. (2005); Sherman and Bauer (1993); Meerkerk et al. (2007); Arens (1996); Arens (1994); Hesp et al. (2009); Bauer and Davidson-Arnott (2002)). For example, field studies were conducted in which the amount of sand transport towards the foredune was measured and changes in surface height of the dunes were monitored (Arens (1996)). In addition, research has been undertaken to study sediment transport rates and patterns from the shoreface and/or the beach towards the foredune (Anthony et al. (2006); Aagaard et al. (2004); Sherman and Lyons (1994)). There is also some quantitative knowledge on aeolian sediment transport on human-altered foredunes (Gares (1990); Nordstrom et al. (2007)) as well as knowledge on the morphologic effects of human interventions on the foredune at small scales. Gares (1990) for instance studied the differences between dunes at developed and undeveloped sites in the volume of sediment transported by the wind as measured by sand traps and in elevation changes. It appeared that the trapped sediment affects factors as dune height and width. Another study was carried out by Hotta et al. (1991) who examined the effects of different sand fence configurations on foredune development and accretion rates.

At these small scales, also called process-scales, the foredune can be viewed as a morphodynamic system, which means that energy delivered to the system induces air flow at a scale, which triggers a sediment transport process at the same scale, which results in morphological change (e.g. changes in surface elevation) of the foredune at the same scale (Larson and Kraus (1995)). The foredune in turn alters the air flow pattern, which affects the sediment transport process and so on (see Figure 1.5).

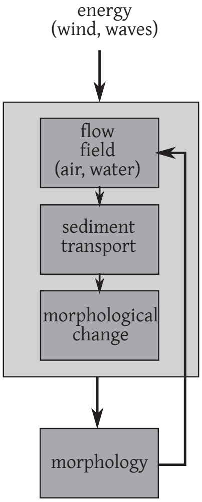

Figure 1.5: The morphodynamic loop.

This direct coupling between the scales of processes and the scales of forms is called the primary scale relationship (De Vriend (1991)). The primary scale relationship assumes that processes operating at a certain scale level are in dynamic interaction with morphological behavior on a similar scale. This means that morphological behavior at a certain scale is mainly the result of processes operating at the same scale (De Vriend et al. (1993); De Boer (1992)). Processes operating at a smaller scale than the scale of interest are considered to be noise or residuals, whereas the larger scale processes are assumed to impose the boundary conditions to the scale under consideration.

In principle, we can predict the state of the system (foredune morphology) over 50 years provided we have full knowledge, that is complete time series, on factors such as vegetation establishment and colonization, changes in beach width, morphological developments of the beach, moisture content of the beach (which means we have to predict when it rains for the coming 50 years) and hydrodynamical conditions during storm events which result in dune erosion. Of course, this is not feasible, since not all of this information is available.

As a result, knowledge on process-scales is often schematized or parameterized to be represented at the scale of interest, which often involves temporal and spatial averaging of processes of interest for which mathematical equations have been formulated (Wijnberg (1995)). This is known as upscaling or aggregation and this technique is widely used to explain system behavior at larger scale levels (e.g. Ranasinghe et al. (2011); Van der Wegen et al. (2008); Roelvink (2006); Aagaard et al. (2004); Bierkens et al. (2000); Bauer and Davidson-Arnott (2002); Sherman (1995)). Thus, there is a loss of small-scale information when applying upscaling techniques, which results in a loss of detailed morphologies at larger scales. Especially in the scope of long-term safety projections, where information on cross-shore morphology is important, this loss of information is not desirable.

Apart from the limitations associated with the upscaling of process-scale knowledge, there are other reasons why the primary scale relationship, in which a direct coupling between the scales of processes and those of morphologic behavior is assumed, seems applicable only at small scales. First of all, at larger scales the time lag between a process and the morphological response increases. This has as consequence that the morphologic response to a process usually takes place at a higher scale level than that of the process (Von Bertalanffy (1950); Howard (1965); Van Rijn (1998)).

Second of all, when applying the primary-scale relationship, we (unawarely) assume that the system under study is linear. This implies that the summation of all small scale processes should explain system behavior at the larger scale. However, there is ample evidence from the field that most, if not all, natural systems are non-linear (Von Bertalanffy (1950); Wright and Thom (1977); Baas (2002); Malanson (1999); Werner (1999); De Vriend (2003); Hanson et al. (2003); Phillips (2009)). Non-linearity implies that the morphological response of a system (output) can not be explained by merely studying the ‘inputs’ individually (Wright and Thom (1977)) since the system might exhibit what is called emergent behavior: The properties of a larger scale level cannot be deduced from the functioning of properties at a smaller scale level (Bergkamp (1995)). However, since in process-based research, the process of interest is often examined in isolation and studied under controlled conditions (De Vriend (1991); Haff (1996)), interactions between processes operating at different scales and feedback mechanisms which might explain this emergent behavior are ignored.

Non-linear systems can be extremely sensitive to small changes in the initial and boundary conditions, which poses a major limitation towards the predictability of the system. A deterministic solution, hence a prediction, is only possible if the system is stable, thus insensitive to these small perturbations. Research shows that in some cases small changes in one element of the system might cause considerable change in the total system (Von Bertalanffy (1950); Gleick (1988); Phillips (2003); Church (2010)). This sensitivity to perturbations may result in a completely unpredictable solution, which is called deterministic chaos (Gleick (1988)). The system exhibits “irregular, random behavior, which arises deterministically due to nonlinear couplings in sometimes relatively simple systems” (Phillips (1992)).

The discussion above mentions the difficulties that are encountered when going from lower (small) scale levels to higher (larger) ones. There are, however, also factors that impose difficulties from higher scales levels onto the (lower) level of interest, that do not follow from upscaling of process knowledge. These factors are the boundary conditions of the system of interest and include, for instance, climate change, sea level changes, changes in sediment supply and demand elsewhere and interferences with the biological system (Wright and Thom (1977)). These factors affect the system at larger scales and could be ignored on the process-scale, since at smaller scales these boundary conditions could be considered as unchanging. At even larger scales, often associated with the Holocene time period, changes in, amongst others, the geological framework and post-glacial subsidence of the North Sea basin become important in affecting the system at a lower scale level. Finally, changes in forcing conditions (energy supplied to the system) vary stochastically through time, which further complicate predictions (De Vriend (2003)).

De Vriend (1991) who formally introduced the concept of a primary scale relationship already concluded in his article that “... the primary relationship seems a reasonable starting point for process research: The explanation of a phenomenon in coastal behavior is primarily sought in physical processes in a similar scale range.” This conclusion was more generally summarized by Montgomery (1991) who mentioned that “...scientific statements are valid only within the confines of the approach and scale of study adopted at the outset of the inquiry.” Thus, some caution should be used in applying theories at scales different than those for which they were constructed, since there is no single theory or mechanism which can explain the behavior of the system at all scales (Levin (1992)). Nevertheless, if the research interest lies in the overall trends of coastal behavior, upscaling from process-knowledge is useful. However, in our case we want to have more detailed insight into the morphologic changes of the foredune and therefore we need to look for an alternative approach towards obtaining long-term insights into the morphologic behavior of foredunes.

1.6 Research objective and research questions

A major limitation towards assessing the long-term safety of a dune-protected coast, is that there is limited insight into the long-term morphologic behavior of foredunes (Section 1.5). Therefore, the aim of this thesis is *to assess the cross-shore morphologic behavior of foredunes over decadal time spans in relation to management interventions.*

As with most large-scale morphological research the first insights into system behavior are usually obtained through analyzing a real world situation through case study research (e.g. Hutton (1795)). Therefore, the first objective of this study is to determine the character of cross-shore morphologic behavior of foredunes subject to management interventions over a time span of at least several decades (scale of empirical data in Figure 1.6). The second objective is to develop an analysis framework that assists in making decadal-scale projections of foredune morphology in relation to intervention measures (scale of interest of present study in Figure 1.6).

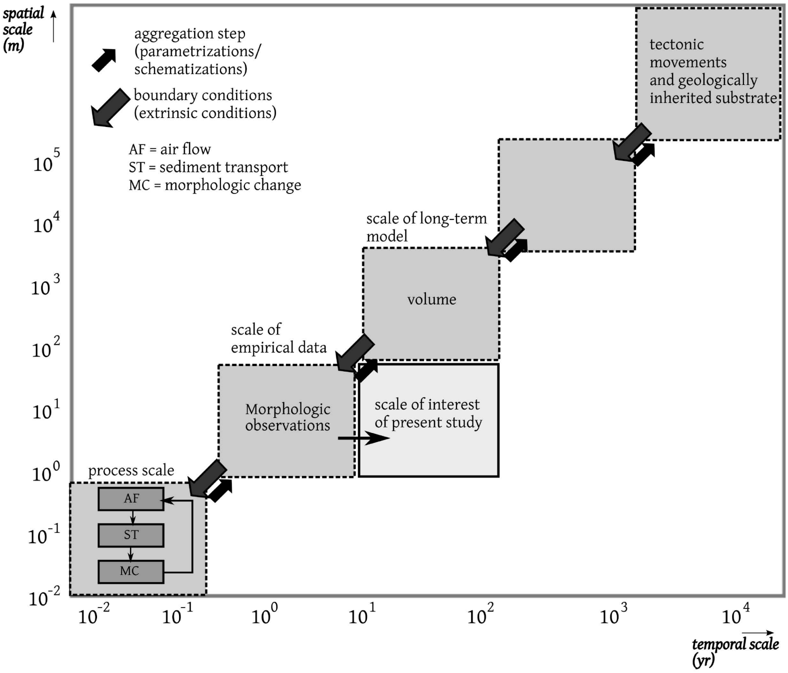

Figure 1.6: Graphic representation of the scale of focus in the present study.

To achieve the two objectives, the following research questions (Q) are formulated:

Q1. What is the spatio-temporal variability of the cross-shore morphology of foredunes subject to intervention measures over a time span of several decades?

Q2. Which relationships exist between the observed spatio-temporal variability of the cross-shore morphology of foredunes and applied intervention measures over a time span of several decades?

Q3. How can the insights obtained from case study research be generalized to support the development of decadal-scale projections on the behavior of foredunes subject to intervention measures?

1.7 Research approach and thesis outline

To assess the past morphologic behavior of foredunes subject to interventions over a time span of decades, a data-analysis approach is chosen. In this study, the sub-aerial part of yearly cross-shore profile measurements extending from the foot of the foredune up to and including the foredune crest are analyzed. These measurements cover a time period of 45 years (1965-2009). The data-analysis is applied in two different settings, namely the central part of the Netherlands' coast and the barrier island Schiermonnikoog, the Netherlands.

Chapter 2 presents the results of the data-analysis for the central part of the Netherlands' coast. This Chapter discusses the overall spatio-temporal variability of a large foredune stretch (97 km) subject to management interventions during the time period 1965 to 2009 (Q1).

Chapter 3 aims to explain the observed spatio-temporal variability discussed in Chapter 2, and discusses the role of intervention measures in this variability. This Chapter first provides an overview on the applied interventions during the 45-year time period along the Central Netherlands' coast. Information on the applied interventions is obtained from questionnaires put to dune managers. In addition, unpublished records from two water boards and Rijkswaterstaat were consulted.

To examine whether unique relationships exist between observed spatio-temporal morphologic variability of the foredunes and the applied interventions, two 'subareas' are selected for detailed examination (Q2). From the data-analysis of these two areas, several morphometric parameters (e.g. foredune crest height, seaward facing slope and curvature of the seaward face of the foredune) are extracted which characterize the morphologic variability of the foredunes on the time period of interest.

In Chapter 4, the analysis is shifted to an artificially initiated foredune in a setting with different external conditions, namely the Wadden Sea Island Schiermonnikoog, the Netherlands. Q1 and Q2 are addressed again in this Chapter.

Chapter 5 presents a frame of reference regarding the morphologic variability of foredunes subject to intervention measures (Q3). This frame of reference is partly based on the findings of Chapters 2, 3 and 4. In addition, different concepts established in the field of systems analysis are applied not only to provide a theoretical explanation for the observed cross-shore morphologic behavior of foredunes, but also to provide a basis for making projections on future morphologic behavior of foredunes under changing intervention scenarios.

The conclusions and recommendations for future research are provided in Chapter 6.

Chapter 2

Decadal-scale morphologic variability of managed coastal dunes[1]

“We live on this planet in a materialistic manner and hold time and space in high regard. In other words, we live according to these values and are more or less ruled by them as they form our physical boundaries.”

after: Andrei Tarkovsky

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[1] This Chapter has been published as Bochev-van der Burgh, L.M., Wijnberg, K.M., Hulscher, S.J.M.H., 2011, Decadal-scale morphologic variability of managed coastal dunes, Coastal Engineering 58, 927-936

Abstract
Coastal dunes located in densely populated areas provide various services to man, such as protection against flooding during storm surges. Since coastal dunes are dynamic features, the level of protection they provide varies in time. Therefore, management interventions are often undertaken to stabilize the dunes to reduce the natural variability. This study assesses the morphologic variability of managed foredunes over time spans of decades. We used Empirical Orthogonal Function (EOF) analysis on a 45 year data set of annually surveyed dune profiles along 97 km of the Netherlands' coast. On average, 70% of the deviations from the time-averaged profiles could be related to cross-shore coherent changes in foredune shape as mapped onto EOF 1. These changes are often largely due to morphologic developments occurring near the dunefoot. Changes in dune shape were coherent over time as well as in the longshore direction, albeit with different characteristic patterns along the coast. These results show that managed foredunes may still exhibit considerable morphologic variability that should not be ignored in long-term dune safety assessment studies.

Keywords: managed foredunes, EOF analysis, morphologic variability

2.1 Introduction

Dunes protect large sections of low-lying coasts against flooding during extreme storms (European Environmental Agency (2006); Nicholls et al. (2007)). On the long term, rising sea level and more frequent and severe storm conditions might jeopardize the safety provided by the dunes (see e.g. Church et al. (2001); Carter (1991); Pye and Blott (2008); Sterr (2008)). To anticipate future changes in the safety provided by these 'soft' flood defenses not only insight is needed into the current dune strength, but also how this strength might change over periods up to 200 years, (Jorissen et al. (2000)).

To test the strength of coastal dunes as flood defenses, dune erosion models are used. Different types of dune erosion models exist, ranging from process-based models (Larson et al. (2004); Van Thiel de Vries et al. (2007); Van Rijn (2009)) to more behavior-oriented, equilibrium type of models (Vellinga (1986); Van de Graaff (1986)). The essence of dune erosion modeling for safety assessments is to compute dune erosion volumes and the landward recession distance (called erosion point) of the dune as a result of a storm event. Several studies illustrated the importance of dune morphology in the dune erosion process. Hughes and Chiu (1981) for instance, conducted laboratory tests which showed that an increase in dune height leads to an increase in eroded volumes, considering other factors as wave height, wave period, surge level and duration as constant. More recent investigations in the dune erosion process by Van Thiel de Vries (2009) show that longshore variability in dune height also affects dune erosion volumes. These results support the need to assess the morphologic variability in time and space for dunes that fulfill a role in coastal flood protection.

Currently, little is known on dune behavior over decadal to century time spans. So far, research on coastal dune dynamics has mainly focused on either examining sediment transport from the beach to the dunes and vice versa on event or process scales (e.g. Svasek and Terwindt (1974); Adriani and Terwindt (1974); Kroon and Hoekstra (1990); Sherman and Bauer (1993); Arens (1994), Steetzel et al. (2004); Van der Wal (1999a); Bauer and Davidson-Arnott (2002); Aagaard et al. (2004); Anthony et al. (2006)), or on studying coastal evolution at the scale of Holocene evolution (e.g Klijn (1990); Beets et al. (1992); Martinho et al. (2008); Clemmensen et al. (2009)). The few studies that exist on dune dynamics over a decadal to century time span mostly present conceptual insight rather than quantitative information on morphologic variability (Psuty (1988); Sherman and Bauer (1993); Davidson−Arnott (2005)). These studies emphasize that dunes form important links in the coastal sediment budget and therefore need to be considered in the scope of coastal management and engineering practices (Arens and Wiersma (1994); Saye et al. (2005)). Information on dune variability on a decadal to century scale is usually represented in terms of sediment budget changes (Psuty (1988); Sherman and Bauer (1993); Arens and Wiersma (1994)). However, knowledge on sediment budgets does not provide information on how the sediment is distributed in the dune system, hence it does not provide morphological information. Furthermore, a budget reflects a sediment volume stored within spatially fixed boundaries of a coordinate system. Since the physical boundaries of morphological features change through time – such as the dunefoot separating the beach from the dune – and the spatial expansion, reduction or translation of a morphological feature is not accounted for, budget studies may include volumes related to different morphological features. As a consequence, budgets are only applicable at those temporal scales where the location of physical boundaries can be regarded at static. Over decadal to century time spans this may often not be the case.

Finally, research usually focuses on natural dune coasts (e.g. Aagaard et al. (2004); McLean and Shen (2006); Aagaard et al. (2007)), whereas dunes in inhabited areas are often subject to human interventions to some degree (Nordstrom (1994)). For dunes that fulfill a safety function this often means that the (fore)dune is stabilized by methods such as vegetation plantings and erection of sand fences.

The purpose of this paper is to provide quantitative insight in morphologic variability of managed foredunes over a time span of several decades. These insights are obtained through a case study of foredune behavior over a 45-year time period along the central part of the Netherlands' coast, covering a longshore distance of 97 km.

2.2 Study area

The study area is situated along the central part of the Netherlands' coast, between Den-Helder (transect number 20) and Scheveningen (transect 9725) (Figure 2.1).
The dunes along this part of the coast form a closed barrier over a distance of about 120 km. The study area is divided into two sections, Noord-Holland and Rijnland, which are under the auspices of two different water boards. The dune system is interrupted by hard structures at the Hondsbossche and Pettemer seawall (between transects 2000 and 2600), at the entrance of the Amsterdam Harbor at IJmuiden (transect 5500) and at the discharging sluice of Katwijk (transect 8600).

Studies on long-term shoreline behavior showed that north of Egmond (transect 3800) and south of Scheveningen (transect 9700) the coast is retreating. In between, the shoreline is slightly prograding (Beets et al. (1992); Wijnberg and Terwindt (1995)). This

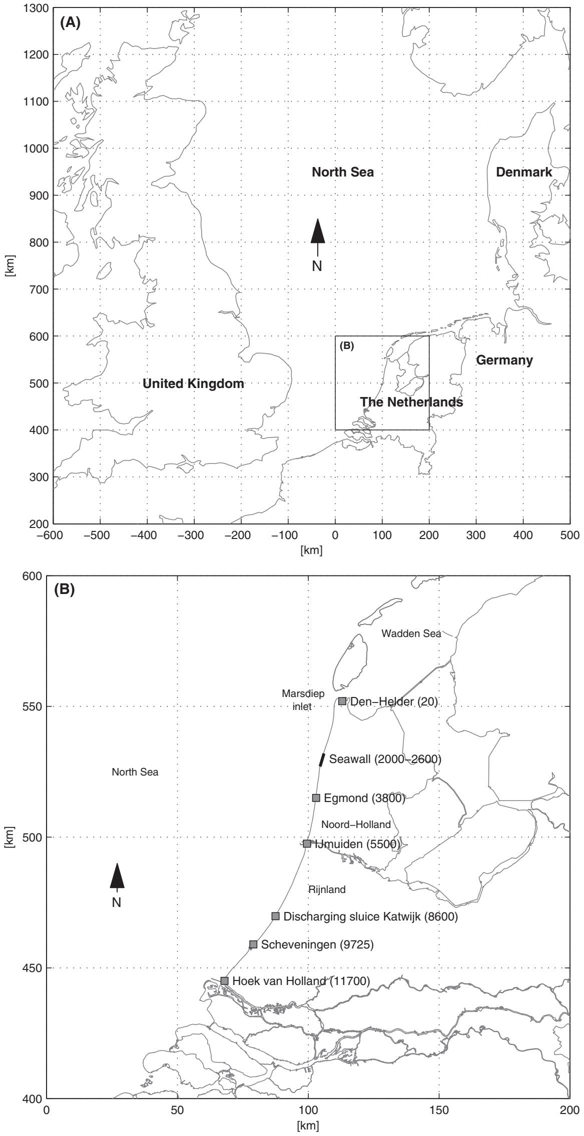

Figure 2.1: Study area. Transect number 20 corresponds to the northernmost transect location used in this research and transect 9725 to the southernmost transect location.

large-scale erosion-progradation pattern is often ascribed to the concave shape of the coast, which induces gradients in the wave-driven longshore transport. However, Beets et al. (1992) also stress the importance of cross-shore transport in the coastal progradation between Egmond and Scheveningen. The northern part of the coast is affected by longshore sediment transport gradients to the Marsdiep tidal inlet north of Den Helder (Beets et al. (1992)). The effect of sediment import to the Wadden Sea via the Marsdiep inlet is believed to reach as far as Egmond (Stive and Eysink (1989)).

Some management measures along the coast date back to the 16^{th} century (Stolk (1989)). The Hondsbossche and Pettemer seawall was built in 1823. Groins were constructed during the period 1838 to 1935 between transects 200 and 3100. The harbor extension at IJmuiden, which took place between 1962 and 1967, led to beach widening just north and south of the harbor and resulted in embryo dune formation around transect 5400 and between transects 5800 and 5900. As a result of increased sedimentation at these locations, adjacent locations experience coastal retreat and enhanced foredune erosion.

Human interventions in the foredune area of the central Netherlands' coast date back to the 15^{th} century (Schoorl (1973)) and intensified from 1850 onwards (Klijn (1990); Ruessink and Jeuken (2002)). Large-scale stabilization of the (fore)dune area was completed in the beginning of the 20^{th} century (Klijn (1990)). Nowadays, only a few kilometers of the foredunes along this part of the coast is considered to be in a natural state (Arens and Wiersma (1994)).

Arens and Wiersma (1994) made a classification of the foredunes along the entire Netherlands' coast based on aerial photographs from 1988. The foredunes were classified according to the most prominent type of intervention at that moment. Their classification shows that the foredunes between Den-Helder and IJmuiden have been affected by different management measures, with the type of measures applied changing over longshore distances of one to a few kilometers. Measures include nourishments, vegetation plantings, sand fence erections and slope adjustments using ground moving equipment. In addition, Arens and Wiersma (1994) classified some parts of the foredunes in Noord-Holland as being natural, with none or very little management interventions. According to Arens (1994) these natural dunes occur between transects 300-400, 800-1100, 1800-1900 and 5300 to 5500. The foredunes north of the Hondsbossche and Pettemer seawall are at many locations interrupted by beach entrances. These were constructed to ease access to the groins for maintenance purposes.

The foredune area between the IJmuiden harbor and Scheveningen (Rijnland) is highly managed; adjustments of the seaward facing slope using ground moving equipment were carried out along the entire foredune area. Sometimes, foredunes were completely remodeled or reconstructed. The same type of intervention measures (e.g. smoothing of seaward facing slopes, foredune remodeling) are carried out over longshore stretches of several to tens of kilometers. This does not mean however, that measures such as vegetation plantings did not take place in Rijnland. In fact, after slope adjustments, *Ammophila arenaria* (marram grass) was planted and sand fences were erected (Nordstrom and Arens (1998)), but the morphologic effect on the foredunes using ground moving equipment is considered to be far more striking than the effect of plantings (Arens and Wiersma (1990)).

Beach and shoreface nourishment intensity increased after 1990, when Dutch government decided the coastline had to be maintained at its 1990 position (First Coastal Policy Document, Ministerie van V&W (1990)). Nourishment may lead to accretion of the beach and the formation of embryo dunes (Arens (1999); Van der Wal (2004)). Nourishment frequency has been higher in Noord-Holland than in Rijnland. Especially around the coastal towns of Callantsoog (transect number 1300), Bergen (transect 3100) and Egmond (transect 3800) nourishment intensity is high. In Rijnland, only a few beach and shoreface nourishments have been carried out since 1990.

The change in coastal policy in 1990 also aimed at a more natural dune area, allowing the development of erosive features such as blowouts in the foredune crest and even the creation of foredune breaches where this would not jeopardize the safety function of the dunes. The latter occurred close to the coastal town of Schoorl near transect 3000 in 1997 (Meerkerk et al. (2007)). Local increases in naturalness have been reported around transects 2600 - 3600 and 5900 - 6250 since the 1990s by Arens (1999) and Löffler and Veer (1999)).

2.3 Methods

2.3.1 Data collection and selection

We analyzed a 45-year data set of cross-shore profiles for the coast of Noord-Holland and Rijnland (Figure 2.1), starting in 1965. These cross-shore data were obtained from the Jarkus database of the Dutch Department of Public Works (Rijkswaterstaat). This database contains annual measurements of coastal profiles (transects) extending from the foredune (often even further landward) to approximately 1000 m seaward. Measurements are taken with respect to a series of permanent beach poles along the coast. The alongshore distance between the profiles is 200-250 m. For the province of Noord-Holland we analyzed transect numbers 20 to 2000, starting at Den-Helder up to the Hondsbossche and Pettemer seawall (Figure 2.1) and transect numbers 2650 to 5450, starting south of the seawall up to the IJmuiden harbor. In the case of Rijnland, we analyzed transect numbers 5700, starting just south of the IJmuiden harbor, up to transect number 9725 at the coastal town of Scheveningen. We analyzed a total number of 409 transects. North of the dike 128 transects were analyzed, south of the dike 119 transects and 162 transects were analyzed in the case of Rijnland.

In this study, we only used the sub aerial part of the profile data. For this part, elevation measurements are taken at 5 m intervals (Van der Wal (2004)), but we linearly interpolated these measurements to a 1 m resolution. Measurements are carried out between April and October of each year (Minneboo (1995)). The data collection method has changed throughout the 45-year time period. First, data were gathered by means of leveling, followed in 1977 by aerial photography. Aerial photographs were taken in the area between low water level and 200 m landward of the top of the foredune on a yearly basis (Minneboo (1995)). Since 1996, measurements are carried out by means of laser altimetry. The laser altimetry measurements are corrected for vegetation, objects and other ‘peaks’, which might veil the actual dune heights. The accuracy of leveling is estimated to be 0.01

m (Oosterwijk and Ettema (1987)). Accuracy of the photogrammetric measurements is about 0.1 m (Veugen (1984)). Laser altimetry measurements have an accuracy of 0.1 m for ‘soft’ topography (De Graaf et al. (2003)).

2.3.2 Data transformation

Because of our interest in morphologic variability of the foredunes on a decadal-scale time period, we transformed the Jarkus data set in such a way that focus is on changes in the shape of the foredune rather than on sediment transport dynamics on this time period. In this respect, a floating reference point was selected, and was set at +3 m Netherlands Ordnance Datum (NOD, approximately mean sea level), roughly corresponding to the position of the dunefoot (Ruessink and Jeuken (2002); Van der Wal (2004)), although other dunefoot definitions also exist (see Guillén et al. (1999)). Each profile was shifted in a horizontal direction in such a way that its origin corresponds with the dunefoot position (Figure 2.2). This guarantees that we examine a single morphologic unit over time. In case the profiles are not shifted with respect to the dunefoot position, but are analyzed with respect to a fixed reference position (RSP), different morphologic units may be included in the analyzed profile through time. For example, in the case of ongoing erosion, the upper beach will appear in the analyzed profile. Using a floating reference implies that morphologic change cannot be directly translated to sediment transport. To obtain some insight into the latter, the shifts in dunefoot position through time for each transect will be examined as well.

2.3.3 Data reduction: Empirical Orthogonal Function analysis

The time-averaged profile shape is the most basic form of data-reduction. A measure for the temporal variability in the elevation h at each cross-shore location x with respect to the time-averaged profile is given by the variance:

$$var(h_x) = (1/(N-1)) * \sum (h_{x,t} - \bar{h}_x)^2 \tag{2.1}$$

where $var(h_x)$ is the variance of the t elevation measurements at each cross-shore position x, $h_{x,t}$ is the elevation at cross-shore position x at time t, $\bar{h}_x$ is the time-averaged elevation at cross-shore position x and N is the number of years of observations.

The variance gives a measure for the deviation from the time-averaged profile, but does not provide information on the possible spatial coherence of the deviations. In this respect, EOF analysis can be used. EOF analysis provides a method to reduce the number of data variables required to represent the data set (Aubrey (1979)). With EOF analysis, so-called shape functions, which are extracted from the data itself, describe the data in the most optimal statistical way (Jackson (1991); Larson et al. (2003)). These shape functions do not have an a priori assumed shape. EOFs in themselves are purely mathematical in nature and do not necessarily have a physical meaning, although a physical interpretation is often possible (see e.g. Aubrey (1979); Wijnberg and Terwindt (1995); Miller and Dean (2007)). With EOF analysis, temporal and spatial patterns can be analyzed separately. Using the EOF technique, we aim to reveal a simple spatial and/or temporal structure that is present within the foredune profiles data set.

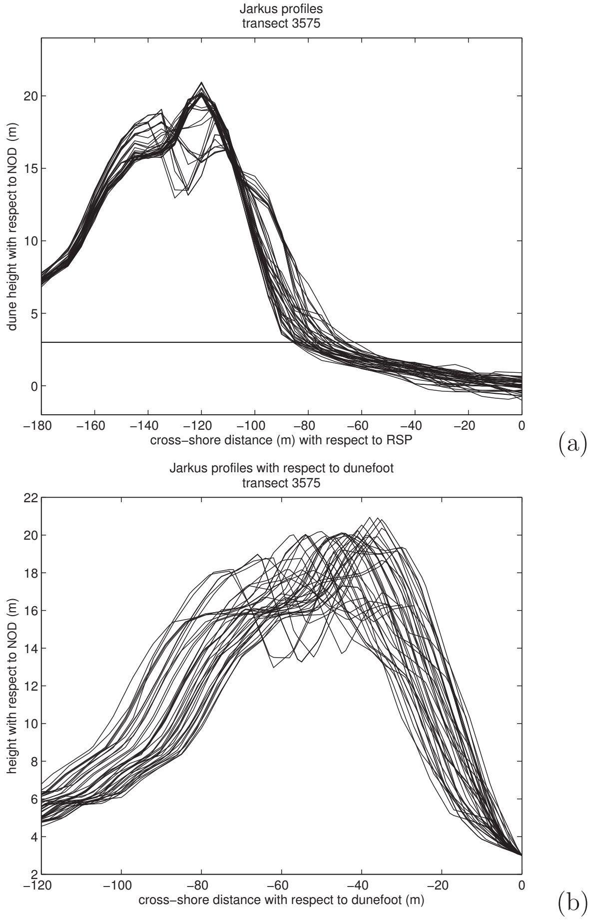

Figure 2.2: Cross-shore elevation measurements for transect 3575 over the period 1965-2004. Figure (a) shows the measured Jarkus profiles with respect to a fixed reference position (RSP). The horizontal black line indicates the + 3 m NOD level. Figure (b) shows the same profiles shifted with respect to the dunefoot position at + 3 m NOD.

EOF analysis can be conducted in several ways. The choice is to either remove the time-averaged profile or not prior to performing EOF analysis. In this study, the time-averaged profile was subtracted from each measured profile prior to the analysis. Larson et al. (2003) point out it is preferred to remove the mean since the mean usually dominates the signal. In addition, since the first eigenfunction has to pass through the origin of the data space, the first eigenfunction is not necessarily in the direction of maximum variance in the case the mean is not removed. If the data are demeaned prior to EOF analysis, the origin of the data space is shifted to the arithmetical center of the observed data and the first eigenfunction is defined in the direction of maximum variance in the data (Wijnberg and Terwindt (1995)).

The procedure for deriving the EOFs is as follows. Let X be the original data matrix containing the annually repeated elevation surveys with respect to the dunefoot position of a cross-shore transect. Hence, in our case a maximum of 45 surveys per transect is used. Matrix $\bar{X}$ contains the time-averaged elevations at all cross-shore measurement positions of the transect. Then a matrix R containing the residuals can be defined:

$$R = X - \bar{X} \tag{2.2}$$

Matrix R, which contains the differences between the measured profiles and the time-averaged profile, can be represented as the product of three matrices, U, S and V^*. This is also known as singular value decomposition (Golub and Van Loan (1996); Davis (2002)):

$$R = USV^* \tag{2.3}$$

Matrix U contains the temporal EOFs or weightings, diagonal matrix S the singular values (which are the square roots of the eigenvalues of the corrected sums of products matrix (Davis (2002)), and matrix V^* contains the spatial EOFs or loadings. The columns of U and V^* are orthonormal, which means that the columns are linearly independent. Since we performed EOF analysis on a dataset with the mean removed, we obtain the variance explained by each EOF by multiplying the squared singular values with $1/(N-1)$, where N is the number of years of observations.

To determine the statistical significance of the EOFs for each transect, we applied the rule of thumb provided by North et al. (1982), which states that

$$\delta\lambda \approx \lambda * \sqrt{2/N}, \tag{2.4}$$

where λ contains the amount of variance attributed by an EOF. Thus $\delta\lambda$ actually reflects the sampling error in the estimation of the variance, which is due to the fact that the data set is not infinite. N reflects the number of years of measurement.

In the above explained approach, EOF analysis provides information with respect to how deviations from the mean profile are correlated in space. This method can thus be used to examine whether there exists a certain spatial and temporal coherence in sediment distribution in cross-shore and longshore direction, which cannot be resolved by considering the time-averaged profile shapes alone.

EOF analysis requires the profiles to be of equal length. In this case, we examined dune profiles extending from the dunefoot to a cross-shore distance of 120 m land inward, which corresponds for almost all profiles to a position just landward of the foredune crest.

2.4 Results

2.4.1 Time-averaged profile shapes

The upper panel of Figure 2.3 shows a planview of the time-averaged dune shapes for all transects. The profiles start at the dunefoot position at a height of +3 m NOD and extend land inward to a distance of 120 m. Dune height generally increases in a southward direction. Largest longshore variability in time-averaged dune shapes is found in the northern section of Noord-Holland, where the lowest time-averaged dune crest height is +6 m NOD at transect 994 and the highest dune crest is +25 m NOD at transect 1213. The highest dune crests in the southern section of Noord-Holland and Rijnland are 23 m, whereas the lowest dune crests are 7,5 m and 6,5 m respectively. In the case of the southern section of Noord-Holland, this low dune crest elevation is situated near the location of an artificially created breach in the foredune around transect 3050. The low dune crest elevations in Rijnland are located near the discharge sluice in Katwijk (transect number 8600) and south of the IJmuiden harbor, where extensive embryo dune formation occurs.

2.4.2 Deviations from the time-averaged profiles

Deviations from the time-averaged profile shape are summarzied in the second to fourth panel in Figure 2.3). The second panel in Figure 2.3 shows that the deviation in meters from the time-averaged profile shape can be up to 5 m. The largest deviations from the time-averaged profile occur at the seaward facing slope. Higher up in the profiles (i.e. more land inward) the standard deviations generally decrease. The third panel of Figure 2.3 shows the deviations from the time-averaged profiles expressed as the variance at each cross-shore position. Summing all these variances results in the total variance per transect (bottom panel of Figure 2.3). The highest total variances are found south of the IJmuiden harbor, around transects 5700 to 5900 and near the southern margin of the study area, at transects 9600 and 9625.

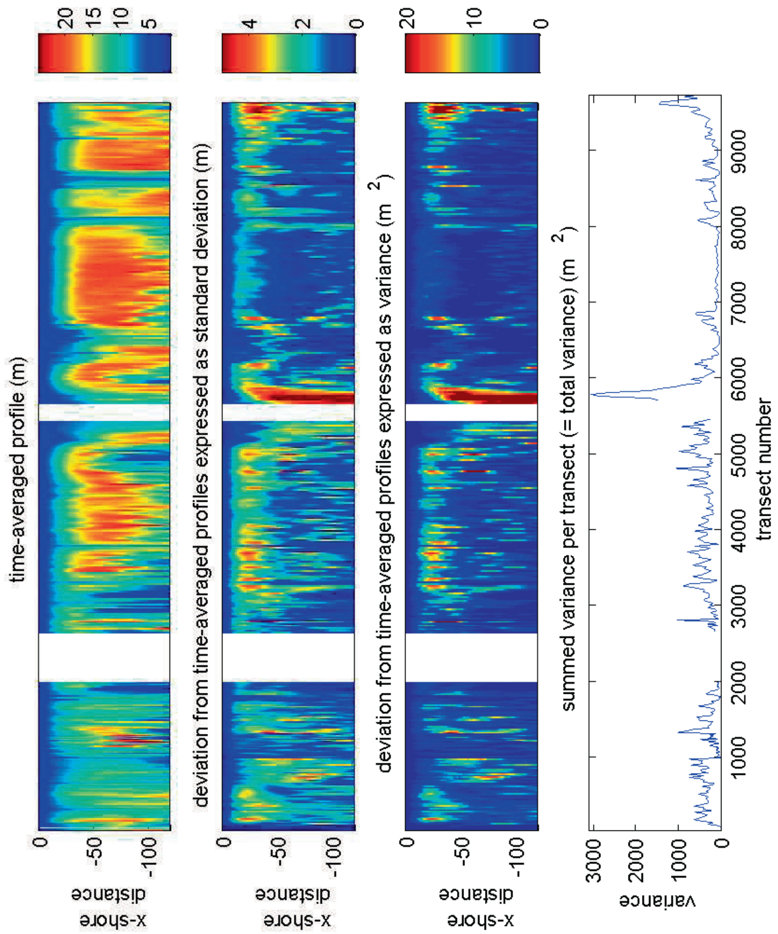

Figure 2.3: Alongshore variations in foredune characteristics. Top panel: Elevations of time-averaged foredune profiles. Second panel: Deviation from the time-averaged foredune profiles expressed as standard deviations at each cross-shore position. Third panel: Deviation from the time-averaged foredune profiles expressed as the variance at each cross-shore position. Bottom panel: Summation of the variances at each cross-shore position for each transect.

2.4.3 EOF results

The cross-shore coherence in the deviation from the time-averaged profiles (the total variances) can be described by the EOFs, where the first EOF explains the largest part of the observed variance. The percentages of the variance explained by EOF 1 and EOF 2 for each transect are shown in Figure 2.4 (third panel from the top). In case the 'errors' associated with EOFs 1 and 2 overlap, it is unclear whether the first EOF indeed explains the largest part of the observed variance, or that rather the second EOF might be of greater importance in this case. Yet another possibility is that the first and second EOFs are a mixture of the true underlying pattern (North et al. (1982)). The situation where the first EOF is not statistically significant occurs at a few transects, which are indicated by the circles in Figure 2.4, and these transects are omitted from further analysis (indicated by the vertical white lines in the fourth panel of Figure 2.4). Note that we assume the annual measurements to be independent, which can be questioned since it is likely that deviations from the time-averaged profile shape in a certain year are to some extent related to the deviations observed in the preceding year.

Overall, the first EOF explains between about 60 to 90% of the total variance, with 70% on average. The higher the value of the percentage variance explained by the first EOF, the more the morphologic behavior of the foredune is described by the pattern of the first temporal EOF. Low values of the percentage variance explained indicate that temporal changes in elevation across the foredune are only weakly correlated in the cross-shore direction.

Figure 2.5 shows for transect 3225 the morphological interpretation of the EOFs. The first spatial EOF or shape function 'modulates' the time-averaged profile shape. This shape function more or less resembles a standing wave, with the nodes at a fixed position. The amplitude of these waves might change through time which is represented by the first temporal EOF (in the case of Figure 2.5 for the years 1990 and 2004).

The first temporal EOF (also called weighting) indicates whether the deviation from the mean profile, as described by the first spatial EOF, increases or decreases through time. In the case of Figure 2.5, a negative weighting causes the profile to become more concave-shaped, whereas a positive weighting results in a more convex-shaped profile.

The fourth panel of Figure 2.4 shows the first spatial EOF for all transects, each multiplied with its singular value (contained in matrix S, see Equation (2.3)). The spatial EOF reflects how the surveyed elevations generally tend to deviate from the mean profile shape. The spatial EOFs reach the highest values at the seaward facing slope of the foredune. Multiplication with the value of the first temporal EOF in a given year results in a deviation in meters at the given transect location.

The first temporal EOFs, extracted at each alongshore location, describe a pattern in time and space of the changes in profile characteristics and thus provide an indication of the longshore coherence in morphologic behavior of the foredune system (Figure 2.4, bottom panel). The temporal pattern of the EOFs shows distinct behavior for the area north of the seawall (Noord-Holland north), the area south of the seawall up to IJmuiden harbor (Noord-Holland south) and Rijnland (south of the IJmuiden harbor up to Scheveningen)

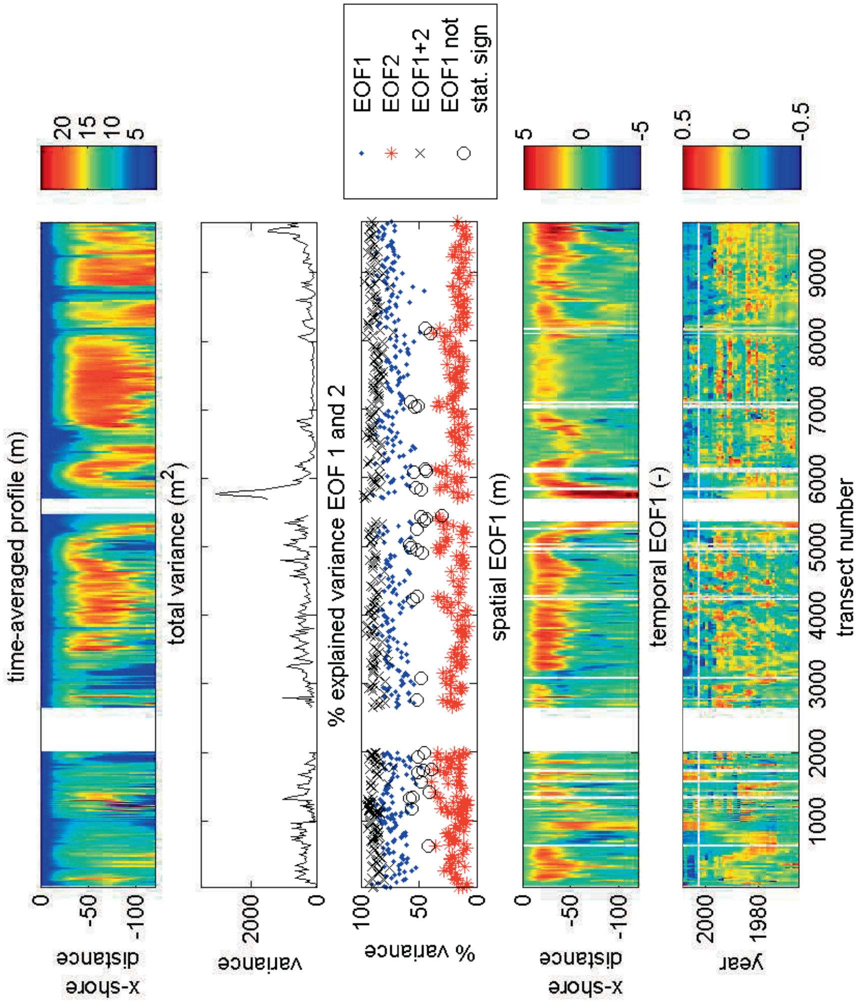

Figure 2.4: Alongshore variations in foredune characteristics. Top panel: Elevations of time-averaged foredune profiles (meters). Second panel: Total variances. Third panel: Percentage of the variance explained by EOF 1 and 2. Fourth panel: First spatial EOF (meters). Bottom panel: First temporal EOF (-).

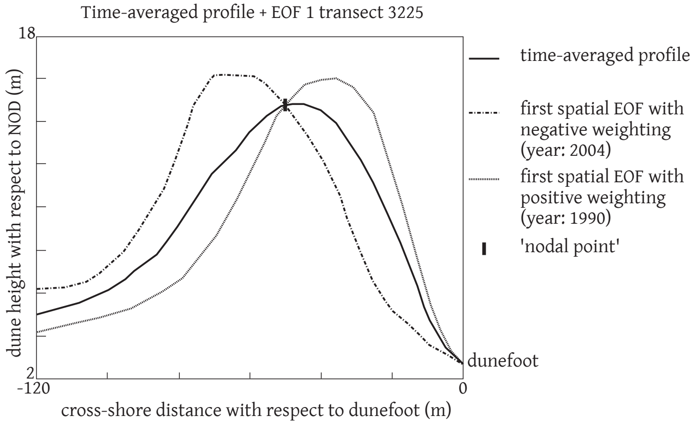

Figure 2.5: The morphological interpretation of a positive or negative weighting on the first spatial EOF for transect 3225.

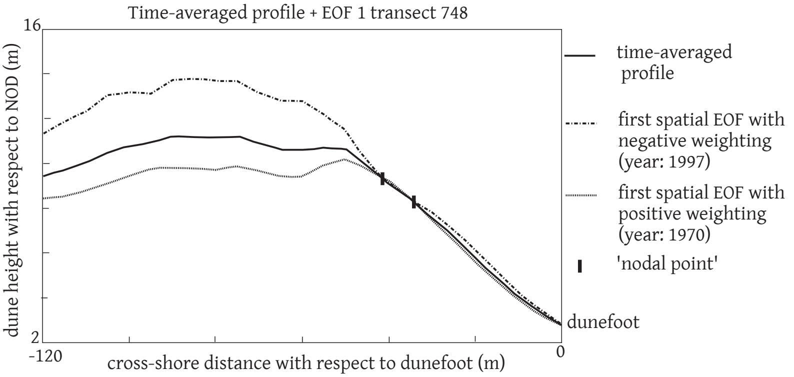

Figure 2.6: The morphological interpretation of a positive or negative weighting on the first spatial EOF for transect 748.

up to the mid-1990s. Overall, the values of the first temporal EOF tend to become predominantly negative from 1996 onwards. Combined with the patterns described by the spatial EOFs, this implies a general decrease in elevations near the dunefoot and an increase in elevations landward of the first nodal point from the dunefoot (see Figure 2.5). Note that where the spatial EOF has a distinctly different shape, which is e.g. the case roughly between transect numbers 600-800 (fourth panel of Figure 2.4), the interpretation of a negative weighting in terms of changes in the foredune shape is different too (compare Figures 2.5 and 2.6).

In the case of Noord-Holland south, a longshore alternating pattern of negative and positive weightings can be distinguished. This pattern seems to migrate through time, mainly in a southward direction. The temporal EOF values of Rijnland seem to exhibit mostly longshore uniform temporal changes in the sign of the temporal EOF. In the case of Noord-Holland north, changes in the sign of the first temporal EOF seem to fluctuate

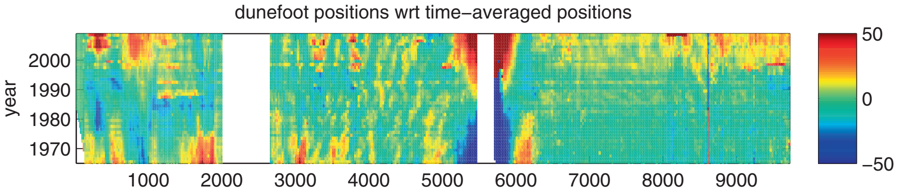

Figure 2.7: Alongshore variations in dunefoot characteristics. The dunefoot positions are calculated relative to their time-averaged positions (meters).

more slowly than in the case of Noord-Holland south and Rijnland. The areas directly north and south of the IJmuiden harbor show a distinct temporal EOF pattern. Temporal changes in this region seem to be slower than in the adjacent areas. In general, north of the harbor, until about 1980, the profile elevations are higher than average, followed by lower than average profile shapes. South of the harbor, profiles tend to get lower than average around 1990.

2.4.4 Dunefoot behavior

Figure 2.7 shows the shifts in dunefoot position in meters for each transect with respect to the time-averaged dunefoot position for that same transect, hereafter abbreviated with deviation dunefoot positions. Again, the white zones indicate no-data areas. The deviation dunefoot positions show a distinct pattern in each of the three regions. Largest shifts occur just north and south of the IJmuiden harbor, around transects 5300 to 5800. In Rijnland, shifts in dunefoot position show similar behavior over rather large longshore distances, meaning that either a seaward or landward shift of the dunefoot occurs over a longshore distance of around 30 km (approximately between transect numbers 6300 and 9300). In the case of Noord-Holland south, the dunefoot exhibits a longshore oscillating pattern through time. This sandwave like pattern results in regions of alternating seaward and landward movement of the dunefoot over longshore distances of around 2 km. Changes in deviation dunefoot positions in Noord-Holland north fluctuate more slowly in time than the deviation dunefoot positions in Noord-Holland south. Regions of a more landward position of the dunefoot with respect to the time-averaged dunefoot position, notably between transect numbers 200 to 1000, are followed by a more seaward position of the dunefoot with respect to the time-averaged position from the end of the 1990s onward.

The patterns in deviation dunefoot positions seem to resemble the patterns in the shifts of the +1 m contour from Wijnberg and Terwindt (1995) and the shifts in residual dunefoot positions from Guillén et al. (1999).

Comparing Figures 2.4 and 2.7, there also seems to be a relationship between the pattern of the first temporal EOF and the deviation dunefoot positions. When we compute the correlation coefficients between the deviation dunefoot positions and the temporal EOFs (Figure 2.8), we can see that in the case of Noord-Holland north there is a large scatter in correlation values, with a mean correlation coefficient of -0.2. In the case of Noord-Holland south and Rijnland, most transects show a strong negative correlation with mean

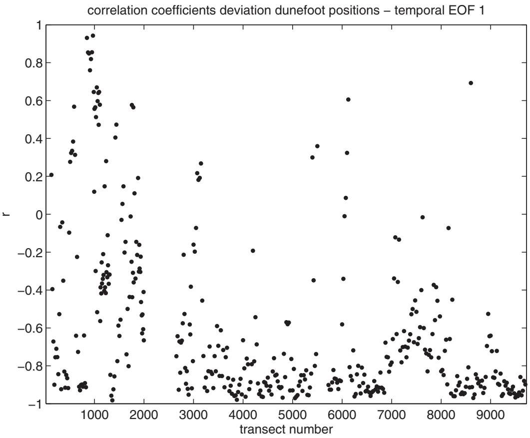

Figure 2.8: Correlation coefficients between the deviation dunefoot positions and the first temporal EOF.

correlation coefficients of -0.75 for both regions, indicating that a negative value of the first temporal EOF co-occurs with a seaward movement of the dunefoot.

2.5 Discussion

Although large scale stabilization of the foredune area in Noord-Holland and Rijnland has been practiced as early as the mid-19th century, the results show that the foredune area remained variable both in time and space.

In general, the pattern of the first temporal EOF and deviation dunefoot positions resemble the pattern of the +1 m contour of Wijnberg (1995) and the pattern of residual dunefoot behavior of Guillén et al. (1999). The strong negative correlation between the dunefoot and the seaward facing slope in Noord-Holland south and Rijnland indicates that the pattern of the first temporal EOF can largely be ascribed to the behavior of the dunefoot. In other words, in the case of Noord-Holland south and Rijnland, the behavior of the dune front is strongly dependent on the behavior of the dunefoot, that is the changes in the shape of the seaward facing slope are concentrated in the lower part of the profile. For instance, the change in sign of the first temporal EOF from 1996 onwards, which indicates in most cases an increase in profile concavity, co-occurs with a more seaward position of the dunefoot with respect to the time-averaged dunefoot positions. The explanation for this change is sought in the change in coastal policy in 1990 (see Section 2.2). After implementation of the first coastal policy document (Ministerie van V&W (1990)), nourishment activity increased, which might have resulted in large-scale changes of the foredune. In Noord-Holland north no such relationship between dune front changes and dunefoot shifts could be found. The spatial EOFs show a larger longshore variability in this region, whereas the changes in time of the temporal EOF are slower compared to the other regions.

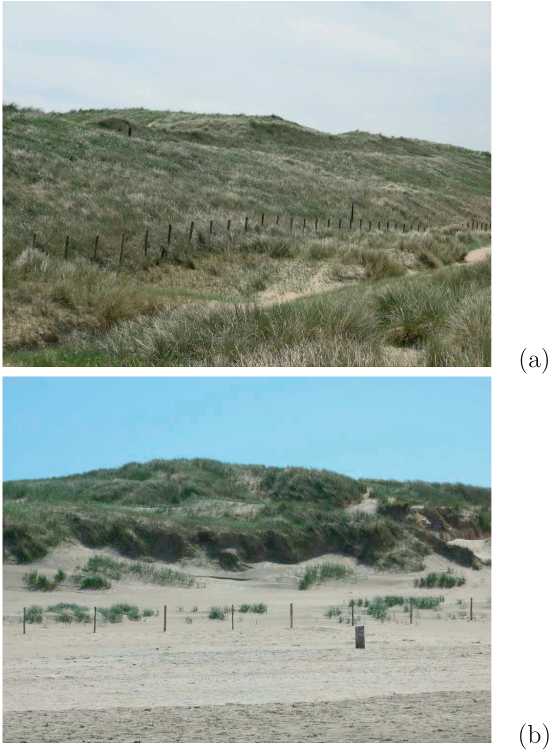

Figure 2.9: a. Foredune in Rijnland. The fence marks a former position of the dunefoot. The foredune in the front has developed after the change in management in 1990, and is also densely vegetated with *A. arenaria*. b. Foredune in Noord-Holland at transect 1050.

Hence, despite all the measures undertaken to stabilize the foredune (Arens (1994); Arens and Wiersma (1994); Löffler and Veer (1999)), at least the dunefoot continued to exhibit spatial and temporal changes, which strongly affected the behavior of the seaward facing slope. Hence, changes in time and space of the seaward facing slope are mainly concentrated around the dunefoot, and the remainder of the slope is more static in time and space, which might indicate that stabilizing measures (sand fences, vegetation plantings) were effective higher up in the profile. This can be illustrated by Figure 2.9, which shows a foredune in Rijnland that is densely vegetated with *A. arenaria*, while the foredune in the northern section of Noord-Holland shows more bare patches.

The densely vegetated dune results in a rigid foredune appearance, which might be more static in time than dunes that are not densely vegetated (Wiedemann and Pickart (1996)). Overall, *A. arenaria* cover is less dense in Noord-Holland compared to Rijnland, which might explain the lower correlation coefficient between the first temporal EOF and deviation dunefoot positions.

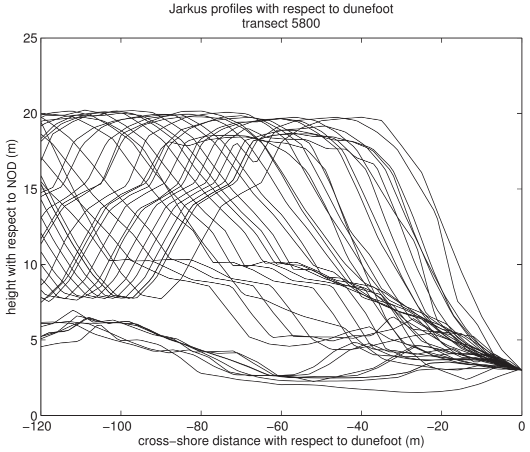

Figure 2.10: Cross-shore elevation measurements for transect 5800. The low profiles occur in years with extensive embryo dune formation, and these embryo dunes are backed by the older, established foredunes.

The largest changes in deviation dunefoot positions occur directly north and south of the IJmuiden harbor. In this area, embryo dune development induced a very large seaward shift of the dunefoot (see Figure 2.10). The first 120 m landward of the dunefoot now consisted of embryo dunes instead of the established foredune of the earlier years. The lowering of the profile is thus caused by accretion rather than by erosion. This is a limitation of the EOF method. By using a fixed cross-shore interval we should take notice of the fact that at some transects the foredune crest is not reached yet within the distance of 120 m from the dunefoot. This occurs e.g. in the case of locations with extensive embryo dune formation, which cause a large lateral shift of the +3 m NOD level in a seaward direction. However, this situation is restricted to only the few locations near the IJmuiden harbor.

Summarizing, although management measures such as vegetation plantings and erection of sand fences have been carried out along almost the entire Central Netherlands' coast, each of the three regions displays distinct decadal-scale morphologic behavior, which is largely attributed to morphologic changes near the dunefoot.

2.6 Conclusions

The analysis of a 45-year dataset revealed that the shape of highly managed foredunes, where interventions mainly aim at foredune stabilization, is indeed variable over a time period of several decades, both in cross-shore as well as in longshore direction. It appeared that the temporal changes in the shape of the seaward facing slope in the case of Rijnland and the part of Noord-Holland south of the seawall were due to changes near the dunefoot. For Noord-Holland north this percentage was much lower. Overall, from 1996 onwards, the morphologic variability in time and space of the seaward facing slopes decreased, which is likely due to the effects of large-scale nourishment schemes.

So far, management interventions aiming at the maintenance of the foredunes as flood protection mainly concentrate on preserving or obtaining a predefined volume of sand in the dunes. In this study we showed that the shape of even quite intensely managed foredunes is not necessarily constant at decadal time scales. Therefore, combined with the knowledge that the shape of the dune affects the amount of dune erosion due to storm events, our results imply that long-term management schemes should also consider possible changes in the spatial distribution of the volume of sand in the dunes.

Acknowledgments

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Chapter 3

Foredune management and foredune morphodynamics: A case study of the central Netherlands' coast [2]

How often we forget all time, when lone
Admiring Nature's universal throne; Her woods – her wilds – her
mountains – the intense Reply of HERS to OUR intelligence!

Edgar Allan Poe, Stanzas

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[2] This Chapter has been accepted for publication as Bochev-van der Burgh, L.M., Wijnberg, K.M., Hulscher, S.J.M.H., Foredune management and foredune morphodynamics: A case study of the central Netherlands' coast, Journal of Coastal Conservation

Abstract

This study examines the role of management interventions on foredune morphodynamics on a time period of decades along the central part of the Netherlands' coast. Information on types of measures, their intensity and locations were collected through interviews with dune managers. Foredune morphodynamics were quantified from a 40-year data set of annually repeated elevation surveys across the foredune. Using Empirical Orthogonal Function (EOF) analysis, various morphometric foredune properties were extracted. We found that, prior to 1990, foredunes with lower management activity were generally less dynamic than the more intensely managed foredunes. This followed from the fact that before 1990, interventions were mainly reactive in nature, meaning that different countermeasures were undertaken after erosion occurred. Following a change in coastal policy in 1990, interventions became more proactive: Large-scale nourishments are carried out to provide a buffer to coastal erosion. These nourishments led to a consistent change in foredune shape. In general, the seaward duneface became more concave-shaped and the foredunes became more uniform in a longshore direction. At the decadal scale, the mix of reactive measures prior to 1990 did not result in distinctive dune shapes, while the proactive approach does seem to have an effect on dune shape as it affects the sediment budget of the system.

Keywords: foredune morphodynamics, foredune management, questionnaire, EOF analysis

3.1 Introduction

Foredunes around the world have been modified by human actions for centuries (Klijn (1981), Pye and Neal (1994) Nordstrom (1994), Anthonsen et al. (1996), Catto et al. (2002), Clemmensen and Murray (2006)). Nowadays, modifications are often conducted either to establish a predefined safety level provided by the (fore)dunes, or for recreational purposes, e.g. preventing dune growth to increase ease of access to the beach (Nordstrom et al. (2000)). In the Netherlands, modifications are mainly carried out to maintain a prescribed safety level. Especially along the central part of the Netherlands' coast, management interventions have been intense at least up to 1990. Interventions aimed at stabilizing the foredunes, since it was thought that only through complete fixation the role of the foredunes as coastal defense could be maintained (Arens and Wiersma (1990)). When in 1990 a new coastal policy came into practice, the idea of complete foredune fixation was largely abandoned. To counteract coastal erosion, large-scale nourishment projects were – and still are – undertaken.

Several studies illustrated the importance of (fore)dune morphology in the dune erosion process and in dune safety assessments (e.g. Edelman (1968), Hughes and Chiu (1981), Van der Burgh et al. (2007)). Hence, since management interventions affect the shape of the dune (Nordstrom (1994)), the type of management interventions carried out affects the safety provided by the dunes. Therefore, in the scope of sustainable coastal zone management and future spatial planning policies, it is important to have quantitative insight into the evolution of managed foredunes on time periods of years to decades.

Studies on the effects of management interventions on the shape of the foredune usually only qualitatively describe the effects of measures on morphology. For instance, *Ammophila arenaria* (marram grass or European beach grass), which has been introduced in many countries for stabilization purposes since around 1850 (Wiedemann and Pickart (2004), Wiedemann and Pickart (1996), Hertling and Lubke (1999), Hilton et al. (2006), Lubke (2004)), is believed to result in unnatural foredune appearances, with foredunes being higher, wider and more linear than their natural counterparts (Nordstrom (1994), Wiedemann and Pickart (1996)). Also, the effects of single type of measures on dune morphology are usually examined, instead of the effects of a combination of measures on dune morphology. An example is given by Hotta et al. (1991), who describe a variety in dune shapes resulting from different sand fence configurations. Furthermore, the effects of interventions on dune morphology are often considered over short time periods only (Nordstrom (2000), Gares (1990)). For instance, studies on the effects of nourishment on dune morphology usually concern the direct effects as a result of the placement of the fill material on the cross-shore profile (Nordstrom (2000)). Effects on the longer term (several years) have been represented in terms of volumetric changes rather than changes in dune morphology (Van der Wal (2004), Arens (2009)).

Therefore, the objective of this paper is to obtain a quantitative insight into the relationship between dune morphology and a combination of interventions on an aggregated temporal scale, in the order of years to decades. In this respect, we analyzed a 40-year record of annually repeated cross-shore foredune profile measurements at 400 locations along the central part of the Netherlands' coast starting in 1965. In addition, since management is poorly documented, interviews with coastal managers were conducted to obtain insight into the type, locations and intensity of interventions during this time period.

3.2 Study area

The study area geographically belongs to the North Sea Region, which covers the coastal stretch from Calais in northern France up to the northern end of Jutland, Denmark (Heslenfeld et al. (2004), Klijn (1990)) (Figure 3.1). The dunes along the central part of the Netherlands' coast form a closed barrier over a distance of about 120 km. The study area is divided into two sections, Noord-Holland and Rijnland, which are under the auspices of two different water boards. Study area locations are denoted by transect numbers, which refer to locations of cross-shore profile measurements.

Especially in the northern and southern part of the study area the coast is eroding, while the central part of the coast is more or less stable (Beets and Van der Spek (2000)). The longshore drift is directed towards the north (Beets et al. (1992)). Since approximately 1850, the coast between Hoek van Holland (transect number 11700) and Scheveningen (transect number 9725) shows a retreat of 0.35 m/year. Between Scheveningen and Egmond (transect number 3800) the coast is slightly prograding at a rate of 0.25 m/year. North of Egmond the coast retreats at a rate of 0.70-0.95 m/year (Stolk (1989), Beets et al. (1992)). To counteract coastal erosion, human activity in the dune area in the Netherlands increased after the Medieval Period, but only around the second half of the 19th century large scale foredune management which has led to the closed foredune area as we know it today started. At this time, large scale interventions to prevent sand drift were undertaken (Klijn (1990)). Stabilizing the dunes through *A. arenaria* plantings mainly took place at locations which were important as sea defense or where sand drift would threaten to cover houses and lands. Interventions were most intense in narrow dune areas, which resulted for instance in the initiation of straight dunes, generally referred to as sand drift dikes, in the northern part of Noord-Holland (Figure 3.1) around 1550-1600 (Klijn (1981)).

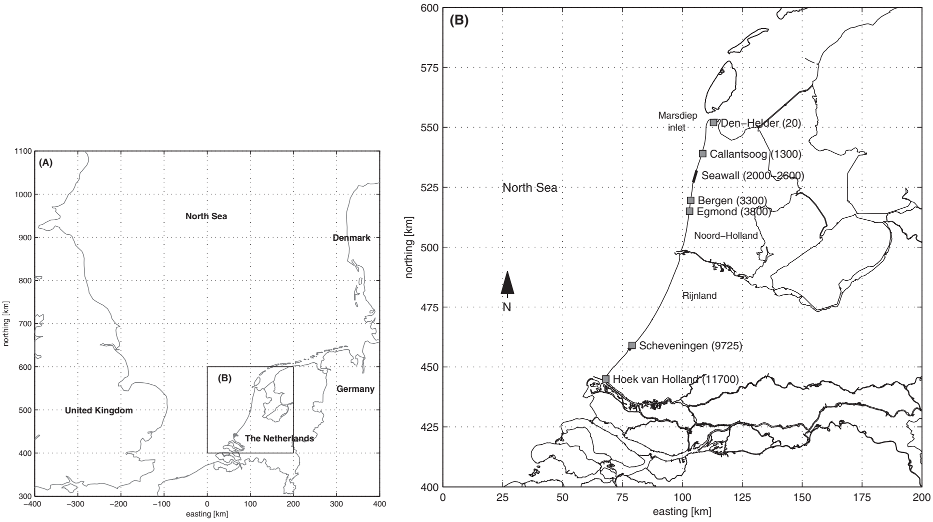

Figure 3.1: Study area. Transect numbers are indicated in brackets.

The large-scale coastal retreat is now ‘masked’ by the nourishment projects, which started after 1990. Some coastal managers mention that because of the nourishments, erosive coasts do not occur anymore (pers. comm. R. Buursink and P. Goessen). Nourishment locations, dates, volumes and type of nourishments (dune, beach or shoreface) are documented by the Directorate-General for Public Works and Water Management. Figure 3.2 shows nourishment locations, date and intensity up to and including 2004. To derive the nourishment intensity, we assume that the fill material is evenly spread over the nourished area. Before 1990, at a few locations in Noord-Holland, dune reinforcement took place. Dune reinforcement using nourished sand can take place either around the dunefoot (which is called a banquet), along the entire seaward front of the foredune, on the foredune crest, or at the landward side of the foredune (Van der Wal (1999a)). Also, prior to 1990, beach nourishments were carried out in 1979, in 1986 and in 1987 at different locations in the northern part of Noord-Holland. Starting in 1990, beach and shoreface nourishment frequency and intensity increased. Nourishment frequency is higher in Noord-Holland than in Rijnland. Especially around the coastal towns of Callantsoog, Bergen and Egmond, nourishment intensity is high.

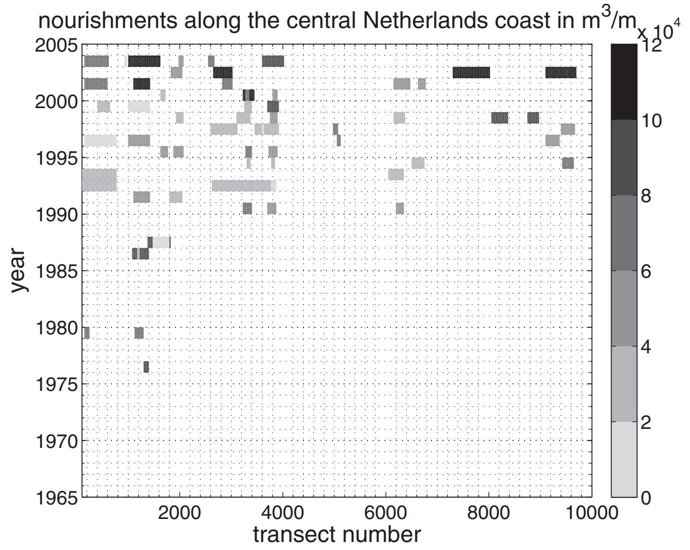

Figure 3.2: Nourishment location, frequency and intensity.

3.3 Methods

3.3.1 Dune management history: Interviews and questionnaire

Arens and Wiersma (1994) made a foredune classification of the Netherlands' coast based on aerial photographs of 1979 and 1988. The foredunes were classified according to the most prominent type of intervention at that moment. Since this classification concerns two snapshots situations, probably characterizing two years, it is not necessarily representing the prevailing management type over longer time periods. Therefore, to obtain a more complete understanding of dune management practices between 1965 and 2004, interviews were conducted with a dune manager from water board Hoogheemraadschap Noord-Hollands Noorderkwartier (hereafter indicated by water board Noord-Holland) and a dune manager from water board Hoogheemraadschap Rijnland (hereafter indicated by water board Rijnland). The managers are involved in foredune maintenance since 1986 in the case of water board Noord-Holland and since 1976 in the case of water board Rijnland.

The questionnaire consists of a combination of open-ended questions and closed questions. The questionnaire is divided into questions concerning management interventions in the period before 1990 and the period after 1990, hence the periods before and after the change in coastal policy.

Prior to these interviews, two other employees of water board Noord-Holland were contacted, who provided general information on management and we consulted unpublished records and correspondence from water board Rijnland. In addition, research reports on dune management from Arens (1999), Arens (2009) and Löffler and Veer (1999) were consulted. Using these additional sources can be seen as a form of 'triangulation' (Yin

(2009)), indicating that multiple data sources are used to increase the trustworthiness of the interviews, especially since only two persons were interviewed. As a final check, after working out the interviews, they were sent back to the dune managers for confirmation.

3.3.2 Data selection and transformation

Jarkus database

To examine whether a relationship between foredune shape and management interventions exists, we select one region in Noord-Holland and one region in Rijnland for detailed examination. For both regions a number of profiles – referred to as transects – is examined. These transects are obtained from the Jarkus database. The Jarkus database provides annual measurements of coastal transects extending from the foredune (often even further landward) to approximately 1000 m seaward. Measurements are taken with respect to a series of permanent beach poles along the coast. The alongshore distance between the transects is 200 to 250 m (Minneboo (1995)). Unfortunately, no measurements were conducted in the years 2000 and 2002. For the sub-aerial part of the coastal profile, elevation measurements are taken at 5 m intervals (Van der Wal (2004)), which are linearly interpolated to a 1 m resolution. Hence, morphologic features and dynamics will be identified on a somewhat spatially aggregated level. However, since focus is on morphodynamics on a decadal-scale time period, small scale features are considered to be of less importance in determining the overall foredune morphodynamics on this time period.

Selection of the regions is based on the results of the questionnaire. Firstly, both regions contain locations which have been intensely and less intensely managed throughout the analyzed time period. Secondly, both regions contain locations which have been nourished and locations which have not been nourished up to 2004.

Data transformation

We examine foredune profiles extending from the dunefoot to a cross-shore distance of 70 to 130 m land inward, depending on the horizontal location of the foredune crest with respect to the dunefoot. Each transect is shifted with respect to a floating reference position, which is set at a height of +3 m Netherlands' Ordnance Datum (NOD, approximately mean sea level). This height roughly corresponds to the dunefoot position (Ruessink and Jeuken (2002)). The shifts in dunefoot position are analyzed separately from the seaward dune slopes. The shifts in dunefoot position provide information on erosional and accretional events.

Data preparation

Prior to quantifying the seaward dune slope characteristics, Empirical Orthogonal Function (EOF) analysis is performed on the Jarkus measurements, since the measurements may contain errors, such as the inclusion of vegetation, which can give a wrong indication of the actual dune crest height. EOF analysis is used to filter these effects and other small-scale or site-specific features. EOF analysis is widely used to characterize morphological features and patterns (see e.g. Aubrey (1979), Wijnberg and Terwindt (1995), Larson et al. (2003), Miller and Dean (2007), Houser et al. (2008), Kroon et al. (2008)).

With EOF analysis, the data is described statistically in the most optimal sense. The measured Jarkus transects are represented in terms of shape functions, where the first shape function explains the largest part of the observed variability. Since we analyze each transect on a time period of forty years, we obtain for each transect a maximum number of forty shape functions. Adding all the shape functions of a transect results in the original Jarkus profile belonging to that transect.

The time-averaged profile is removed from each profile prior to EOF analysis, so that we perform the analysis on a 'corrected sums of products matrix'. This matrix is, except for a constant factor ($1/(N-1)$), equal to the variance-covariance matrix (with N being the number of observations). Hence, the eigenvectors obtained are similar to the eigenvectors of the variance-covariance matrix (see e.g. Kroon et al. (2008)), but the eigenvalues differ with a factor $N-1$ from those of the variance-covariance matrix.

The procedure for deriving the EOFs is as follows. Let X be the original data matrix containing annually repeated elevation surveys (40 in total) along a fixed cross-shore transect. Matrix X_{aver} contains the time-averaged elevations at all cross-shore positions. A matrix R containing the residuals is defined by:

$$R = X - X_{\text{aver}} \tag{3.1}$$

Matrix R can be represented as the product of three matrices, U, S and V^*. This is also known as singular value decomposition (Golub and Van Loan (1996), Davis (2002)):

$$R = USV^* \tag{3.2}$$

Matrix U contains the temporal EOFs or weightings, diagonal matrix S the singular values (which are the square roots of the eigenvalues of the corrected sums of products matrix (Davis (2002)), and matrix V^* contains the spatial EOFs or loadings. The columns of U and V^* are orthonormal, which means that the columns are linearly independent. The variance explained by each EOF is obtained by multiplying the squared singular values with $1/(N-1)$, where N is the number of years of observations, which in our case equals 40.

Finally, profile reconstructions are made by adding the time-averaged profile shape of the analyzed transect with its first and second EOF:

$$X_{\text{rec}} = X_{\text{aver}} + U_1S_1V_1 + U_2S_2V_2 \tag{3.3}$$

The first and second EOFs describe between 63 and 96% of the variability in the case of Noord-Holland and between 80 and 97% of the variability in the case of Rijnland.

3.3.3 Quantification of profile characteristics

Changes in foredune shape are quantified by computing for each reconstructed profile X_{rec} for each year its seaward facing dune slope, foredune crest height, horizontal distance between dune crest and dunefoot, foredune curvature and dunefoot position. The *dune slope* is represented as a straight line between the dunefoot position (set at +3 m NOD) and the foredune crest.

A new morphometric parameter, the foredune curvature, is introduced to express the deviation of the profile from the dune slope. Profile curvature is either concave or convex. In the case of a concave profile, the major part of the seaward dune slope is present below the dune slope, whereas in the case of a convex profile, the major part of the seaward dune slope is present above the dune slope. Figure 3.3 shows a definition sketch of profile curvature.

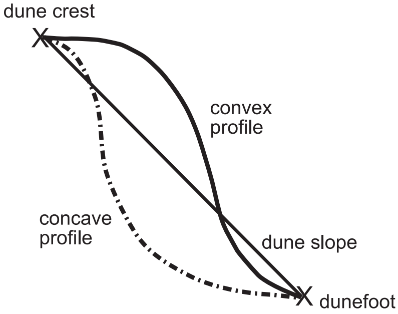

Figure 3.3: Concept of profile curvature.

For assessing the profile curvature, we only consider that part of the reconstructed profile and the dune slope between the dunefoot position ($x_{\text{dunefoot}} = 0$) and the intersection x_{inters} of the dune crest of the reconstructed profile with the dune slope. Next, we compute the integrals below the reconstructed profile I_{profile} and below the straight line I_{slope}:

$$I_{\text{profile}} = \int_{x_{\text{inters}}}^{0} f_{\text{profile}}(x)dx \tag{3.4}$$

and

$$I_{\text{slope}} = \int_{x_{\text{inters}}}^{0} f_{\text{slope}}(x)dx \tag{3.5}$$

The magnitude of profile concavity or convexity C is expressed as the absolute sum of deviations of the profile I_{abs} from the dune slope:

$$C = I_{\text{abs}} - I_{\text{slope}} \tag{3.6}$$

Where I_{abs} is

$$I_{\text{abs}} = A_{\text{pos}} + |A_{\text{neg}}| \tag{3.7}$$

A_{pos} is the total area above the dune slope, whereas A_{neg} is the total area below the dune slope. A high value indicates a large deviation of the reconstructed profile from the dune slope, and hence a large profile concavity or convexity. To determine whether the profile shape is predominantly concave or convex, a 'shape factor' (S) is introduced, which gives a measure of profile convexity/concavity:

$$S = A_{\text{pos}}/(A_{\text{pos}} + |A_{\text{neg}}|) * 100 \tag{3.8}$$

In this case, a low value of S indicates that the profile is predominantly concave-shaped, whereas high values indicate a more convex profile shape.

In addition to computing profile concavity, the height of the dune crest for each reconstructed profile for each year and the horizontal distance between the dune crest and the dunefoot are computed. We remove the time-averaged value of each transect location, to focus on temporal changes rather than alongshore differences between transects. The changes in dunefoot position are also calculated for each transect with respect to the time-averaged dunefoot position of that specific transect.

3.4 Results

3.4.1 Spatio-temporal variation in dune management interventions

Figures 3.4 and 3.5 show a summary of management interventions before and after 1990. A division is made between management intensity and management type. An explanation of these Figures is provided below.

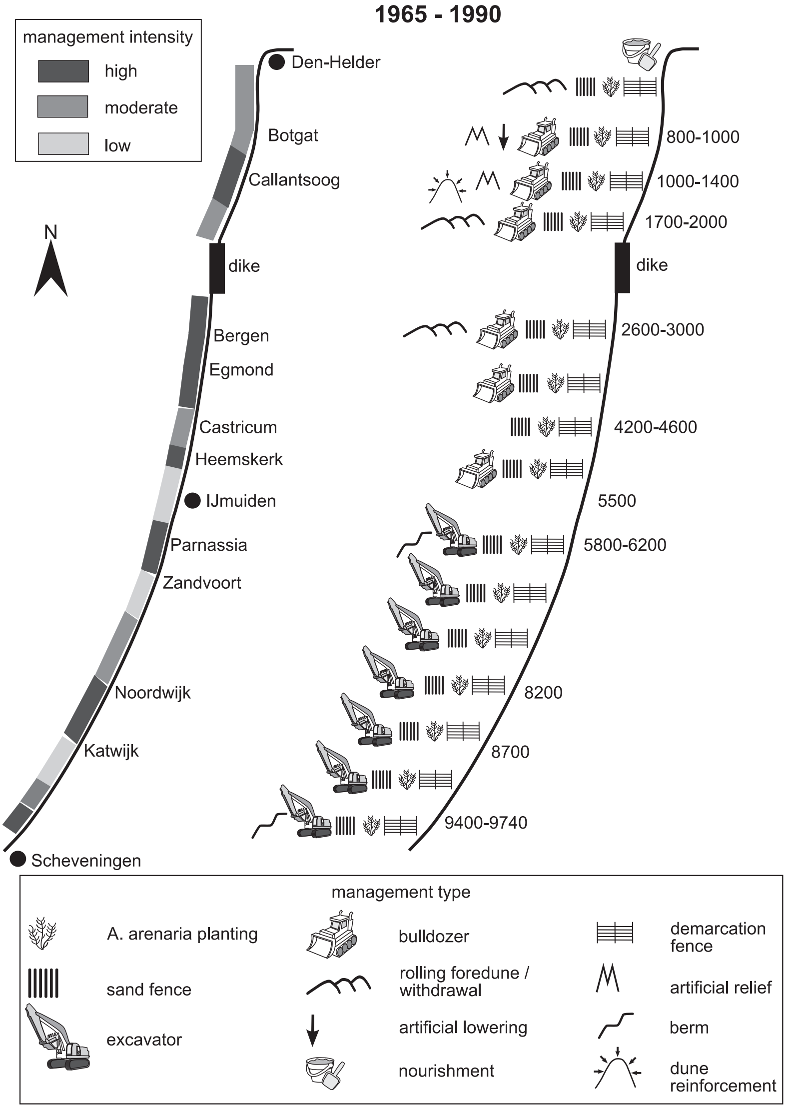

Figure 3.4: Management intensity and type before 1990.

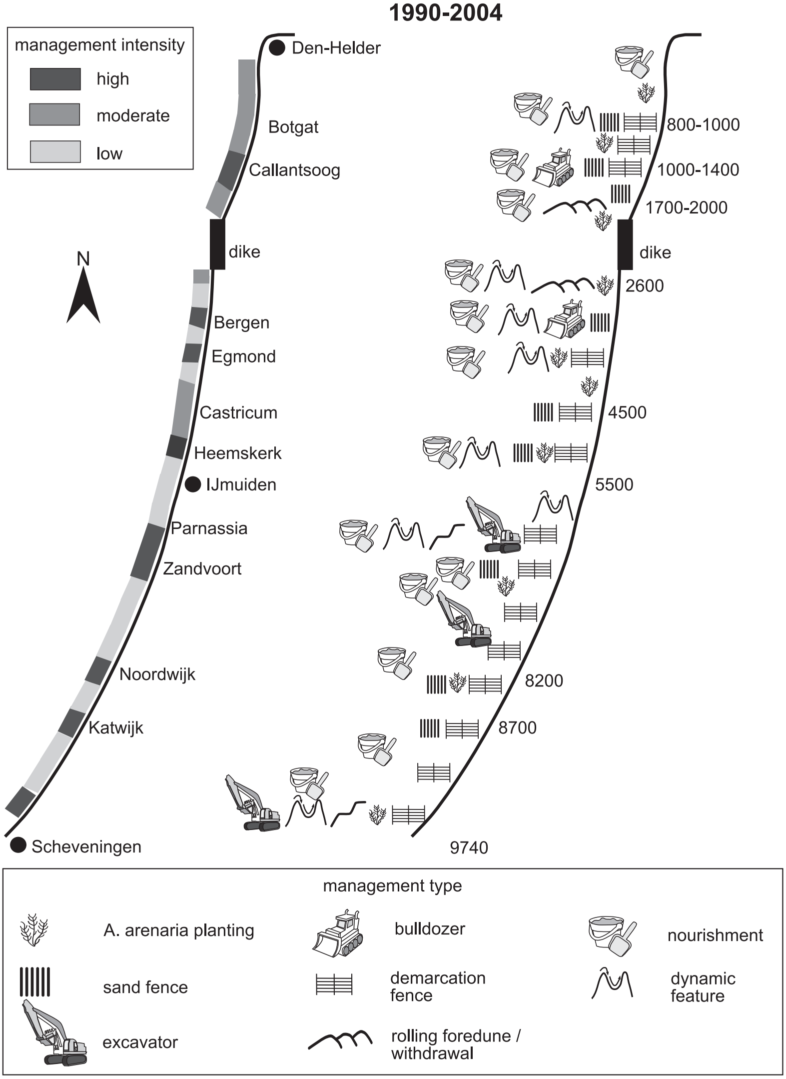

Figure 3.5: Management intensity and type after 1990.

Dune management practice in Noord-Holland

Up to 1990, from Den-Helder (transect 100) to IJmuiden (transect 5500) a combination of measures was carried out, with spatially varying intensity (Figure 3.4). Foredunes in front of sea-side villages had the highest maintenance efforts. Especially transects 1000 to 1400 (around the sea-side village Callantsoog), 2600 to 3900 and transects 4800-4900 (Heemskerk) had high maintenance efforts. Callantsoog is bordered by a narrow dune area which required frequent maintenance. Heemskerk suffered from erosion due to the IJmuiden harbor moles extension. Storm damage near coastal towns was restored on a yearly basis. The area which had the lowest maintenance effort was Wijk aan Zee, located between transects 5100-5500. This was also due to the extension of harbor moles at IJmuiden, which resulted in coastal progradation immediately north and south of the harbor (see also the questionnaire results of Rijnland later in this Section).

Whenever blowouts or bare patches developed, these were filled up and planted with *A. arenaria*. Between the end of the seventies and beginning of the eighties, bulldozers were first used in dune management practice. Every bare patch was smoothed by the bulldozer and the entire seaward foredune slope would be visually adjusted to approximately 1:3. Next, *A. arenaria* was planted and subsequently sand fences and a demarcation fence were erected. The bulldozer created topographic differences in the foredune crest to give a more ‘natural’ appearance. Demarcation fences were constructed along the entire coast of Noord-Holland to keep the public out of the foredune area.

The foredunes near Castricum, transects 4200 to 4600, have never been bulldozed. Measures at this location consisted of constructing sand fences and demarcation fences every now and then and occasionally planting of *A. arenaria*.

The implementation of the Dynamic Preservation Policy of 1990 into actual dune management practice, took between 5 to 10 years. As in Rijnland, pre-1990 measures have not been completely abandoned in Noord-Holland. Management measures nowadays consist of vegetation plantings, and construction of sand fences and demarcation fences. Sand fences are still erected in front of sea-side villages to prevent sand from being transported in a land inward direction.

A. arenaria is still planted at locations where vegetation is destroyed by trampling and at locations where the amount of sand transported to the dunes is so high that vegetation is buried. Also, locations where ‘dike-in-dune’ constructions have been built (e.g. at the margins of the Hondsbossche- and Pettemer seadike, near transects 2000 and 2600), *A. arenaria* is planted on a regular basis. Slopes are no longer smoothed using bulldozers, except on rare occasions where there is a direct safety threat of dune collapse after storm induced erosion.

Dynamic features are only allowed on a local scale with the restriction that these features do not recede below a level of +7.5 m NOD (HHNK (1998)). Whenever lowering beneath +7,5 m NOD is imminent, sand fences are erected to stimulate dune growth (Figure 3.6). At many locations, the foredune has extended in a seaward direction and, on a local scale, embryo dunes develop.

Figure 3.6: Dynamic features near Callantsoog, Noord-Holland.

Dune management practice in Rijnland

The dune manager of Rijnland mentioned that the most intense interventions took place at locations which suffered from storm damage. Most activities to recover storm damage started after April 1^{st} and sometimes continued up to August. Locations which always had high maintenance efforts were situated between transects 8300-8600 (between the coastal towns of Noordwijk and Katwijk), around transect 9700 and around 6000-6100 (Parnassia). These high maintenance efforts were due to coastal erosion. A combination of measures was always conducted to restore storm damage rather than a single type of measure; single types of measures, i.e. *A. arenaria* plantings, were only carried out on a small scale e.g. at locations where blowouts developed, and these types of measures were more related to daily maintenance.

Locations with less intense maintenance efforts are situated south of IJmuiden (transect 5800), around Langevelder Slag (transect 7250) and between Katwijk-Wassenaarse Slag (transects 8600-9250). The coast around transect 5800 progrades due to the extension of harbor moles at IJmuiden and therefore erosion hardly occurs. The reason for the low maintenance effort around 7250 is unclear, but according to the manager possibly related to minimum vegetation damage by rabbits and perhaps a more favorable sediment structure than at other locations. Between Katwijk and Wassenaarse Slag, *A. arenaria* is vital and dune crests have a modest height, resulting in a relatively small seaward slope area for maintenance, as compared to other parts of Rijnland.

The entire foredune area has been affected by ground moving equipment to various degrees throughout the period 1965 to 2004. From the mid-seventies to the beginning of the nineties, excavators were used to adjust damaged seaward dune slopes, resulting in slopes of a maximum of 1:2.

Between the end of the seventies and beginning of the nineties, at locations with a high dune a terrace of about 6 meters in width was created at an elevation of +11 to 13 m NOD.

This was called the berm technique. In case storm damage around the dunefoot occurred, a hydraulic crane pushed downward an amount of sand from the terrace to the eroded dunefoot, which equaled the amount of sand lost from the dunefoot. In front of the recovered dunefoot, demarcation fences were constructed, to keep the public out of the dunes. Seaward of the demarcation fences, sand fences were erected, which caused sand accumulation in front of and behind the sand fence. An advantage of the berm method was that the part of the slope above the berm remained mostly intact, and only required some *A. arenaria* plantings on a local scale. Note that the terrace would lower after storm damage (see Figure 3.7). The berm method was applied between transects 5800 to 6200 and 9400 to 9740.

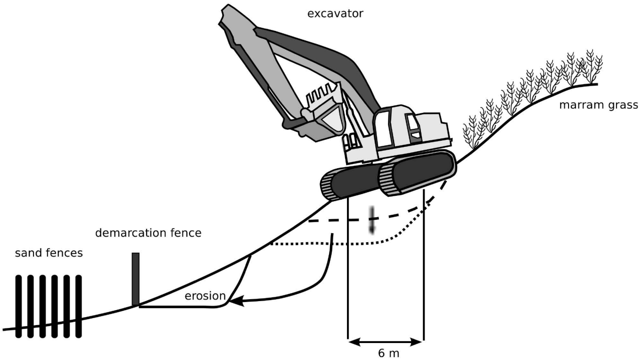

Figure 3.7: The berm method.

The implementation of the coastal policy of 1990 took between 5 and 10 years. Pre-1990 measures have not been completely abandoned however. Wherever infrastructure (roads, parking lots) and buildings are present behind the foredune, around beach entrances and at locations where a ‘dike-in-dune’ is present (in front of the coastal town Noordwijk, since 2008), the dunes are still regularly planted with *A. arenaria*. Sand fences are still constructed at locations where during the summer beach cabinets are present, in order to maintain a high beach level at these locations. Along parts of the coast with less human pressure, traditional management measures hardly take place anymore.

Recovery from storm damage only takes place when dangerous situations might occur. Slope adjustments take place using the excavator. The adjusted seaward slopes are not planted with *A. arenaria* anymore, but instead sods of *A. arenaria* which were removed from the eroded slopes are laid down again.

The foredunes in Rijnland are still characterized by a dense *A. arenaria* cover, with dynamic features as blowouts only present on a local scale. The manager mentions that nitrogen deposition might play a role in maintaining the dense vegetation cover (see also Kooijman (2004), Martinez and Garcia-Franco (2004)), and thereby inhibiting blowout formation.

Figure 3.8: Dense *A. arenaria* cover with blowout in the front near transect 9550, Wassenaar, Rijnland.

3.4.2 Spatio-temporal variation in foredune shape and dunefoot position

This Section presents results on changes in foredune shape and dunefoot position over the time period 1965 to 2004. The selected regions, one in Noord-Holland and one in Rijnland, include areas with high and lower management intensity as well as nourished and non-nourished areas (see Figures 3.4 and 3.5).

In Noord-Holland, transects 3100 to 4600, covering a longshore distance of 15 km, were analyzed. For this region, a total number of 61 transects were analyzed. In Rijnland, 57 transects, from transect number 8300 to 9700, along a 14 km stretch of coast were analyzed. In 2000 and 2002 no Jarkus measurements were conducted in Noord-Holland and Rijnland (De Graaf et al. (2003)). Therefore, these years are missing in the analysis.

Foredune shapes and dunefoot positions in Noord-Holland

Figure 3.9 shows a planview of dune crest heights and slopes between 1965 and 2004 for transects 3100 to 4600, based on the EOF reconstructed profiles.

Crest heights (Figure 3.9 a) show a large longshore variation with rather low foredunes occurring in the northern part of this area and in front of sea-side villages, i.e. transects 3325, 3800 and 4500. The highest dunes are found at transects 3475 to 3525, 4050-4075, 4275 and 4550-4575. To examine the yearly changes in dune crest height, the crest height

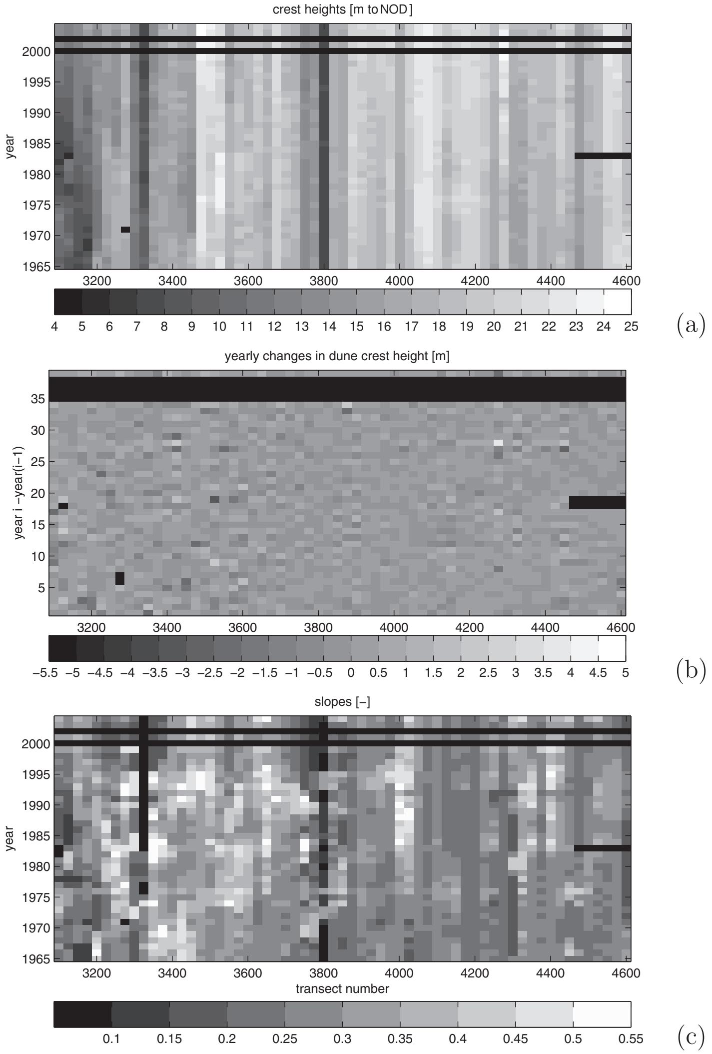

Figure 3.9: Spatio-temporal variation in dune crest height (a and b) and duneface slope (c) for transects 3100-4600 (Noord-Holland) over the period 1965-2004.

of a certain year is subtracted from that of the following year (Figure 3.9 b). Dune crest heights usually change on a yearly basis, with height fluctuations of usually less than 1 m but occasionally up to 2 m. Crest height variations thus occur both in time and space (longshore direction), but longshore differences are larger than the local temporal changes.

The foredune slopes also show large variation in longshore direction (Figure 3.9 c). Steepest slopes of a maximum of about 1:2 are found between transects 3350 to 3750, around 4000 and around 4400. In general, the more gentle slopes show less variability through time. Transects 4200 and 4275 hardly show any slope variability in time. The most gentle slopes of about 1:20 are found at the beach entrances, hence at transects 3325 and 3800. Near Bergen (3325-3450) and Egmond (3725-3800), slopes tend to get more gentle from 1996 onwards.

Figure 3.10 provides information on the duneface shape, expressed as the magnitude of profile concavity or convexity. Most transects show an absolute deviation from the dune slope (the straight line between the dunefoot and dune crest) between 0 and 150 m^2 (Figure 3.10 a). Large values of 150 to 250 m^2 are found at transects 3875, 3975, 4025, 4200 and 4300, although these large values are not persistent through time. Looking at the percentage of positive area with respect to the total area (Figure 3.10 b), we can recognize mainly small (0 to 20%) and large values (80 to 100%) for the period 1965 to about 1995. From 1996 onwards, the smaller values seem to prevail more consistently, with the exception of transects 3100 to 3200 and 4175 to 4550. Hence, at locations where the percentage of positive area decreases, the profile shape becomes more concave.

Figure 3.11 a shows dunefoot behavior with respect to the time-averaged dunefoot position of each transect. The dunefoot positions seem to exhibit a somewhat oscillating pattern, which was previously recognized by Ruessink and Jeuken (2002) and Guillén et al. (1999). For transects 3100 to 3725, up to 1974, the dunefoot has a more seaward position with respect to its time-averaged position, followed by a more landward position up to 1996/1997. Dunefoot behavior between transects 4000 and 4600 alternates between slight seaward and landward shifts with respect to the time-averaged positions.

In some years, the dunefoot shows a large landward position with respect to its time-averaged position. Unpublished records on storm surge heights mention surges with high waterlevels leading to considerable erosion in January 1976, in the Februaries of 1983, 1990 and 1993 and in January 1994. Pictures from water board Noord-Holland show exposure of peat layers and considerable foredune erosion as a result of the February 1983 storm (Figure 3.12). In Figure 3.11 these erosion events can be seen as a strong landward dunefoot position around transect 3300 and 3800. In addition, some ‘patches’ of landward dunefoot positions can be observed for the years 1993 and 1994, when considerable storm damage occurred. The storm of January 1976, which in Noord-Holland reached the highest waterlevel since the storm of 1953, did not leave a profound effect in terms of a strong landward dunefoot position. Only at a few transects, i.e. 3800, 3850, 4125, 4150, 4175, 4250 and 4475 can strong dunefoot retreat be observed. A seaward shift of the dunefoot with respect to time-averaged dunefoot positions occurs at Bergen, Egmond and Castricum from 1996 onwards.

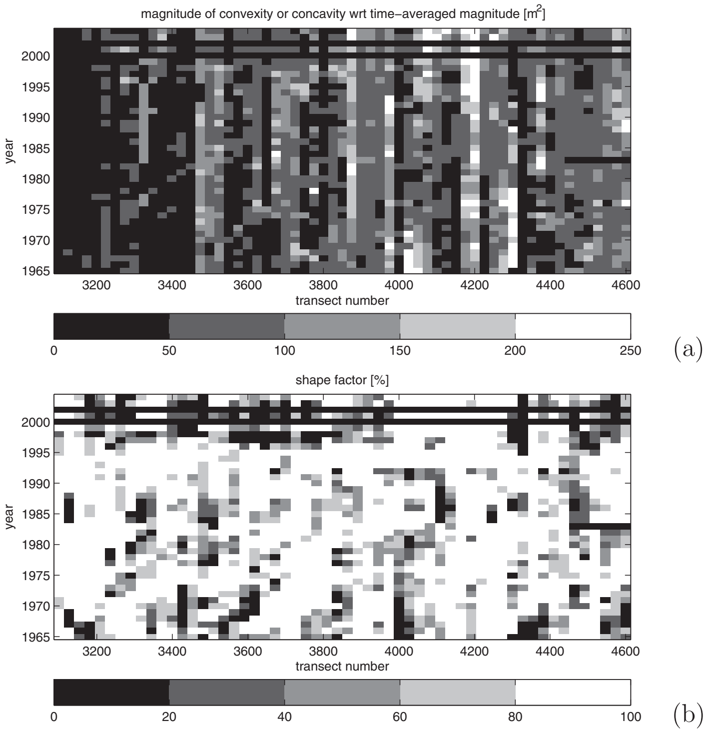

Figure 3.10: Spatio-temporal variation in dune face curvature for transects 3100-4600 (Noord-Holland) over the period 1965-2004.
a. Magnitude of convexity or concavity (Equation 3.6) b. Shape factor: Profile shape predominantly convex or concave (Equation 3.8).

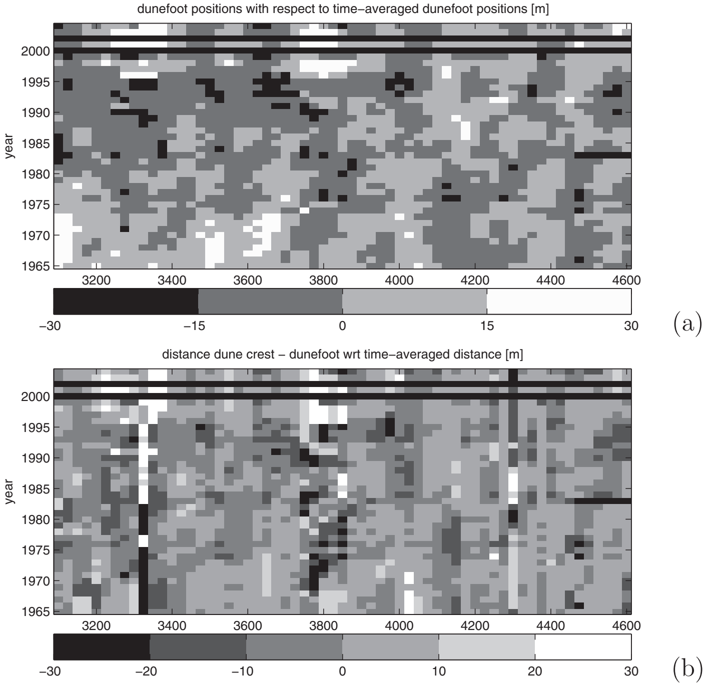

Figure 3.11: Spatio-temporal variation in dunefoot behavior (a) and horizontal distance between the crest and dunefoot (b) for transects 3100-4600 (Noord-Holland) over the period 1965-2004.

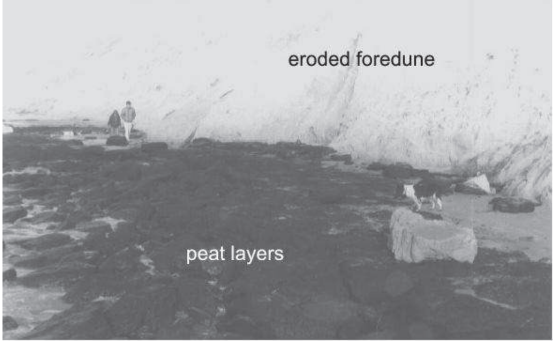

Figure 3.12: Peat layers and eroded foredune due to the February 1983 storm, near Bergen. Courtesy of A. Terhoeve.

The horizontal distance between the dune crest and dunefoot also seems to exhibit oscillating behavior, with deviating behavior at transects 3325 and 3750, which can be ascribed to the presence of beach entrances at these locations.

An increase in distance between dunefoot and dune crest does not necessarily co-occur with a more seaward position of the dunefoot. For instance, between 1965 and 1970, transects 3100 to 3150 show a prograding dunefoot position, while the horizontal distance between the dune crest and dunefoot is smaller than the time-averaged distance of these locations. From 1996 onwards, the distance between the dune crest and dunefoot increases at many locations and often corresponds with prograding dunefoot behavior, e.g. at transects 3350 and 3800.

Foredune shapes and dunefoot behavior in Rijnland

Figure 3.13 shows a planview of dune crest heights and slopes between 1965 and 2004 for transects 8300 to 9700, based on the EOF reconstructed profiles. A discharging sluice is present at transect 8600, so this transect will be omitted from further analysis. Crest heights vary in a longshore direction with lowest dunes between transects 8625 and 8800 (Figure 3.13 a). Highest dunes are found between 8825 and 9200. The low dunes are situated in front of the coastal town of Katwijk, with a boulevard present on top of the dunes. Similar to Noord-Holland, dune crest heights vary almost on a yearly basis, with fluctuations in the order of at most 1 to 2 m (Figure 3.13 b). In some transects height changes of about 4 to 5 m are occasionally observed (e.g. transect 9625 for the difference between 1999 and 1998 and between 1998 and 1997). These years are usually followed by years which also show large height differences, but of the opposite sign, which might suggest that the profile measured in the previous year contains a measurement error. Alternatively, when a large negative value is followed by a large positive value it may indicate that erosional features such as blowouts were counteracted.

Foredune slopes also exhibit spatial (longshore) and temporal variability (per transect) (Figure 3.13 c). Similar to Noord-Holland, the more gentle slopes seem to exhibit less variability through time than locations with steep slopes. Steepest slopes of about 1:2 are not persistent through time. In general, the slopes tend to become more gentle after 1995.

There is a large range in magnitudes of the deviation of the foredune profile from the straight slope (Figure 3.14 a). High magnitudes occur between transects 8825 and 8975 and at 9700, with most values ranging between 200 and 250 m^2.

Figure 3.14 b shows the percentage of positive area with respect to the total area. Throughout almost the entire time period, high values are found between transects 8825 and 9000. Hence, profiles are dominantly convex at these locations. Conspicuous changes occur between transects 9400 and 9700. The percentage positive area was high until 1995 and was followed by low values from 1995 onwards. Hence, dune face shapes at these transects changed from convex to concave. Furthermore, between transects 8575 and 8700 the percentage of positive area decreases from 1995 onwards. Although the percentage positive area has never been high at these locations, from 1995 onwards the low values are more persistent through time.

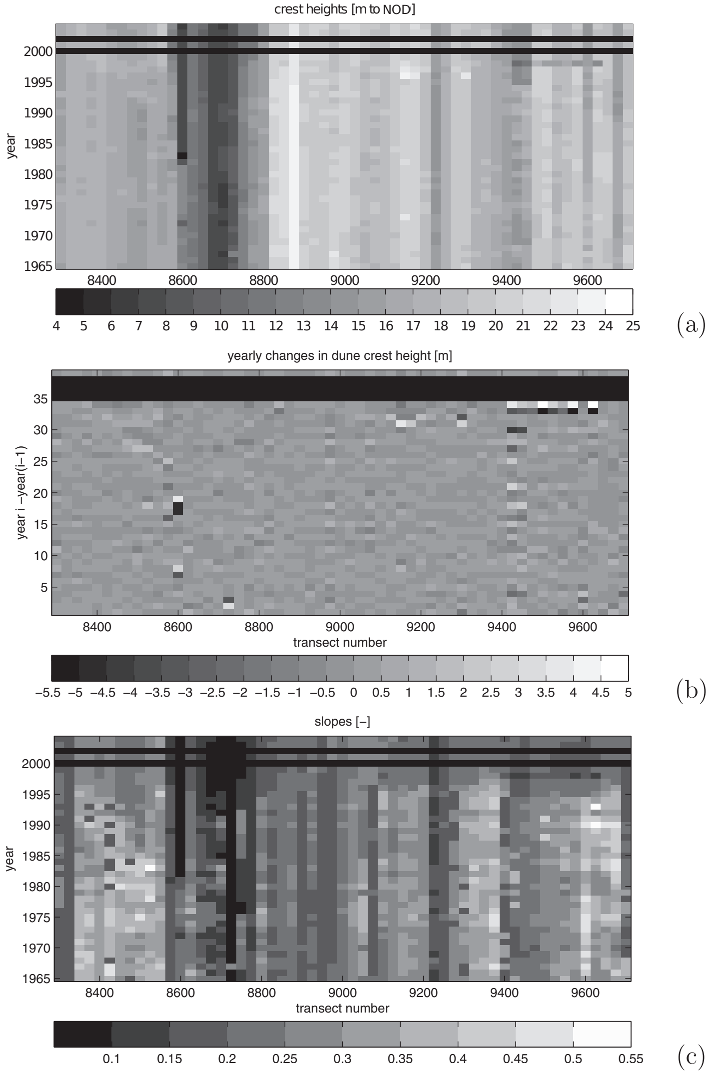

Figure 3.13: Spatio-temporal variation in dune crest height (a and b) and duneface slope (c) for transects 8300-9700 (Rijnland) over the period 1965-2004.

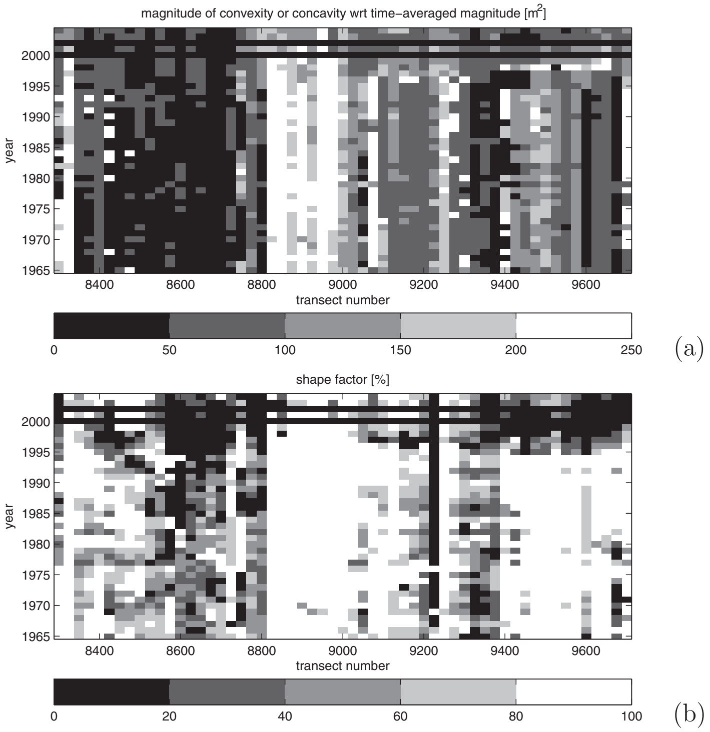

Figure 3.14: Spatio-temporal variation in dune face curvature for transects 8300-9700 (Rijnland) over the period 1965-2004.
a. Magnitude of convexity or concavity (Equation 3.6) b. Shape factor: Profile shape predominantly convex or concave (Equation 3.8).

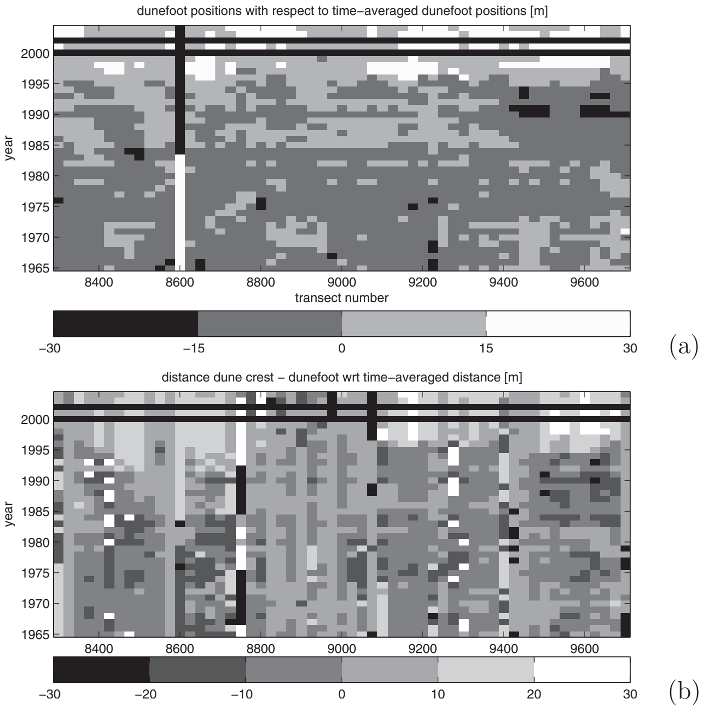

Figure 3.15: Spatio-temporal variation in dunefoot behavior (a) and horizontal distance between the crest and dunefoot (b) for transects 8300-9700 (Rijnland) over the period 1965-2004.

Figure 3.15 a shows dunefoot behavior with respect to the time-averaged dunefoot position of each transect. Up to 1985, almost all transects show a slight landward position of the dunefoot with respect to the time-averaged dunefoot position. From 1985 up to around 1995, this situation changes towards a more seaward position of the dunefoot, and increases further from 1995 onwards. Locally, dunefoot positions were shifted relatively far landward in 1976 at transects 8300, 8800 and 9225 and in the years 1990, 1991 and 1993 at some transects in the southern part of the study area. Apart from 1991, when no severe storms were recorded, these landward dunefoot positions may be the effect of the occurrence of severe storms in 1976, 1990 and 1993, which was also recognized for some transects in Noord-Holland.

The distance between the dune crest and the dunefoot increases by 10 to 30 m for most transects from 1995 onwards (Figure 3.15 b). This does not hold for transects 8325, 8775, 8825 to 9000, 9075 and 9400, which mainly show a decrease in the distance between the crest and the dunefoot.

3.5 Relation between long-term foredune evolution and foredune management

3.5.1 Intervention intensity and morphologic variability

Foredune profile characteristics change in time and space. Based on the results of the interviews with the dune managers, we expect the difference between intensely and extensively managed transects to be illustrated by one of the following two (hypothetical) situations: The first situation suggests that locations which are intensely managed are more static through time and space than less intensely managed transects. In this case, intervention measures are thus successful in fixating the dunes. The second situation, as opposed to the first situation, is that the most intensely managed locations are those which are most dynamic, that is which show the largest variability in time. The more extensively managed locations on the other hand show less variability, and this lower variability results in less intervention measures. Some examples will now be given to illustrate these situations.

Transects 4200 to 4600 in Noord-Holland have not been bulldozed during the period of analysis. Since bulldozing results in creating gentle slopes of about 1:3 (see Section 3.4.1) and since bulldozing was carried out almost on a yearly basis to recover storm damage, we might expect the slopes in the bulldozed-free area to show more variability through time as a result of natural processes whose imprints on foredune morphology would not be erased by ground moving equipment. Hence, at certain years foredune slopes might be expected to be more steep at the non-bulldozed transects in this area, since post-storm erosion profiles were not flattened. However, this expectation could not be confirmed in this area. Rather, transects that have a steep slope in certain years occur throughout the bulldozed and non-bulldozed sections of the study area. Possibly, since the coast between transects 4200 to 4600 was more stable and dunes were therefore less prone to erosional events, bulldozing was not necessary at these locations. In addition, natural causes might have caused the dunes to have a more gentle slope than at the more intensely managed locations. Hence, less intensely managed locations do not show larger morphologic variability than the more intensely managed locations.

In the case of Rijnland, transects 8300 to 8600 and 9400 to 9700 were characterized by highest maintenance efforts up to 1990, with the berm technique having been applied between transects 9400 and 9700 (Section 3.4.1). Transects 8600 to 9250 had relatively low maintenance efforts. Despite the difference between intensely and more extensively managed locations, no large differences were found in dune crest height, horizontal distance between dune crest and dunefoot, profile curvature and dunefoot positions between the intensely and extensively managed transects. The results of Rijnland show that only a few transects show little variation through time for certain profile characteristics and also that these transects occur both in extensively and intensely managed regions. For instance, at transects 8325 and 8950 the slopes, the deviation magnitude of the duneface from the straight slope and the horizontal distance between the dunefoot and crest vary only slightly during the studied period.

Therefore, differences in morphologic variability seem to be more related to autonomous coastal developments (natural developments without human interference) than to management interventions. Most pre-1990 measures only stimulated what would have happened under non-managed circumstances as well, but likely at a faster rate than under natural circumstances.

3.5.2 Intervention type and morphologic variability

Similar to intervention intensity, no clear relationship can be established between intervention *type* and foredune morphology. This was already partly illustrated in the previous Section, which showed that for transects 3100 to 4600 no relationship could be found between gentle dune slopes and bulldozing as intervention measure. The reason of the discrepancy between the slopes of 1:3 after bulldozing which was mentioned by the dune manager in Noord-Holland and the sometimes steeper slopes of 1:2 at e.g. transects 3350 and 3425 remains unclear. Possibly, natural developments and additional measures as *A. arenaria* plantings and sand fence construction might have partly erased the effects of ground moving equipment. Hence, using a combination of measures might reduce the possibility to establish clear relationships between the type of measure and foredune morphology.

Nourishments on the other hand, seem to have caused large changes in dune morphology, especially at locations that have been most intensely nourished (Figure 3.2). These morphological changes are most strikingly expressed as changes in foredune curvature and dunefoot changes from about 1995 onwards. The most plausible reason why nourishments lead to changes in morphology is that this type of interventions intervenes with the system boundary conditions, resulting in a change of dune type.

The differences in foredune morphology prior to and after the onset of large-scale nourishments can be summarized as follows. Prior to 1990, most interventions aimed at recovering storm damage. However, these interventions did not prevent erosion to occur, but did more likely speed up the recovery rate of the dune. Therefore, *before* 1990, management interventions can considered to be *reactive*: Measures were carried out as a response to natural processes (e.g. storm-induced erosion). Hence, measures did not interfere with forcing processes, such as the supply of sand. Carter and Stone (1989) for instance mention that dune plantings do not reduce erosion, but may only alter the way foredune failure takes place during a storm. As a consequence, stabilizing measures seem to be effective only on the time period between two consecutive storms which induce dune erosion.

With the large-scale nourishment projects, sand is artificially added to the beach-dune system, and hence, nourishments do alter the seaward boundary conditions. This artificially created sand buffer might largely prevent erosion to take place and as a result, the dunes become more uniform in shape. Hence, the intervention method after 1990 can considered to be *proactive*.

Following the ideas of Bakker et al. (1979), these differences between reactive and proactive interventions can conceptually be placed in their dune landscape model.
This dune landscape model shows that the effects of intervention measures might leave an imprint in the landscape at different spatial and temporal scales. Factors and processes at the top dominate over processes and factors at lower levels. Hence, the effects of ground

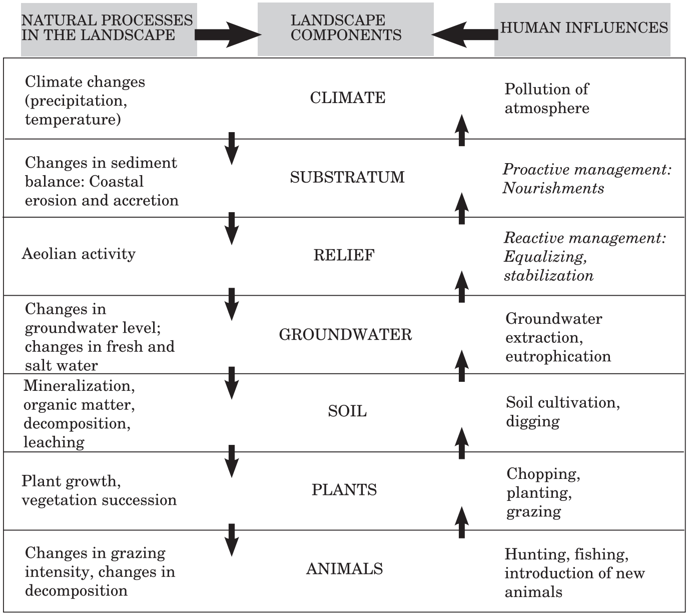

Figure 3.16: Dune landscape model. Adapted from Bakker et al. (1979).

moving equipment will leave a more profound effect on the foredune than plantings and sand fences. The model also shows that changes in substratum dominate over changes in e.g. relief and plants. Hence, nourishments, the proactive type of intervention measure, alter the substratum, while reactive intervention measures, such as human-induced changes in relief (using ground-moving equipment) and human-induced changes in vegetation (planting of *A. arenaria*) operate on a lower scale level. We can thus expect the effects of nourishments in terms of changing foredune morphology to occur over longer longshore distances. This is for most profiles represented by the increase in slope concavity starting around 1995/1996.

3.6 Discussion

The Jarkus data-set has a number of limitations, which should be considered when interpreting the data and in drawing conclusions from this interpretation.

Cross-shore resolution

The coastal manager of Rijnland mentioned the construction of a berm over large distances (see Section 3.4.1). These berms, with a horizontal extent of about 6 m, could not be detected in the Jarkus profiles. This has to do with the spatial resolution of the Jarkus data: Measurements are taken at 5 m intervals, hence, small-scale interventions, which may have a profound effect on dune morphology, cannot always be detected as such.

Longshore resolution

In Noord-Holland, the number of dynamic features increased after implementation of the Dynamic Preservation Policy. However, since the number of these features is still rather limited and because of the limited dimensions of these features and their occurrence between transects, this increase in dynamics could not be confirmed in our study.

Temporal resolution

The reason that the effects of severe storms in terms of dunefoot retreat was not always observed (e.g. in 1976 and 1980 hardly any erosion was observed for most transects in Noord-Holland and Rijnland), is possibly due to the timing of the Jarkus measurements and the onset of post-storm recovery measures: Most storm damage in 1976 and 1980 had already been recovered before Jarkus measurements were carried out. Only at a few transects, erosional marks due to winter storms are present in the measurements, while for most transects, this seasonal information is either underestimated or erased, because the dunefoot erosion is already (partly) restored. This was also discussed for the Sefton coast in the UK by Pye and Blott (2008). Thus, the behavior of the dunefoot does not always adequately reflect the net yearly erosion/accretion rates, but can be seasonally biased. This might also have effects on the entire seaward dunefront characteristics, but since erosion is usually concentrated around the dunefoot position, and the largest part of the slope remains more or less unaffected, this erosion effect will become less pronounced while considering the entire seaward facing slope.

Length time series

In Rijnland, the number of dynamic features as blowouts and breaches was still rather limited after 1990. Kooijman (2004) relates this to a decrease in storm activity between 1990 and 2000 and to an increase of wet years in the same period. The coastal managers also mentioned a decrease in storm activity since the 1990s, with the exception of the particularly stormy years 1990, 1993 and 1994. Hence, in this case the length of the time series used in our study might be a limiting factor in detecting a possible increase in dynamics.

3.7 Conclusions

This case study aimed at establishing a quantitative relationship between intervention measures and foredune morphology on a time period of decades. Interviews with dune managers provided detailed information on both measure type and measure intensity throughout the time period 1965 to 2004. Because of this long time period and the data restrictions, this relationship could only be examined at an aggregated spatial and temporal level. As a result, the Jarkus database proved to be effective only in establishing a general relationship between foredune morphology and intervention measures, such as the increase in duneface concavity due to nourishments. The Jarkus database proved to be less suitable in detecting small-scale morphologic features. For example, the artificially created berms in Rijnland could not be detected, even though these measures clearly affected foredune morphology.

At this aggregated level, a clear distinction could be made in foredune morphology before and after 1990. Prior to 1990, interventions were mainly aimed at recovering storm damage and can therefore be characterized as a reactive type of intervention method. Despite these interventions, morphologic variability in time (i.e. variability per transect) and in space (variability between transects) remained. Autonomous coastal developments are considered to have played the most important role in foredune shape variability and dunefoot behavior during the period 1965 to 1990. After 1990, intervention methods are proactive. Sand is artificially added to the beach-dune system to prevent erosion to occur. This buffer has decreased morphologic variability between transects.

The increase of dynamic features such as blowouts during 1990 and 2004 was very localized in space. Whether this is due to the effects of nourishments or to a decrease in storm activity or both remains to be investigated.

Therefore, on a decadal-scale time period, a qualitative relationship could be established between foredune morphology and intervention measures when this concerned measures that affected large parts of the foredune. This mainly applies to nourishments, with foredunes becoming more concave-shaped in profile.

Acknowledgments

The following persons are thanked for their help and time in answering the many questions we had and for providing useful documentation: Leen van Duijn from water board Rijnland and Adri Terhoeve, Rob Buursink, Petra Goessen and Joost Veer from water board Noord-Hollands Noorderkwartier.
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Chapter 4

The role of human interventions on long-term foredune evolution

It is a capital mistake to theorize before one has data

Sir Arthur Conan Doyle, A Scandal in Bohemia

Abstract
The purpose of this study is to understand how intervention measures affect foredune morphology at time periods of years to decades. We examine the evolution of an artificially initiated foredune on the barrier island of Schiermonnikoog, the Netherlands. Using aerial photographs and annual cross-shore profile measurements, the evolutionary history of the foredune over the last 57 years is reconstructed. We conclude that it is not so much the type of measure that is carried out that affects foredune morphology on time periods of years to decades, but rather the intervention method, or approach, underlying the measure. A distinction can be made between reactive and proactive intervention methods. Reactive methods, that aim at erasing erosional features in the foredune, have less morphological impact on the foredune at the time scale of interest than proactive intervention methods, that aim at preventing erosion. Furthermore, it is concluded that an understanding of system behavior at scales larger than that of primary interest is needed to adequately assess the possible effects of intervention measures on foredune morphology. The insights obtained from this study can be used in qualitatively assessing the effects of human interventions on foredune morphology over time periods of interest for coastal management.

Keywords: artificially initiated foredune, intervention method, intervention approach, sediment-sharing system, decadal-scale

4.1 Introduction

Effects of human interventions on foredune morphology are well studied on process-scales (e.g. Gares (1990); Hotta et al. (1991); Nordstrom (2000)). However, in designing sustainable coastal management schemes and also in developing models to simulate long-term coastal behavior, it is important to gain insight into the effects of human interventions on foredune morphology at temporal scales in the order of 10 to 10^2 years and spatial scales in the order of 10 to 10^2 km (French and Burningham (2009)). This is especially important for the future flooding defense function of the foredunes as sea level and storm climatology are expected to change in the near future.

Bochev-van der Burgh et al. (2011) and Bochev-van der Burgh et al. (2012) examined the decadal-scale cross-shore morphologic variability of foredunes along the central part of the Netherlands' coast. The foredunes along this coastal stretch have a long history of management interventions, dating back to at least the 15^{th} century (Schoorl (1973)). Bochev-van der Burgh et al. (2012) make a distinction between reactive and proactive intervention methods. In the case of a reactive intervention method, measures are carried out after erosional features have developed in the foredune. This intervention method thus aims at restoring the foredune morphology to its pre-erosional state. Proactive methods aim at preventing erosion of the existing foredune, for instance through creating a buffer by means of nourishments, either directly (for instance through a nourishment at the dunefoot) or indirectly (e.g. through a beach nourishment). In the case of the Central Netherlands' coast, reactive measures included vegetation plantings (of *A. arenaria* (marram grass)), sand fence erections and the use of ground moving equipment. Proactive measures consisted of nourishments.

In the case described above it appeared that, at the decadal-scale, nourishments had a more profound effect on foredune morphology than the measures that were characterized as being reactive. Based on their effect on foredune morphology at the decadal-scale, the different measures were ordered using the concept of a hierarchical structured dune landscape with natural processes and intervention measures interfering at different levels in the hierarchy, based upon the ideas proposed by Bakker et al. (1979). Proactive measures – in this case nourishments – were considered to operate at a higher hierarchical level than the reactive measures (e.g. vegetation plantings), thereby having a more pronounced effect on cross-shore foredune morphology at the decadal-scale than the reactive measures.

Since in the case outlined above two ‘variables’ (method and measure) were considered at the same time, it was not possible to determine whether the intervention method is more important in affecting the decadal-scale morphologic variability of the foredunes, or rather the intervention measure.

In this paper, we examine the decadal-scale morphologic effects of measures that are placed at a low level in the hierarchy of Bakker et al. (1979), but which are applied in a proactive manner. A case study is presented regarding the evolution of an artificially initiated foredune, generally referred to as a sand drift dike, on the barrier island Schiermonnikoog, the Netherlands. In this case study, measures that were placed at a low level in the hierarchy, namely vegetation plantings and sand fence erections, were used in a proactive way, to artificially initiate the development of a foredune. If the hierarchical ordering of measures as proposed by Bakker et al. (1979) holds to be true, little to no observable morphological effects of vegetation plantings and sand fences are to be expected at the decadal-scale. If, on the other hand, the way the measure is being applied (reactively or pro-actively) proves to be of greater importance in affecting cross-shore foredune morphology at the decadal-scale, this would imply that the position of a measure in the hierarchy depends on the intervention method.

Besides the aim mentioned above, the initiation and development of the artificially initiated foredune at Schiermonnikoog is of specific interest to study, since there are some contradictory accounts on its initiation and development (see Van Tooren et al. (1993); Oost and De Boer (1994); Ten Haaf and Buijs (2008); Hoekstra et al. (2009); De Groot (2009)). Therefore, the secondary aim of this study is to provide a more conclusive account on the history of this foredune. To achieve both aims, aerial photographs and annual cross-shore profile data are used to examine the evolution of the foredune from its initiation phase during the late 1950s up to 2009. In addition, a dune manager was interviewed who was involved with dune maintenance practice at Schiermonnikoog.

4.2 Study area description and intervention history

Schiermonnikoog

Schiermonnikoog is a barrier island situated in the Wadden Sea, in the south-eastern part of the North Sea (Figure 4.1). The island is approximately 15 km long (from west to east) and 0.5-3 km wide (from north to south) (De Groot (2009)). The mean annual significant wave height is 1.1 m and the dominant wave direction is from the north-west, which results in an easterly directed residual sediment transport (Israel and Dunsbergen

(1999)). Due to this eastward directed longshore drift and due to changes in the tidal inlets, the island has migrated in a south-eastern direction since the Middle Ages (Oost and De Boer (1994)). Presently, the island extends at the eastern part, which results in the formation of new beach plains, dunes and salt marshes (De Groot (2009)). The North Sea coast of Schiermonnikoog can be classified as a mixed-energy, mesotidal coast (Hoekstra et al. (2009); Oost and De Boer (1994)). Winds mainly blow from the west (70 % of the time), while shore perpendicular, northerly winds induce most onshore directed sand transport on the beach (Van der Wal (2004)).

Oost and De Boer (1994) and Oost et al. (1993) point out that along the North Sea coasts of the Wadden Sea Islands sites of erosion and sedimentation shift in an eastward direction following a wave-like pattern. These patterns have a period of 18 to 19 years and are mainly responsible for erosion and sedimentation along the North Sea coasts, since they dominate the higher order, annual scale sedimentation and erosion patterns attributed to seasonal variations. According to Stolk (1989), the North Sea facing coast of Schiermonnikoog has been prograding at a rate of 4 to 5 m/yr and the sediment budget of the dune area is slightly positive (4 m^3/m/yr, in the period 1997 to 2008) (Arens (2009)).

The western part of the island, roughly between cross-shore profile measurement locations (hereafter referred to as transect numbers) 100 and 700, is characterized by a large dune complex consisting of foredunes, parallel dune ridges and parabolic dunes (Hoekstra et al. (2009)). The central part of the island is characterized by former beach plains, eroded dune valleys and the artificially initiated foredune (see Figure 4.2). The eastern coast of the island is a washover region, where foredunes and remnants of the artificially initiated foredune alternate along the coast (Hoekstra et al. (2009)). Inland, a large salt marsh is present, which is drained by several creeks, that are roughly oriented north-south. Some of these creeks (notably the 4^{th} and 5^{th} creek, see Figure 4.3) are connected to overwash channels in the north (De Groot (2009); Oost and De Boer (1994); Hoekstra et al. (2009)).

Intervention history

Although the coast does not suffer from structural erosion and dune erosion during storms is limited, the dune area has not been free from human interventions (Figure 4.3).

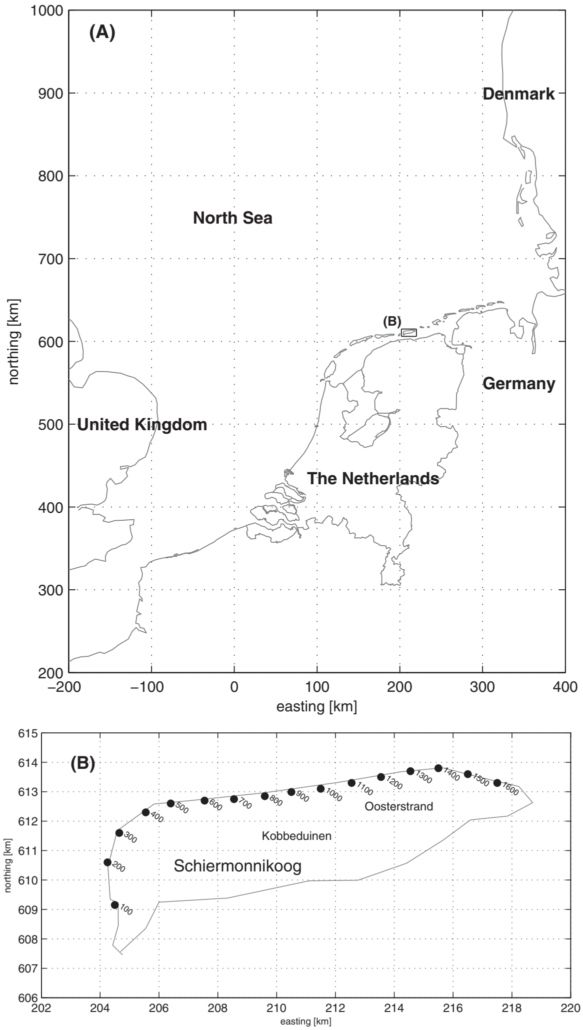

Figure 4.1: Location of the study area. The numbers refer to the locations of cross-shore profile measurements along a number of permanent beach poles (RSP locations).

Overall, intervention intensity reached a peak in the 1980s. Up to 1990, measures consisted of sand fence erections and marram grass (*A. arenaria*) plantings, although once an excavator was used between transects 500 and 660 to lower the foredune crests (pers. comm. C. Visser, *Rijkswaterstaat*). The main purpose of the applied interventions was to prevent land inward sand drift and to stimulate foredune growth. Recovery of scarped dune fronts took place through sand transport by wind from the beach to the dunes. The dunes between transects 100 and 500 are part of the sea defense and were subject to highest maintenance efforts on the island. Management intensity was lower between transects 500 to 700.

Figure 4.2: The artificially initiated foredune around RSP location (transect number) 700, June 2006. Courtesy of Alma de Groot.

Management intensity between 700 and 1000 was high in the late 1950s, when the growth of a foredune was stimulated (pers. comm. C. Visser). The initiation of the foredune was realized through erecting sand fences and vegetation plantings. The sand fences consisted of sticks and branches that were stuck vertically into the beach plain (Oost and De Boer (1994)). During the first years of foredune initiation, these measures were carried out on a yearly basis, during winter season. During summer time, natural growth took place (pers. comm. C. Visser). Some years after its initiation, intervention intensity at the foredune greatly decreased (pers. comm. C. Visser). The purpose of the foredune initiation was to prevent the island from breaching during storm surges (Van Tooren et al. (1993); Grootjans et al. (1999)). Prior to the initiation of the foredune this part of Schiermonnikoog consisted of a broad beach plain with isolated dunes. Due to the development of the artificially initiated foredune, a large part of the beach plain was cut off from direct influence of the North Sea (De Groot (2009)). This greatly stimulated the growth of a salt marsh that was already present south of the beach plain.

Table 4.1 summarizes different accounts on the evolution of the artificially initiated foredune. This table shows that although in some cases the same type of source was used to describe the evolution of the artificially initiated foredune, there is no uniform agreement with respect to the timing of the initiation phase, the phase of foredune extension, the timing of foredune breaching and the point in time when interventions ceased.

In 1990 there was a change in coastal policy, which resulted in complete abandonment of interventions within a year time along the entire coast of Schiermonnikoog. Since then, only gaps in the dunes due to pedestrian trampling are filled up (pers. comm. C. Visser) (Figure 4.3). Schiermonnikoog has never been nourished.

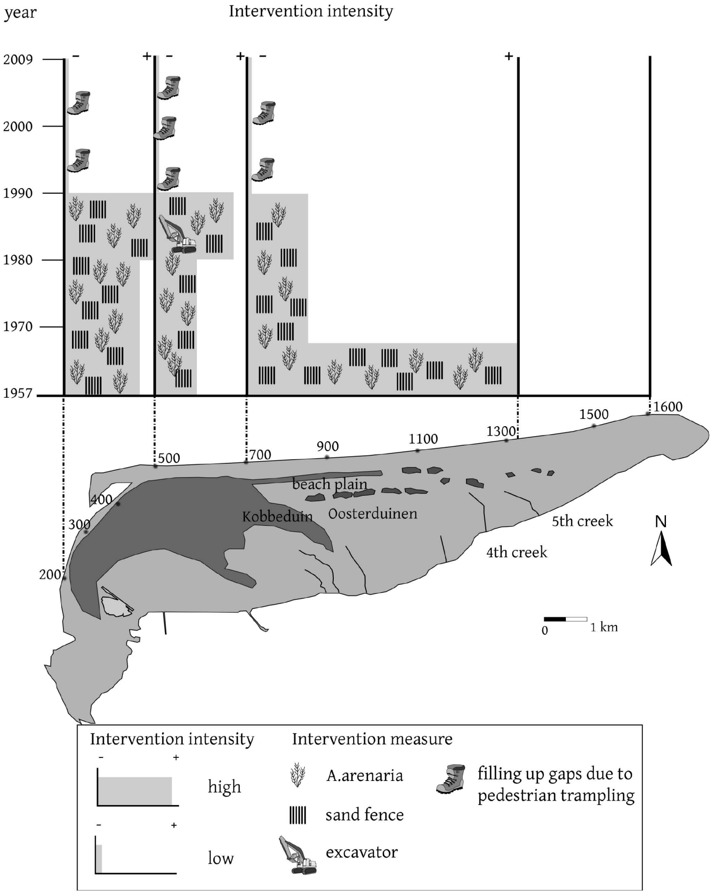

Figure 4.3: Intervention measures and intensities from 1957 to 2009. The numbers refer to the transect locations (Jarkus profile measurement locations).

Author	Period of initiation and transect numbers	Extension of foredune and transect numbers	Breaching and transect numbers	Stop maintenance and transect numbers	Source
Van Tooren et al. (1993)	1957-1959, between transects 700 and 1400	-	frequent breaching up to 1972	1972, east of 1040	unknown
Oost and De Boer (1994)	1950-1978, no transect numbers provided	-	e.g. at transect 1000, no dates provided	1984, no transect numbers provided	unknown
Ten Haaf and Buijs (2008)	1957-1959, between transects 720 and 1000	in 1968 extension from transect 1000 to just east of transect 1300	in 1968 breaching at transects 1000 and 1100, in 1976 breaching at locations of former washover systems	-	aerial photographs and Jarkus measurements
Hoekstra et al. (2009)	start in 1959 up to early 1960s, no transect numbers provided	-	1969 and 1976	1983, no transect numbers provided	aerial photographs
De Groot (2009)	1959, no transect numbers provided, but originally a length of 5.5 km	-	-	unclear, but reshaping of foredune in 1970 and total reworking east of *4th* creek in 1989	aerial photographs, Oost and De Boer (1994), Rijkswaterstaat (1991)

Table 4.1: Written documents on the artificially initiated foredune.

4.3 Methods

4.3.1 Coastal cross-shore profile data

To examine the development of the artificially initiated foredune, a number of transects (cross-shore profile measurements) is examined. These transects are obtained from the Jarkus database. The Jarkus database contains annual cross-shore coastal measurements since 1965, hence starting some years after the initiation of the artificially initiated foredune. The measurements usually extend from the foredune crest (but often even further landward) to about 1000 m seaward. Measurements are carried out with respect to a series of permanent beach poles along the coast (RSP). Measurements were first carried out by means of leveling, followed in 1977 by aerial photography and since 1996 by means of laser altimetry (Minneboo (1995)). The alongshore distance between the transects is approximately 200 m. For the sub-aerial part of the coastal profile, elevation measurements are taken at 5 m intervals (Van der Wal (2004)). We examined the time period 1965 up to and including 2009. No surveys are available for the years 1998, 2001 and 2003. We examine both cross-shore profiles to provide a comprehensive insight into the cross-shore morphological variability at individual transect locations, as well as planviews at certain moments in time that capture the entire artificially initiated foredune.

For the planviews, the cross-shore distances (i.e. along a transect line) were exaggerated 5 times to improve the visibility of the foredune in the planviews. Subsequently, the adapted Jarkus coordinates were transformed to the national grid reference system (RD (Rijksdriehoek) coordinate system), after which the elevation values were linearly interpolated.

4.3.2 Aerial photography

Aerial photographs from 1952, 1959, 1969 and 1980 are used to expand the analysis both in time as in space. The photographs add both larger areal coverage and higher spatial resolution between transect locations than the Jarkus measurements, but lack elevation information. The aerial photographs were digitized, geometrically corrected and adjusted by Ten Haaf and Buijs (2008) to study the morphological development of washover systems at Schiermonnikoog (Hoekstra et al. (2009)). The photographs were geo-referenced in the RD coordinate system, such that the positive y-axis points to the geographic north.

The aerial photographs have as great advantage that they show the situation at the island at specific moments in time some years before the initiation of the artificial foredune, during the initiation stage, and also after the initiation. The colors of the photographs of 1952, 1959 and 1969 are inverted to enhance the distinctness of the artificially initiated foredune.

4.4 Morphological evolution of the artificially initiated foredune

4.4.1 Aerial photographs

The aerial photographs are shown in Figures 4.4 to 4.7. In 1952, the entire area east of the Kobbeduinen consists of a beach plain with scattered low dunes, known as 'eye dunes' (Hoekstra et al. (2009)) (panel A in Figure 4.4). The aerial photograph of 1959 shows the presence of the artificially initiated foredune between transects 700 and 1000 (Figure 4.4 B and Figure 4.5). The area east of transect 1000 still consists of a beach plain with eye dunes dissected by washover channels. Some of these washover channels are connected to tidal creeks in the south.

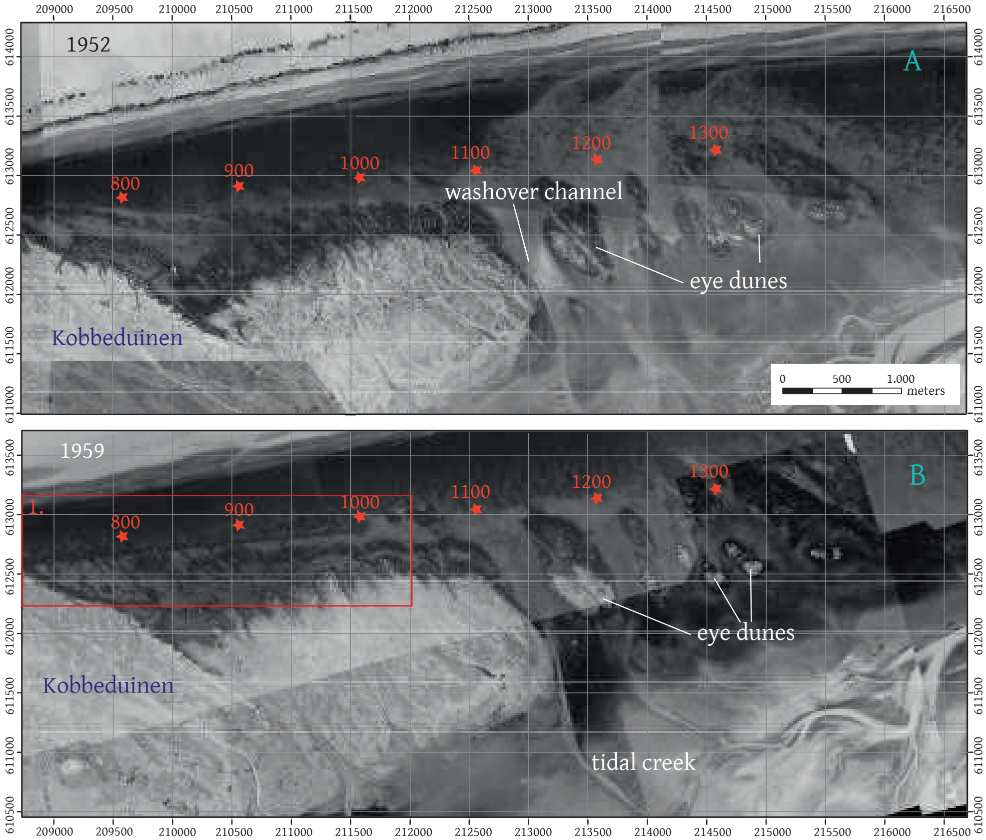

Figure 4.4: Aerial photographs of 1952 and 1959.

Figure 4.5: Zoom of artificial foredune in 1959. The numbers refer to the transect locations.

In 1969, the artificially initiated foredune extends up to transect 1300 (panel A in Figure 4.6 and Figure 4.7). Thus, somewhere between 1959 and 1969 the artificial foredune initiation was extended in an easterly direction, adjoining the existing artificially initiated foredune.

The orientation of the foredune between transects 1000 and 1300 differs from the orientation of the foredune between transects 700 and 1000. In the 1969 photograph it appears that the foredune between transects 1000 to 1300 more or less follows the coastline contour (which is roughly directed SW-NE), while the orientation of the artificially initiated foredune between transects 700 and 1000 is more directed towards the W-E. In 1980, washovers dissect the artificially initiated foredune at several locations between transects 1000 and 1300 (B in Figure 4.6). West of transect 1000, the artificially initiated foredune develops into an uninterrupted foredune.

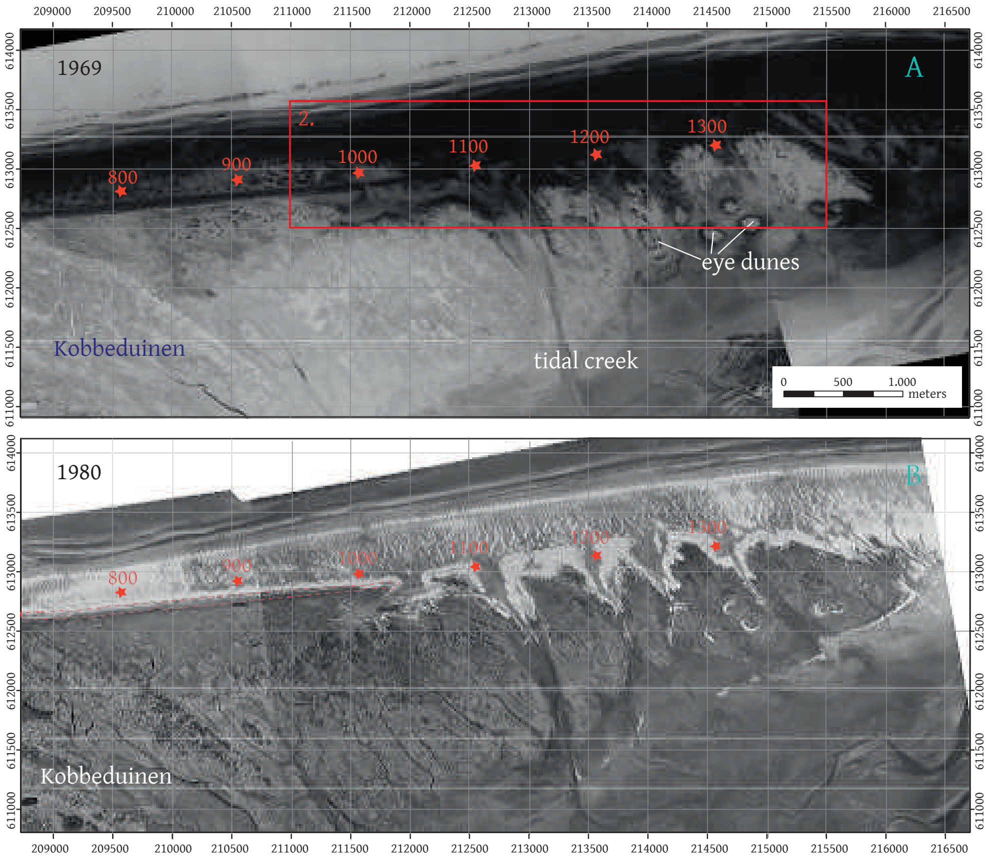

Figure 4.6: Aerial photographs of 1969 and 1980.

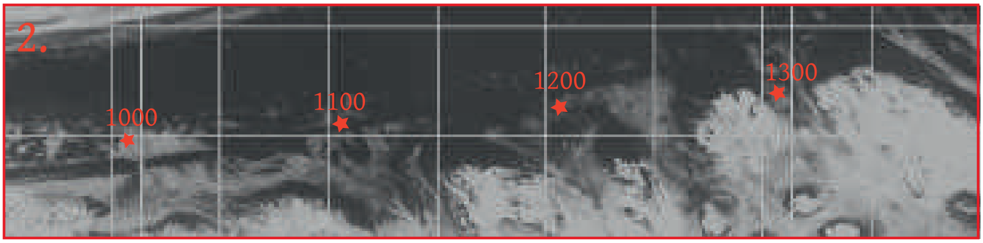

Figure 4.7: Zoom of artificial foredune in 1969. The numbers refer to the transect locations.

4.4.2 Profile data

Figures 4.8 and 4.9 provide an overview of the development of the artificially initiated foredune based on the Jarkus data.

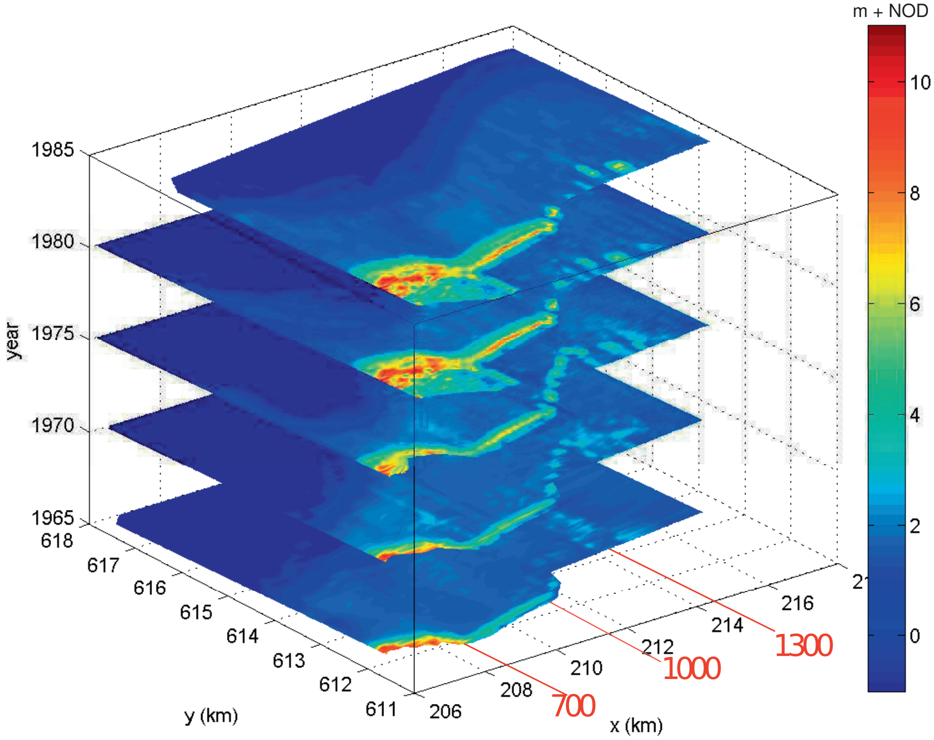

Figure 4.8: Planview of the evolution of the artificially initiated foredune between 1965 and 1985. Transect numbers are indicated in red.

Between 1965 and 1980, the artificially initiated foredune between transects 700 to 1000 generally increases in height. The orientation of the foredune in this area is more or less similar to that of an existing (natural) foredune west of transect 700, that is west of x-coordinate 208.5, although the artificially initiated foredune has a more landward position than the natural foredune (Figure 4.8).

By 1970, some foredune development can also be observed east of transect 1000, although the foredune does not seem to develop into an uninterrupted dune here. Also, the orientation of this dune differs from the orientation of the artificially initiated foredune between transect numbers 700 and 1000, which was also observed in the aerial photographs.

In 1980, the foredune east of transect 1000 is clearly dissected at several locations by washovers, while some parts of the foredune that continue to exist increase further in height, notably between transects 1000 and 1100.

By 1985, a new foredune develops around 50 meters seaward of the artificially initiated foredune between transects 700 and 1000, which also occurs seaward of the natural foredune west of transect 700 (west of x-coordinate 208.5) (Figure 4.8) (see also Wijnberg et al. (2011)). East of transect 1000 some scattered dunes develop, but their cross-shore position differs from that of the artificially initiated foredune between transects 1000 and 1300. Figure 4.9 gives an impression of the evolution of the artificially initiated foredune between 1990 and 2009.

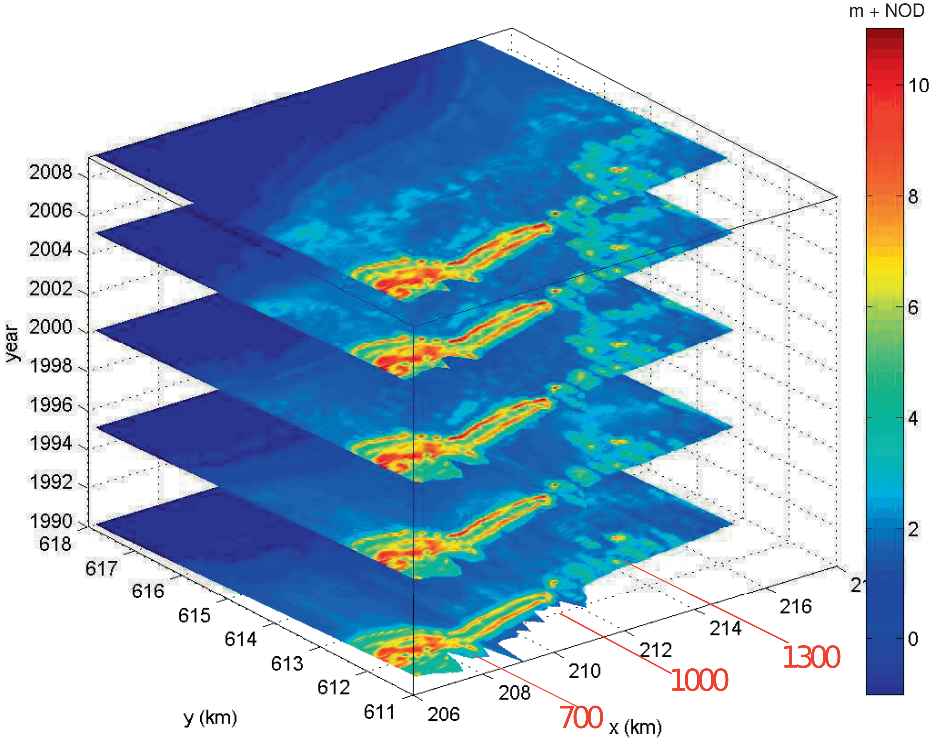

Figure 4.9: Planview of the evolution of the artificially initiated foredune between 1990 and 2009. Transect numbers are indicated in red.

Around 1990, the natural foredune that started to develop between transects 700 and 1000 since 1985 has already obtained a crest height similar to that of the artificially initiated foredune. The area east of transect 1000 shows some scattered dunes with crest heights comparable to that of the artificially initiated foredune between 700 and 1000 and the natural foredune. These dunes occur land inward of the previous artificially initiated foredune and also some low dunes seaward of the previous artificially initiated foredune location develop.

The growth curve of the artificially initiated foredune between transects 700 and 1000 is represented in Figure 4.10. In 1992, the crest height of the natural foredune exceeds the crest height of the artificially initiated foredune (Figure 4.10 a). Up to 1975, the cross-shore position of the crest of the artificially initiated foredune changes considerably, while after 1975, the crest position more or less stabilizes. The largest fluctuations in time in cross-shore crest position of the natural foredune occur prior to 1992 (Figure 4.10 b).

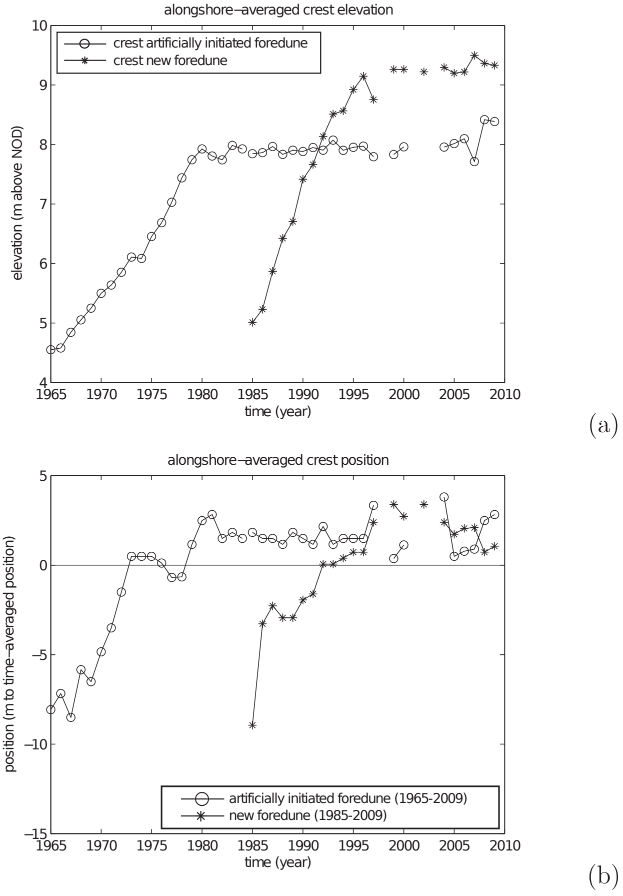

Figure 4.10: Temporal development of the artificially initiated foredune between transects 700 and 1000. After Wijnberg et al. (2011).

The evolution of the artificially initiated foredune between transect numbers 1000 and 1300 cannot be captured in a single growth curve, since in this area, different modes of morphological evolution are distinguished. Overall, the initiation of the artificial foredune between transects 1000 and 1300 is recognized as starting around 1968 (Figure 4.11).

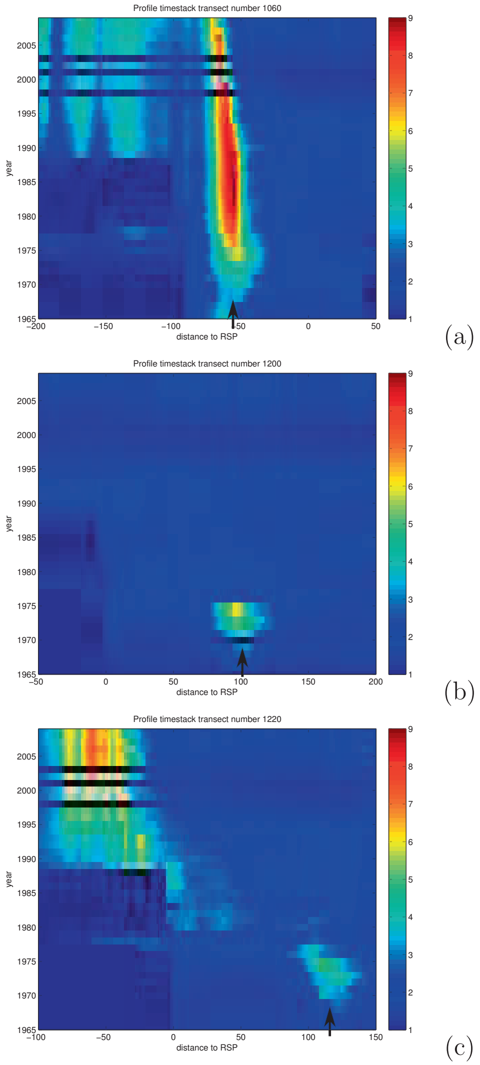

Figure 4.11: Typical examples of the evolution of the artificially initiated foredune between transects 1000 and 1300. Arrows indicate the location of the artificially initiated foredune.

Subsequently, the temporal evolution of the foredune at transects 1020, 1060 and 1080 is similar to evolution of the foredune between transects 700 and 1000; the foredune increases in height through time, but at these locations, a new foredune in front of the artificially initiated foredune from 1985 onwards, does not develop (Figure 4.11 a). At transect 1200, foredune evolution can be seen up to 1975. In 1976, the foredune does no longer exist. Since then, a washover occurs (Figure 4.11 b). The existence of a foredune up to 1975, followed by the occurrence of washovers also takes place at transects 1040 and 1120. Finally, at some locations we observe the growth of a dune starting around 1990 (Figure 4.11 c).At these locations, the new dune develops at a more land inward position than the position of the artificially initiated foredune, and therefore seems to develop independent of the artificially initiated foredune. Hence, it cannot be affirmed nor denied whether reworking and reshaping of the artificially initiated foredune indeed took place.

At some locations, we suspect that dunes were already present land inward of the artificially initiated foredune prior to 1990. However, it was not until 1990 that measurements were extended in a land inward direction (Figure 4.12).

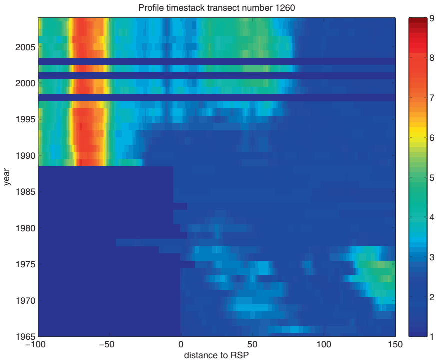

Figure 4.12: Dune evolution at transect 1260.

These dunes occur at the lateral boundaries of the washovers (compare with Figure 4.6). Hoekstra et al. (2009) recognize these ‘dunes’ as being the result of the northward migration of the washovers. As a result, the southward part of the washovers became less active and were partly filled in with eolian and marsh deposits.

4.5 Discussion

The analysis of the aerial photographs and Jarkus profile data from 1952 up to 2009 showed the artificial initiation of a foredune between transects 700 and 1000 around 1959, followed by an eastward extension up to transect 1300 around 1968. Interventions east of transect 1000 likely stopped around 1975, since most profiles show a lowering which is not directly followed by an increase in elevation which would have indicated that restoration measures were undertaken (e.g. erecting sand fences and vegetation plantings). In the 1980s, a foredune started to develop in front of the artificially initiated foredune up to transect 1000, which was also reported at transects west of 700 (Wijnberg et al. (2011)). Around 1990, in the area east of transect 1000, new dune formation is also observed. Based on the planviews of the artificially initiated foredune, we assume that the foredune up to transect 1100 remained intact, with the exception of the overwash at transect 1040. De Groot (2009) and De Groot et al. (2011) report a complete reworking of the dunes east of transect 1000 by 1989. Whether the new dunes that developed between transects 1100 and 1300 around 1990 (partly) consist of material of the former artificially initiated foredune, which would suggest reworking of the foredune, cannot be confirmed in this study.

So far, insight is provided into the temporal and spatial evolution of the artificially initiated foredune at Schiermonnikoog. However, apart from documenting the evolution of this foredune, the principal aim of this study was to examine the effects of intervention measures and methods on foredune morphology over a time period of years to decades. Between transect numbers 700 and 1100 morphologic effects of applied intervention measures are observed at the decadal-scale (apart from the breach at transect 1040). The observation showed that the proactive use of vegetation plantings and sand fence erections had morphologic effects at the decadal-scale, since these measures resulted in the development of a foredune. Therefore, it is plausible that the intervention method is more important than the measure in inducing morphologic effects on the time scale considered. However, between transects 1100 and 1300 the proactive use of sand fences and vegetation plantings did not result in the development of a foredune. Hence, this second observation shows that proactively applied measures do not necessarily result in the same type of morphological response everywhere. To reconcile these opposing observations, the concepts of a sediment-sharing system and sensitivity to initial conditions are used.

Sediment-sharing system

The discussion above suggests that if we want to fully understand the evolution of the artificially initiated foredune, we need to look for an explanation outside the borders of the artificially initiated foredune 'system'. Different authors (e.g. Dean (1988); Oost and De Boer (1994); Cowell et al. (2003)) already stressed the importance of considering the entire sediment-sharing system when we wish to understand why changes in one part of the system may result in changes in other parts of the system.

The concept of a sediment-sharing system is extensively discussed by Cowell et al. (2003). They introduce the Coastal-Tract, a morphological composite that comprises the lower shore-face, upper shoreface and backbarrier. They argue that in order to forecast long-term shoreline movements, we need to include knowledge on the evolution of the lower shoreface and knowledge on the interaction between the shoreface and backshore environments. In addition, they mention that changes at any scale in any of the morphological complexes or units constituting the Coastal-Tract, e.g. the upper shoreface, are bounded by the antecedent morphology, sea-level change and littoral sediment budgets. The Coastal-Tract is considered to form the highest scale level in a hierarchy of processes and morphologies. Each level in this hierarchy forms a system that shares sediment internally. Sediment-sharing implies that morphological changes in one part of the system cause changes in another part of the system and that there are constraints with respect to the morphological changes of the system at a given scale.

The concept of a sediment-sharing system for a barrier island situation was already elaborated by Oost and De Boer (1994). They mention that in the case of a barrier island, it is important to consider changes in the ebb-tidal delta, the inlets, the island itself and the backbarrier drainage area to explain the changes in either part of the system.

In this case study, the artificial initiation of a foredune created favorable conditions for salt marsh formation (De Groot (2009)). The process of salt marsh formation at Schiermonnikoog is described by Olff et al. (1997). On a bare beach plain, embryonic dunes are formed mostly due to sand trapping by *Elymus farctus*. Next, *A. arenaria* establishes which leads to continued sand trapping, which can eventually result in the formation of large dunes. As a result of dune formation, the sand flat behind the dunes is no longer frequently inundated from the North Sea. Instead, the sand flat is only inundated during high spring tides from the Wadden Sea. Sedimentation of silt takes place, which results in a higher nutrient availability that stimulates the growth of vegetation. The presence of vegetation contributes to further sedimentation of silt. Finally, the surface level will reach its highest elevation around highest astronomical tide or mean high water level (De Groot (2009); Allen (1990); Van Wijnen and Bakker (2001)). Hence, through the initiation of the artificially initiated foredune, a threshold was exceeded which through a number of positive feedback mechanisms (colonization of halophytes, salt marsh sedimentation, increase in marsh bed level) led to a new system state which is now maintained through negative feedback mechanisms (maximum salt marsh level).

Summarizing, due to the initiation of the artificial foredune, a redistribution of sediment within the sediment-sharing system took place that induced morphological changes in another part of the system. However, between transects 1100 and 1300, this virtuous circle was apparently not triggered through the proactive use of sand fences and vegetation plantings. A possible explanation is a difference in initial conditions between transects 1100 and 1300 compared to transects 700 and 1100 (Figure 4.4). Although aeolian sand delivery potential from the beach appears quite similar in both areas, the potential for marine erosion in front of the more low-lying wide washover channels that are present between transects 1100 and 1300 appears much larger than the potential for aeolian sand delivery.

Intervention methods and system boundaries

In the Introduction of this Chapter, proactive interventions were defined as those interventions that add sediment to the foredune system before there is a need given the actual state of the system. The difference between proactive and reactive intervention methods on the state of the system, for example described by the sediment volume of the foredune or the dunefoot position, is graphically represented in Figure 4.13.

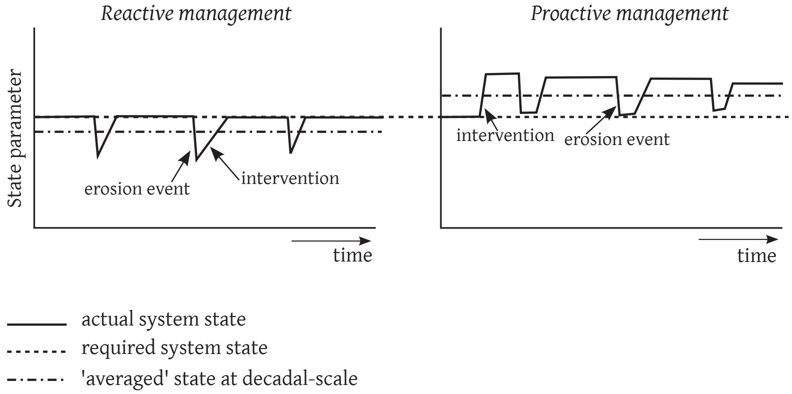

Figure 4.13: Sketch of difference between reactive and proactive intervention approach on the state of the system

The actual system state shows the evolution of the system through time. The required system state represents the minimum requirements with respect to the state of the system, for example a minimum required foredune sediment volume or a dunefoot position that should not be exceeded in a landward direction. The averaged state of the system at the decadal-scale represents the time-averaged state, leveling out erosional and accretional phases.

The left panel of Figure 4.13 shows the evolution of a system that is subject to reactive intervention methods. The system at the start is at the required system state, e.g. the accommodation space of the foredune is zero. Then an erosional event occurs resulting in a loss of foredune sediment volume. Subsequently, restoration measures are undertaken to increase the sediment volume of the foredune again and as such to bring the system back to its original state. Due to the fact that the actual system state will repeatedly be below the required state, the averaged state at the decadal time scale will be below the required state.

With proactive interventions, a surplus of sediment is added to the foredune system to prevent the foredune system from getting under the required system state (at the decadal-scale) (right panel of Figure 4.13). For instance, if the volume of the foredune is at the required system state, there is no nett erosion or accretion. With proactive interventions, the sediment volume of the foredune will increase (nett accretion). In case an erosion event occurs and proactive measures are properly undertaken, the sediment volume will in the worst case be at its required state again. Hence, in the case of proactive interventions the sediment volume of the averaged state of the foredune system will normally be higher than that of the required system state.

Note that the example as described above refers to the extreme states within one and the same system. In other words, they represent the ends of a spectrum of one system state at the decadal-scale. Thus, the example above does not refer to for instance the change from a tidal-inlet coast to a closed barrier coast. If this would have been the case, then the required system state would be positioned differently in the two examples.

This does not mean however, that interventions are not capable of shifting the state of the system. The development of the salt marsh at Schiermonnikoog which was in accordance with the changed situation at the barrier island due to artificial foredune initiation, suggests that proactive interventions are capable of shifting the state of the system, in this case through redistributing sediment on a bare beach plain which resulted in a change of the system state, at least at the decadal-scale.

However, most likely the interventions were well tuned with natural developments that occurred in this area: Since the mid 1980s, a natural foredune developed in front of the existing (natural and artificially initiated) foredune. This suggests that sand supply was already sufficient for foredune development. Therefore, the artificially initiated foredune might also have developed naturally, but at a later moment in time. Between transects 1100 and 1300, the system might have been too far away from this new system state (barrier island with continuous foredune), to be ‘pushed’ towards this new state by means of interventions.

In the case of the artificially initiated foredune at Schiermonnikoog, sediment was added to a location where initially a foredune did not exist. Hence, in this case sediment is added to the (initially non-existent) foredune system. However, when we include the beach within the boundaries of the system of interest, only a redistribution of sand took place. Sand supply rates from outside the beach-foredune system were not altered through the initiation of the artificial foredune, but sand which otherwise would have been blown across the beach plain was now trapped behind fences and in vegetation. Hence, the recognition of sediment redistribution or supply greatly depends on the boundaries of the system under study.

With respect to the hierarchy of Bakker et al. (1979) that was adapted in Bochev-van der Burgh et al. (2012), we can conclude that the hierarchical ordering of measures that was proposed in the latter paper is site-specific and that the position of a measure in the hierarchy will change according to the way the measure is carried out. Therefore, we cannot assign a single hierarchical level to an intervention measure, since in principle a measure can be placed at any level in the hierarchy, according to the way it is used and the initial state of the system in which the measure is applied.

4.6 Conclusions

This paper presented the results of a data-analysis covering a time period of 57 years regarding the evolution of an artificially initiated foredune at the Wadden Sea island Schiermonnikoog. In this study, we showed that the proactive use (intervention method) of sand fences and vegetation plantings (intervention measures) at a large spatial scale can result in observable morphological changes at a time period of years to decades. Along a part of the coast, the proactive use of sand fences and vegetation plantings led to the development of a foredune with a height similar to that of an adjacent natural foredune. From this development we conclude that it is not so much the type of measure that is carried out which has an effect on foredune morphology at a yearly to decadal timescale, but rather the intervention method, being proactive or reactive. This has consequences for the hierarchical position of intervention measures: According to the way the measure is applied, reactive or proactive, the position of a measure in the hierarchy can change. The notion that it is the intervention method rather than the intervention type that determines the morphological effects of interventions at the decadal-scale is important, since often intervention measures are assumed to dictate the morphological response of the foredunes with certain interventions dominating over others.

However, the proactive use of sand fences and vegetation plantings did not result in the development of a foredune everywhere along the coastal stretch where these measures were undertaken. The concepts of a sediment-sharing system and sensitivity to initial conditions were used to explain these differences in morphologic development.

The insights obtained from this case study can be of use when understanding and qualitatively assessing the effects of human interventions on foredunes in other settings as well, at temporal scales exceeding those of the process-scales, that is from years to decades.

Acknowledgments

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Chapter 5

Synthesis & Discussion

It is the nature of an hypothesis, when once a man has conceived it, that it assimilates every thing to itself as proper nourishment, and, from the first moment of your begetting it, it generally grows the stronger by every thing you see, hear, read, or understand

Laurence Sterne, The Life and Opinions of Tristram Shandy, Gentleman

5.1 From past foredune behavior towards long-term projections

So far, Chapters 2, 3 and 4 addressed the first research objective mentioned in the Introduction. This objective was 'to assess the past morphologic behavior of foredunes that are subject to interventions over a time span of decades'. It appeared that an unequivocal relationship between cross-shore foredune morphology and applied interventions could not be established at the decadal-scale, which was ascribed to the following reasons.

- Throughout the time period of interest, a combination of measures was carried out with varying alongshore and temporal intensity.
- A distinction was made between reactive and proactive intervention methods, with proactively applied interventions resulting in more pronounced morphologic effects on the foredunes at the decadal-scale.
- At the decadal-scale, there was a signal from natural processes on foredune morphology, which was most clearly visible when reactive intervention methods were undertaken. As a result, we could not resolve a morphological signal that could be attributed as being solely the result of interventions.
- Some interventions (such as the berm method in Rijnland, see Chapter 3) could not be resolved because of data limitations.

Due to the above mentioned reasons, we descriptively explained the observed morphologic behavior of foredunes subject to management interventions at the decadal-time span. The lack of a unique relationship between intervention type and foredune morphology at decadal time spans seriously complicates the translation of observed morphologic behavior to future projections on foredune morphology under different intervention scenarios. The latter being related to the second objective of this thesis.

This Chapter deals with the second objective of this thesis, namely 'to develop an analysis framework that assists in transforming the insights obtained from the first objective into decadal-scale projections of foredune morphology in relation to intervention measures'. Two aspects are crucial in this respect. Firstly, a precise notion of foredune morphology does not only include the shape of the dune (which was examined so far), but also the size, that is the volume, of the dunes. Secondly, from a long-term safety perspective it is not only the end situation (safety *over* e.g. 50 years) that is important, but also the path towards this end situation (safety *during* the 50 year time period). These two aspects will now be elaborated in more detail.

The notion that foredune morphology includes both the shape of the dune and the volume of the dune provides an important link towards long-term model projections on morphologic behavior of foredunes. This can be explained as follows. In the Introduction, we stated that long-term model forecasts are about volumes, not about shapes. Hence, if a model is capable of making projections on foredune volumes (keeping in mind the assumptions made in the model and model uncertainties), and if we are able to translate these volumes into foredune morphologies, we have a means of making long-term projections on the morphologic behavior of foredunes (see Figure 5.1).

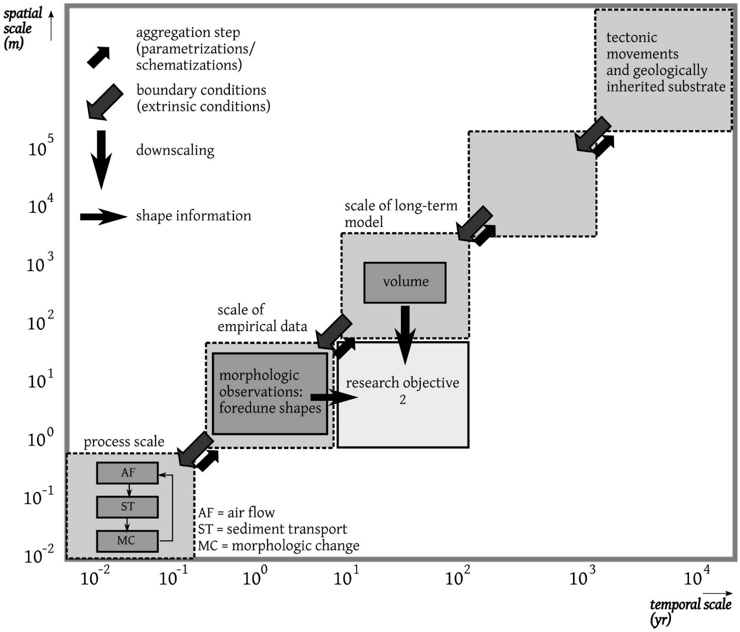

Figure 5.1: Graphic representation of the scale of preferred morphological information of the present study.

This procedure is formally known as downscaling. With downscaling we aim at "reconstructing the variation of a property at scale $s1$, given that only the value at the larger scale $s2$, which is the arithmetic average of the property values at scale $s1$ within $s2$, is known" (Bierkens et al. (2000)). Downscaling asks for additional information to obtain a foredune morphology at a lower spatial scale level (spatially more detailed) than that of the long-term volume forecast, since there is a non-unique solution: In principle there is an infinite number of morphologies that can be derived based on a specific volume (Bierkens et al. (2000); Kirkby (1996)). Fortunately, the shape functions derived from Empirical Orthogonal Function (EOF) analysis that were discussed in Chapters 2 and 3 can provide the right type of spatial information (see Figure 5.1). In Chapters 2 and 3, the shape functions characterize the foredune shapes that occurred in the time period 1965 to 2009. A range of shape functions were found during this time period. We could make a major distinction in shape functions characterizing the foredune shape before 1990 and shape functions characterizing the foredune shape after 1990. Recall that in 1990, there was a change in coastal policy, resulting in a change of intervention strategy. Before 1990, interventions were carried out in a reactive way, i.e. after the occurrence of an erosional event, while after 1990, interventions were undertaken in a proactive way, which means that a buffer is created. So, for these two types of intervention method, empirical functions exist that can be used in downscaling. The problem that remains now is that we have to assess what might happen to the shape of the foredune if the characteristics of interventions change.

The notion that not only the end situation, but also the path towards the end situation matters from a long-term safety perspective is explained as follows. The interest in the long-term morphologic behavior of foredunes originated from the need to have long-term projections on the safety level provided by the foredunes. In this Chapter, a time span of 50 years is used as a concrete interpretation of decadal-scale. In this respect, the path towards the desired end situation is important as well, which implies that at any point in time safety needs to be guaranteed. Thus, we need not only assess the foredune morphology 50 years from now, which can be achieved through downscaling a foredune volume to a foredune morphology as sketched above, but also how foredune morphology might change *during* this 50 year time period.

It is important to note that at a time span of 50 years, there might be changes in natural forcing conditions, which can leave an imprint on foredune morphology besides the interventions that are carried out. There is extensive literature on the changes in storm climate, wave climate and sea level fluctuations in the North Sea Region (e.g. WASA (1998); Vikebø et al. (2003); Bärring and von Storch (2004); Smits et al. (2005); Tsimplis et al. (2005); Bärring and Fortuniak (2009)). For instance, Bärring and von Storch (2004) and Bärring and Fortuniak (2009) studied the history of storminess in Northern Europe back to 1780 at different stations in Scandinavia. They conclude that the period from 1980 to the mid 1990s showed enhanced storminess, but that this is within the natural variability of the records. Storminess during the entire period remained stable, with no systematic changes. The European project group WASA (Waves and Storms in the North Atlantic) concluded that neither the storm climate nor the wave climate had undergone significant systematic trends during the last 100 years (WASA (1998)). Vikebø et al. (2003) found for the time period 1955-1999 that there is variability in the monthly mean significant wave height on a broad range of scales, and that apparent trends in time series of limited extent may be part of longer period variations. Yearly mean sea level pressure (SLP) changes from 1955 to 1999 indicate an increase in the north-south SLP gradient resulting in a strengthening of the westerlies. Analysis of the annual maximum significant wave heights for the period 1955-1999 indicates an increase in wave height and rougher wave climate in the northern part of the North Sea and Norway, while no or only a minor increase of the trend can be observed for the mid and southern parts of the North Sea (including the Netherlands).

Overall, even though storm and wave climate are variable at different scales, there is not enough conclusive evidence to assume significant changes in natural forcing factors that need to be taken into account in projections on foredune morphology 50 years from now (Clarke and Rendell (2009); Clarke and Rendell (2011)).

It already appeared that the concept of hierarchy, a concept developed in the field of natural systems analysis, proved to be of use in explaining the behavior of a foredune that was modified through human interventions. In this Chapter, we start by providing a summary of the hierarchy concept and explain why we need additional information to reach the second research objective. Next, we provide an elaboration regarding the preferential use of proactive intervention methods above reactive intervention methods from a safety perspective. Consequently, the discussion that follows in this Chapter is concentrated on the possible morphologic effects on the foredune based upon proactive intervention methods. The concept of hierarchy also motivated us to explore other concepts established in the field of natural systems analysis, and to investigate whether these concepts can assist in assessing likely morphologic developments at the foredunes under different intervention schemes. Finally, the analysis framework is introduced and we illustrate how this framework can be used in assessing likely morphologic developments of the foredune area under different nourishment scenarios.

5.2 Hierarchy

Chapters 3 and 4 illustrated that the concept of hierarchy, a concept that was developed in the field of natural systems analysis (Von Bertalanffy (1950); Howard (1965); Allen (1974); Huggett (1980)), proved to be useful in qualitatively understanding the effects of different types of interventions on foredune morphology at the decadal-scale. The hierarchy concept allowed us to structure different types of intervention methods and to understand how, that is at which hierarchical scale levels, the interventions interfere with the natural system.

In short, the concept of hierarchy can be summarized as follows. It is widely recognized that natural systems are open systems, since there is a continuous delivery of energy to the system and exchange of materials with the environment (Von Bertalanffy (1950)). Open systems strive to decrease the level of entropy, hence to increase the level of order, of complexity and of heterogeneity (Von Bertalanffy (1950)). Research by a.o. Schumm and Lichty (1965); De Boer (1992); Malanson (1999)); Haigh (1987); Levin (1992); Bergkamp (1995); Viles (2001) and Cowell et al. (2003) shows that natural, open systems aim at attaining a state of order where every morphologic system consists of and physically contains a hierarchy of ever smaller scale systems, which are called intrinsic conditions to the scale of interest. At the same time, the system is part of and physically contained (nested) by a hierarchy of ever larger scale systems, called extrinsic conditions to the scale of interest (Cowell et al. (2003); De Boer (1992); Bergkamp (1995)). Any level in a hierarchy maintains itself through self-regulating processes (negative feedbacks) which activities are constrained by the higher order level in the hierarchy (Haigh (1987)).

The hierarchy concept was useful for understanding why proactive intervention methods, mainly through adding a surplus of sediment to the system of interest (the foredune), could be placed at a higher position in the hierarchy than reactive intervention methods.

However, at this point we cannot yet say whether proactive intervention methods should always be placed at the same hierarchical level or that the hierarchical position of a proactive measure can also change if certain intervention characteristics change, for instance the cross-shore location of an applied buffer or the frequency with which the measure is applied. Hence, the notion of a hierarchical ordering of intervention methods alone does not provide insight into the morphological impact of the interventions on the foredune during a time span of 50 years. We thus need additional information to describe the potential morphologic effects of an applied intervention on foredune morphology at this time span.

5.3 Reactive or proactive intervention methods?

In designing an intervention strategy, first a choice has to be made between a reactive intervention method and a proactive intervention method.

In theory, 'predicting' the shape of a foredune that is subject to interventions is possible if we would be able to continuously maintain the shape of the foredune at a prescribed shape, a shape which is considered to be most desirable in terms of safety guarantee. In practice, this would require a 24/7 maintenance on the foredunes in order to preserve this desired shape. This type of intervention will always be reactive in nature, since there is always a time lag between the aerodynamic and hydrodynamic processes acting on the foredune and the measure that is carried out as a response to these processes. Hence, not at any instantaneous moment in time prescribed safety requirements can always be met.

We can therefore argue that from a long-term safety perspective proactive types of measures are preferred to guarantee that safety requirements are met. With proactive measures we add a surplus of sediment to the foredune system, either directly, e.g. through applying a banquet (dunefoot nourishment), or more indirectly for example through initializing an artificial foredune (see Chapter 4).

The next Section discusses the likely cross-shore morphological developments at the foredune as a result of changes in coastline position, which we will link to the use of proactive intervention methods.

5.4 Analogies with morphologic behavior of natural foredune systems

Chapters 2 and 3 showed that at several locations along the Central Netherlands' coast some years after nourishments were first carried out, a new foredune started to develop in front of the existing one. Apparently, due to nourishments, the coast (temporarily) changes into a prograding system, which has effects on the morphologic developments at the foredune system. When the existing foredune cannot cope with the surplus of sediment that is being added, the foredune morphology resembles the type of morphology that is found along natural prograding coasts. This is shown in Figure 5.2, panel B. Figure 5.2 summarizes the types of foredune morphologies that occur as a result of different types of coastal behavior, reflected in the position of the coastline (see Pye (1990)). Panel A shows that when even more sediment is added to the beach-dune system than in the case of panel B, there is simply no possibility for a new foredune to develop, in stead beach ridges will develop. This can be ascribed to the fact that the development of a foredune greatly depends upon the presence of sand-binding vegetation (in the case of the North-Western Europe largely dominated by *A.arenaria*) (Klijn (1990); Wiedemann and Pickart (2004); Saunders and Davidson-Arnott (1991)). However, when rates of sediment supply get too high, *A.arenaria* will not be able to fulfill its sand-binding function anymore, and the dune will no longer increase in size.

It was earlier concluded that when reactive measures are undertaken, the cross-shore shape of the foredune at the decadal-scale is largely steered by natural processes. The erosive character of the coast at decadal time spans is not affected through these interventions, and therefore we can assume that the shape of the foredune will largely resemble the shapes characteristic of natural erosive coasts, which are often characterized as being high and steep-sloped (Klijn (1981); Hesp (2002); Psuty (2004)) (see Figure 5.2, panel D). Since reactive measures aim at erasing ‘small-scale’ erosive features as erosion scarps and blow-outs, we might expect these features to be absent.

The model of Pye (1990) thus shows some generalized foredune morphologies under different types of coastal behavior. The shape functions obtained from EOF analysis, provide a means to refine these generalized morphologies (see also Section 5.1). The shape functions describe most of the morphologic variability of the foredunes that occurred on a time span of up to 45 years, under different intervention types and methods. This morphologic refinement is useful from a (long-term) safety perspective.

At this point we cannot yet say under which intervention measures and intensities a specific type of foredune morphology as described in the model of Pye (1990) is to be expected and whether a certain morphology will occur on a local or regional scale. Neither can we say what time period should be associated with the development of a certain foredune morphology, or how long this morphology might exist. Hence, additional information is needed to assess these aspects. The next few Sections will describe some concepts that may be of use for making this assessment.

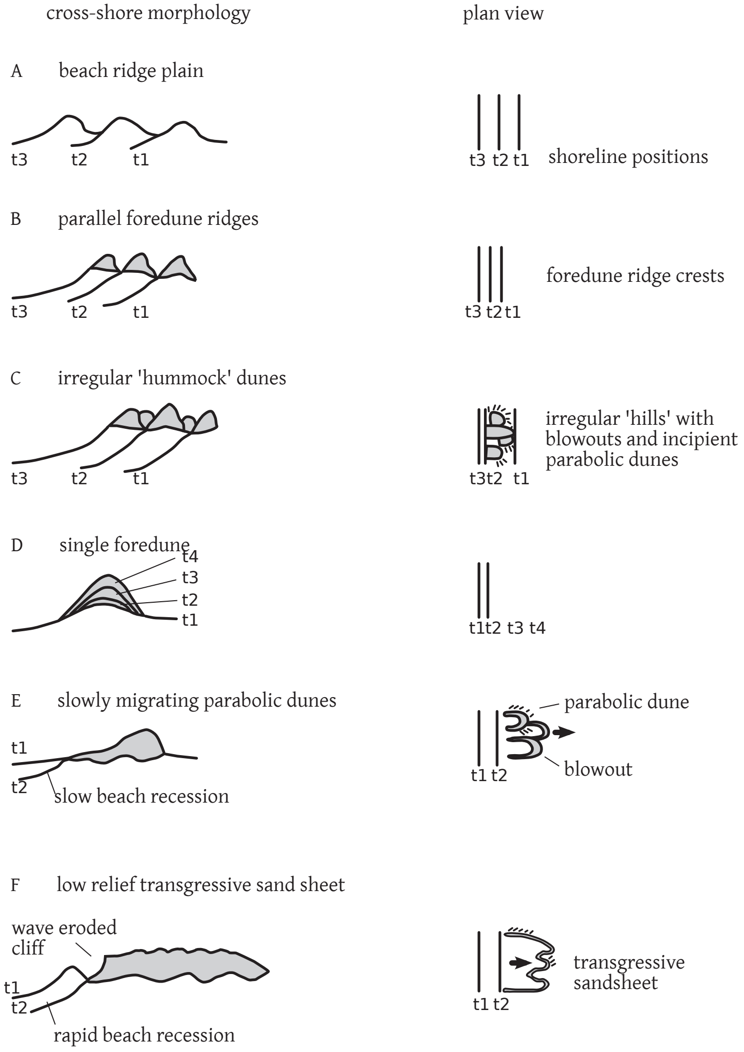

Figure 5.2: Schematic model showing the relationship between (fore)dune morphology and coastline positions. Adapted from Pye (1990).

5.5 Reaction time, relaxation time and characteristic form time

Responses of morphological systems to changes in external forcing conditions involve three time periods. The first time period is the reaction time of the system, that is the time period between the onset of a disturbance (for instance a change in external forcing conditions) imposed on the morphological system and the beginning of observable morphological change (Allen (1974)). The second time period is the time period between the onset of morphological change and the attainment of a new steady state situation, termed the relaxation time (De Boer (1992)).

It is generally assumed that when a disturbance is imposed on a system, the (morphologic) adaptation is at first fast, while as the system gets closer to a new state, the rate of adaptation slows down. Brunsden and Thornes (1979) and Van de Kreeke (2004) for instance believe that the relaxation path follows a first-order exponential path towards the new characteristic system state.

Schwarzer et al. (2003) state that the morphological response of a system to a process at an arbitrary scale can be represented by

$$R \approx F(S - S_{eq})^m \tag{5.1}$$

in which R is the morphological response, F represents the forcing, S the current morphology, S_{eq} the equilibrium morphology and m a power expressing the non-linearity of the process.

Wright and Short (1984) qualitatively state that "...morphodynamic changes result from gradients in sediment transport. When the divergence of sediment transport is zero everywhere ... equilibrium will exist." Hence, when the actual system state is far from its equilibrium state, the rate of system change is fast, whereas as the system approaches its equilibrium state, the rate of change slows down.

The third time period is called the characteristic form time (Brunsden and Thornes (1979)). This is the time period over which the characteristic morphology (or system state) persists (Figure 5.3). Phillips (2009) mentions that characteristic morphologies can continue to exist in response to all but the largest perturbations.

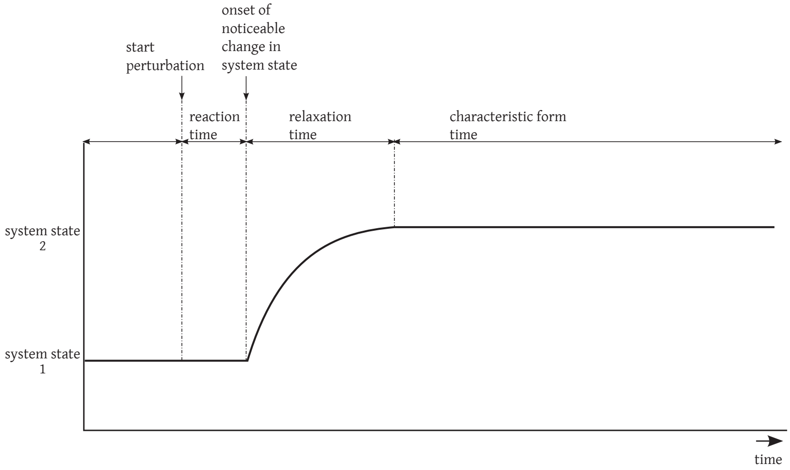

Figure 5.3: Concept of reaction time, relaxation time and characteristic form time.

The following examples illustrate the meaning of the three time periods in relation to foredunes subject to human interventions.

Example 1 - Artificially initiated foredune

Chapter 4 discussed the development of an artificially initiated foredune, at the island of Schiermonnikoog, the Netherlands. The artificially initiated foredune originally extended 3 km from west to east (starting at transect number 700 in the west to transect number 1000) and was later extended in an eastward direction, up to transect 1300 (Figure 5.4).

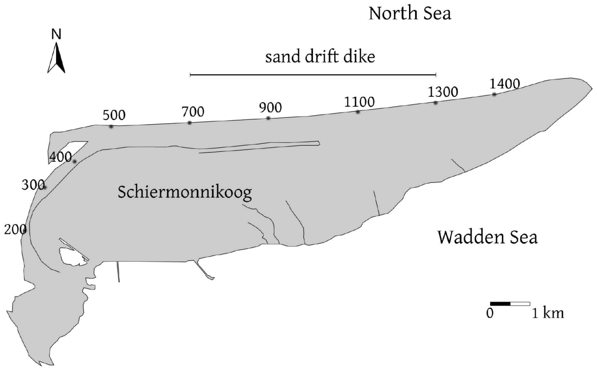

Figure 5.4: Location of artificially initiated foredune at Schiermonnikoog.

The initiation of the foredune took place through erecting sand fences and vegetation plantings. During relaxation time, the artificially initiated foredune between transect numbers 700 and 1000 increased in size, obtaining crest heights of around 8 m. In this area, the artificially initiated foredune still exists, although no measures are undertaken any longer. Apparently, its characteristic form is in accordance with the prevailing conditions, which sustain the foredune (see Figure 5.5). This may indicate that at this location a foredune was likely to develop under natural conditions as well and the system might already have been on its way to this new system state. Two factors support this suggestion. First of all, the artificially initiated foredune continued to exist despite that measures were no longer undertaken and second of all, a new foredune started to develop in front of the artificially initiated foredune and also in front of an existing foredune west of the artificially initiated foredune, which is considered to be fully natural (Wijnberg et al. (2011)) (see also Chapter 4).

Between transect numbers 1000 and 1300 a different situation occurred. Despite the measures that were undertaken, the foredune breached at several locations and around 1975 it was decided to cease interventions along this part of the foredune. At some locations, the foredune continued to exist, while at other locations the foredune is removed through washovers or reshaped and reworked by wind and water (De Groot (2009); De Groot et al. (2011)). Around 1990, new dunes also developed at this part of the island. This development is graphically represented in Figure 5.5.

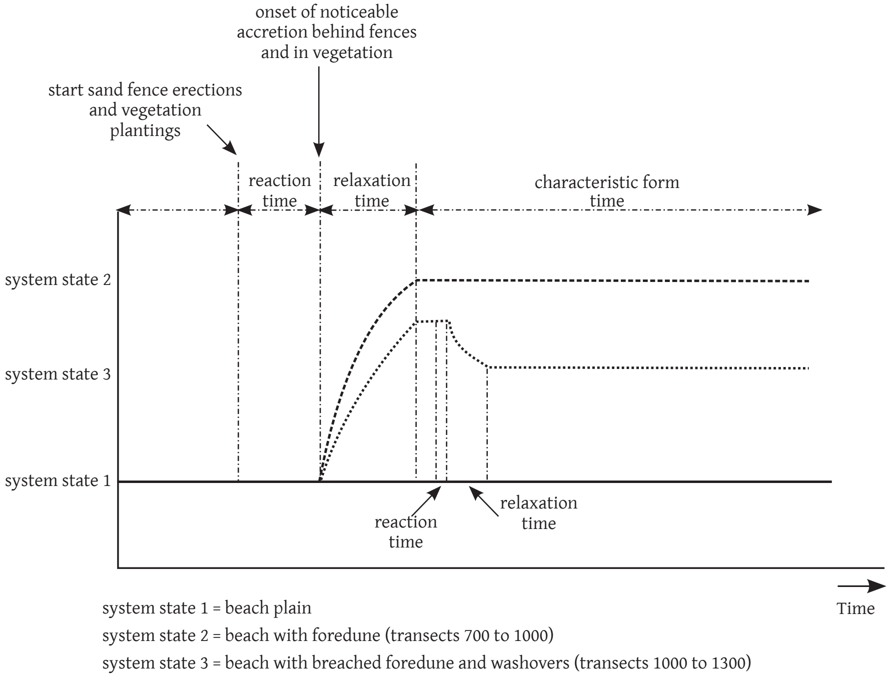

Figure 5.5: Concept of reaction time, relaxation time and characteristic form time following the artificial initiation of a foredune at Schiermonnikoog.

Example 2 - Nourishment schemes

In this example we apply the concept of reaction time, relaxation time and characteristic form time to a shoreface nourishment and a banquet (dunefoot nourishment). A banquet reduces the reaction and relaxation time of the foredune to almost zero, since the shape of the foredune almost immediately changes after the banquet is applied. A shoreface nourishment on the other hand takes time to result in morphological changes of the foredune. Hence, the morphological response of the foredune to the shoreface nourishment involves some reaction time, followed by a nonlinear trajectory towards the ‘new’ characteristic form during the relaxation time, which might follow a path which can also occur under natural circumstances, e.g. when a sandbar merges with the beach (Figure 5.6).

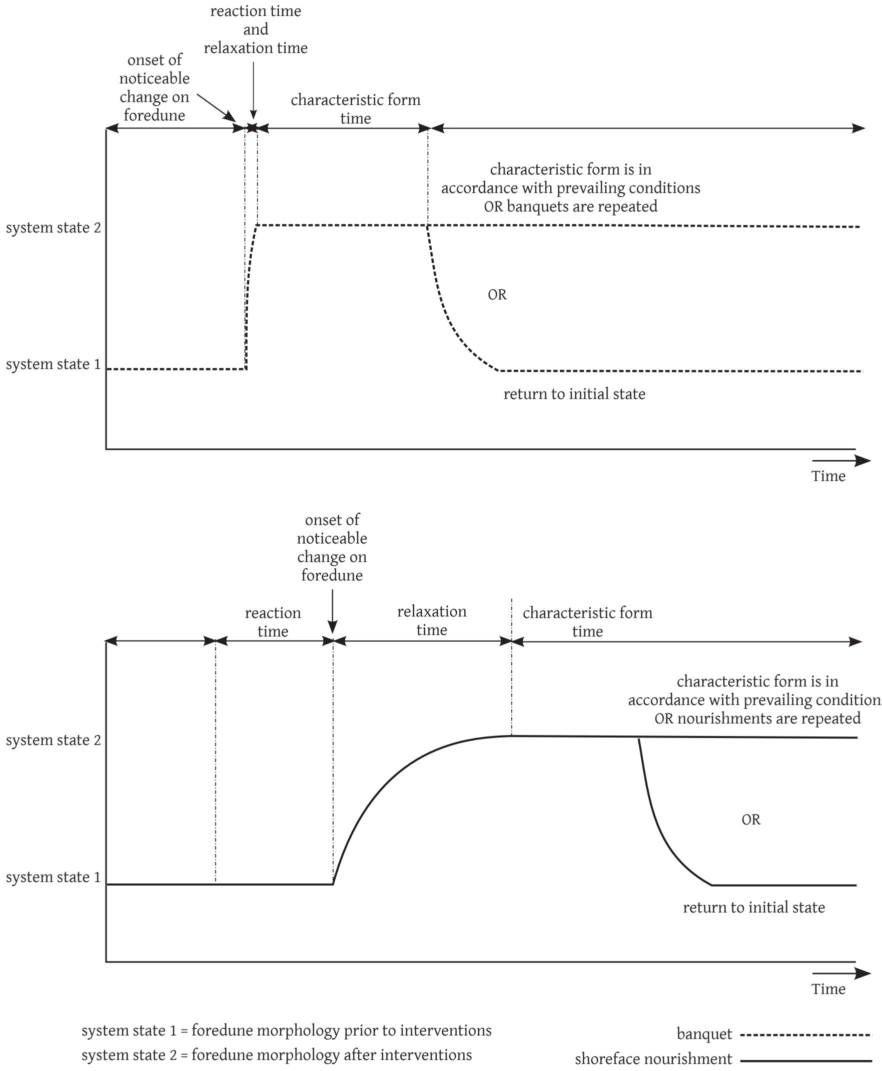

Figure 5.6: Concept of reaction time, relaxation time and characteristic form time following two nourishment schemes: A banquet (dotted line) and a shoreface nourishment (solid line).

The path towards the characteristic form is thus different for the two types of nourishment, but the characteristic form of the foredune is also different. With a shoreface nourishment, it is unclear whether and how much of the nourished material will end up at the beach. If the nourished material does end up at the beach, the beach width will temporarily increase, which results in an increased fetch. This in turn results in an increased sand supply to the foredunes. Depending on the amount of sediment that has been nourished and accordingly the total increase in beach width, either the existing foredune will increase its dimensions, or a (temporal) prograding beach or dune system comes into existence (panels A and B in Figure 5.2).

A banquet results in a different type of morphological response at the foredune. In case a banquet is applied, the foredune will benefit directly in terms of sediment budget increase. Note that the shape or characteristic form of the foredune is different than in the case of a shoreface nourishment (see e in Figure 5.7).

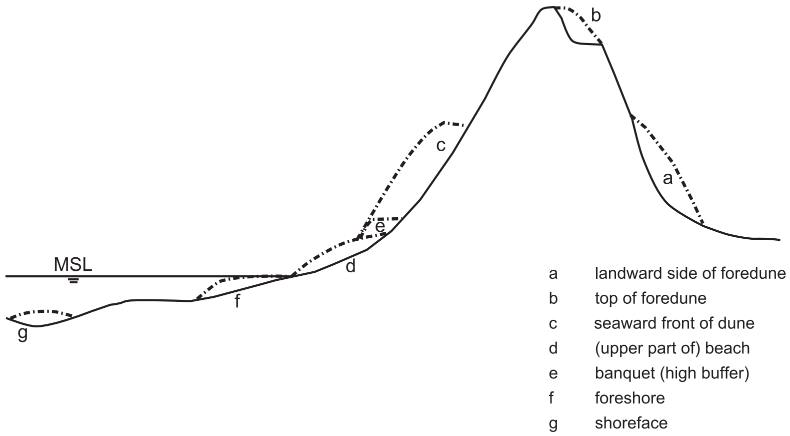

Figure 5.7: Different cross-shore nourishment locations. After (Van der Wal (1999b)).

Although the time periods relating to morphological change at the foredune due to a shoreface nourishment and banquet are different, we cannot say whether the characteristic form time of a foredune with a banquet will always be longer than that of a foredune fed by a shoreface nourishment or vice versa. The characteristic form time of a foredune with a banquet might be long when the new characteristic form (foredune with banquet) is in accordance with the prevailing conditions (hence, whether this form was also likely to occur under natural circumstances). If this is not the case, and nourishments will not be repeated, then, after some time, the foredune system will return to its original state (again following a period of reaction time and relaxation time). We can expect this to happen along naturally eroding coasts, the new characteristic form is not stable: There is a surplus of material at the seaward facing part of the foredune, thus a positive sediment budget, but a negative sediment budget at the beach, otherwise the coast would not erode. The beach will thus ‘demand’ sediment from the foredune, which will result in erosion of the banquet. In case of a shoreface nourishment, the applied nourishment is more evenly spread in the shoreface-beach-dune-system. The surplus of sediment in the shoreface-beach system will partly end up in the foredunes. Since in this case there is no negative sediment budget at the shoreface-beach system for some time, the buffer material that has reached the foredune is more likely to contribute to a positive foredune sediment budget for a longer time than in the case of a banquet. Therefore, it is likely to assume that the characteristic form time of the foredune due to a shoreface nourishment will be longer than the characteristic form time of the foredune due to a beach nourishment or banquet.

Life span of intervention

Preferably, intervention strategies should aim at designing interventions with as a long a life span as possible, since the longer the life span of an intervention, the higher the guarantee that safety requirements will be met during the time interval of interest (assuming no changes in external forcing conditions). The life span of a measure has a direct link with the characteristic form time: An intervention changes the cross-shore morphology of the foredunes, either directly or indirectly. The change in morphology in turn has an effect on the safety level of the foredunes. The characteristic form time of the new foredune morphology is therefore a measure for the effectiveness of the applied intervention. Wolman and Gerson (1978) define effectiveness as the ability of an event (the event in this case is the intervention) or combination of events (multiple interventions) to affect the shape or form of the landscape, which largely depends on the magnitude and frequency of an event (intervention). Thus, when an intervention is applied, the intervention should (a) be capable of meeting the required safety level of the foredune and (b) be able to sustain the newly developed characteristic form of the foredune, which is successful under the condition that the frequency (recurrence interval) and magnitude (dimensions) of the applied intervention are in line with the requirements laid down at the strategy level (see also Chapter 4)).

The characteristic form of the artificially initiated foredune at Schiermonnikoog between transects numbers 700 and 1300 (see Example 1, this Section and Chapter 4) can considered to be the result of an effective intervention at the decadal-scale, since the characteristic form continues to exist. The notion of a characteristic form time is very important from an intervention point of view, since it might give an indication on the desired dimensions (magnitude) and recurrence interval (frequency) of an intervention, in order to sustain a characteristic form that is considered desirable from a safety point of view (see Section 5.6).

Some final remarks on the time periods of morphological change

Finally, some last remarks with respect to the time periods of morphological response identified in this Section. First of all, there is a large range of relaxation times coexisting in a morphological system, which makes it difficult to assess whether a stable system state (hence characteristic form) has been reached or not (Kirkby (1996)). Second of all, the length of the three time periods usually increase with increasing spatial scale. That is, the length of the three time periods depend directly upon the size of the landscape or morphological system that is considered. For instance, Cowell et al. (1995) mention that the response of coastal barriers following the post-glacial marine transgression, involves a relaxation time of 10^2 to 10^3 years. (Note the order of magnitude difference of this relaxation time; a large uncertainty exists in determining the relaxation time of a system to a perturbation.) Third of all, the duration of the reaction, relaxation and characteristic form times depend on the material of the system undergoing a perturbation. Carter (1991) for instance mentions that since coastal dunes consist of comparatively low-strength material, they have a short reaction time and a short relaxation time. The three time periods associated with morphological change greatly increase for bedrock material (Brunsden and Thornes (1979); Phillips (2009)).

5.6 Magnitude and frequency

The previous Section already briefly mentioned the concept of magnitude and frequency. This concept is discussed in more detail in this Section. Wolman and Miller (1960) argue that the work accomplished by an event (process) depends both on the magnitude of the applied force, as well as on the frequency or recurrence interval of the event. At a particular frequency, most of the morphological effective work is done (Brunsden and Thornes (1979)) (see Figure 5.8).

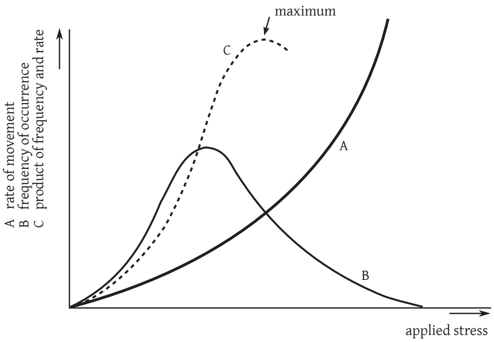

Figure 5.8: Relation between applied stress, rate of transport (A), frequency of the applied stress (B) and product of frequency and rate (C). Adapted from: Wolman and Miller (1960).

Wolman and Miller (1960) show that the distribution in time of many events (e.g. wind speeds) approximates a log-normal distribution. These events can be seen as cumulative applied stresses acting on a landform. If the applied stress follows a log-normal distribution (events with small magnitude occurring frequently, and events with a high magnitude occurring sporadically) (B in Figure 5.8) and if the quantity or rate of change is related to a power of this stress (A in Figure 5.8), then the product of A and B attains a maximum (C in Figure 5.8). This product is a measure for the work performed by an event of a specific magnitude and frequency. The frequency at which the largest part of the total work is accomplished is therefore not necessarily related to the largest, extreme events (Wolman and Miller (1960)). In fact, the morphological importance of these extreme events at longer time periods is questioned (Brunsden and Thornes (1979); Schwarzer et al. (2003)).

When an intervention strategy is designed, a choice has to be made with respect to how often the intervention will be carried out and what the dimensions of the intervention will be. Based on Figure 5.8 it seems reasonable to assume that there is a particular frequency and magnitude at which the foredune might benefit most from an applied intervention from a safety perspective. The important question we now need to answer is how can we assess this magnitude and frequency? There are some difficulties associated with this concept in designing an intervention scheme which has the most positive effect on guarantying safety over and during a time interval of 50 years. The moderate events that occur regularly with 'small' magnitude are usually associated with events that occur within the depositional regime, while the rare events occurring with a high magnitude are associated with erosional events. In the case of interventions, this is clearly not the case. In relation to this, the magnitude-frequency concept implicitly assumes one system trend, one system state which cannot evolve towards another state. For instance, if the state of a system changes from a closed barrier system towards a tidal inlet system as a result of a major storm event, clearly this development has a major morphological impact. Apparently, the transition from one system state to another cannot be accounted for in this concept.

Furthermore, we substituted the notion of magnitude for dimensions of the intervention. Hence a large magnitude of an event, is substituted for large intervention dimensions. We thus assume that the force related to an intervention with large dimensions is greater than that of interventions with smaller dimensions (which may sound plausible since $F = m * a$).

Buffer dimensions and safety consequences

Proactive measures aim at creating a buffer which assists in obtaining a predefined safety level of the foredunes. However, as soon as the buffer is applied, it will be subject to external forcings of different frequencies and magnitudes (winds, waves, storms). These forcings will therefore directly affect the initial safety provided by the buffer. If this is an unwanted development, a solution would be to apply an even larger buffer. When an ever increasing amount of sediment is added to the system, then from a safety perspective, the shape of the dune becomes less important. In this situation, there is ample sediment available to be eroded during storms and to guarantee that the existing foredune will be unaffected by erosional events. The shape of the dune is therefore of particular importance when it concerns a critical condition, a minimum prerequisite to guarantee the safety level.

The extreme consequence of aiming at minimizing the effects of storm events in terms of erosion volumes and recession distances of the foredunes, is to apply a buffer along the entire coast with a high recurrence interval. However, in this case, we do not speak about a buffer any longer but about artificially induced coastal expansion. Since the policy aim was to guarantee safety and not to induce coastal expansion, we need to gain insight into the degree of pro-activity that is needed to reach the policy aim. This degree of pro-activity is related to the frequency and dimensions of an intervention.

In principle, interventions are carried out as either high frequency-low magnitude interventions, e.g. a number of nourishments with a recurrence interval of for instance 5 years, or as low frequency-high magnitude interventions, for instance a single mega-nourishment with a recurrence interval of 30 years (figure 5.9).

Figure 5.9 shows how the buffer material might affect different parts of the coast through time. In the case of the mega-nourishment, it takes more time for the nourished material to arrive at location X, than in the case that the buffer is applied at several longshore locations. (see Figure 5.9). We might therefore argue that if the main aim is to guarantee

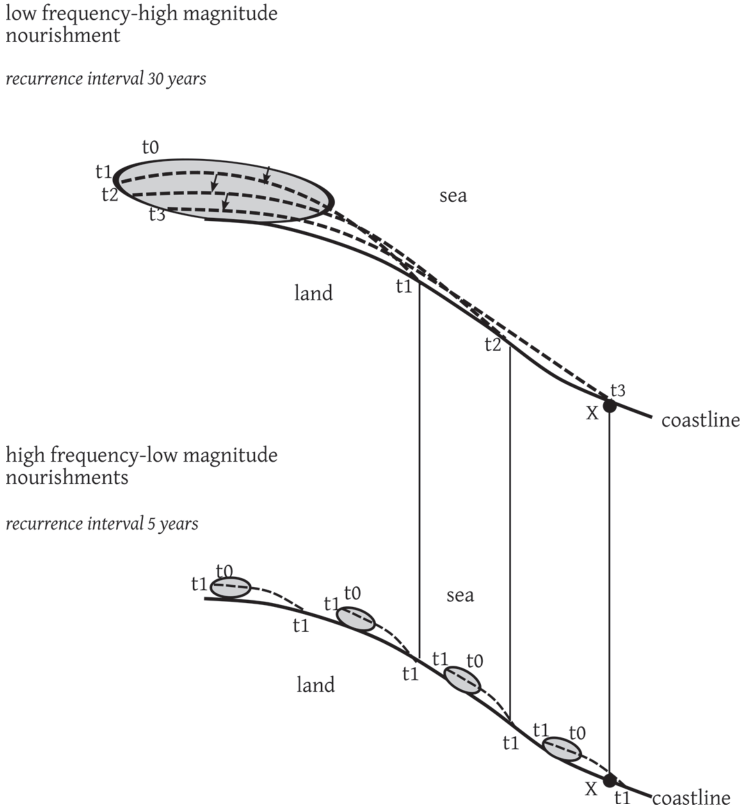

Figure 5.9: Concept of magnitude and frequency using different nourishment schemes.

safety at any point in time, it would be advisable to apply nourishments as high frequency-low magnitude 'events' at many alongshore locations, in stead of a single high magnitude event at one location. Thus, in relation to Figure 5.8, a single mega-nourishment is not necessarily more effective than a number of nourishments with smaller dimensions. However, there are of course minimum requirements with respect to the frequency and dimensions of a nourishment to have morphological effects on the foredune. In other words, with respect to magnitude and frequency of the intervention, a threshold has to be exceeded.

If we now look again at the model of Pye (1990) (Figure 5.2), we might argue that at certain intervention frequencies and dimensions, the rate and direction of shoreline movement will change. This change in shoreline movement in turn will result in morphological changes at the foredune. A major challenge is thus to investigate which intervention frequencies and dimensions induce a certain rate and direction of coastline movement that is most desirable from a long-term safety perspective, hence to determine the degree of pro-activity that is most desirable from a long-term safety perspective.

Dispersion of buffer material

The discussion hitherto mainly considered the effects of interventions on the cross-shore foredune morphology. However, Figure 5.9 also shows that the longshore dispersion of the applied buffer plays a role in affecting the cross-shore foredune morphology at different longshore locations and therefore affects the safety provided by the foredunes. This discussion of course mainly applies if the nourishments are carried out at the beach or further offshore. When a banquet is applied, this longshore dispersion is of less importance.

The following example illustrates the longshore dispersion of a nourishment. A nourishment is applied at a certain location at the beach. Soon after the buffer is applied, the nourishment will spread in a longshore direction and to a lesser amount in a cross-shore direction due to winds and waves and longshore currents (diffusion and advection (Hamm et al. (2002))). The transport of the buffer material has a diffusive character. Hence, the nourished material will not be evenly spread through time and space. Also, since morphologic changes follow an exponential path through time, the greater the disturbance (the greater the dimensions of the applied buffer) the faster the system will try to clear up the disturbance. This has consequences for the safety provided by the foredunes: At some locations the foredune might benefit more from an applied nourishment in terms of increasing the foredune budget, than at other locations (see Figure 5.10).

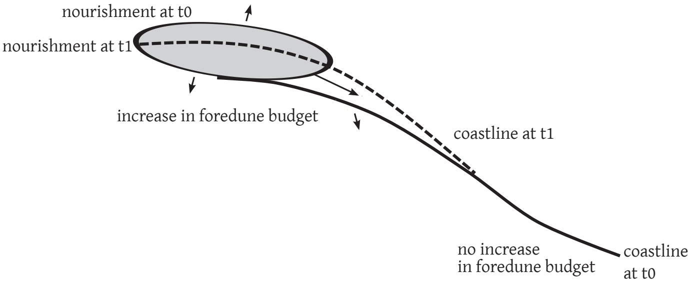

Figure 5.10: Cross-shore and longshore dispersion of buffer.

5.7 Sediment-sharing system

Chapter 4 mentioned the importance of considering the sediment-sharing system when we want to explain the morphologic changes in a part of the sediment-sharing system and how these changes might induce changes in other parts of the sediment-sharing system. It was also mentioned that it is important to determine whether sediment is added to the 'system' or whether it is redistributed within the 'system'. We thus need to have a precise definition on the boundaries of the system under study. Consider the following example. A sediment buffer is applied at the dunefoot. Sediment is thus added to the foredune system. If the material of this buffer is extracted from the beach (for instance using bulldozers) and if we extend the physical boundaries of the system under consideration to include the beach as well, then sediment is redistributed within the beach-dune system (panel A in Figure 5.11).

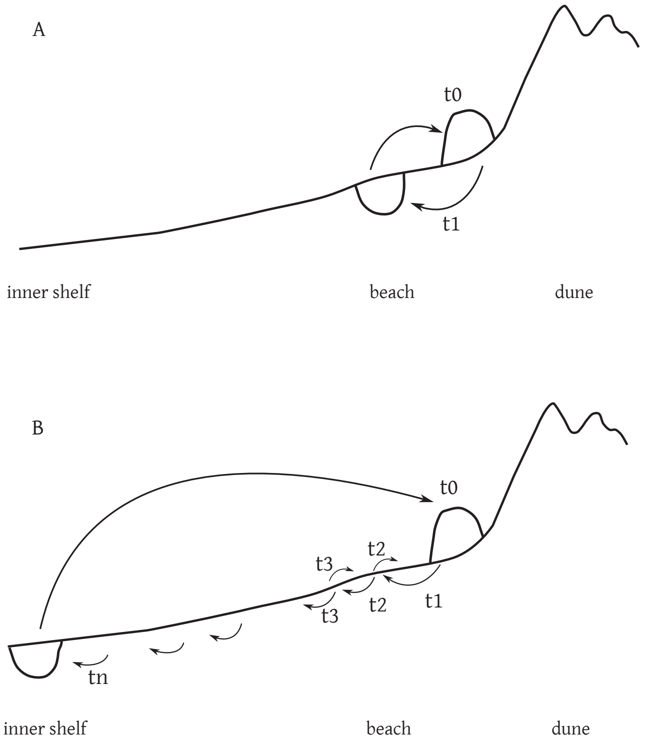

Figure 5.11: Sketch of the meaning of the source area of the applied buffer.

Since there is now a surplus of sediment in the foredune system, but a sediment scarcity at the beach, the beach will 'demand' sediment from the foredune. Note that this notion only holds when the artificial sediment redistribution drives the system away from the equilibrium it is striving towards. However, interventions do not necessarily drive a system away from an equilibrium, but can also assist in obtaining a new equilibrium towards which the system would also have evolved under natural conditions (see Chapter 4). In other words, the foredune budget is overfull (positive), but the beach budget is negative, hence accommodation space is available here. This is not a stable system state. The beach-foredune system aims to accomplish zero accommodation within the two sub-systems (the beach and the foredune) which is in equilibrium with respect to the sedimentation regime (Cowell et al. (2003)). Since the time periods associated with observable morphological changes at the beach-dune system are far less than the decadal-scale of interest – in fact we might already observe sediment exchange between the beach and the dune on a seasonal time period, one storm event suffices – the morphological effects of this intervention at the decadal-scale may be negligible.

In the case that the buffer material is extracted from the inner shelf, the inner shelf will become part of the sediment-sharing system. Since in this case the physical boundaries of the sediment-sharing system become much larger, so do the time periods associated with observable morphologic change in the entire system (Cowell et al. (2003); Schumm and Lichty (1965)) (panel B in Figure 5.11). There will of course be some sediment exchange between the beach and the dune and the beach and the shoreface and so on, but there will be a surplus of sediment within the beach-dune for some time, and no direct sediment scarcity in the beach system, which will demand sediment from the foredune. Therefore, if the aim of the intervention is to add a surplus of sediment to the foredune system at the decadal-scale, the buffer material should be extracted from outside the boundaries of the system of interest, and preferably from a system that can be associated with observable morphological changes on a temporal scale exceeding the decadal-scale. In this case, the characteristic form time of the foredune system will be extended. Hence, the sediment should be preferably extracted from a system that is placed at a higher hierarchical level than that of the system of interest.

Another example which illustrates this matter is the artificially initiated foredune at Schiermonnikoog. Sand fences and vegetation plantings were used in a proactive way to initiate the development of an artificial foredune. However, for the sand fences and vegetation plantings to be effective in terms of creating a foredune, a minimum supply of sediment is required. In the case of the artificially initiated foredune at Schiermonnikoog, sand blown land inward from the beach was trapped in the sand fences and vegetation, which was successful at the time period that was considered. In the long term, under changing climatic conditions and changes in for instance wave climatology, we do not know whether there will always be a sufficient supply of sand. Thus, in order for proactive measures to be successful in terms of guarantying safety of the foredunes at the decadal-scale, we need to add sediment to the foredune system from a location which is situated outside the system boundaries that can be associated with morphological changes at the decadal-scale.

5.8 Analysis framework

Chapter 1 mentioned that sustainable coastal zone management not only asks for insight into the current strength provided by the foredunes, but also how this strength might evolve over time spans of at least 50 years. Recall that long-term safety includes both the ‘end situation’, that is the safety level of the foredunes 50 years from now, and the path towards the end situation, that is the safety level of the foredunes during this time interval. Thus, at the *policy level* the aim is to guarantee safety provided by the foredunes at a 50-year time period. Decisions on how this aim can be reached are made at the strategy level. At this level, a choice is made with respect to the intervention method, being either reactive or proactive, and the intervention type to reach the policy aim. The choice for a proactive intervention method can already be made at this stage, since it has been argued in this Chapter that proactive measures are a prerequisite to guarantee safety at any moment in time (see Section 5.3). However, there are other aspects that need to be considered in the design of an intervention strategy. These aspects are the following.

- the physical boundaries of the sediment-sharing system
- the source area of the buffer material
- the cross-shore position of the applied buffer
- the frequency and magnitude (dimensions) of the applied intervention
- the dispersion of the buffer material.

Together, these aspects will determine the level at which the intervention will interfere in the hierarchically ordered sediment-sharing system, and as such can give an indication of the expected life span of a proactive intervention. A crucial part in the design of an intervention strategy is therefore to apply interventions in such a way that the expected life span of the intervention is in accordance with the time period that safety needs to be guaranteed.

Some choices with respect to the design of an intervention can readily be made. These choices are concerned with the first two aspects listed above (physical boundaries of the sediment-sharing system and location of source area). These aspects are important in affecting the duration of sediment redistribution within the sediment-sharing system (under the assumption that accommodation space is created through the removal of sediment) (Section 5.7). We concluded that the further away the source location in terms of hierarchy, the longer it takes to accomplish zero accommodation in all subsystems within the sediment-sharing system. This notion automatically implied the choice for nourishments as intervention type and to extract the material from as far away as possible, that is from outside the borders of the sediment-sharing system.

Section 5.5 qualitatively compared the characteristic form time of the foredune associated with a banquet and a shoreface nourishment. It was argued that the characteristic form time of the ‘adapted’ foredune is likely to be longer in case a shoreface nourishment is carried out in stead of a banquet. Therefore, the cross-shore position of an intervention also matters from a safety perspective. It is important to realize that the morphological response of the foredune differs according to the cross-shore position of an intervention.

The next issue that needs to be addressed is to assess whether we can expect differences in morphological response of the foredune under different frequencies and magnitudes of nourishment schemes. In Section 5.6 we mentioned that nourishments are either carried out as a high frequency-low magnitude event (often adding a little bit), or as a low

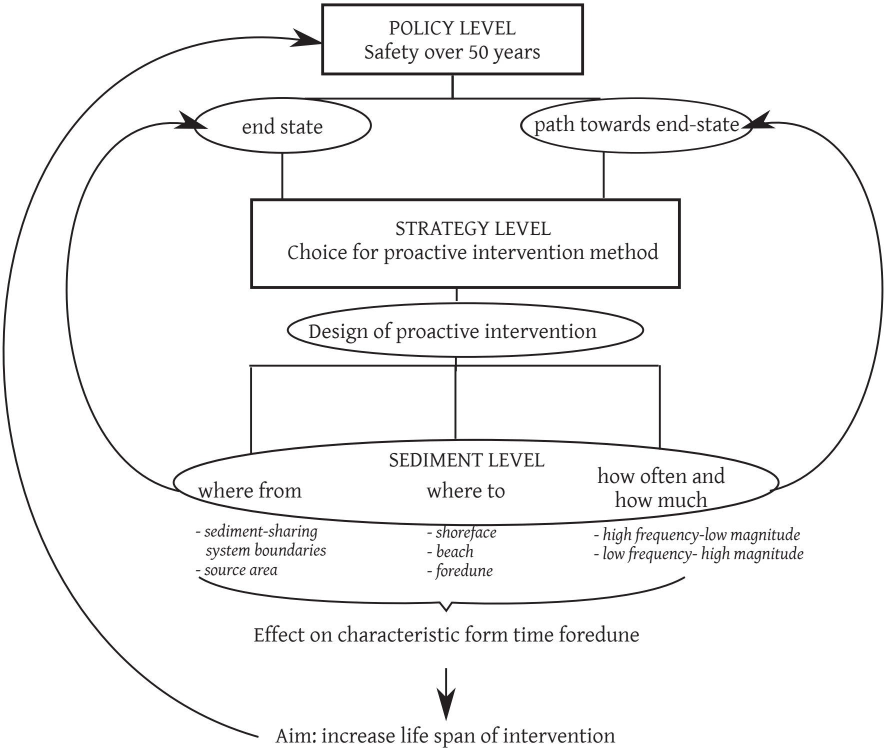

Figure 5.12: Analysis framework. Conceptual diagram showing the aspects that need to be considered for qualitative projections on the morphologic behavior of foredunes subject to interventions at decadal time spans.

frequency-high magnitude event (sporadically adding a huge amount). The concept of magnitude and frequency is crucial in affecting the path towards the end state. It directly links to rates and directions of shoreline movements, and as such has a major effect on foredune morphology and the characteristic form time of the adapted foredune. The longer the characteristic form time of the foredune that is affected through an intervention, the longer the life span of the intervention at the decadal-scale. Thus, the longer a characteristic foredune form prevails, the longer safety can be guaranteed. We therefore consider the characteristic form time as a central factor in reaching the policy aim.

Figure 5.12 summarizes the aspects that are considered to be important for developing decadal-scale projections on the behavior of foredunes subject to intervention measures. Figure 5.13 shows in more detail how the characteristics of the intervention, that operate at the sediment level, qualitatively affect the characteristic form time of the foredune.

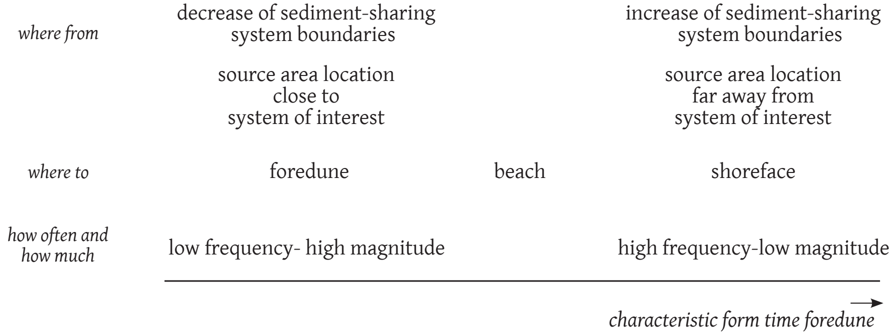

Figure 5.13: Effect of intervention characteristics on the characteristic form time of the foredune.

5.9 Using the analysis framework

The previous Section introduced the analysis framework, which is mainly based on the concepts discussed earlier in this Chapter and on the case study results of Chapters 2, 3 and 4. In this Section, we illustrate how the analysis framework can be of help in qualitatively assessing how intervention strategies will affect decadal-scale foredune behavior, or which information should be obtained to make such an assessment.

Example 1 - nourishments in Denmark

Nourishments are not only a Dutch matter. Many countries in Europe have applied nourishments since as early as 1950 (Hamm et al. (2002)), but also countries outside Europe undertake (beach) nourishment projects in response to coastal erosion (Benedet et al. (2007); Platt (1994)). Nourishments are usually undertaken when there is a safety issue involved, but also coastal development projects (resorts and infrastructure) may be a reason to nourish the coast.

In Denmark, since 1982, a new coastal protection scheme was implemented to stop or slow down coastal retreat (Hanson et al. (2002)). *At the policy level, it was decided that* the dunes along the west coast of Denmark should be able to provide a safety level corresponding to a 100-yr storm return period. This means that a predefined 'minimum dune profile' should be maintained. However, unlike the Netherlands, where coastline recession should be stopped completely by building a buffer, the Danish policy aim is to slow down or stop the coastal retreat rate. The time period over which safety should be guaranteed is unspecified, therefore it is assumed that both the end state and the path towards the end state are of importance from a safety perspective (see Figure 5.12).

At the strategy level, nourishments were chosen as a means to reach the policy aim (safety level of the dunes to withstand a 1/100 year storm). Besides nourishments, dune revetments were placed at locations where the dunes were not able to increase in height and width (Laustrup et al. (1996); Laustrup and Toxvig Madsen (1998)). The revetments resulted in a typical 'dike profile (see Figure 5.14) (pers. comm. Per Sørensen and Holger

Figure 5.14: Dune with revetments near Thorsminde, along the North Sea coast of Denmark

Toxvig Madsen, *Danish Coastal Authority*).

However, apart from the policy aim, societal and political aspects had an influence on the choices made at the strategy level. Since people had more confidence in hard coastal defenses than in soft measures, hard structures such as shore parallel breakwaters were constructed to stabilize the nourishments.

The measures resulted in a reduction of natural coastal retreat from a calculated 2 to 5.5 m/yr during 1996-2008, to a rate of approximately 1 m/yr at Thorsminde during the time period 1996-2008 (Kystdirektoratet (2008)). As a result of the nourishments, the dunes at Thorsminde generally became higher and wider. Because of the positive effects of the nourishments on the sediment budget of the dunes, intervention measures at the dunes such as plantings and sand fences could be reduced.

At the sediment level (see Figure 5.12), it should be possible to qualitatively deduce the characteristic form time of the foredune as a result of the measures, by analyzing the three aspects mentioned at the sediment level (Figure 5.12 and Figure 5.13). Unfortunately, there is no data available on the location of the source area and the sediment-sharing system boundaries, but it seems reasonable to assume that the location should be situated outside the borders of the sediment-sharing system that corresponds to the time scale of interest in the Danish coastal policy. The nourishments were applied above the 6 m depth contour, as in Denmark only losses of sediment above this depth contour have to be compensated for. Nourishments were carried out on the shoreface and beach, but not up against the foredune itself. This implies that changes in foredune morphology due to the nourishments are expected to last longer than if sediment was applied directly at the foredune. To be able to state how the location of the buffer affects the characteristic form time of the foredunes in Denmark, it should first be clarified which time periods can be associated with morphologic changes at 6 m water depth, and also over what time period the policy aim operates, that is, over which time span coastal retreat rates need to be slowed down.

Figure 5.13 further shows that the characteristic form time of the foredune is expected to increase when nourishments are carried out as high frequency-low magnitude types of intervention. As explained earlier, in Denmark also hard structures were constructed that stabilized the nourishments and as such could increase the characteristic form time when offshore losses are reduced. However, according to Hanson et al. (2002) the nourishments have resulted in a steepening of the coastal profile, which in turn might result in (increased) erosion of the coastal profile. Either way, hard structures need to be reinforced over time to maintain their effectiveness. With time, and with changing external forcing conditions (e.g. sea level rise), this reinforcement might become a high frequency event itself with increasing maintenance costs. Also, the hard structures prevent the redistribution of the applied buffer within the sediment-sharing system. In the long run, since the nourishment has led to a positive sediment budget at the nourishment location, it has caused a sediment deficit (negative budget) at the location where it is extracted (the source area), which will result in erosion elsewhere. This erosion cannot be cured through natural sediment redistribution from the nourishment location.

Regarding the ‘end state/path to end state’ aspects in the analysis framework, the model of Pye (Figure 5.2) can be used to qualitatively assess the type of foredune morphology that will prevail under the given interventions. Due to a clear reduction in the shoreline recession rate, it is expected that the morphologic state of the foredune will be of the ‘single foredune ridge type (Figure 5.2), which increases in height and width over time. This behavior seems consistent with the observations of foredune development over the past decade.

Example 2 - monitoring recommendations mega-nourishment

The dimensions of human interventions in the coastal zone continue to increase. There is a strong tendency in coastal management in bringing sand to locations where it would likely not have been present under natural circumstances, at least not at the rate and/or in the shape as it is applied. In this example, the analysis framework is used to indicate which parameters are essential to monitor to assess the effects of mega-nourishments on foredune development.

In the Netherlands, recently a mega-nourishment (‘The Sand Engine’) between the coast of Ter Heijde and Kijkduin was completed (Figure 5.15). In 8 months, a total of $21.5 * 10^6 m^3$ of sand has been attached to the beach. It is expected that an intervention of these dimensions will guarantee safety against flooding for at least the coming 20 years. Simulations with a process-based model (Delft3D) (Tonnon et al. (2009)) show the expected spread of the nourished material in time and space, thereby assuming an averaged representative wave climate (no storms, no sea-level rise) and an empirically derived relationship between beach width and dune growth (De Vriend and Roelvink (1989)). Since there is no experience to date with interventions of this size, the behavior of this buffer is being monitored (Tonnon et al. (2011)). To design an appropriate monitoring scheme, there are a number of factors that need to be considered.

First of all, we need to determine at what point in time after the nourishment has been

Figure 5.15: The Sand Engine (Zandmotor). Source: https://beeldbank.rws.nl, Rijkswaterstaat / Joop van Houdt

applied and under which conditions a specific dune morphology will develop. This means that a critical rate of shoreline movement has to be assessed (see Pye (1990)). Monitoring activity should therefore aim at accurately measuring shoreline behavior at a high spatial and temporal density.

Second of all, we need to assess the area of influence of the buffer, i.e. the dispersion of the buffer material. The area of influence may be bounded in either longshore or cross-shore directions, through natural controls (e.g. geological boundaries) or by man-made structures, such as harbors (Hamm et al. (2002)). In the case of the Sand Engine, the dispersion of the buffer is bounded by the Rotterdam harbor in the south and the Scheveningen harbor in the north. However, if there are no hard structures or natural boundaries present, the area of influence likely increases through time. This also has consequences for the rate of shoreline movement.

Third of all, we need to assess the length of time over which the buffer will be active, in other words, we need to assess the characteristic form time of the morphologies that are in the area of influence of the Sand Engine. Because of the non-linear behavior of the disturbance, monitoring frequency should be highest the first years after the placement of the fill material. In this respect, the magnitudes of seasonal and annual variability need to be considered as well (Hamm et al. (2002)). As time proceeds, the monitoring frequency can decrease somewhat again.

Fourth of all, since the characteristic forms directly affect the safety level of the dunes, the longshore monitoring density should be high in order to capture the longshore morphologic variability of the foredunes. Also, apart from calculating volume changes at the dunes, focus should be on quantifying the morphologic changes. This asks for a high cross-shore monitoring density.

Since the policy aim in the Sand Engine case is to guarantee safety for the coming 20 years, this means that both safety over and during this 20 year time period has to be guaranteed. At the sediment level, qualitative estimations with respect to the characteristic form time of the foredunes can be made. First of all, the location of the source area of the buffer material is located beyond the -20 m depth contour and the time periods associated with morphological changes at this water depth are considered to be far greater than 20 years. This will have a positive effect on the characteristic form time of the foredune. The buffer material has been attached to the beach and as such this intervention will have a longer life span than if it were applied at the foredune. The Sand Engine is a typical example of a low frequency-high magnitude type of intervention. However, in Section 5.6 it was argued that purely from a safety perspective, it is advisable to undertake nourishments as high frequency-low magnitude type of interventions. This also relates to the characteristic form time of the foredunes. Because of the nonlinear behavior of the disturbance (the nourishment), in the case of a low frequency-high magnitude type of intervention the longshore dispersion will be greater than in the case of a high frequency-low magnitude type of intervention. At the location of the Sand Engine, soon after the nourishment is completed, a beach ridge plain might come into existence, due to the enormous (artificially induced) coastline movement. Since the dispersion of the buffer material affects the rate of shoreline movement, this automatically affects the morphologic state of the foredunes. It is therefore expected that the beach ridge plain will not be sustained and that foredune morphologies will change over time. What types of morphologic states will occur, will depend on the dispersion rate of the nourishment and hence, on the rate of coastline movements.

5.10 Summary

In this Chapter, we provided conceptual insights in the long-term morphologic behavior of foredunes that are subject to interventions. The concepts allow us to qualitatively identify which intervention characteristics have a greater imprint on foredune morphology than others at the decadal-scale, and also if a characteristic morphology as a result of the applied intervention might persist at the decadal-scale. The examples that were presented illustrate the importance of having (qualitative) knowledge on the behavior of the system at scales beyond those of process information in order to grasp which effects the interventions might have on the behavior of the sediment-sharing system.

In essence, we can state that the higher a proactive measure can be placed in the hierarchy, the longer its potential morphological effects will last. The hierarchical position of nourishments (proactive intervention) depends on the source area of the buffer material (which is directly connected to the physical boundaries of the sediment-sharing system), the magnitude and frequency of intervention, the cross-shore position of the applied buffer and the alongshore spread of the nourished material. In this Chapter, we hypothetically illustrated the difference between a nourishment as a high frequency-low magnitude intervention and a nourishment as a low frequency-high magnitude intervention.

Thus, the morphologic impact of management interventions should be viewed as where in the system, that is at which hierarchical scale level, the interventions redistribute sediment. This mainly determines the duration of the characteristic form time of the foredune and hence, the effectiveness of the intervention. An intervention can considered to be effective or successful, when the characteristic form of the morphological feature continues to exist given a certain frequency and magnitude of the applied intervention as designed at the strategy level.

Increased conceptual insights into the long-term behavior of foredunes subject to management interventions provides insight into the kinds of morphologic behavior a ‘predictive’ model should be able to simulate. In order to establish long-term projections on the morphologic behavior of foredunes subject to interventions, we should quantify the changes in shape of the foredune on this time span under different types of intervention strategies. This will provide a means to translate the long-term volume forecast of a model to (a range of) foredune morphologies.

We mentioned before that the next challenge will be to deduce a rate of shoreline movement due to an applied intervention. If we are able to achieve this, we have found a way to obtain generalized dune morphologies as presented in the model of Pye (1990). The EOF shape functions that were discussed earlier, can provide a means of refining these generalized morphologies. Since the shape functions reflect the past morphologic behavior of foredunes under different intervention strategies, they can give a first clue towards determining the foredune shapes that have occurred due to applied interventions in the past, under a specific rate of shoreline movement. This of course involves uncertainties, since a number of nourishments were carried out, with different source areas, different cross-shore positions of nourishment application and with different magnitudes and frequencies. Thus, it is difficult to determine when exactly a ‘threshold’ was exceeded that resulted in a change of direction and rate of shoreline movement. Also, we should be aware of the fact that EOFs are empirically determined, which means that they are site-specific. The morphological response of the foredune to interventions might vary in different climatic and geographic zones (Van der Meulen (1990); Hesp (2004); Klijn (1990)).

Chapter 6

Conclusions and recommendations

All disorder is a divine order not understood

Stephen Graham, The Way of Martha and the Way of Mary

6.1 Conclusions

In the Introduction, three research questions were formulated. This concluding Chapter summarizes the answers to these research questions based on the conclusions drawn in the previous Chapters. Finally, some recommendations for future research activities are proposed.

Q1. What is the spatio-temporal variability of the cross-shore morphology of foredunes subject to intervention measures over a time span of several decades?

Chapter 2 illustrated that the foredunes along the Central Netherlands' coast, which were subject to high intervention intensity, exhibited morphologic variability, despite that interventions, at least up to 1990, were mainly carried out to stabilize the foredunes.

Foredune morphology varied over time and space, which was explained by the fact that natural processes still exerted influence on foredune morphology, which could not be stopped by the (reactive) interventions. For the Central Netherlands' coast, the larger part of the morphologic changes in the foredune were concentrated near the dunefoot and the lower part of the seaward facing slope of the foredune, which are most prone to wave attack during storms and consequently showed the largest morphologic variability. The remainder part of the cross-shore foredune profile was usually well vegetated with *A. arenaria*, which reduced morphologic variability.

Q2. Which relationships exist between the observed spatio-temporal variability of the cross-shore morphology of foredunes and applied intervention measures over a time span of several decades?

Chapters 3 and 4 illustrated that it was not possible to establish a unique relationship between cross-shore foredune morphology and applied intervention measures. The reasons for this lack of an unequivocal relationship were the following. First of all, the intensity of the interventions fluctuated through time and space and a combination of interventions was carried out. Especially before 1990, interventions were undertaken as a response to natural processes that resulted in erosion of the dunes. As a result, there was a signal from natural processes that exerted influence on foredune morphology. However, there was a clear qualitative distinction between reactive and proactive intervention methods, with proactively applied interventions resulting in more pronounced morphologic effects on the foredunes at the decadal-scale. An explanation for this more pronounced morphologic effect was suggested in Chapter 4: Proactive interventions add sediment to the foredune system, rather than to redistribute sediment within the foredune system.

Despite that there was not a unique relationship between foredune morphology and intervention measures, we did obtain a range of shape functions from EOF analysis (as described in Chapter 2), that reflect the foredune morphologies that resulted from a combination of management interventions and natural forcings.

Q3. How can the insights obtained from case study research be generalized

to support projections on the behavior of foredunes subject to intervention measures over a time span of decades?

Chapter 5 identified the aspects that should be considered in making long-term projections of the morphology of foredunes that are subject to interventions. Chapter 5 illustrated that long-term safety includes both the 'end state' (safety 50 years from now) as well as the path towards the end state (safety during the 50 year time interval). This should have important consequences for the design of an intervention strategy, since the morphologic response of the foredunes is different if for instance interventions are undertaken as either a high frequency-low magnitude type of intervention (often adding a little bit of sand) or as a low frequency-high magnitude type of intervention (adding once in a while a lot of sand).

The aspects that were identified as being important in affecting the decadal-scale morphologic variability of foredunes that are subject to interventions, were summarized in an analysis framework. These aspects included the physical boundaries of the sediment-sharing system, the source area of the buffer material, the cross-shore position of the buffer material (location in the cross-shore profile where the buffer material is deposited), magnitude and frequency of the applied intervention and the longshore and cross-shore dispersion of the buffer material. These factors will determine the level at which the intervention will interfere in the hierarchically ordered sediment-sharing system, and as such can give an indication of the expected life span of a proactive intervention. The longer the life span of the intervention, the longer the characteristic form time of the 'adapted' foredune. Also, a link was made to the model of Pye (1990). This model qualitatively illustrates the types of foredune morphology that can occur under different types of coastline behavior. Hence, if we are able to determine how an intervention changes the rate and direction of shoreline movement, we can qualitatively project foredune morphologies.

So far, long-term projections on coastal evolution focused on changes in sediment budgets in stead of changes in shape. The study presented in this thesis provides the first essential steps towards including information on the shape of the foredune in long-term model projections, that is needed from a long-term safety perspective.

6.2 Recommendations for future research

This study has gained qualitative insights towards including information on the shape of the dune needed for long-term safety projections. We suggest that future research activities should focus on (1) transforming the qualitative insights into quantitative properties, that is to translate a dune volume to a dune morphology, which includes both the shape and the volume of the dune and (2) establishing critical rates of shoreline movements under different intervention strategies to identify thresholds for specific dune morphologies (see the model of Pye (1990), Chapter 5). Figure 6.1 schematically illustrates the next research steps that can be undertaken.

Behavior-oriented models (for instance PONTOS), can be used to obtain projections on long-term dune volumes under different nourishment scenarios (steps 1 to 3 in Figure 6.1). The concepts discussed in Chapter 5 can provide criteria to qualitatively assess changes in foredune shape under different intervention strategies. The model of Pye (1990) defines

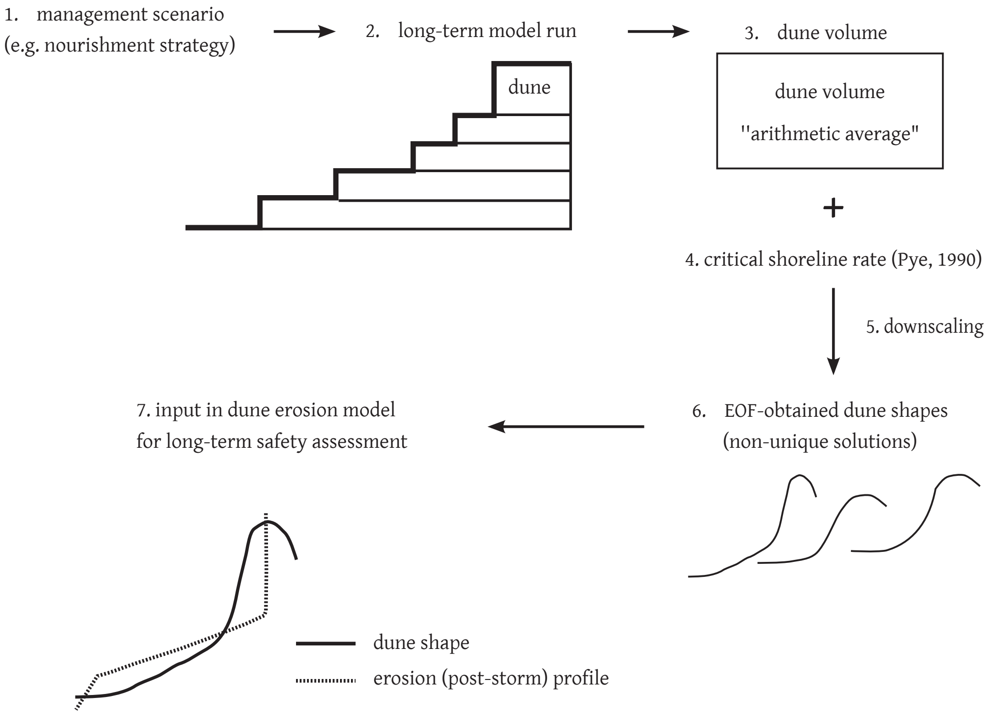

Figure 6.1: Suggested next steps in future research activities

generalized foredune shapes related to the rate and direction of shoreline movement (step 4 in Figure 6.1). The next step would be to refine these generalized morphologies, in other words, to 'downscale' the volumes to a series of realistic dune morphologies. The shape functions obtained from EOF analysis can provide the required refinement (steps 5 and 6 in Figure 6.1). Finally, the dune morphologies can be used as input to a dune erosion model (see Chapter 1) to compute future safety levels of the dunes (step 7 in Figure 6.1).

To close this Section, some remarks are given with respect to documentation and monitoring activities. Firstly, it appeared that interventions were usually poorly documented. In order to examine whether quantitative relationships between intervention measures and methods and foredune morphology do indeed exist, the types and intensities of intervention measures should be accurately documented. Contrary to the measures that were applied in a reactive manner (e.g. vegetation plantings), nourishments were and still are documented. However, in this study, we assumed that the fill material was evenly spread over the area that was documented as the area to be nourished in the records of *Rijkswaterstaat*. Whether this assumption is valid remains unclear. Hence, apart from documenting the amounts of nourished material, the date of nourishment and the time period over which the nourishment was carried out, information on the longshore distribution of the fill material would be useful as well. For instance, different types of coastline behavior can occur if the fill material is either concentrated at certain locations within a coastal stretch, or if the fill material is evenly distributed within this same stretch of coast.

Secondly, the Jarkus database is invaluable in adequately assessing the possible effects of interventions measures and methods on foredune morphology. Unfortunately, the Jarkus measurements were lacking for some years, as a result of which additional insights on morphologic behavior of the foredunes could not be obtained. We therefore argue that Jarkus measurements should continue to be carried out at least at a yearly frequency.

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Curriculum Vitae

I was born on the 5th of May, 1978 in Hoorn, Noord-Holland. Already soon after my birth our family moved to Alkmaar, Noord-Holland. Although we lived close to the sea, my fascination for the beach and dunes was not triggered yet. I took the beach and the dunes for granted and did not notice the beauty of this fascinating system.

Already at an early age, I decided I wanted to do ‘something with nature’. Some 12 years later, in 1997, this idea was given a concrete shape when I decided to study Earth Sciences at the Free University of Amsterdam. I became more and more interested in studying landforms and different field work projects and two MSc projects aimed at grasping the evolution of different types of landforms.

I graduated in 2002 and in 2003 I was employed by the Netwerkstad Twente, to work at different projects at different local authorities. In 2005, I started my PhD research at the Department of Water Engineering and Management of the University of Twente. Besides working on my thesis, some other nice events took place during my PhD career: I got married in 2006 and in 2008, my first daughter Masja was born, followed by her sister Varvara in 2010. Currently, I am working for the Studium Generale at the University of Twente.