Dune growth on natural and nourished beaches: *'A new perspective'*

M.Sc. Thesis

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April 2009

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‘A new perspective’

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Preface

This thesis concludes my Master of Science program at the Faculty of Civil Engineering and Geosciences at Delft University of Technology, The Netherlands. The thesis work is financed by Royal Boskalis Westminster, and was carried out at Deltares.

This thesis describes dune development on natural and nourished beaches on an engineering timescale. Using a study of both literature and data gathered from the Dutch coast, a new hypothesis regarding the causes of variability in dune evolution is proposed. Following this hypothesis assumptions are made on the basis of which a conceptual model is developed that includes both the accretive and erosive processes that govern dune evolution.

I would like to thank my supervising committee for guiding me through the process of writing this thesis. Special thanks are due to Stefan for offering me the opportunity to do this work for Boskalis, to Mark for guarding the process, and to Sierd for being a great sparring partner during the writing process.

Thanks are rendered to Bert, for his geological know-how and for helping me find literature.

More special thanks are due to Mark, Gerben and Kees for sharing their MATLAB knowledge, and especially for the effort they put in the development of the UCIT, McTools and OpenEarth projects; without these projects it would not have been possible to access, process and study the vast amounts of data that have been gathered from the Dutch coast.

Finally, I would like to thank my family for their support, my (ex-)housemates for the wonderful years at the OIP, and my fellow students at Deltares for all the lunches and lunch walks: Robert, Johan, Anton, Claartje, Renske, John, Claire, Anna, Carola, Steven, Marten, Roald, Arend, Sepehr, Wouter, Chris and Lars, thanks!

Thijs Damsma

Delft, April 2009

Summary

To be prepared for the expected changes in our climate, the Delta Committee recommends to significantly strengthen the dunes along the Holland coast. It is possible to nourish the dunes directly, but this is an expensive and intrusive operation. Foreshore nourishments are cheaper, and less intrusive to both the natural and human environment. It is expected that large-scale foreshore nourishments can also positively affect dune development.

As the Zuid-Holland coast must be extensively nourished anyway, the idea has risen to do a single, concentrated (in time and space) nourishment, instead of repeating many smaller ones. This will reduce both the costs and the impact. Also, this large nourishment is expected to locally stimulate dune development. As a pilot project a 20 million m^3 nourishment is currently being prepared, named "the sand engine".

As potential dune development is one of the design criteria, it is desired to know in advance what influence on dune development can be expected from such a nourishment. As current understanding of this subject is limited, the objective for this thesis is found in this knowledge gap. The thesis strives to answer the following question: "*How will the coastal dunes develop in the ten years after the sand engine plan has been executed?"*

In chapter 2 the state of the art of dune evolution research is presented. Dune evolution is found to depend on the balance between the erosive hydrodynamic forces during storms and the (mainly) accreting influence of aeolian (wind-blown) sand transport. The rate of transport by both of these processes is found to depend on the beach width, and this effect is empirically quantified for a 165-year dataset of the Dutch coast. A wider beach both offers more protection from dune erosion and allows for higher rates of aeolian transport.

Current numerical models are found to be capable of making predictions of the hydrodynamic influence for the 10 year temporal and 10 km spatial scales. The influence of changes in foreshore bathymetry on rates of dune erosion is also well understood. While several authors find circumstantial evidence that relate aeolian transport to beach width, the fundamental understanding of aeolian transport is limited. No predictions of transport rates can be made, nor how this rate is quantitatively influenced by the beach width.

In chapter 3 dune development described by the two main datasets of the Dutch coast (the Dutch Beach Line and JARKUS datasets) is analyzed using various techniques. No meaningful empirical relations between beach width or coastline migration rates for the time and space scale of the sand engine project can be uncovered.

Due to the annual character of both datasets, the individual influence of aeolian and hydrodynamic forces cannot be easily distinguished. Variations in susceptibility to erosion are found to correlate better to measured dunefoot development than just the beach width, a strong indication that the variability in rates of erosion, and not in rates of aeolian deposition are the main cause of variability in dune development. Together with other circumstantial evidence this leads to the following hypothesis:

"Variability in dunefoot migration rates is determined by variability in the erosive (hydrodynamic) processes, not by variability in the accretive (aeolian) processes."

The assumption that spatial and temporal variability in aeolian transport to the dunes can be neglected provides an opportunity for dune growth modelling. A conceptual model based on this assumption is proposed in Chapter 4. The model is able to qualitatively describe how a nourishment influences dune evolution.

In chapter 5 the main conclusions of this thesis are reiterated and the implication this has for dune evolution modelling with respect to the sand engine is discussed. It is concluded that the main question posed at the beginning of the thesis cannot yet be answered, but that the conceptual model provides encouraging results.

Finally, in chapter 6 it is recommended to use the insights of this thesis to qualitatively compare alternative designs for the sand engine by their capacity to reduce erosion. The more protection a design provides to dune erosion, the higher the rate of dune growth a design is expected to invoke.

It is also recommended to make more measurements of dune evolution, timing measurements in such a way that the observed volume changes can be explicitly attributed to either aeolian or hydrodynamic processes. Suggestions for further development the conceptual model are made, starting with a validation study.

Contents

1 Introduction

1.1 Context

A well-known cliché is that God created the world, but the Dutch made Holland. Luckily, this is not entirely true for most of the Dutch coast. On the beaches and in the dunes most sand is still free to go where nature wants it to go. In the past a few hard elements (dykes, groins, seawalls) were built in the most critical areas, but for the most part the Dutch coast is a sandy coast; there are still far more dunes than dykes along the North Sea.

Every once in a while too much sand moves from one place to the other, weakening the coast below acceptable safety standards. Where the coast became too weak, it was usually strengthened. Sometimes by building hard structures like dykes and groins, sometimes by less intrusive measures as planting marram grass and placing sand trap fences, and sometimes by bringing extra sand to those places that need it most.

For generations the Dutch have interfered with the natural processes just enough to keep the low lands safe, but since 1990 a formal policy for coastal management was adopted: the dynamic coastline preservation policy. To prevent the Dutch coast from retreating, the Dutch coast is nourished everywhere the coastline would otherwise retreat landward of its position in 1990. Since the adoption of the policy some 6 million m^3 of sand have been brought to the shore from deeper water every year. In 2000 the annual amount was increased to 12 million m^3.

Up to the present this policy has proven to be quite adequate (van Koningsveld et al., 2008). But with the anticipated acceleration of sea level rise in the near future, the Delta Committee recommends to not only maintain the coastline in its current position, but to gradually extend the coast by extensive sand nourishments (Veerman et al., 2008)

Traditionally coastline expansion is realized by nourishing the beach, foreshore and dunes directly. Though this method is proven and gives instant result, it is very expensive, and very intrusive. Pipelines and bulldozers are used to nourish and reshape the dunes.

The effectiveness of beach and foreshore nourishments is traditionally often measured in terms of volume increase of the beach and the foreshore. Sand that is transported offshore to the deeper water, or onshore to the dunes, is often considered lost as it is outside of the measured area. With the refocusing of the coastal management from coastline preservation to coastline expansion, sand transport to the dunes must not be considered a nuisance, but as one of the main goals of a nourishment.

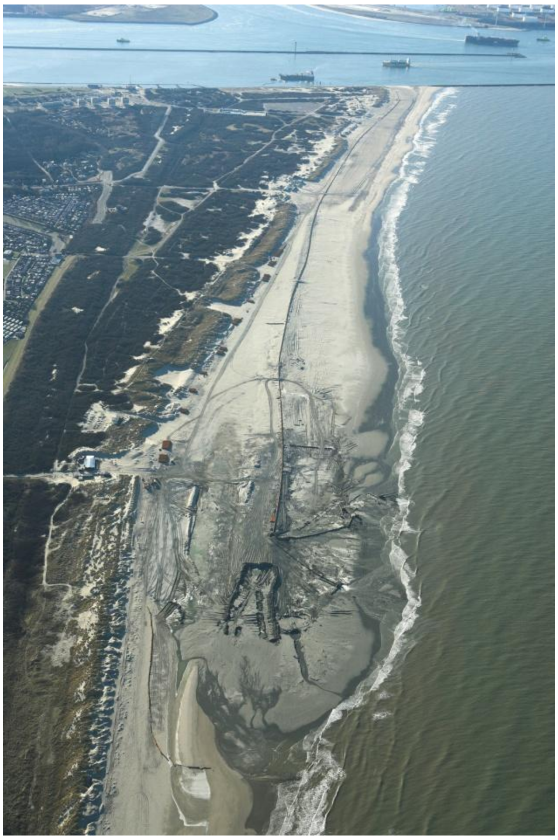

Figure 1. Beach nourishment near Hoek van Holland

If sand transport to the dunes due to foreshore or beach nourishments is considered as a benefit instead of a loss, and if a substantial amount of the nourished sediment is indeed redistributed to the dunes by natural forces, this provides an opportunity to realize coastline expansion at a lower cost and in a more natural, gradual way as compared to direct dune nourishing. By using the power of the wind and the sea to gradually redistribute nourished sand to the dunes one is effectively building *with* nature, rather than against it.

Coastal research in the Netherlands has primarily been focussed on guaranteeing the safety of the hinterland. A large effort has therefore been made to develop models to accurately predict dune erosion during storms, and this effort is still ongoing. The reverse process of erosion, dune formation, is much less understood, although this understanding is essential for effective coast line expansion. This M.Sc. thesis focuses on exploring the natural, longer-term, evolution of a dunefront, and how its growth can be stimulated by large-scale shoreface nourishments.

Building with Nature

As awareness of the often negative human impact on the environment has risen globally, the environmental impact of large hydraulic engineering works as land reclamations and harbour expansions attracts a lot of publicity. Often it is presumed that the impact is large and negative, as it often was in the past. With a thorough understanding of the natural system, however, it is possible to design and construct hydraulic engineering projects in such a way that it has a minimal, or possibly even a positive environmental impact.

To explore these possibilities of hydraulic engineering with a thorough understanding of the natural system, and to turn these into a competitive advantage, the two leading Dutch dredging companies (Royal Boskalis Westminster and Van Oord) have teamed up in a consortium (EcoShape) to fund an extensive five-year research program: “Building with Nature”.

> *The new knowledge imperative Building with Nature is an innovative, long-term research programme aimed at developing new design concepts for the layout and sustainable exploitation of river, coastal and delta areas. Its special feature is the synergy and cooperation that will allow natural ecosystems and human intervention to reinforce each other. Ecology and technology are involved at all phases of a project: design, assessment, selection, construction and management. The primary goal is ecologically, technically and socially sustainable development.*
>
> *Whereas in the past infrastructural plans were mainly assessed for ecological threats (to assure minimal environmental degradation), the new design approach will lay emphasis on the opportunities an ecosystem offers, yet obviously without ignoring infrastructural and economic conditions. Here, nature’s status will serve as the starting point for the design process.*
>
> *[…]*
>
> *A key objective is to share new design and assessment methods based on scientific insights into the working of ecosystems with parties involved in the assessment, development, realisation and utilisation of hydraulic engineering projects in fresh, brackish and salt water zones. Ultimately, better insight into natural dynamics, whether or not affected by the hand of man, will provide ever more valuable contributions to sustainable, socially responsible, physical development. Where nature and construction integrate and combine from the very beginning to strengthen and reinforce each other.*
>
> *www.ecoshape.nl*

Other businesses (Shell, IHC and large engineering firms), the relevant Dutch government bodies (the Ministry of Transport, Public Works and Water Management; the ministry’s Civil Engineering Division; the Ministry of Agriculture, Nature and Food Quality, and the Ministry of Housing, Spatial Planning and the Environment), universities, and knowledge institutions have also joined the consortium. Amongst these partners are Royal Boskalis Westminster, Deltares and Delft University of Technology, who together have made this research possible.

1.2 The sand engine

In the Dutch province of Zuid-Holland structural erosion at a number of locations is likely to cause the dunes to retreat further than what is found to be acceptable for safety standards. In line with the dynamic preservation policy, ad-hoc nourishments are and will be carried out to prevent this.

On a slightly longer term, climate change and sea level rise will increase this demand for nourishments even further. Also there is a great need for more recreational and natural areas in the southern tip of the Randstad metropolitan area. Both of these problems can be addressed by a seaward extension of the dune area.

As large quantities of sand are required at sometime in the future anyway, the idea has risen to address both the safety issue as the need for more space simultaneously by nourishing a large quantity of sand before it is strictly needed. The assumption is that this large quantity of sand will be redistributed by natural forces over the course of time, and thus provide a natural and gradual strengthening of the coast. This idea has caught on, and under the name ‘Sand engine’ a pilot project is launched. The name refers to expected capacity of a large scale nourishment drive the sand transport over the course of several years.

The project is a pilot as it will be the first nourishment of its kind, no comparable intervention has ever been made before. It is seen as a unique and innovative project, in which the goal is not only to strengthen and expand the coast, but also tincrease the understanding of building with nature.

In the start note of the sand engine (Jonker and van Veen, 2008) a single nourishment of 20 million m^3 is proposed, which will be closely monitored over at least ten years. Several alternative designs have undergone a preliminary testing, the results for the ‘hook alternative’ are presented in Figure 2.

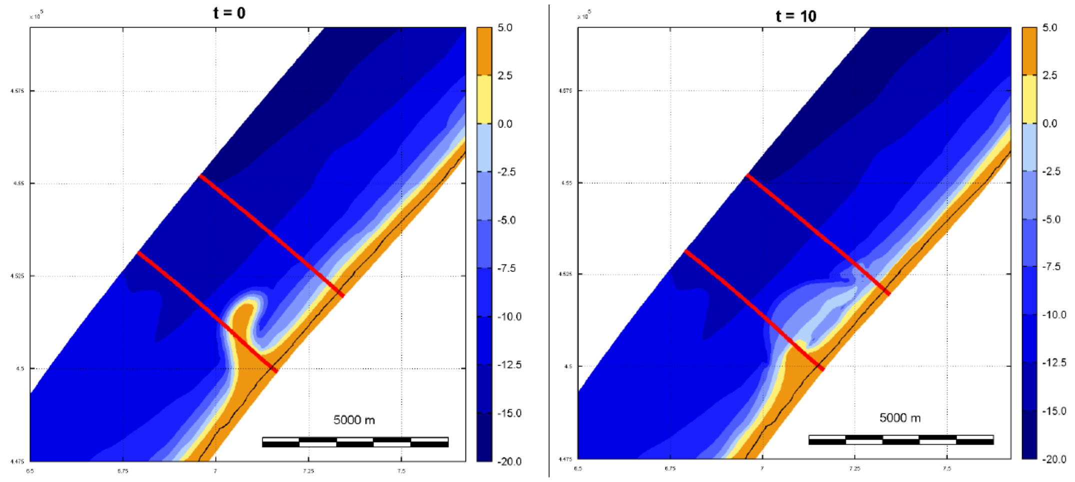

Figure 2. Model results for 'hook alternative'. Left the initial design, and on the right the predicted redistribution after 10 years. In this model dune growth has been accounted for by implementing Roelvink's relation (see paragraphs 2.1.1 and 3.2.1). In this thesis the validity of this relation for short term calculations (compared to timescale over which Roelvink derived his relation) is questioned. (Jonker and van Veen, 2008)

With a state of the art model it is believed to be possible to make predictions for a time span of 10 years, at least of the underwater development of the nourishment. To model the dune accretion which is expected after the nourishment has been placed, a lot is yet unknown.

One of the criteria on which the decision for one of the alternatives will be based is the amount of dune accretion that is realized. As current knowledge is insufficient to estimate dune growth in general, this judgment cannot be properly made at the time. This thesis studies dune growth, and how it is influenced by foreshore interventions in general. The attention is focused on the particular case of the sand engine.

1.3 Objectives

The main objective of this research is to determine if and how a major (subaqueous) coastal intervention will influence the dune system, both qualitatively and quantitatively. Initial focus will be on nourishments in general, and the proposed sand engine pilot project in particular. Further insight into the natural processes can also help understand the influence of 'hard' interventions.

The sand engine pilot project is expected to influence an area of several kilometres alongshore, and the measurement program of the project will last at least ten years. From this the specific temporal and special scales of interest are derived: 10 kilometres alongshore, and 10 years from the time of the intervention.

In the context of the current events, the main question for this thesis comes down to the following: "*How will the coastal dunes develop in the ten years after the sand engine plan has been executed?"*

1.4 Outline of report

In chapter 2 the state of the art of dune evolution is presented. An overview of the relevant processes and current understanding is discussed first, then the capabilities of various models are presented.

To gain further insight into a number of issues and suspicions that arise from this overview, complementary analysis on two large datasets of the Dutch coast is performed in chapter 3.

Taking into account the limitations and opportunities, a conceptual model for dune evolution is developed in chapter 4. State of the art understanding is complemented with pragmatic assumptions to produce a working model. Several qualitative comparisons are done to gain insight into the sensitivity to variations of different model parameters.

The final conclusions are presented in chapter 5, and recommendations for further research can be found in chapter 6.

2 State of the art

Over the last decades researchers with different backgrounds have been interested in coastal dune evolution. Amongst the disciplines involved are geology, sedimentology, ecology and coastal engineering. Each of these disciplines has looked at coastal dunes in a different way.

Geologists tend to focus on very large timescales (hundreds of years), and accompanying changes on a system scale (lifecycle of a coastal dune system, system response to sea level rise). A lot of sedimentological research is focussed on explaining instantaneous levels of transport as a function of wind and sediment characteristics, building on R.A. Bagnold's 1941 (Bagnold, 1941) standard work: *The Physics of Blown Sand and Desert Dunes*. A lot of the work is related to desert dunes, and therefore overlooks some of the processes of interest for coastal dunes, as for instance the influence of varying moisture levels and erosion by the sea during storms.

Ecologists are interested in the natural value of the entire coastal dune area, often overlooking the first dune row. Coastal engineers are traditionally primarily interested in the capability of a the dune row to protect the hinterland. Their focus is on dune erosion on the scale of a storm, not on the slower process of dune recovery.

To gain insight in the effects of construction of the sand engine for the dune system the cycle of dune erosion and recovery must be well understood, but it appears that none of these specializations has explicitly been interested in describing the cycle of erosion and recovery of the first dune row for a time scale of several years.

Nonetheless a lot of relevant work has been done on the processes observed involved in dune erosion and recovery which can help to qualify and quantify the influence of (large interventions on) the foreshore on dune evolution. Firstly an overview of relevant literature is given in 2.1. Then in 2.2 current modelling capabilities are discussed. The conclusions drawn from this analysis in 2.3 form the basis for the next chapters.

2.1 Literature on dune beach interactions

2.1.1 Empirical relation for dunefoot evolution as a function of beach width.

A starting point for dune evolution research is the empirical relation derived by Roelvink (de Vriend and Roelvink, 1989). This relation, which will be referred to as the 'Roelvink relation' from hereon after, is the only explicit formulation known to the author that can be used to predict dunefoot movement as a function of the near-shore bathymetry. In the formulation, the state of the near-shore is measured in terms of the beach width. The basic principles of the balance between dune growth and erosion are described as follows:

"Cross-shore transport between the high active zone and the dunefront is caused mainly by aeolian processes (sand blow from the beach to the dunes) and hydrodynamic processes (dune erosion during storms). When a stretch of coast is in equilibrium over a certain time, these forces are in balance. An important parameter in this equilibrium is the beach width. When the beach is relatively wide, more wind driven sand transport is possible and storm erosion is reduced. When the beach is narrower, dune erosion is more likely and wind driven sand transport is reduced."

Using the Dutch beach line data set (see Appendix A.2), an empirical relation has been derived between the beach width (measured as the cross-shore distance between the dunefoot position (DF) and mean low waterline position (MLW), see Appendix B) of a certain transect, and the averaged dunefoot migration speed.

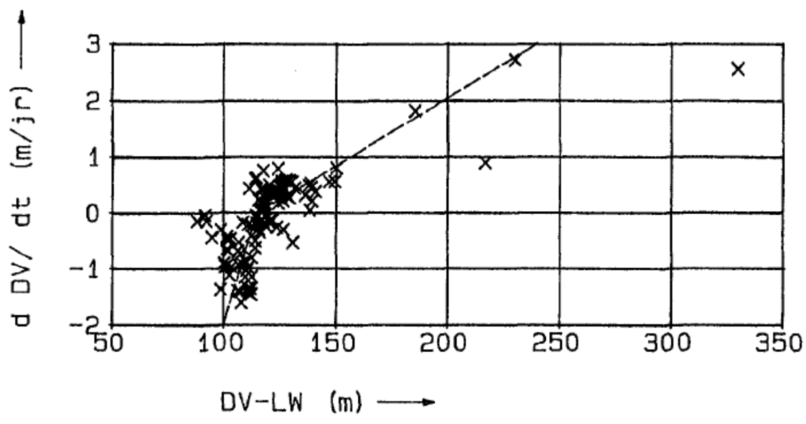

Figure 3. Trend in dunefoot location versus average beach width. Dashed line: approximation near 'equilibrium'-beach width. From (de Vriend and Roelvink, 1989)

For each location the mean beach width is determined by averaging all measurements at that location (between 1843 and 1989). The dunefoot migration speed per transect is determined by linear regression over all dunefoot positions in that transect (between 1843 and 1989); the slope of the trend line is the dunefoot migration speed.

In Figure 3 the beach width vs. dunefoot migration speed is plotted for all transects along the Holland coast; every point in the graph corresponds to one location. Through this scatter plot two trend lines are derived, one for accreting dunes and one for eroding dunes, resulting in the following equation for dunefoot movement with respect to beach width:

$$\begin{aligned} \frac{\partial DF}{\partial t} &= 0.024 \quad DF - MLW \quad -115 \;, \quad DF - MLW > 115 \\ \frac{\partial DF}{\partial t} &= 0.13 \quad\; DF - MLW \quad -115 \;, \quad DF - MLW \leq 115 \end{aligned} \qquad (0.1)$$

with:

DF = Cross shore dunefoot position

MLW = Mean low waterline position

The derived empirical equation can easily be used as a rule of thumb, or implemented in a coastline or 3D area model (e.g. UNIBEST-CL+ or Delft3D), which makes it potentially very useful. The relation is derived by averaging in time over 146 years, and in space over 116 km. These scales are about an order of magnitude larger than the sand engine case: 10 years and 10 km: Further research is needed to see if this relation is applicable in the sand engine case (this analysis is presented in paragraph 3.2.1).

Based on empirical evidence, other researchers have also related dunefoot development to the beach width. Davidson-Arnott and Law (1996) measured rates of aeolian sediment supply in a study of a seven year long annual data set covering part of the dune system bordering Lake Erie (CA). Variations in sediment deposition from year to year, and between sites, were found to be controlled primarily by variations in beach width. Similar observations where made by Saye et al. (2005): "*Eroding dunes were found to be associated with narrower, steeper beaches whilst accreting dunes were associated with wider, low-angle beaches*.", DHV BV et al. (2007): "*There appears to be a correlation between the dune growth and the beach width*." and Ruessink and Jeuken (2002): "*[…] implying that dunefoot variability is controlled by temporal and spatial variability in beach characteristics".*

This observation that *"changes in beach and/or near-shore morphology are likely to be reflected by changes in the erosion/accretion status and morphology of the frontal dunes"* Saye et al. (2005) imply that the realization of the sand engine will indeed have an effect on dune development. As no project similar to the sand engine has yet been realized, use of an empirical relation seems a good way to estimate the effect.

The above-mentioned studies have looked at beaches in a more or less natural state. In a study of various nourishment sites along the Dutch coast van der Wal (2004) observed that dunes accreted more than reference locations in the first years after a beach nourishment. The positive effect of beach nourishments on dune growth is mostly attributed to an increase of the aeolian sand transport, due to increased fetch length and sediment availability. Using the same annual dataset (JARKUS, see Appendix A) DHV BV et al. (2007) quantified the positive effect of artificially widened (nourished) beaches on natural dune growth as an additional 10 m^3/m/year.

Thus there is a broad consensus that wider beaches stimulate dune growth. Saye et al. (2005) attempted to quantify the parameters in this process, but as the critical beach width separating eroding dunes from stable or accreting dunes were found to vary widely between sites, no generally valid relations could be obtained. Other than Roelvink's relation, no explicit quantification of this relationship is found.

To be able to predict dune growth related to foreshore interventions an understanding of the underlying processes is essential. Many authors agree that the two main processes that govern dune evolution are (1) erosion by storms (hydrodynamic processes) and (2) accretion by wind (aeolian processes). The magnitude of transport rates for both of these processes are assumed to be influenced greatly by width of the beach (de Vriend and Roelvink, 1989; van der Wal, 1999; Guillen et al., 1999; Ruessink and Jeuken, 2002; Ruz and Meur-Ferec, 2004). With a thorough understanding of these governing processes, a good qualitative and quantitative estimation of the effect of a sand engine on dune development might be obtained.

2.1.2 Scale dependency of beach and dune behaviour

Due to the hydrodynamic and aeolian processes dunes sometimes accrete, and sometimes erode. When the net effect is about zero for a prolonged period of time (several years), the dunes are said to be stable, or 'in dynamic equilibrium'. To qualify and quantify the effect of foreshore interventions on this equilibrium, one must thus understand the influence of an intervention on both the rates of accretion and rates of erosion.

Along the Holland coast, the mean sand gain of beach and dunes from 1963 to 1986 is found to be some 3 to 3.5 m^3 per meter of length of coast per year (de Ruig and Louisse, 1991), and for more recent years some 5 m^3/m/year is found (DHV BV et al. 2007).

Research by Guillen et al. (1999) of the dunefoot evolution over decadal scales indicates the existence of spatial and temporal oscillations in the shoreline position with magnitudes of 2-3 km length and a periodicity of 4-15 years (Figure 4). This existence of paternal behaviour in space and time is also observed, and has later been studied in more detail by Ruessink and Jeuken (2002).

Guillen also found a very high correlation between the dunefoot position throughout the examined profiles, and the +1 m NAP crossing positions (close to the mean high waterline (MHL), see Appendix B). Examined separately in each coastal zone, this correlation coefficient (R) is in the range of 0.90 - 0.97, indicating that on some aggregated level the dune position is almost one to one related with beach evolution. The scale in time and space to which this high correlation applies is not stated explicitly.

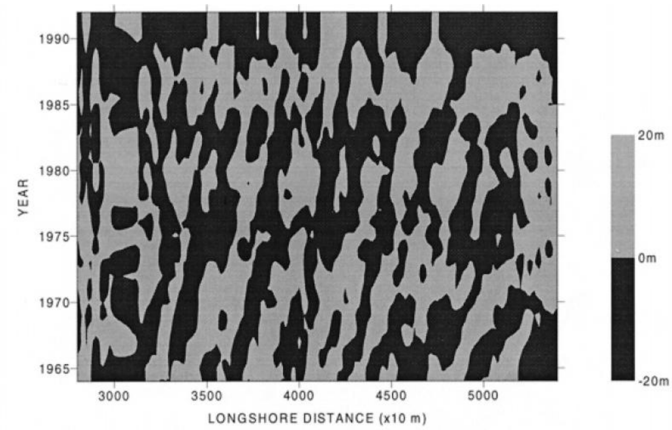

Figure 4. Dunefoot position relative to linear trend position. Location is the Holland coast, distances are from Den Helder southbound. 3000 is near Bergen aan Zee, 5000 near IJmuiden. From Guillen et al. (1999).

The averaged dune behaviour gives little information on the internal dynamics of the system. The yearly accretion rates were found to vary between +250 m3/m and -150 m3/m and a single storm is believed to be able to cause an erosion of at least 400 m3/m under design conditions (van de Graaff 1986). So on different scales, large temporal and spatial variations to the average behaviour exists. For the sand engine case, the relevant time scale is 10 years, and the relevant spatial scale 10 km in alongshore direction. A closer look at this scale dependent behaviour is therefore important; strong variations on a smaller scale may have little effect on a larger scale.

Stive et al. (2002) have attempted to order the different time and space scales of shoreline behaviour. They found that the time scales of coastal changes can often be related to the time scales of changes in forcing, but that there can also exist a certain amount of free behaviour. It is argued that at centennial and decadal scales, we have too little insight into this possible free behaviour: in process models deviations due to free behaviour are either calibrated out or encapsulated in the margins of prediction accuracy.

As an example (see Figure 5) the development of the dunefoot in time for a certain location on Schiermonnikoog is found to be seemingly independent of the waterline, whereas the waterline and dunefoot development at Goeree are almost identical.

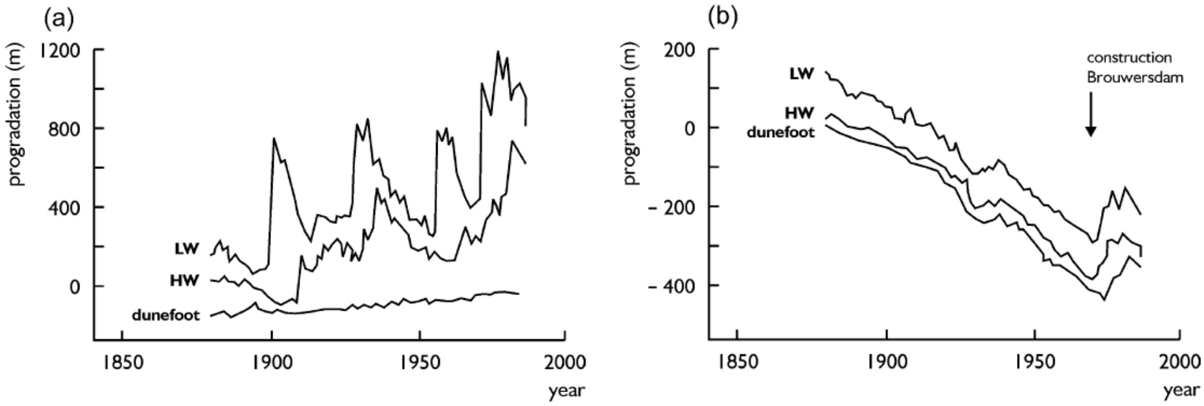

Figure 5. Developement of the MLW, MHW and DF (see Appendix B) since 1880. (a) Northwest location of Schiermonnikoog. (b) West location of Goeree (NL). From Stive et al. (2002)

On all timescales, ranging from decadal to individual storms, forced behaviour can be found. For example on a decadal scale, variations in storminess are found to have an effect on the rates of frontal dune erosion and accretion for the Sefton (UK) coast (Pye and Blott 2008).

Shoreline evolution along the Holland coast on a several-year timescale is found to be mostly forced: after removing short (<one year) and long (>two decades) variations in measurement data of the Holland coast Guillen et al. (1999) identified two main controlling processes of the shoreline evolution: (1) the foreshore morphology (especially the behaviour of the bar system), and (2) variations in the cumulative annual storm-wave climate affecting the near-shore.

Seasonal scale variations are studied by Quartel et al. (2008). The alongshore-averaged (over the entire 1.5 km wide study area) cross-shore position of the dunefoot fluctuated around 0 m and showed a pattern of gradual seaward migration under normal conditions and abrupt landward shifts during storms (see Figure 6 on page 18).

To get a better insight into scale dependency of dunefoot behaviour the hydrodynamic and aeolian processes are looked into separately in the next paragraphs. For both processes the driving forces of variability on temporal and spatial scales are examined.

2.1.3 Storm induced dune erosion

From a safety point of view, it is very useful or even necessary to be able to accurately predict dune erosion rates for a design storm. As dunes function as the primary sea defence along most of the Holland coast, this subject is especially well studied for the Dutch case.

There is a great degree of variability in dune erosion. Some of this can be explained by direct human interference (e.g. armouring of the dunes with concrete mattresses), and some because of a highly non uniform coastline (e.g. near harbour moles). For other cases, the common practice (e.g. predictions for the current coastal management strategy of the Netherlands, (van Koningsveld and Lescinski 2007)) is to predict dune erosion from a 2D profile model (assumption of local alongshore uniformity), and to thus ignore the 3D effects of structures.

For an uninterrupted sandy coast (where the assumption of alongshore uniformity holds locally), van de Graaff (1986; 1994) identified six main factors which influence short-term dune erosion under storm conditions: (1) maximum surge level, (2) significant wave height during the maximum of the surge, (3) particle diameter of the dune material, (4) shape of the initial profile, including height of the dunes, (5) storm surge duration, and (6) occurrence of squall oscillations (an increase in the sustained winds over a short time interval) and gust bumps (short blasts of wind) during the storm. In addition to these factors, van Gent et al. (2008) added wave period (7) to this list.

Finally, variability in dune scarping has also been associated with variability in vegetation levels (8) (Carter and Stone 1989).

The process of dune erosion

Dunes erode when the water level is high (due to tides, wind setup and wave setup), and the waves are high. During such a storm, the foredune is eroded in a matter of hours. Sediment is taken from the dune and deposited on the beach. Dune erosion in general is caused by collision of the swash bores with the seaward face of the foredune (Carter and Stone, 1989; Sallenger, 2000). When waves are high enough, a complete overwash of the first dune row can cause a net landward sand transport (Sallenger, 2000). For the Holland Coast overwash of the dunes is unlikely as the dunes are generally very high compared to the storm levels.

Spatial variability in storm induced dune erosion

For the Holland Coast storm parameters (duration, water level elevation, wave height and wave period) are found to have little spatial variability. On stretches of coast up to 10 km the storm impact can thus be seen as uniform (Ruessink and Jeuken, 2002). Even at the scale of the entire Dutch coast, relative storminess varies little for it's different regions (Wadden Sea, Holland coast and Zeeland), (Ruessink and Jeuken, 2002).

Grain size along the Holland Coast is known to vary between 100µ and 400µ, but local (10 km) spatial variability is very low (Wijnberg, 1995). Three parameters remain to explain spatial variability in erosion rates of the sandy dunes: the occurrence of squall oscillations and gust bumps during the storm, variability in vegetation levels, and shape of the initial profile. The first is assumed to have a very local (<<1000 m, well below the scale of interest) influence and to be of a stochastic (unpredictable) nature. It's influence can thus be considered noise or scatter.

During very large storms with several metres of dune erosion, it is unlikely that vegetation will have much of an influence on the total erosion volumes, as the vegetation is only present in the upper layers. Vegetation might have an influence during smaller storms, but since no studies are known that study the contribution of local variations in vegetation (density) to dune erosion rates, this effect is not further looked into. This leaves variability in the initial profile shape as the primary factor for explaining local variations in storm induced dune erosion.

Spatial variability of foreshore bathymetry is relatively easily observed, and variability in dune erosion rates is indeed found to be linked to the foreshore bathymetry, both for (semi-)natural alongshore non-uniformities by Davidson-Arnott and Stewart (1987), Guillen et al. (1999), Ruessink and Jeuken (2002) and Pries et al. (2008). For artificial alongshore non-uniformities (beach nourishments), a link has been established by van der Wal (2004).

Temporal variability in storm induced dune erosion

The only parameter which can safely be assumed to be constant in time is the particle diameter of the dune material. Vegetation levels are likely to vary on the time scales of storms, human intervention (marram grass planting), seasons (winter/summer) and even decennia (variations in precipitation and temperature). However, no mention of temporal variations in levels of dune erosion due to a varying vegetation levels have been found in literature. This suggests that this effect is of little importance and will thus be ignored.

The dune erosion parameters that are more likely to vary in time are the shape of the initial profile and the storm parameters. When no alongshore transport gradient exists, temporal variations in the shape of the initial profile are most likely caused by storm events, leaving storminess parameters as the main driver of temporal variations in dune foot erosion rates.

For different time scales, temporal variations in dune erosion rates have been linked to variations in storminess:

- For the long scale (100 year), variations in dune erosion have been linked to temporal variations in storm climate (Pye and Neal, 1994).

- On a decadal scale, a correlation between variations in storminess and variations in frontal dune accretion/erosion rates has been observed for the Sefton (UK) (Pye and Blott, 2008) and Holland (Guillen et al., 1999) coasts.
- Yearly variations in storminess correspond to yearly variations in dune erosion rates, especially in very stormy years dunes are likely to erode significantly (Ruessink and Jeuken, 2002).
- Seasonal variation in storminess is observed to greatly influence dune erosion rates near Calais (FR) (Ruz and Meur-Ferec, 2004) and in the Danube delta (RO) (Vespremeanu-Stroe and Preoteasa, 2007)
- Data from one of the few medium-term (years) studies with a monthly resolution (Quartel et al., 2008) suggest a very strong relation between the dune foot location and individual storms (Figure 6, page 18).

2.1.4 Temporal and spatial variations in aeolian transport to the dunes

The reverse process of dune erosion, dune growth, is much less understood than dune erosion. For dune erosion the effect of the different forces and processes that play a role is well understood, so a clear distinction in their contribution to spatial and temporal variability can be made. For dune growth, this is much less the case.

At a broad level, the form and scale of aeolian sand accumulations is governed by at least six factors: (a) sand availability, (b) grain size distribution, (c) wind energy, velocity distribution, (d) vegetation cover, (e) the presence or absence of topographic obstacles, and (f) sequential climatic changes which may bring about any of the first four factors and lead to the modification of existing dune forms (Pye and Tsoar, 1990) .

Causes of variability

Rates of windblown sand transport naturally depend to a large degree on wind speed. In Bagnold's (Bagnold, 1941) widely adopted transport formula the transport rate q is a cubic function of the shear velocity. Many alternative transport formulations also include a shear velocity to the third power (Sherman et al., 1998). Variability in wind speeds will therefore cause variability in sand transport rates. But next to the forcing, also the resistance to transport varies. The most discussed factors that explain variance transport are (a) fetch length (b) moisture level (influenced by the sea, groundwater levels and rainfall) and (c) beach topography (obstacles, vegetation).

In literature several other factors are mentioned, but not further looked into here. Examples are algae growth on the beach (Arens, 1996), temperature (frozen ground) (Nordstrom et al., 2007), armouring (strengthening of beach after smaller particles are blown away) (Smith and Stutz, 1997) and salt crust formations (Ruz and Meur-Ferec, 2004).

Sand transport is also known to be very dependent on grain size diameters, but because of little spatial variance (Wijnberg, 1995) and virtually absent temporal variance in particle sizes along the Holland coast, this factor is also left untouched. Only in the case of a beach nourishment significant changes in particle size can be introduced. It is therefore common practice to use sand with similar properties for nourishments.

Wind velocity

Sand transport rates have been studied as a function of wind speed by many researchers. The most basic formula, derived by Bagnold, states that the transport depends on the wind speed over the threshold velocity to the third power. Though adapted, the formula is still widely used in literature. This, however, holds for steady wind conditions in a wind tunnel. In the field there is seldom one constant wind speed. Wind speed tends to fluctuate rapidly and widely. E.g. Gares et al. (1996) found maximum wind velocities on a beach to typically exceed the mean velocity by a factor two or more, and minimum velocities to be less than half the mean, for only five minute measurement intervals. Sand transport rates are found to vary on an equally short timescale. In the words of Arens (1996):

Transport of sand by wind is a short term process. According to Butterfield (1991) rates of transport respond almost instantaneously (1-2 s) to velocity accelerations. Butterfield states that the grain flux under steady wind speeds are more variable than might have been expected from time-average values. Our measurements indicate that for almost all periods of 10 min the minimum transport rate (measured at intervals of 5 s) equals zero, even at very high wind speeds. This implies that even within such a short period, transport is not continuous.

Therefore, the use of long term averages (hourly or even daily wind speeds) will lead to inaccuracies, because of unsteady conditions, and the predictive power for transport will be reduced.

In an attempt to explain transport events in high resolution field data Wiggs et al. (2004a) achieved the best results when calculating a threshold based on time-averaged (40 s) wind velocity measurements.

Compared to the scale of the sand engine (10 years), the mentioned time scales of actual wind and sand transport (seconds to minutes) are extremely small.

Fetch length

The fetch length in the context of aeolian sand transport on beaches is the length of a beach skimmed over by (no sediment carrying) wind from the sea, enabling it to gather sediment. Cross-shore winds give the shortest fetch length, equal to the beach width. When the wind direction is parallel to the beach, the available fetch length is virtually infinite.

The critical fetch length is the length of beach needed to saturate the wind with sand; a stretch of sand beyond that length yields no extra sand transport. The exact value for this length was found to vary greatly. Dong et al. (2004) found values of only a few metres in wind tunnel tests. In fieldwork campaign on the Benone Strand (UK) by Jackson and Cooper (1999), observations were made within a fetch range of 10-58 m, but no discernable fetch effect was found. Horikawa (1988), as cited by Kuriyama et al. (2005) also found no fetch length effect for lengths greater than 10 m.

In a dataset measured by Levin et al. (2006), of a coastal dune field in Israel, transport rates are measured at varying distance from the waterline (15-400 m); only a weak (18%) correlation between the transport rates and this distance to the waterline was found.

Observations by Arens (1994) on Schiermonnikoog (NL) however did indicate an important fetch effect, even on very wide (hundreds of metres) beaches sand transport rates increased with increasing fetch length. For measurements at sites along the Holland Coast, van der Wal (1999) found that measured transport rates increased with fetch. Davidson-Arnott et al. (2005) also attributed the spatial variation in observed transport rates on a beach in Skallingen (DK) to fetch effects. Based on more literature indicating a fetch length of several tens of metres (e.g. the above-mentioned and Nordstrom and Jackson (1992), Gillette et al. (1996), Jackson and Nordstrom (1998)), he suggests that the vastly varying fetch lengths might be related to surface moisture content.

In a later field research on the Greenwich Dunes (CA), Davidson-Arnott et al. (2008) found values for the critical fetch length (the distance at which the transport rate reaches a maximum) ranging from about 80 m to over 200 m for the combination of wind speeds and beach surface moisture conditions encountered. Mass flux is found to increase with increasing fetch length, the relationship being best described by a power function. One controlling factor on the critical fetch length is indeed identified as the beach surface moisture, but insight into the controls of critical fetch length is judged to be insufficient for good predictions. To develop a theoretical function to predict the increase in transport with fetch distance as well as the critical fetch distance, the current understanding of the processes is argued to be insufficient.

If the critical fetch length is lower than the minimal beach width, this implies that sand transport to the dunes does not depend on the beach width; any further increase of available fetch over the critical fetch length yields no increase in sediment transport.

Moisture level

A very extensive research on the effect of moisture levels has been done by Wiggs et al. (2004b). The general working of surface moisture on transport rates is explained to be dependent on capillary forces and adhesion, that combine to retain water in the sediment matrix against the action of gravitational force, and so increase the resistance of surface particles to aeolian entrainment and erosion.

From literature it is concluded that the concept of threshold velocity being dependent on moisture level is widely confirmed by wind tunnel tests. The existence of a critical moisture content above which entrainment is difficult and sediment transport is suppressed is also suggested. However, comparison of independent wind tunnel studies demonstrates that the findings vary widely.

In field tests, the suspected existence of a time dependant effect in moisture levels due to drying of the beach is confirmed. Results indicate a time-dependent change in dominant control of the sand transport system from moisture to wind speed, dependent on the moisture content of the surface sediment. The interchange between controlling parameters on both entrainment and transport was found to be very sensitive to prevailing moisture conditions. The involved time scale of this process was in the order of minutes to hours.

On a more aggregated scale, Arens (1996) found that rates of transport are lower on wet days than on dry days when wind speeds are below 12 m/s, but for higher wind speeds the differences are small. Sometimes even larger rates of transport are found on wet days. This is explained in terms of wind direction and relative humidity. The frequency of sand transport, however, decreases during wet days. This is argued to be in agreement with observations of Kuhlman (1958). He concluded that the magnitude of rates of transport measured during a wet year was comparable to the magnitude during a dry year, but the frequency of occurrence was much less.

Beach topography

Obstacles on a beach ranging from small debris washed on the shore, big obstacles as dunes and buildings all greatly influence the wind field and thus the transport levels. Each of these obstacles is associated with its own scales in time and space. E.g. sand fences and storm wrack are found to have great local but temporary effects on transport rates by Nordstrom et al. (2007), and reed stems were found to be so effective at sand trapping that a test site was completely covered within a year (Arens et al., 2001). As the formation of dunes, however, is associated with much larger scales than that of individual obstacles, they are not taken into account in this study. The influence of vegetation *levels* and the shape of the dunes on transport rates is seen to be most important.

The great effect of vegetation was quantified by e.g. Kuriyama et al. (2005): along the Hasaki Coast (JP) aeolian transport rates were reduced by 95% with a vegetation cover of 28%. The effect of differences in vegetation density have also been studied by Arens et al. (2001). In literature a wide range of vegetation density levels and associated reductions of transport rates are found. For field research varying densities of reed stems were planted in patches on a beach along the Holland coast. Vegetation density greatly influenced qualitative profile evolutions on a weekly basis, but total trapped quantities over the yearlong campaign yielded very similar amounts for all patches.

Vegetation height and density can vary on a seasonal basis, but vary also due to sand transport: if the rate of deposition is higher than the growth rate of the vegetation, it will be covered. On the other hand, deposition of sand might stimulate vegetation growth, the plants might try to ‘keep up’.

Another major influence of spatial varying deposition rates is the dune face itself. Arens et al. (1995) found that this effect is also dependent on wind speeds: During strong onshore wind, the acceleration of the wind over the dune lifts sand from near the dunefoot and moves it over the foredune in suspension. During weaker winds, vertical wind velocities do not exceed fall velocities of the sand grains, and most of the sand is deposited near the dunefoot. Similar results were obtained from a dune system in the Danube delta (RO): *"The seaward dune face accretes during low to medium onshore winds (5.5–12 m/s) and erodes during high winds (>12 m/s)"* (Vespremeanu-Stroe and Preoteasa, 2007).

Free spatial variability

In two sets of experiments where all known sources of variability were eliminated, still a high spatial variability at small scale was found. Gares et al. (1996) measured trapping rates for several traps placed at a very short interval (0.5) under apparently uniform conditions. The cumulative trapped volumes at 15 minute intervals typically varied ±30% to the mean. In an extension of this work, Jackson et al. (2006) came to similar conclusions. Trapping volumes of five traps placed at a 1 m interval varied as much as 200%, for measuring intervals of 25 to 60 minutes, even though wind and upwind source characteristics were relatively uniform.

This high variability is attributed to streamers. The occurrence of streamers is a form of highly variable free (unforced) behaviour, which is therefore unpredictable.

2.1.5 General aeolian transport findings

With so many sources of variability, each greatly influencing transport rates, it is hardly surprising that it has proven very hard to grasp observed transport rates in simple formulae. The formulae that are derived from different experiments have little generic applicability.

Arens (1996) notes: "*Only under special conditions can aeolian transport of sand on a beach in a temperate humid climate be predicted using current transport equations. On a time scale of hours to days, potential rates of transport may be approached, but actual rates deviate from the potential rates on a longer time scale. The main reason for the deviation of actual from potential rates is in the variation of threshold velocity with time. Within a time period of days the critical threshold velocity may vary substantially. An accurate prediction of transport of sand by wind on beaches in a humid climate is, therefore, only possible if the variation of the threshold velocity is taken into account*."

Even more pessimistic are Bauer et al. (1996). They come to the conclusion that accurate predictions of aeolian sediment flux may never be universally realized, attributing this to indeterminacy. According to Bauer the number of unknowns exceeds, by more than one, the number of available equations. Smith and Stutz (1997) support this finding stating: *"It is not immediately apparent what the relevant fundamental variables are, how they might be linked in a system of equations, nor how the inherent uncertainty in their specification, measurement, and spatio-temporal character might be surmounted."*

On an aggregated scale (annual transport rates) results are a bit more hopeful. Examples discussed above indicate that on an annual scale the variability associated with varying moisture and vegetation levels are levelled out: the sand volumes trapped for very different vegetation densities were found to be nearly equal (Arens et al., 2001), and similar transport rates were found for wet and dry years (Arens, 1996).

Also the sensitivity to fetch length might be fairly limited. The width of the beaches along the Holland coast is mostly well over 50 metres, so even if the critical fetch length is 80 metres, a slightly oblique wind will yield an aeolian transport to the dunes not limited by the fetch length. The power relation between fetch length and transport rates suggested by e.g. Davidson-Arnott et al. (2008) implies that the highest sensitivity to varying fetch length lies at the lower end of the fetch range. The closer the actual fetch length to the critical fetch length, the less sensitive the transport rate is to varying beach width. Nevertheless, many studies reported measured rates of aeolian deposition to correlate well with the beach width, also for higher beach widths.

The monthly dataset spanning several years created by Quartel et al. (2008) of the coast near Noordwijk (NL) provides some additional insights, though dune erosion and recovery is not the focus of that study. Some observations can be made by interpreting the results (see Figure 6):

- The monthly dune growth rate seems very constant throughout the measured interval.
- The dunefoot erosion seems to be determined only by the few highest storms throughout the measured period, where both H_{RMS} is over 3 m, and η_0 is over 1.5 m.

It is clear that annual measurements would not have sufficed to explain this dunefoot movement; the yearly summer position is just about the same every year. An interesting question is whether the dunefoot would have continued to grow if the few storms had not taken place.

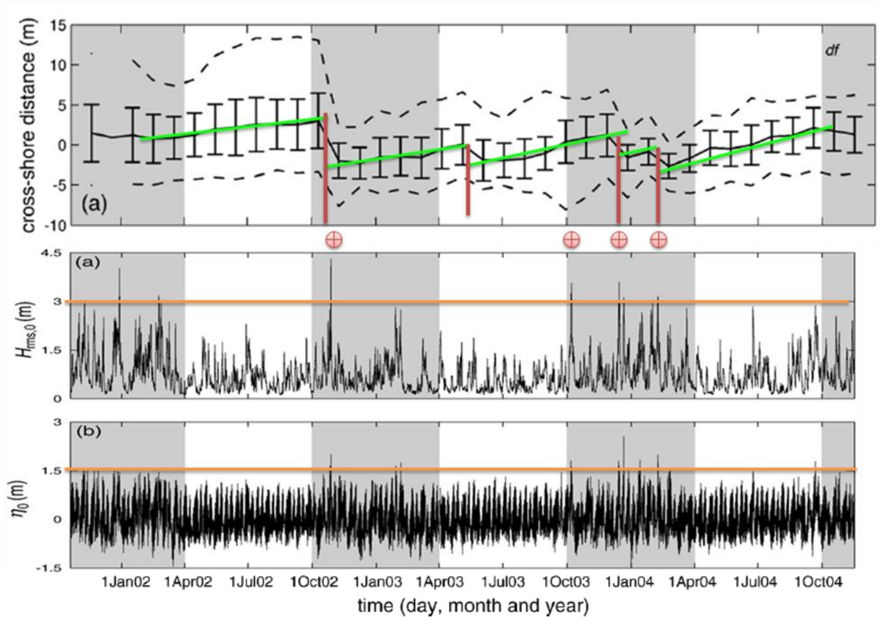

Figure 6. Dunefoot evolution of the coast near Noordwijk (NL), modified from Quartel et al. (2008). The stormy (winter) season is shaded grey. Dune growth can be approximated by a gradual growth (green lines) throughout most of the year, sudden erosion events (red lines). Four storm events can be identified in which the water level rises over 1,5 m and the wave height is over 3 m (red circles) . These four events coincide with three of the four observed major events of dunefoot retreat observed.

2.2 Modelling capabilities

A 'model' in this paragraph refers to an abstraction of part of reality to computable values. A model can thus refer to a basic transport formulation, as well as the implementation of such a formulation in a complete software package that includes a whole range of processes and assumptions.

Only two relations have been identified that give some insight into the way dune development is influenced by foreshore activities, and this insight is very limited. For the modelling of sand transport due to both aeolian and hydrodynamic processes however a great variety of formula's and models has been developed.

These models focus on either of the driving forces, wind or water. Both play a role in dune evolution, so no one model can simulate the full cycle of dune erosion and recovery. But on a temporal and spatial scale where both processes can be adequately modelled separately, opportunities lie for development of a framework in which different models can work together. In this chapter the general capabilities of various hydrodynamic and aeolian models will be explored for different scales in time and space. This is done by interpreting the results of various validation and model development studies.

If a model is able to provide insight into where erosion and where accretion will occur, without being able to make useful predictions of what kind of volumes one can expect, it is judged as a model with qualitative capabilities. If a model not only predicts general patterns of erosion and accretion, but also gives a reasonable indication of associated quantities, it is rated as a quantitative model. Thus a model with moderate quantitative skills will also have good qualitative skill.

The reader must keep in mind that all studies were done with different objectives, so a fair one-to-one comparison cannot be made. Some of these studies have been calibrated so that they best reproduce the measured outcome. Predicting an outcome already known beforehand is known as hindcasting. Though a model with good hindcasting capabilities not necessarily has a good predictive skill, it does give a good indication if the model is able to include the relevant physical processes, and thus if a model 'understands' reality. A model with good hindcasting skills, calibrated to accurately reproduce observed changes to a system, is likely also to be able to qualify, and possibly also quantify the effects of a planned intervention to the system. For best results, (interventions occurring in) the hindcast dataset must be comparable to the planned interventions.

A more or less subjective interpretation by the author of the capabilities of different models is summarized in Table 1a - Table 1d. A graphical overview is presented in the figures at the end of this paragraph.

General coastal dune evolution modelling

Only two papers have been found that explicitly describe relations for dune evolution as function of state of the foreshore. Neither of these relations provides enough insight on their own to make predictions on the scale of the sand engine, but they provide a starting point.

Table 1a. General dune evolution modelling (shaded rows in tables are only formatting)

Nr.	*Short description*	*Model type and name*	*Along shore length scale*	*Time scale*	*Modelling results*
(1)	To study the impact of beach nourishments on the development of coastal dunes a qualitative description of beach dune interactions is made. For several sites, similar qualitative dune evolution is found as function of time after a beach nourishment. (van der Wal, 2004)	Empirical descriptions	1 km	1-5 Years	Moderate, qualitative
(2)	An empirical model relations for beach dune interactions (see paragraph 2.1.1) (de Vriend and Roelvink, 1989)	1D Empirical relations	100 km	170 Year	Moderate, quantitative

Hydrodynamic sand transport modelling

A lot of effort has been put into the creation and validation of models that can predict morphological changes in the coastal zone. A whole range of models for different applications has been developed; from relatively simple empirical line models assuming a constant cross-shore profile to fully process based 3D area models that can cover entire coastal cells.

A selection of studies of a selection of models is presented in Table 1b. Here attention is focused on state of the art process based models UNIBEST-TC and Delft3D, but there are many other (but usually less documented) models available. The capabilities of these other models is assumed to be at best comparable to the ones discussed here.

Table 1b. Overview of various modelling efforts for hydrodynamic sand transport

Nr.	*Short description*	*Model type and name*	*Along shore length scale*	*Time scale*	*Modelling results*
(3)	As a part of a validation study of the state of the art Delft3D-FLOW module several theoretical and real life scenario's are simulated. Sediment transport calculated by Delft3D is compared with measured transport rates in a flume. The transport is measured and calculated at various depths. (Lesser et al., 2004)	2D Profile, Delft3D-FLOW	n.a.	Instant	Very good, quantitative
(4)	Predictions of a coupled, wave-averaged, cross-shore waves-currents-bathymetric evolution model are compared to observations for various test cases. Consistent with observations offshore bar movement is predicted for storms, onshore movement for energetic conditions and no movement for calm conditions. (Ruessink et al., 2007)	2D Profile, Unibest-TC	n.a.	Days-Months	Reasonable, quantitative
(5)	In an attempt to assess the validity of the UNIBEST-TC model, the model is thoroughly examined. For two sites simulations and observations are compared. (Elsayed, 2006)	2D Profile, UNIBEST-TC	n.a.	1-10 days	Reasonable, quantitative
(6)	UNIBEST-TC is applied to support hypotheses that can explain the development of a nourishment of the outer bar on the foreshore near Egmond aan Zee (NL). The model is able to predict detachment of the outer bar from the nourishment, and some of the resulting shoreward bar movement. (van Duin et al., 2004)	2D Profile, UNIBEST-TC	n.a.	1 Year	Reasonable, quantitative

(7)	A conceptual model is developed and analyzed to investigate the relevance of tidal motion for the emergence of undulations of a sandy coastline. In the model the shape of the cross-shore profile at all alongshore locations is represented by one fixed idealized profile. Gradients in alongshore profiles allow this fixed profile to move in cross-shore direction as a whole. Qualitative aspects of the undulations produced by the model are found to agree with observations (time and spatial scale) (van der Vegt et al., 2007)	2D alongshore	10-100 km	50-100 Years	Reasonable, qualitative
(8)	Also part of the validation study, the morphological response to the 1960's IJmuiden harbour mole lengthening is simulated using Delft3D. (Lesser et al., 2004)	3D area, Delft3D-FLOW	1 km	1-8 Years	Reasonable, quantitative
(9)	For the hypotheses testing mentioned in (6), also Delft3D-MOR is applied. The model is able to predict similar trends in erosion and deposition as that have been observed, but intensities were smaller. (van Duin et al., 2004)	3D area, Delft3D-MOR	1-5 km	8 Months	Reasonable, quantitative
(10)	Delft3D is applied to hindcast the morphological development of a shoreface nourishment along the barrier island of Terschelling (NL). With respect to smaller scale bar migration and evolution model results are poor, but resorting to larger scale integrated bulk volumes the model clearly has skill in predicting the effects of the nourishment. (Grunnet et al., 2004)	3D area, Delft3D	1-5 km	Months	Reasonable, quantitative

Dune erosion modelling

Though, strictly speaking, also being hydrodynamic sand transport models, dune erosion models are very different from the models discussed above. The time scale of interest is only short, a single storm; nevertheless huge volumes of sand can be transported from the dunes to the foreshore. Notable models are the empirical DUROS+, semi empirical SBEACH and process based DUROSTA and XBEACH. All these models are able to provide useful, quantitative estimates for a range of for specific cases. For a detailed comparison of these models the reader is referred to Walstra et al. (2008).

The process based models, by definition, have most insight into the underlying processes, and are thus most interesting as they can be applied to a wider range of scenarios.

Table 1c. Dune erosion models

Nr.	*Short description*	*Model type and name*	*Along shore length scale*	*Time scale*	*Modelling results*
(11)	After a thorough review of the DUROSTA model it is concluded that despite not all processes are equally well described by the model, observed and simulated erosion volume and profile show a great resemblance. (van Baaren, 2007)	2D Profile, DUROSTA	n.a.	Storm	Good, quantitative
(12)	Four models for dune erosion are compared (DUROS+, SBEACH, DUROSTA and XBEACH), and compared with flume results. DUROSTA and XBEACH both achieved good results. DUROSTA achieved best, but XBEACH has some more potential for further improvements. (Walstra et al., 2008)	2D Profile, DUROSTA	n.a.	Storm	Good, quantitative
(13)	See above. (Walstra et al., 2008)	2D Profile, XBeach	n.a.	Storm	Good, quantitative

(14)	A 3D area XBEACH model is adapted to include dune overwash modelling. Test results are compared with observed erosion rates. It is concluded that XBEach is able to model the complex hydrodynamics associated with dune overwash and inundation. The model also appears to be able to reproduce morphological features associated with such hydrodynamics. However, the magnitude of erosion in the simulations is an order greater than the measured erosion. (McCall, 2008)	3D Area, XBeach	1 km	Storm	Reasonable, qualitative

Aeolian sand transport modelling practise

Though many studies have focussed on predicting rates of aeolian transport, our understanding of it is still not far enough to make accurate, process based predictions. None of the modelling efforts presented in Table 1d is thus capable of making accurate quantitative predictions.

And as a good transport formulation is the basis for a process based morphologic model, it is not surprising that existing profile models have great difficulty making quantitative predictions. Based not on variations in wind forcing due to e.g. roughness and bathymetry some models are able to qualitatively explain some of the patterns of sedimentation and erosion that is observed on beaches.

Table 1d. Overview of various modelling efforts for aeolian sand transport

Nr.	*Short description*	*Model type and name*	*Along shore length scale*	*Time scale*	*Modelling results*
(15)	Aeolian mass flux distribution is measured on a beach as a function of elevation and distance, for time intervals ranging from a minute to an hour. A calibrated numerical simulation of individual particle trajectories is found to be able to reproduce relative distributions to a high degree. (Namikas, 2003)	Transport formulae	n.a.	Minutes – Hours	Good, qualitative
(16)	In a quantitative comparison five models for predicting rates of aeolian sand transport were evaluated using empirical data obtained from field experiments. Data were collected for periods of minutes. None of the models was able to produce a strong correspondence between measured and predicted rates of transport. (Sherman et al., 1998)	Transport formulae	n.a.	Minutes	Very poor, quantitative
(17)	Aeolian transport rates on a beach in a temperate humid climate measured for several months. 10 minute averaged wind speed and transport rates are compared. Actual rates of transport are found to deviate considerably from potential transport rates predicted by transport equations. (Arens, 1996)	Transport formulae	n.a.	Minutes - Days	Very poor, quantitative
(18)	To compare the effect of surface moisture on the entrainment of dune sand by wind eight theoretical and empirical models are evaluated. Model predictions compared to wind tunnel observations for samples with variable moisture content. Large differences in predicted quantities are found, none of them is able to produce accurate predictions. (Cornelis and Gabriels, 2003)	2D Profile	n.a.	Minutes	Very poor, quantitative
(19)	A purely theoretical study at the capabilities of an aeolian dune model gives an indication of the relevant parameters. Depending on the settings dune profiles similar to those found in nature can be generated from initially sine shaped dunes. Simulations are done for an arbitrary timescale estimated to resemble real life changes on the time scale of months. (van Dijk et al., 1999)	2D Profile	n.a.	Months	Moderate, qualitative

(20)	The influence of reed stems planted on a lower foredune on local profile development is measured and simulated with the SAFE-HILL model. Only qualitative results are obtained, as the time step in the model has no physical meaning. The model is run to simulate accretion volumes comparable to that observed in several months. (Arens et al., 2001)	2D Profile	n.a.	Months	Moderate, qualitative
(21)	In a study on the impact of beach nourishments on the development of coastal dunes, cross-shore profiles generated by SAFE-HILL are compared to measured cross-shore profiles. There was a qualitative resemblance, but quantities differed widely. (van der Wal, 2000)	2D Profile, SAFE-HILL	n.a.	Months	Moderate, qualitative
(22)	Measurements are performed to determine a suitable threshold wind speed value for aeolian sand transport. Results suggest that it might be better to represent threshold values by a range of possible values than a single value. Nevertheless time averaged (40s) results explained a high percentage of transport events. (Wiggs et al., 2004a)	Empirical relations	n.a.	Seconds - Minutes	Moderate, qualitative

2.2.1 Interpretation of modelling capabilities

The list of hydrodynamic and aeolian sand transport studies presented in Table 1a - Table 1d is summarized in Figure 7. For each model the qualitative or quantitative applicability in time and space is plotted. Studies 16 through 18 are not included in the diagram, as the models only demonstrated the inability of quantitative aeolian sand transport modelling. The time and space scale of the sand engine, 10 years and 10 km, is also indicated in the figure.

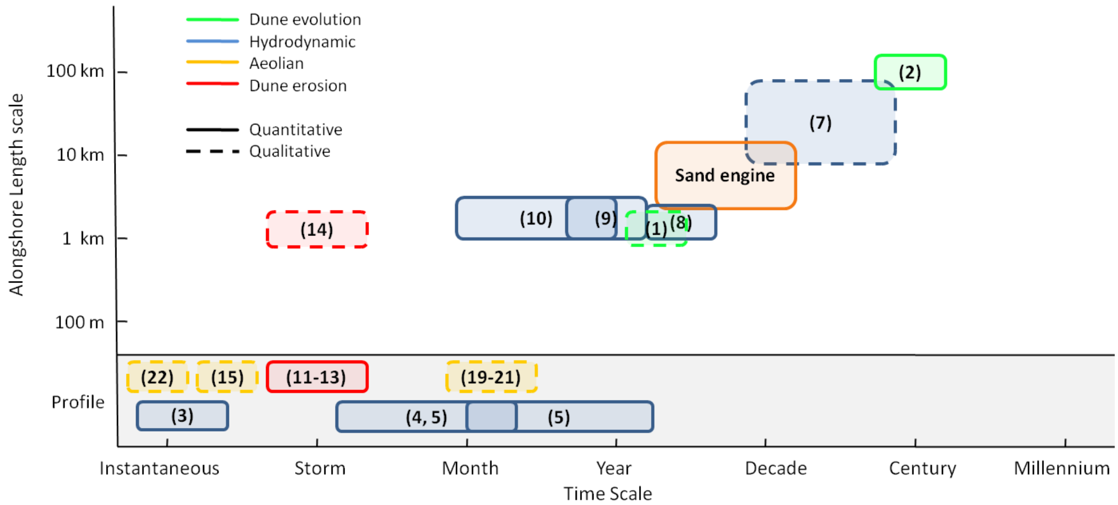

Figure 7. Validity in time and space of the various modelling efforts in Table 1a - Table 1d. Solid lines indicate quantitative results, dotted lines are for only qualitative results. The capabilities of sub-aqueous hydrodynamic models are indicated in blue, those of sub-aerial aeolian driven models in yellow. The general dune evolution models are indicated in green, and dune erosion models in red. Numbers correspond to the table entries.

The models presented in Figure 7 are believed to outline the boundaries of current modelling limits. Interpretation of the studies leads to Figure 8: an explicit schematization of the limits of the current state of the art in modelling. The bounded areas represent the temporal and spatial scales in which current models are somewhat capable of predicting sand transport caused by either aeolian or hydrodynamic processes. Longer prediction horizons are associated with larger spatial scales and vice versa. Also, for every scale that quantitative predictions can be made, also qualitative predictions can be made. This does not hold the other way round.

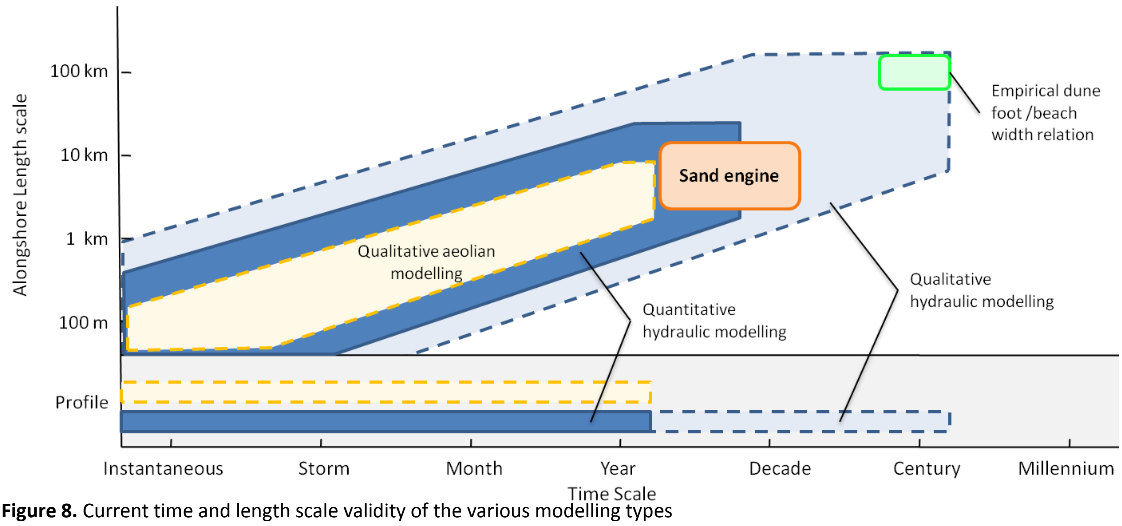

Figure 8. Current time and length scale validity of the various modelling types

2.2.2 Implications for dune evolution modelling on the scale of the sand engine

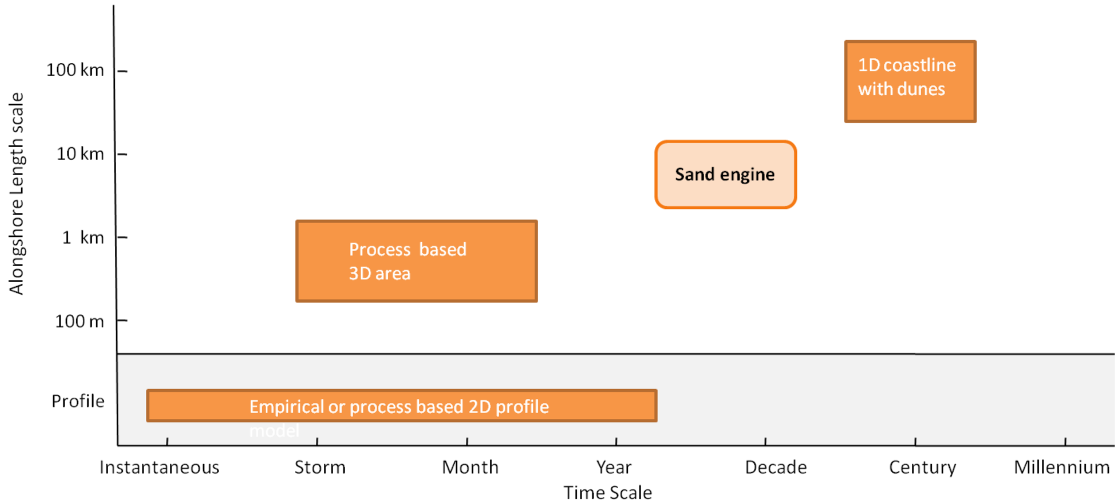

Figure 9. Three opportunities for developing a dune evolution model with their associated temporal and spatial limits, compared to time and length scale of the sand engine.

As both aeolian and hydrodynamic processes are found to greatly influence dunefoot evolution, dunefoot evolution can be modelled only on the temporal and spatial scales that both give valid results. Three approaches seem possible with the current state of the art (Figure 9), but none of these covers the scale of the sand engine.

(1) 1D coastline model

A 1D coastline model is adapted to include the dune front. This can be done by either including the dunefront in the static equilibrium cross-shore profile (following Guillen's observation that dunefront and beach width evolution are highly correlated), or a via coupling between the submerged and emerged profiles via an analytical relation as proposed by Roelvink. The latter relation is derived for greater scales than of interest for the sand engine, this deserves some further attention.

(2) Empirical or process based 2D profile model

For the time scale of the sand engine, sub-aqueous profile modelling is fairly well capable of providing good results. Dune erosion is also well understood, and can be adequately modelled on the time scale of storms. Aeolian models are incapable of quantitative modelling, but acceptable qualitative results are possible. As literature provides some hints that annual transport rates might be relatively insensitive to inter and intra yearly variations, a model might be developed that includes process based hydrodynamics and a (semi-) empirical aeolian component.

For an alongshore non-uniform intervention as the sand engine, a 2D profile model (that assumes alongshore uniformity) cannot provide very detailed results by definition. It would thus function only as a starting point for a 3D model.

(3) Process based 3D area model

In the ideal case the influence of both wind and water induced sand transport are modelled in a 3D area model. For the sub-aqueous profile, models have shown some very good results. Quantitative predictions of 3D dune erosion still is quite a challenge, but the results and developments in this field are very promising. The problem lies with aeolian sand transport prediction. The limited qualitative capabilities, and lack of any reliable quantification of transport rates makes it unlikely that a fully process based 3D model for dune evolution can be developed in the near future.

Though a bit of a simplification, a 3D model can be seen as a series of coupled 2D profiles. Only if such a profile model is successfully developed and tested, the extension to the third dimension is possible.

2.3 Synthesis and conclusion

After the study of literature and the models the following can be concluded:

- Literature:
  - There is consensus that beach width is a steering parameter for dune evolution. Wider beaches protect the dunes from erosion during storms, and the greater fetch distance on a wider beach allows for a greater aeolian sand transport potential. At a certain beach width, the equilibrium beach width, the eroding and accreting forces are in a (dynamic) equilibrium.
  - The relative contribution of the hydrodynamic and aeolian processes in establishing this dynamic equilibrium cannot be easily distinguished because most research is based on annual datasets: only the net effect of a year of erosion and accretion is measured.
  - Studies on rates of aeolian deposition tend to attribute the observed higher quantities deposited at wider beaches solely on an increase in the rate of aeolian transport. A physical explanation is found in the fetch effect. Often the influence of hydrodynamic forces is neglected.
  - Measurements in the field have yielded a wide range of values for the critical fetch length: below ten to over hundreds of metres. Wind tunnel tests generally indicate a length of only several metres. Compared to averaged beach widths along the Holland coast (>50 m), and the fact that winds are often not exactly perpendicular to the coast, the influence of fetch length for the Holland coast can be questioned. If the rate of aeolian sand transport along the Holland coast is indeed not that sensitive to the beach width, it might be more related to the erosion rates. This must be further looked into.
  - Aeolian transport is also reported to be highly dependent on other factors, such as beach moisture level, transport threshold wind speed, vegetation density and height, algae growth on the beach, etc. No consensus exists on applicable values for controlling parameters, if they are even defined at all.
  - Sand transport is also found to be highly dependent on varying meteorological forcing, transport rates varying on time scales of seconds to minutes.
  - Nevertheless literature cautiously suggests that aggregated modelling of accumulated sand transport over longer (yearly) intervals be more acceptable, as inter and intra yearly variations of meteorological forcing seems to have limited effect on total sand transport rates.
  - Interesting patterns have been observed in time and space for dune accretion and erosion rates along the Holland coast, that indicate a temporal and spatial coherence (see Figure 4, page 13). A better understanding of these patterns might provide more insight into the controlling parameters for dune evolution.
  - A very high correlation between dunefoot and coast line positions is mentioned in literature, the time scales associated with this behaviour are not clearly defined.
- Models:
  - No process based models are found that combine hydrodynamic and aeolian processes. Therefore no models are found that are capable of process based dune evolutions modelling.
  - The only applicable empirical relation for dune evolution that is found uses the beach width as steering parameter for dune evolution. The relation is based on large scale averaging in time and space (respectively >100 years and >100 km alongshore), and therefore must be looked into in further detail to judge the applicability for the sand engine scales (10 year and 10 km alongshore)
  - Process based hydrodynamic models are capable of providing good results fur sub-aqueous sand transport predictions for the sand engine time and space scale.
  - Dune erosion can be adequately modelled for alongshore-uniform profiles. Developments for 3D dune erosion are promising, but 3D quantitative dune erosion modelling seems beyond current capabilities.
  - No aeolian sand transport models are identified that are capable of providing good quantitative estimates of sand transport.

The state of the art thus provides no directly applicable method to qualify and quantify dune evolution with respect to (large interventions on) the foreshore. In the next chapter data research will be applied to follow up on a few of the leads found in literature. Of particular interest is insight into the following aspects:

- Scale dependency of empirical relation for dune evolution.
  Does the relationship derived by Roelvink hold for other timescales, specifically that of the sand engine?
- Correlation between dunefoot and coastline position.
  Guillen found that dunefoot and coastline behaviour are correlated, but from the paper the timescale of this relation is not directly clear
- Existence of a time lag in dunefoot position compared to coastline movement.
  The equilibrium beach width concept states that advance or retreat of the coastline does not directly influence the dunefoot position, but only has an indirect influence. Change of the coastline position changes the beach width, and a change of the beach width affects both the rates of accretion and erosion of the dunes. The dunefoot

position is only stable when these are in balance, so when the coastline position is changed, the dunes will adjust to a new equilibrium in time. This implies that dunefoot behaviour responds to coastline movements with a certain time lag.

- Observed patterns in dunefoot and coastline behaviour, and how this is related to aeolian accretion and hydrodynamic erosion.
  The existence of similar patterns in dunefoot and coastline position have already been discussed phenomenologically by Guillen, and Ruessink and Jeuken, but the underlying causes are less well studied. Of special interest is the separate influence of aeolian and hydrodynamic forces.

3 Data analysis

In this chapter the Dutch Beach Line and JARKUS datasets will be examined to acquire better insights into the topics discussed in the previous chapter. Because many references are made to these datasets, and nearly all research regarding the Dutch coast is at least partly based on these datasets, they are discussed in detail in Appendix A.

Paragraph 3.1 provides a brief description of the study area, the Dutch coast in general, and the Holland coast in particular.

In paragraph 3.2 the Dutch Beach Line dataset is analysed to get a further insight into the relations between beach width and dune evolution. Following the analysis by Roelvink discussed in paragraph 2.1.1, a similar analysis is done for the entire sandy Dutch coast, and applied for different timescales. Also the correlation between coastline and dunefoot movement is further examined.

Time-series of dunefoot and coastline data for the Holland coast are examined in more detail in paragraph 3.3. The signals are split in different components to check for different behaviour at different time scales, and existence of time lag effects.

The final data analysis in paragraph 3.4 further explores the observed patterns in dune and coastline behaviour for the entire Holland coast.

3.1 The study area: The Dutch Coast

The total length of the Dutch coastline is more than 400 kilometres. It is often split in three distinct regions, from South to North: the Zeeland Delta, the Holland Coast and the Wadden Sea (Figure 10). Each of these regions is subdivided into several sections.

The sand engine is planned to be constructed along the Holland coast, but as a similar dune system exists along parts of the entire coast of the Netherlands, these area's will also be examined for comparison.

The coast of the Netherlands, and especially the Holland coast, can be considered very well studied as it has attracted a lot of scientific interest. This interest can be explained by the importance the coastal zone has in protecting the densely populated Randstad, a conglomerate of cities, the greater part of which lies well below sea level. The famous Dutch history with water management has lead to the establishment of some of the world's most renowned institutes for coastal research in the Netherlands, namely Delft University of Technology and Deltares (the former WL|Delft Hydraulics). Annual survey data (Dutch Beach Lines) recorded by the Dutch government (Rijkswaterstaat) are available from 1843 onwards. Since 1963 the detailed annual JARKUS measurements are available (see Appendix A)

Only a very brief introduction of the Dutch coast is discussed below, for more detailed information the following studies are recommended:

- **"Morphologic behaviour of a barred coast over a period of decades"** (Wijnberg, 1995):
  A detailed study of the bar system along the Holland Coast. Also includes a thorough description of the Holland Coast.
- **"Holocene evolution of the coast of Holland" (**Beets et al., 1992):
  Geological history of the Holland coast.
- **"The Dutch Foredunes - Inventory and Classification"** (Arens and Wiersma, 1994):
  Classification of the dune system along the Dutch coast
- **"Living with sea-level rise and climate change: A case study of the Netherlands"** (van Koningsveld et al., 2008):
  A general history of Dutch coastal management
- **"Decadal scale performance of coastal maintenance in the Netherlands"** (van Koningsveld and Lescinski, 2007):
  Discussion of current Dutch coastal management strategy
- **"Samen werken met water"** (English: Working with water) (Veerman et al., 2008):
  General outlines for future Dutch coastal management

General overview of the Dutch and Holland Coast

Figure 10. The Dutch coast in regions and sections, modified from Roelse (2002)

Figure 11. Coastal settlements along Holland coast (Roelse, 2002)

The Zeeland Delta is characterized by a series of tidal inlets and estuaries (now mostly controlled by open or closed barriers following the major flooding in 1953). Though critical points along the Zeeland coast have long been heavily managed and fortified, each of the peninsula's also relies on a dune barrier to protect it from the North Sea. Some of these stretches of dunes can be considered almost completely natural (Arens, 1994).

The Holland coast (also known as 'Central Dutch Coast', 'Central Netherlands Coast' and 'Dutch Mainland Coast'), is the part of the Dutch North-Sea coast that forms the western boundary of the provinces Noord-Holland and Zuid-Holland. It stretches from Den Helder in the north, to Hoek van Holland, about 120 km to the SSW. It is characterized by a closed dune row varying in width from less than 100 metres to several kilometres. The alongshore sand transport is (at least partly) interrupted by the harbour moles of Scheveningen and IJmuiden (Figure 11). Seawalls are constructed for the boulevards in most of the coastal towns, there is a large discharge sluice at Katwijk, and there is a 6 km long dyke known as the "Hondsbossche en Pettemer zeewering".

The Dutch Wadden Sea is only the southern end of the Wadden sea, a shallow sea with large intertidal areas that is separated from the North Sea by a chain of barrier islands that extends to Denmark. The islands (known as the Wadden islands) each rely on a row of dunes to provide protection from the North Sea.

Engineering works along the Holland Coast

The closed dune system is present along the Holland coast today, was formed between 800 and 1650 AD (Arens and Wiersma, 1994). From as far back as 1550 large interventions have been undertaken, the most important interventions are listed in Table 2.

Table 2. Engineering works along the Holland coast, taken from Arens (1994)

	Activity	*Period*	*Spatial scale*
Seawalls			
Hondsbossche and Pettemer Seawall (km 20 – km 26)	construction most recent relocation	about 1550 1823	? 6 km (alongshore)
Scheveningen (km 102)	construction most recent relocation	1895/1896 1896, 1902 and 1907	140 m (alongshore) 2.5 km (alongshore)
Groins			
km 2 – km 31 *km 98 – km 118*	construction construction	1838 – 1935 1776 – 1896	
Harbour moles			
IJmuiden (km 55,56)	construction extension	1865 – 1879 1962 – 1967	1.5 km (cross-shore) southern mole +1.5 km northern mole +1 km
Scheveningen (km 102)	construction extension	1900 – 1908 1968 - 1970	groin length + 0.5 km
Hoek van Holland (km 118)	construction extension	1864 – 1874 1968 - 1972	2 km (cross-shore) northern mole: + 3 km
Discharging sluice			
Katwijk (km 86)	construction increase discharge capacity	1807 1984	

Sand waves

The patterns in time and space observed in dunefoot accretion and erosion rates can be linked specifically to sand waves (Ruessink and Jeuken, 2002). Sand waves are defined as transversal wave-like movement of the shoreline, measured in a horizontal plane. The horizontal displacement of the shoreline y can thus be written as a function of time and place along the shoreline (e.g. $y = A \cos(\omega t + kx)$; y is the position of the shoreline, x is the distance along the coast, A is the amplitude, and t is the time). They have been described along several stretches of the shoreline of The Netherlands. Typical values for amplitude, celerity and period for different sections along of the Netherland coast can be found in Table 3.

In general sand waves are often explained by some cyclic event at their origin, as e.g. a cyclic movement of an inlet channel. Theories based on this assumption seem to apply for the Wadden Isles in the north of The Netherlands; the presence of sand waves can be explained by sand banks moving from one island to another in the direction of the alongshore, surf-induced current. For the coast of Walcheren there seems to be a correlation between the occurrence of sand waves and eroding and accreting zones in the outer delta (Verhagen, 1989).

For the specific case of the Holland coast no such explanation is found, and the origin of the sand waves is unknown. Guillen et al. (1999) suggest that shoreline sand waves along a section of the Holland coast with a wavelength about 2–3 km could be just forced by surf zone crescentic bars. Hoiwever, this is a very particular case and the wavelength is at the lower limit of those observed. Another explanation is that sand waves are a free instability caused by high-angle waves. Some theoretical evidence for this theory is found by Falques and Calvete (2005).

Though theories differ in explaining the origin of sand waves, their existence is always related to hydrodynamic forces. This implies that if similar sand waves are found in dune behaviour, this behaviour must then be forced by the foreshore, and not the other way around. This has already been argued by Ruessink and Jeuken (2002).

Table 3. Sand-wave characteristics along the Dutch coast, adapted from Verhagen (1989)

Shoreline	*Amplitude (m)*	*Celerity (m/yr)*	*Period (yr)*
Schiermonnikoog	50-850	240-340	50-100
Ameland	25-2500	310-450	40-90
Terschelling	25-1900	240-400	40-90
Vlieland	25-600	220-270	60-80
Texel	?	?	?
Coast of Holland	40-60	65	75-100
Voorne	50-150	130-160	50-70
Goeree	50-350	220-300	100
Schouwen	50-450	90	40-60
Walcheren	80-400	45	120-150
Zeeuwsch-Vlaanderen	50-200	100	60

3.2 Linear trends

By fitting a trend line through data points extracted from the Dutch Beach Line dataset via linear regression, Roelvink came up with an empirical relation for dunefoot movement. Guillen mentions a correlation between the dunefoot movement and the coastline position. The validity of such relations will be applied to the timescale of the sand engine intervention, 10 years.

3.2.1 Discussion of Roelvink relation

As described in 2.1.1, Roelvink has found a relation that directly links dunefoot behaviour to the beach width. If this relation is valid for the scales of the sand engine, it can easily be added to a model that can predict the response of a coastline to foreshore interventions (e.g. Delft3D). Such a relation could thus be very important in answering the main questions of this thesis. It is therefore essential to critically discuss its applicability.

Roelvink derived the relation by determining the mean beach width (averaged over all measurements between 1843 and 1989), and the dunefoot migration speed (determined by the slope of a linear regression over all dunefoot positions between 1843 and 1989). This is done independently for every location.

In Figure 3 Roelvink's results are presented. A critical examination learns that the slope of the fitted trend line for beaches wider than the equilibrium beach width is mostly determined by the few locations with a beach width higher than 150 m. These points represent the development of the transects close to the IJmuiden harbour moles, as became apparent after the method was replicated (Figure 12).

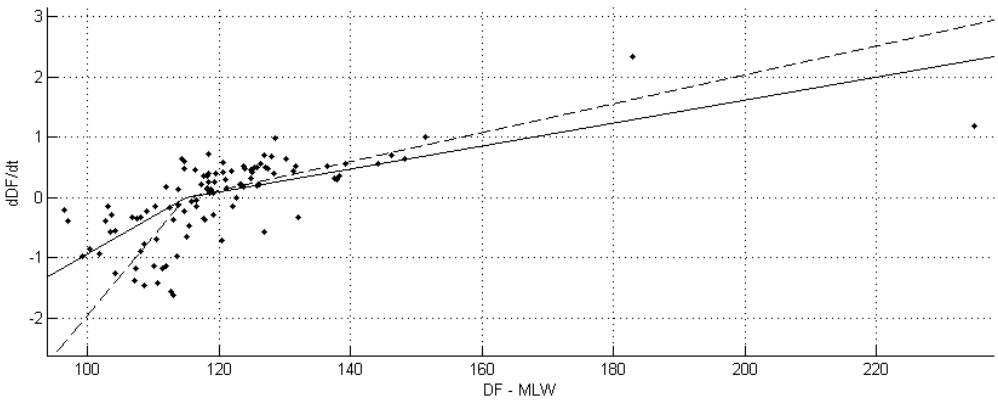

Figure 12. Reproduction of the Roelvink relation All transects along the Holland coast are used except for the dykes at transects 20 (Den Helder) and 2100 (Petten) and the large nourishment known as the van Dixhoorn Driehoek at transects 11700 and 11800. The dashed line is drawn using the coefficients found by Roelvink, the coefficients of the solid line are found by best fitting (using the RMS criteria) of two lines forced through (115,0).

The IJmuiden harbour moles represent a large discontinuity along the otherwise fairly uniform coast, but until 1993 the dune management in this area has been fairly limited (Arens and Wiersma, 1994). The found relation is therefore somewhat justifiable, but relying so heavily on just these few data points still means it could easily be distorted.

For the retreating dunes the slope of the linear regression line seems fairly arbitrary, as is the exact value for an equilibrium beach width. All dunes at beach widths below 110 m have retreated but the fastest retreating dunes have a beach width of about 115 m, whilst dunes at the narrowest beaches have hardly moved. This makes it impossible to determine the coefficient for the linear relation for retreating dunes with any confidence, if such a common relation exists at all for this area. The values for the equilibrium beach width and rate of dune erosion found by Roelvink appear to have been established by visual judgement.

Therefore, the proposed equations should be used only with great reservation, if at all. They suggest a precision which is not really substantiated by the data. A more general conclusion seems valid though: wider beaches tend to be accompanied by progressing (accreting) dunes and narrower beaches by retreating (eroding) dunes.

3.2.2 Method

In analogy to the method of Roelvink discussed above, the measurement data of the Dutch coast are analysed by plotting the mean beach width versus the yearly dunefoot displacement. The analysed area is extended to the entire Dutch coast, and, to get better insight into the temporal dependency of observed relations, the method is repeated for different time-spans.

The mean beach width at a certain location is calculated as the mean of all of the observed beach widths in a certain time period. The yearly dunefoot displacement is calculated as the slope of the trend line fitted to the dunefoot data over a certain period by least squares linear regression analysis.

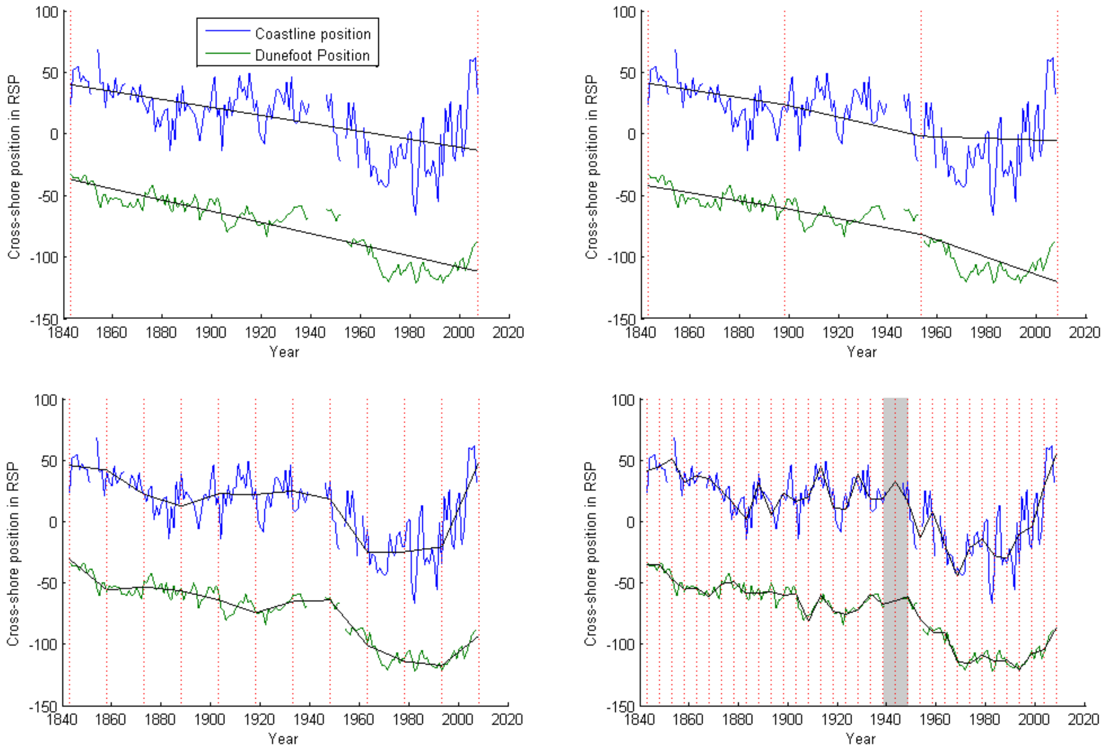

Figure 13. Example of coastline and dunefoot development at transect 3400, near Bergen. From top left to bottom right the time-series is linearized over 1, 3, 11 and 33 time-spans of 165, 55, 15 and 5 years, respectively. Where more than half of the data points within a time-span are missing, the data for that time-span and transect is discarded (marked grey in bottom right plot).

The analysis is repeated for four different time-spans: 165, 55, 15 and 5 years (see also Figure 13). Each of these time-spans represents a time-scale. As an example the procedure for the 55 year timescale: the set is split over 3 time windows, each covering 55 years of the 165 year dataset. For each of these time windows, for every individual time-series of a transect, the mean values of the beach width, the coastline movement and the dunefoot movement are computed.

The mean value of the beach width is the arithmetic mean of all observed beach widths that fall within the time-span (this is not the same as the distance between the linearizations of the CL and DF). The slopes of the coastline and dunefoot movement are determined by fitting a linear function with breaks at an interval of the time-span length. For the best fit the least mean squares criterion is used.

For the 55 year example, every transect is thus condensed into three data points. Each one with a value for the mean beach width, mean yearly coastline movement and for the mean yearly dunefoot movement within that time span. This thus results in three times the number of points compared to the first analysis. All these points are plotted in one graph and the relation is determined by linear regression. The same routine is repeated for 11 time windows of 15 years and 33 time windows of 5 years, yielding 11 and 33 times more data points, respectively, than for the 165-year time-span.

Examples of these plots can be found in Figure 16 to Figure 19. All data from similar figures are condensed in Table 5.

An advantage of this method is that use is made of a very straight-forward method of determining the time-scale for the movement: the time-scale is simply the time-span. But the method also introduces some arbitrariness: because of the linearization with a least squares criteriom, the weight of data-points at the edge of each time-span is greater than of those in the middle of a time-span. In Figure 13, this is evident in the two bottom plots (at 1982-1985). Though more advanced statistical techniques exist to account for this, the simplicity of this method is preferred here. The large number of transects examined is assumed to mask these kind of artefacts sufficiently.

3.2.3 Data selection

Along the Dutch coast the foredunes have been classified by Arens and Wiersma (1994) in degrees of naturalness, ranging from completely natural to fully artificial. In the ideal case only natural dunes would be considered in the analysis, but as almost all of the dunes have been managed in the course of time a more lenient criterion is used to judge which transects to use and which not.

Most important is that the advance/retreat of the foredunes in the transect has been caused largely by (gradual) natural processes (some combination of wind and water), and not by (near-instant) human interference. This excludes profiles subdue to large scale foredune nourishments and large scale mechanical reworking of profile, but does not exclude indirect dune management measures, as they are classified by Arens and Wiersma (1994): planting of marram grass, placement of sand fences, beach nourishments.

Also, only transects are used which are uniform to some degree (i.e. the transect is similar to its neighbouring transects), have a clear first dune row, and have developed gradually over time.

These requirements exclude most of the coastal resorts. The heads and tails of the Wadden islands, and areas as for instance “de Slufter” on Texel are not used. An overview of the used and available transects is given in Table 4 and charted in Figure 15.

To allow visual inspection of the data for artifacts, and to get a better insight into the processes in general, all data have been plotted in GoogleEarth™. More information on the use of GoogleEarth™ for data inspection can be found in Appendix F.

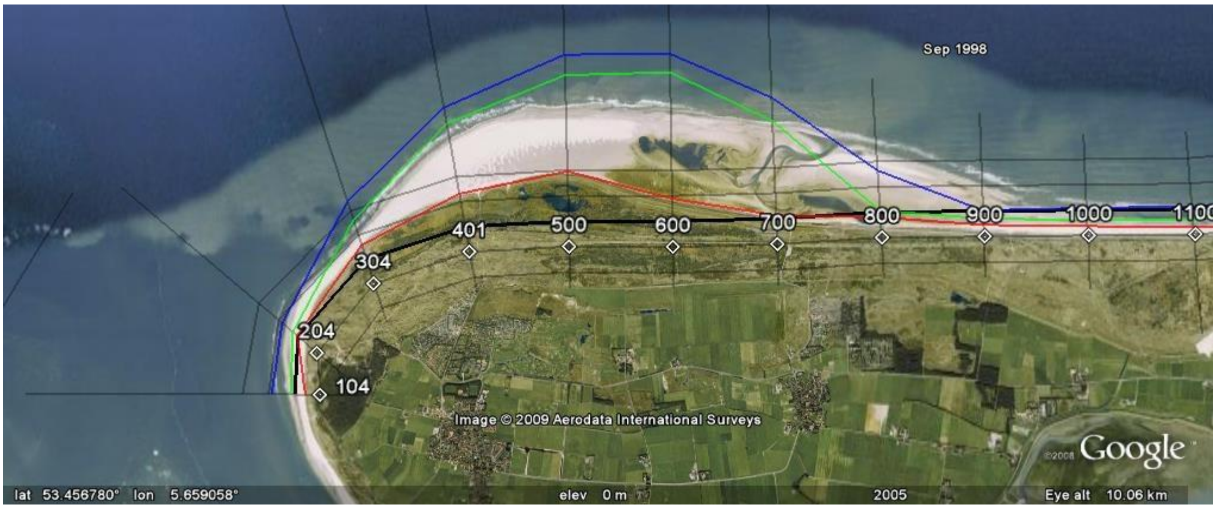

Figure 14. MLW (blue), MWH (green) and dunefoot line (red) as recorded in 1998, visualized in GoogleEarth. The thick black line represents the RSP line, which corresponds to the 1880 dunefoot position. The cross-shore spacing between the black grid lines is 250 m.

Table 4. Transects used in analysis

coastal section	*section number*	*transects analysed / transects section*	*analysis time-span*	*discarded transect(s)*	*comment*
Schiermonnikoog	2	8/15	1966 – 2007	00103 – 00400 01400 – 01600	island head island tail
Ameland	3	13/25	1901 – 2007	00104 – 00401 01800 – 02500	island head island tail
Terschelling	4	13/29	1860 – 2007	00100 – 00500 01900 – 03000	island head island tail
Vlieland	5	10/20	1860 – 2007	03504 – 04187 05309 – 05374	island head island tail
Texel	6	7/27	1850 – 2007	00600 – 01190 02191 – 03200	island head island tail
Noord-Holland	7	40/47	1843 – 2007	00020 01205 – 01295 02100 – 02600 03300 03800	Huisduinen Callantsoog Hondsbossche Zeewering Bergen aan Zee Egmond aan Zee
Rijnland & Delfland	8&9	40/62	1843 – 2007	05700 – 05900 06300 – 06700 08100 – 08300 08600 – 08800 09875 – 10200 10592 11109 – 11196 11611 – 11800	IJmuiden Zandvoort Noordwijk Katwijk Scheveningen Kijkduin Ter Heijde van Dixhoorn driehoek
Goeree	12	27/30	1879 – 2007	01150 – 01250	Flaauwe Werk
Schouwen	13	13/15	1900 – 2007	00155 01750	Insufficient data Insufficient data
Walcheren	16	23/23	1900 – 2007	01832 – 02300 02600 03215	Westkapelsche Zeedijk Zoutelande Dyke
Zeeuwsch-Vlaanderen	17	4/10	1881 – 2007	00031 – 00993	Dyke

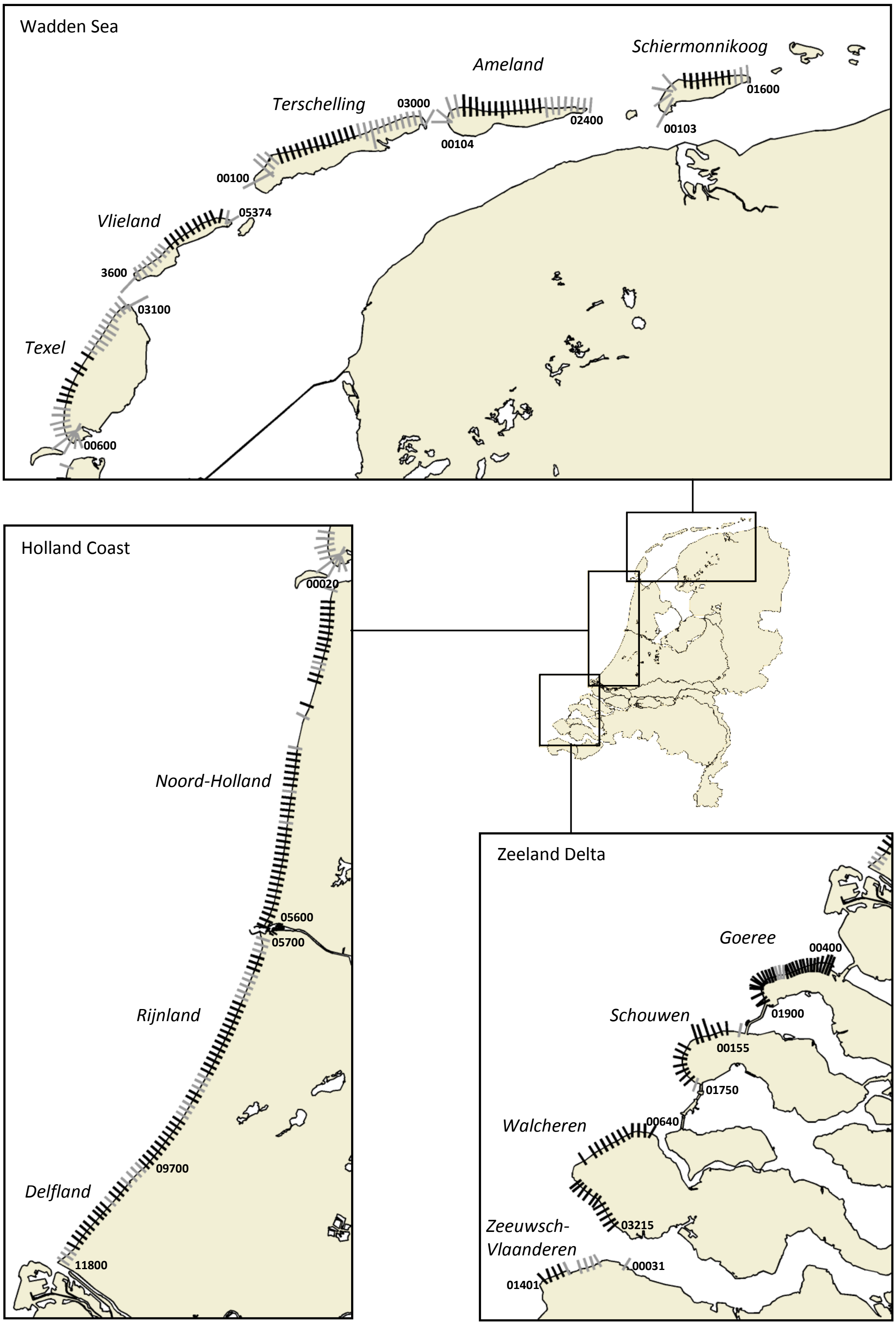

Figure 15. Dutch Beach Line measuring transects per region; Grey transects are not used in the analysis. First and last transect numbers are indicated per section

3.2.4 Results

The plots of the analysis are presented in Appendix E, and in Table 5 these results are summarized. A few examples are also presented in Figure 16 to Figure 19. For every section the linear fit of the dunefoot movement as a function of the beach width, and as a function of the coastline movement is determined. The fit coefficients α and β are the coefficients for the best fit.

$$\frac{\partial DF}{\partial t} = \alpha \ BW - \beta \qquad \textbf{(0.2)}$$

$$\frac{\partial DF}{\partial t} = \alpha^* \left(\frac{\partial CL}{\partial t} - \beta^* \right) \qquad \textbf{(0.3)}$$

with:

DF = Cross-shore dunefoot position

BW = Cross-shore beach width

CL = Coast line position

In (0.2) the fit coefficients can be physically interpreted:

α = Sensitivity of dunefoot movement to beach width variations

β = Equilibrium beach width

In (0.3) this is not the case, but if the dunefoot perfectly follows the coastline movement α* and β* are 1 and 0, respectively.

For the overview, all data are summarized in Table 5. From visual inspection of the data it is observed that a subjective interpretation of the quality of a linear (or possibly other) relation through the scatter plot is not always well represented by objective parameters as the coefficient of correlation. The quality (and value) of a linear fit, for instance, can be strongly influenced by a few outliers. Some advanced statistical techniques might help overcome part of this, but for clarity and simplicity, it is decided to keep the data post processing to a minimum.

Because there are too many data to present graphically, the representation of the data by each fit has been assigned a (subjective) rating. The criteria used are:

++ The relation is well represented by the linear fit, with few outliers

+ The relation is reasonably well represented by the linear fit, but with a fair number of outliers

0 The datasets are somewhat related (but not necessarily linearly).

- There is a slight relation visible between the datasets (but not necessarily linearly).

-- There is no or very little visible relation between the data sets

Only for the fits judged ++ and + the fit coefficients have any meaning. For the other fits the slope of the trend line is mostly determined by a few outliers, and of no useful meaning. A few examples of actual data and their accompanying fits can be found in Figure 16 to Figure 19.

For each of the point sets the average (μ) and standard deviation (σ) of the dunefoot movement, coastline movement and beach widths have also been determined. This gives an indication of the combined spatial and temporal properties of these indicators. Theoretically the average values of these indicators should not depend on the interval length, but as the percentage of the data used somewhat varies with the length of the time-span this is not always the case. The σ for the longest (165 year) time-span represents only the spatial (and not the temporal) variation of the averaged beach widths within a section.

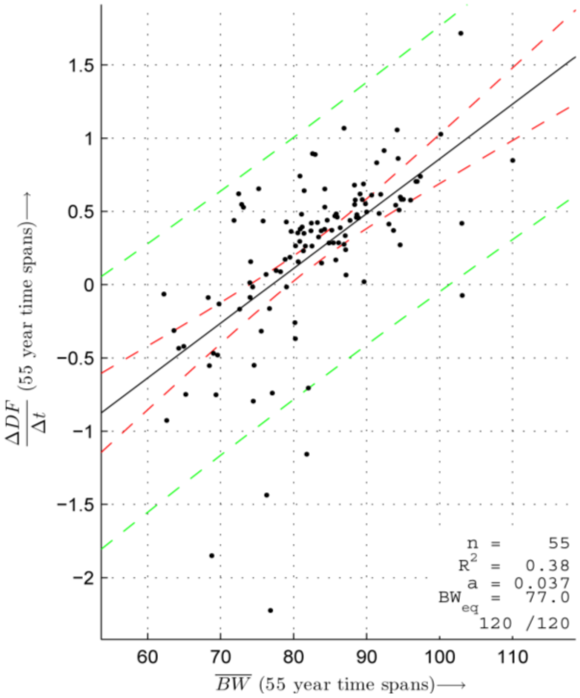

Figure 16. Dunefoot movement versus averaged beach width for 3 55-year time-spans. The relation is visually rated (+); the data are fairly scattered, but the fitted line does describe the general tendency in the point cloud fairly well
The best linear fit (black line) and 95% confidence intervals for new observations (green lines) and for the best fit (red lines) are also plotted.

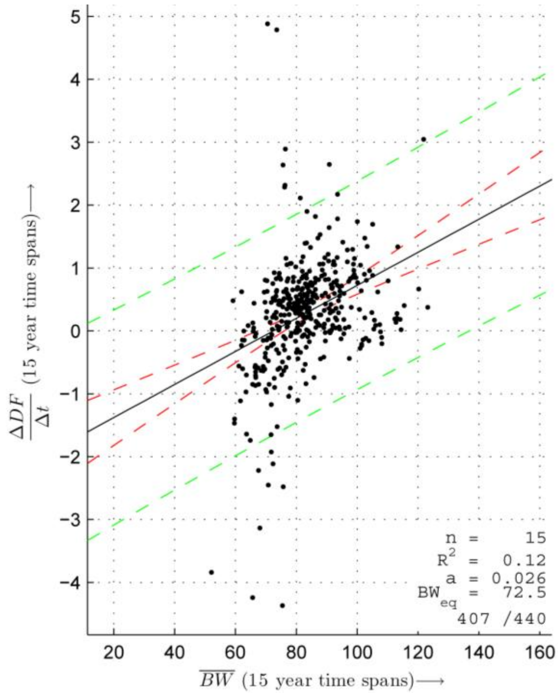

Figure 17. Dunefoot movement versus averaged beach width for 11 15-year time-spans. The relation is visually rated (-) as the data are very scattered, there is no real obvious relation.

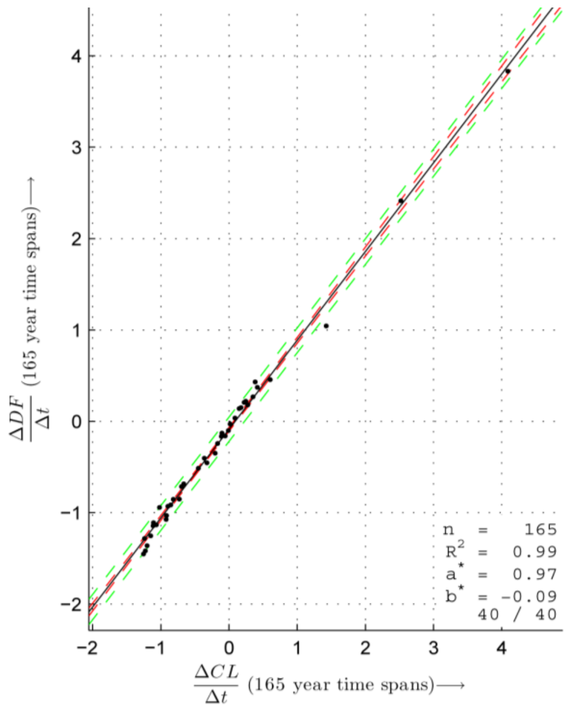

Figure 18. Dunefoot movement versus coastline movement for Noord-Holland, averaged over a 165-year time-span. The fit is visually rated (++) as all points are on the same line.

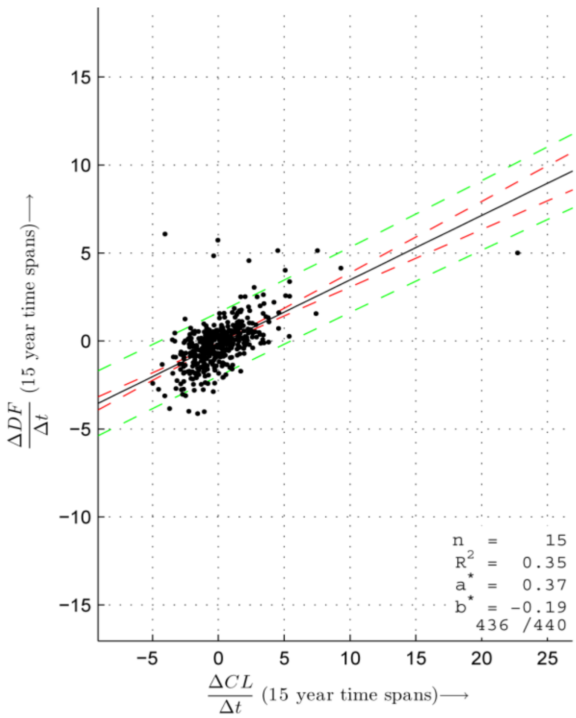

Figure 19. Dunefoot movement versus coastline movement for Noord-Holland, averaged over 11 15-year time-spans. The fit is visually rated (-), as most points are concentrated in one area. The dunefoot movement does tend to be more positive when the coastline movement is larger, but the fit coefficients are largely determined by one outlier.

Table 5. Results of basic linear data analysis

			Yearly dunefoot movement versus beach width				*Yearly dunefoot movement versus yearly coastline movement*				*Statistical properties of variables*					
				Fit coefficients				*Fit coefficients*			*Dunefoot movement*		*Coastline movement*		*Beach width*	
Coastal section	*Time-span*	*Split transects used / total number of split transects*	R^2	*α*	*β*	*Visual quality*	R^2	α^*	β^*	*Visual quality*	*μ*	*σ*	*μ*	*σ*	*μ*	*σ*
Schiermonnikoog	165	5/8	0.45	-0.007	954	-	0.39	0.09	1.9	--	2.5	0.5	6.6	3.5	576	49
	55	5/8	0.45	-0.007	954	-	0.39	-0.07	1.9	--	2.5	0.5	6.6	3.5	576	49
	11	17/24	0.12	-0.008	875	--	0.17	-0.03	2.5	--	2.2	1.9	4.4	10.7	583	90
	5	47/72	0.00	-0.005	1311	--	0.01	0.45	3.6	--	3.4	7.4	4.2	15.9	576	99
Ameland	165	13/13	0.93	0.018	173	++	0.89	0.45	-0.2	+	0.9	2.5	2.4	5.1	225	132
	55	26/26	0.54	0.012	153	+	0.53	0.34	0.1	0	0.9	2.5	2.4	5.4	228	151
	11	91/104	0.12	0.007	127	--	0.01	0.04	0.6	--	0.7	3.7	2.9	10.3	224	176
	5	270/286	0.02	0.004	120	--	0.00	0.01	0.4	--	0.4	4.5	2.2	26.1	223	184
Terschelling	165	13/13	0.75	0.021	215	++	0.81	0.73	-0.2	+	0.5	2.5	1.0	3.1	239	100
	55	39/39	0.48	0.017	222	+	0.29	0.41	0.0	0	0.4	3.0	0.9	3.9	245	119
	11	130/130	0.35	0.016	206	-	0.05	0.12	0.4	--	0.5	3.7	1.1	6.9	241	139
	5	376/390	0.14	0.016	204	--	0.02	0.07	0.5	--	0.6	6.2	0.9	13.2	239	145
Vlieland	165	10/10	0.07	0.009	196	--	0.84	0.66	-0.4	+	-0.8	0.4	-0.7	0.6	107	12
	55	29/30	0.26	0.049	126	0	0.85	0.88	-0.2	+	-1.0	1.7	-0.9	1.8	107	18
	11	98/110	0.25	0.079	124	-	0.80	0.83	-0.3	+	-1.4	3.6	-1.3	3.9	107	23
	5	284/320	0.19	0.071	127	--	0.38	0.47	-0.8	--	-1.4	4.1	-1.3	5.3	107	25
Texel	165	7/7	0.96	0.160	141	++	1.00	1.05	1.2	++	-1.8	3.4	-2.9	3.3	130	21
	55	21/21	0.72	0.065	147	++	0.69	0.99	1.2	+	-1.2	4.1	-2.4	3.5	128	54
	11	60/77	0.56	0.055	141	+	0.44	0.76	1.0	0	-0.6	5.3	-2.0	4.7	131	73
	5	178/224	0.34	0.046	145	--	0.24	0.46	0.2	--	-0.5	5.9	-1.7	6.3	133	76
Noord-Holland	165	40/40	0.71	0.030	98	+	0.99	0.97	-0.1	++	-0.3	1.0	-0.2	1.0	89	29
	55	120/120	0.61	0.028	98	+	0.57	0.55	-0.1	++	-0.2	1.1	-0.2	1.5	89	30
	11	436/440	0.34	0.023	97	0	0.35	0.37	-0.2	-	-0.2	1.4	-0.0	2.2	89	34
	5	1236/1320	0.19	0.026	98	-	0.09	0.16	-0.2	--	-0.2	2.1	-0.0	4.1	88	35
Rijnland&Delfland	165	40/40	0.39	0.032	76	0	0.90	0.97	0.1	+	0.2	0.4	0.2	0.3	83	7
	55	120/120	0.38	0.037	77	+	0.80	0.90	0.1	+	0.2	0.6	0.2	0.6	83	9
	11	407/440	0.12	0.026	72	-	0.32	0.35	0.2	-	0.3	0.9	0.2	1.5	83	12
	5	1141/1320	0.03	0.023	70	--	0.13	0.20	0.2	--	0.3	1.7	0.3	3.0	83	14

Coastal section	Time-span	Split transects used / total number of split transects	Yearly dunefoot movement versus beach width				Yearly dunefoot movement versus yearly coastline movement				Statistical properties of variables					
			R^2	Fit coefficients α	Fit coefficients β	Visual quality	R^2	Fit coefficients α^*	Fit coefficients β^*	Visual quality	Dunefoot movement μ	Dunefoot movement σ	Coastline movement μ	Coastline movement σ	Beach width μ	Beach width σ
Goeree	165	27/27	0.79	0.015	187	++	0.72	0.65	-0.1	+	1.1	3.6	1.9	4.6	261	211
	55	54/81	0.50	0.017	197	0	0.08	0.24	0.5	0	0.9	5.2	1.5	5.9	249	221
	11	243/243	0.08	0.008	127	--	0.00	0.01	1.2	--	1.2	7.6	2.8	9.8	268	263
	5	691/702	0.04	0.010	132	--	0.01	0.09	1.0	--	1.3	13.3	2.7	14.8	262	265
Schouwen	165	13/13	0.19	0.005	215	-	0.33	0.21	-0.5	--	-0.2	1.5	1.2	3.9	167	126
	55	26/39	0.10	0.004	225	-	0.27	0.19	-0.5	--	-0.2	1.9	1.2	5.3	169	153
	11	92/104	0.05	0.004	190	--	0.12	0.10	-0.2	--	-0.1	3.1	1.8	10.6	164	167
	5	261/312	0.02	0.004	196	--	0.03	0.05	-0.2	--	-0.1	5.0	1.6	16.9	165	180
Walcheren	165	23/23	0.19	0.010	121	-	0.67	0.78	0.1	+	-0.2	0.8	-0.4	0.9	104	37
	55	46/46	0.21	0.015	114	+	0.69	0.68	0.1	+	-0.2	1.4	-0.4	1.7	104	42
	11	122/184	0.09	0.014	90	--	0.45	0.57	0.1	0	0.2	2.0	0.1	2.4	103	45
	5	319/506	0.02	0.010	103	--	0.20	0.35	-0.0	--	-0.0	3.4	-0.1	4.4	102	44
Zeeuwsch-Vlaanderen	165	4/4	0.00	0.000	-1140	--	0.70	0.69	0.4	0	0.4	0.3	0.1	0.4	116	8
	55	8/12	0.33	0.024	103	+	0.88	0.56	0.4	+	0.4	0.6	0.1	1.0	119	14
	11	23/36	0.04	0.011	58	--	0.44	0.43	0.6	0	0.7	1.1	0.1	1.8	116	20
	5	69/104	0.01	0.012	65	--	0.47	0.50	0.6	0	0.6	2.2	-0.1	3.1	114	21

3.2.5 Discussion of results

The results for most of the basic linear analysis are presented in Table 5. The most important columns are the ones with the visual assessments of the data fits. Only few fits are rated + or ++, especially for the dunefoot versus beach width fits. No universal relations are found in the data analysis.

Dunefoot movement versus beach width

Reasonable to good fits are achieved for the longer timescales (55 and 165 years) for some of the Wadden Isles and the Holland coast. A few fit coefficients are fairly high, with the extreme at Texel (R^2 = 0.96). Though this relation is not found everywhere, such a high coefficient of correlation found at only one location already indicates that it is extremely unlikely that there is *not* a relation between beach width and the dunefoot displacement. But at most sites, the influence of the beach width on dunefoot migration seems of limited importance compared to other factors.

For the shorter time scales of 5-15 years the beach width cannot be identified as the steering factor for the dunefoot displacement in general. This leads to the conclusion that predictions for dunefoot evolution based on the beach width are at best rough for longer time scales. Making dunefoot predictions for the timescale of the sand engine based solely on the beach width is not possible at all.

A closer inspection of the data plots allows for a few qualitative observations: almost all dunes retreat where beaches are narrow, and within a section the narrower beaches are usually accompanied by higher rates of dunefoot retreat. Dunes at very wide beaches generally do not erode, but the rate of growth (if any) hardly seems to be influenced by the beach width: the growth rate of the dune does not seem to depend on whether a beach is a lot, or just a little wider than a certain threshold value (estimated 150-300 m, depending on the section).

However, when the beach becomes narrower than a certain value due to an eroding coastline, this is almost always accompanied with dune erosion, for every timescale. The exact value of this critical minimum beach is width likely to be site specific. It is estimated to be between 60 to 80 m for the Dutch coast.

These qualitative observations are mostly in line with the earlier assessment of Roelvink and other literature discussed in chapter 2. A discrepancy is found between the observation that dune growth is not stimulated further when the beach width reaches a certain maximum, and Roelvink's relation, which does not limit dune growth.

Dunefoot movement versus coastline movement

The correlations found between dunefoot movement and coastline movement are generally much higher than those for the dunefoot movement versus the beach width. The highest value is again found at Texel (R^2 = 1.00, near perfect fit). For shorter time scales, this value rapidly drops.

Compared to this, Guillen found a rather high value of the correlation between coastline and dunefoot for the Holland coast in an analysis over the length of the JARKUS dataset. In Appendix D these differences are explained.

The coastline position is much more dynamic than the dunefoot position, especially on short time scales. For the 5 year time-span, the standard deviation of the coastline data is typically twice as high as that of the dunefoot data.

On the longer timescales (>50 years) the data shows that dunefoot movement has closely followed coastline movement for most locations along the Dutch coast. This implies that the beaches, though highly variable at shorter timescales, have shown no general, large scale, tendency of steepening or un-steepening: typical values for the beach width have remained constant.

Because of the observed higher sensitivity of dune movement to narrower than normal beaches than to wider than normal beaches, the dune system quickly responds rapidly where the coastline retreats, but slower on advancing coastlines. Nevertheless, for periods of >50 year the dunefoot has shown to be quite capable of adjusting to an advancing coastline, but for periods >15 years variance in the dunefoot movement unexplained by the beach width completely overshadows this kind of behaviour.

When a coastline position is moved seaward by nourishments, it therefore seems reasonable to assume that the dunes can adjust within some 50 years. It might be a lot faster, but not much slower. In the data record the dunes might grow gradually (as to the north of the IJmuiden harbour mole in the last 50 years), but also a sudden jump in dunefoot position is possible when a completely new dune row is formed, that shifts the +3 m contour line over a large distance from one year to the other (e.g. the developments on the beach of Schiermonnikoog).

3.2.6 Conclusions

A general empirical formula for the dunefoot movement could not be established. There is a lot of variability in dunefoot behaviour between and within the different sections that cannot be explained in terms of beach width. However, it is possible to draw some general conclusions:

- Only for long time-spans (>50 years), only for selected sections, historical dunefoot movement can be related to the beach width. In all other cases this is not the case.
- Overall, dunefoot movement responds more directly to narrow beaches than to wide beaches.
- Rapid coastline retreat is often accompanied by similar dunefoot retreat.

- Rapid coastline advance is often not accompanied by similar (if any) dunefoot advance, resulting in large beach width increases.
- The coastline position is more variable than the dunefoot position.
- Dunefoot movement is linked closer to coastline movement than to the beach width.

Using this approach, sensible predictions of dunefoot movement can only be made for longer timescales. It seems better to model this dunefoot movement in terms of coastline movement rather than in terms of beach width. In shorter time periods the movement of the dunefoot is largely determined by other factors than the coastline movement or beach width.

3.3 Decomposed time series

Coastline movement is much quicker than dunefoot movement. This might be because dunes need a certain time before an equilibrium is reached after a certain change is imposed to the system. Along the Holland coast sand waves have been observed, which cause a cyclic movement of the foreshore. The dunes are also known to show a similar cyclic movement at those areas. It has been argued that this movement in the dunes is a reaction to the status of the foreshore. An example of this is the time series of transect 4600 (Figure 20).

It is physically reasonable that the periodicity in coastline movement causes a similar periodic behaviour in dunefoot movement. Also, it would seem reasonable to expect a certain phase difference or lag in the movement of the dunefoot to the coastline, because the dunefoot changes more gradual than the coastline.

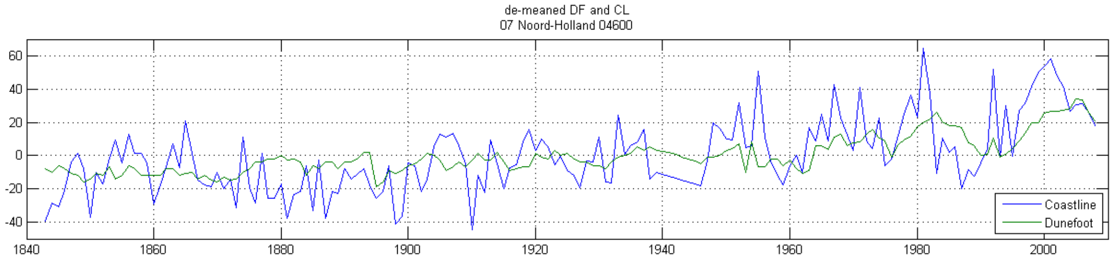

Figure 20. DF and CL evolution of transect 4600 (Noord-Holland). The mean values have been subtracted from the DF and CL positions. Missing values are interpolated.

In the forthcoming analysis the linear and periodic components of coastline and dunefoot movement will be examined and compared. The same method will be applied to all applicable transects along the Holland coast, to check if found relations are just local phenomena, or hold for the entire Holland coast.

3.3.1 Method

To compare the time-series of dunefoot and coastline behaviour, the signals are decomposed. This decomposition is done in such a way that each component represents behaviour on a different timescale. The chosen timescales are 40 years and 10 years. The residual signal is the behaviour that is not described for a 10 year timescale.

The 40 year signal is chosen as this is the longest period over which could be filtered without too much influence of edge effects; it is prescribed by the filter technique and the length of the dataset (for a shorter dataset it would be more difficult to filter for log periods). The 10 year timescale is chosen as it is long enough to greatly simplify the signal (greatly reducing noise like behaviour), but short enough to distinguish cyclic behaviour of the coast.

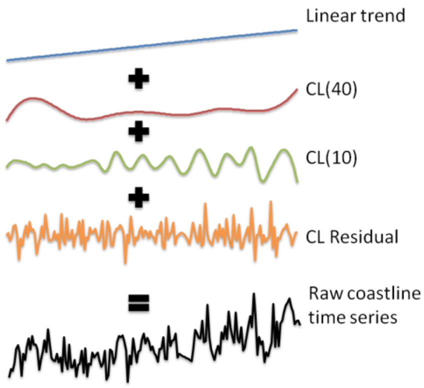

Figure 21. Schematic decomposition of coastline time series for transect 4600

For the raw (original) signal and each of the components individually, the dunefoot and coastline data are compared. This is done by determining the correlation between these signals. To gain insight into any time lag effect, the dunefoot signal is also shifted in time and compared to the coastline signal (cross correlation).

That coastline and dunefoot behaviour highly correlate on the timescale of the dataset is already studied in paragraph 3.2. This common behaviour on the longest timescale is therefore not of specific interest for this analysis. To remove its influence, the common linear component of both raw signals combined is determined and subtracted.

The remaining signals are then split into three different components (independently for dunefoot and coastline). The dunefoot signal is split in DF(40), DF(10) and a residual DF. Together, these components add up to form the linear de-trended dunefoot signal. The coastline is similarly decomposed in CL(40), CL(10) and a residual CL (see Figure 21).

Frequency filter

A well known method to decompose a signal in signals representing different timescale is with a Fourier filter. A Fourier filter works by decomposing a signal (that must be discrete on a regular time interval) into a set of sinuses, each with a different period. By reconstructing the signal using only a subset of these sinuses, the other periods are filtered out.

The DF(40) signal is the combination of the Fourier components with a period longer than 40 years (the original signal is reconstructed by using only the loner term components). The DF(10) signal is obtained by combining the components with a period between 10 and 40 years. The residual is formed by the remaining higher frequency components. A Fourier filter thus can be explicitly associated with a specific time scale.

However, using Fourier techniques assumes cyclic behaviour. Because of this the first and last values of the time series must be at the same level, otherwise the highest frequency components are overestimated. Linear de-trending only partly solves this problem, but one can compensate for this by using only the first and last few data points when determining the linear trend (the linear trend is determined by simply connecting the first and last data points). Another option is to use a different type of filter that does not assume cyclic behaviour. An example is a moving average or loess filter.

A moving average filter has only one setting parameter, the time-span over which to average. This time-span over which is averaged cannot be related explicitly to a time scale in the same way as can be done for a Fourier filter.

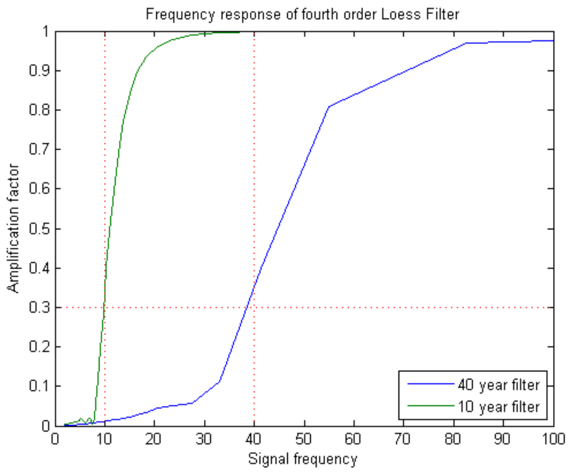

Figure 22. Frequency response of fourth order loess filter tuned at a 10 year and 40 year frequency response with time-span parameter of respectively 25 and 103 data points

Another option is the use of a loess filter. The name "loess" is derived from the term "locally weighted scatter plot smooth". The smoothing process is considered local because, like the moving average method, each smoothed value is determined by neighbouring data points defined within the span. The process is weighted by a polynomial regression weight function of a predefined order, that is defined for the data points contained within the span. A loess filter therefore has two parameters, the order and the time-span. In general, higher order loess filters have a sharper frequency response than lower order or moving average loess filters (van den Boogaard, 2008).

By smoothing sine signals of different frequencies by a loess filter at certain settings, the amplification factor can be determined as a function of the frequencies. The amplification factor is a measure for how much of the original amplitude is reproduced by the filtered signal.

By tuning the settings a frequency response can be acquired that approaches certain thresholds, as has been done in Figure 22. A steeper line indicates a shaper frequency cut-off.

Because the loess filter can be much better associated with a specific timescale than a moving average filter, but does not assume cyclic behaviour like a Fourier filter, this technique is applied for this analysis.

Cross correlations

For the original signal pairs and for each of the decomposed signal pairs the correlations are determined as a function of the time lag. The time lag is the shift of the dunefoot signal component with respect to the coastline signal component. If the dunefoot signal, delayed by two years, is found to correlate better with the coastline signal than a non delayed signal, that would indicate a time lag between the signals. This would be evidence of a physical time lag in the response of the dunefoot to the coastline evolution.

Local maxima in cross correlations

Local maxima and accompanying time lags are computed for the cross correlations. This is done within the time frame bounded by the -10 and +5 year time shift of the dunefoot signal component to the coastline signal component. Greater time lags than these values do not seem physically reasonable (the time window used is already large). For some locations, the maximum value found within this window is a negative value. These values are zeroed out in the overview plot.

Auto-correlations

Each of the signal components is also correlated with itself at different time lags. A time-lag correlation diagram can reveal periodic behaviour, if any. Also this makes a good check for randomness for the residual signal, as a random signal does not correlate with itself, even at small time lags (Chatfield, 2004).

Filtering of results

After visual inspection, the following 11 transects were left out of the overview plots: 20, 2100, 2600, 5700, 9875, 9975, 10075, 10200, 11611, 11700, 11800. At these transects either sudden human interference severely influenced the values of the correlation coefficients, or there were large gaps in the data.

3.3.2 Results

For every of the 109 transects a graphical overview is created in which the individual signals and their mutual dependencies are presented. This results in a figure with eight plots for every transect. These where all visually inspected, but only a selection of three (Figure 23 to Figure 25) are presented and discussed in detail below.

An overview of the alongshore variance of the different values is presented in Figure 26.

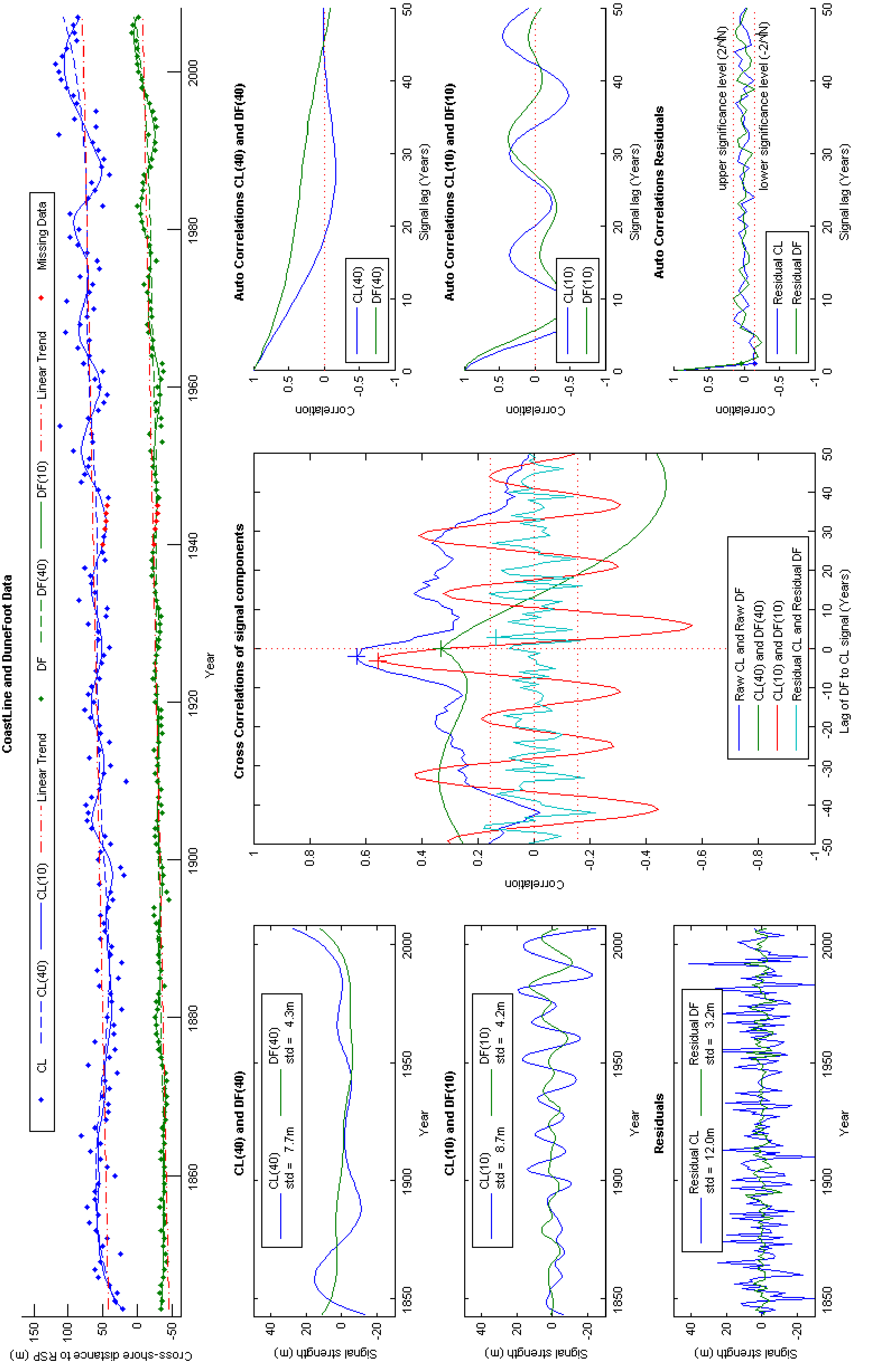

Figure 23. Correlation diagram for transect 4600

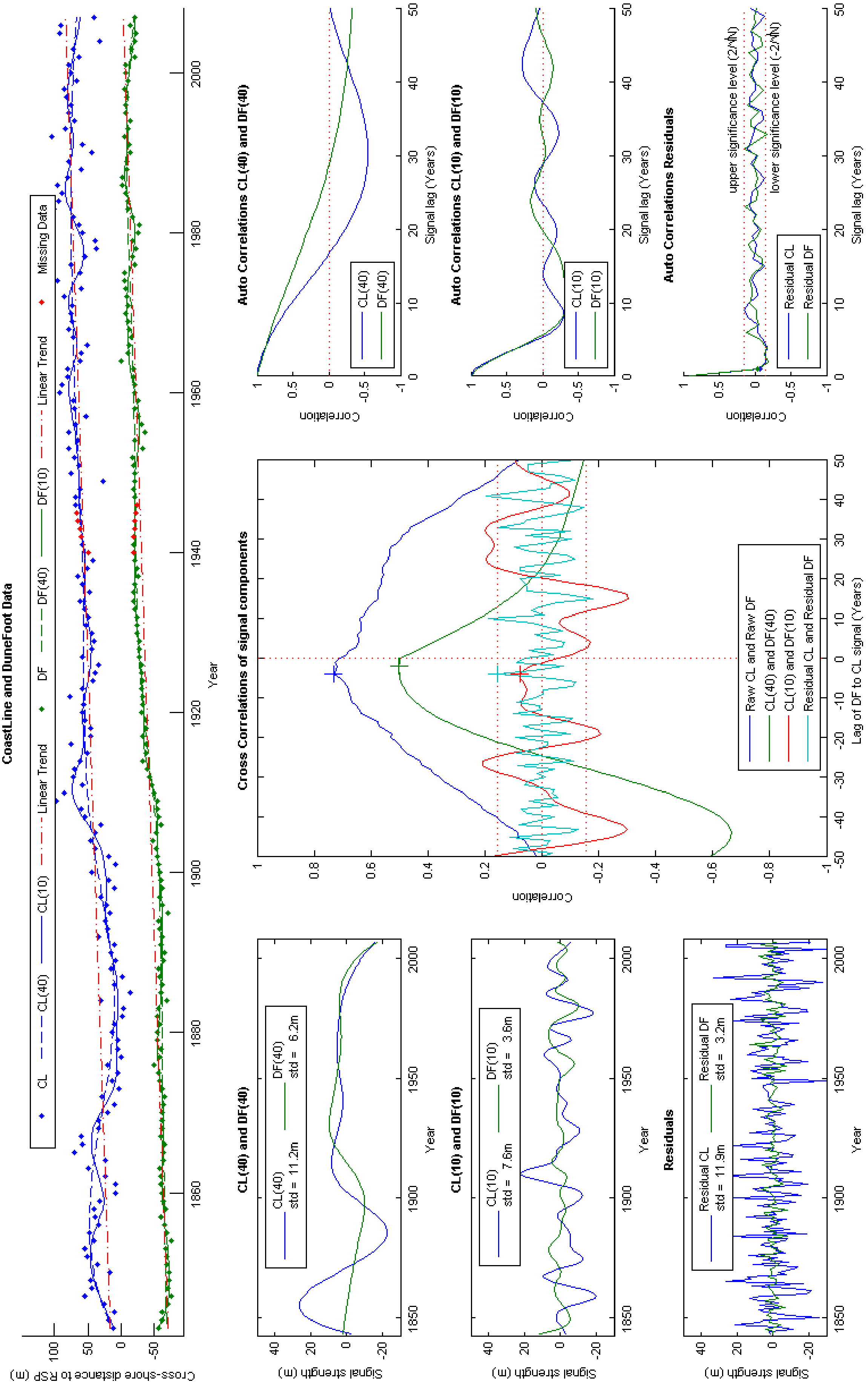

Figure 24. Correlation diagram for transect 4300

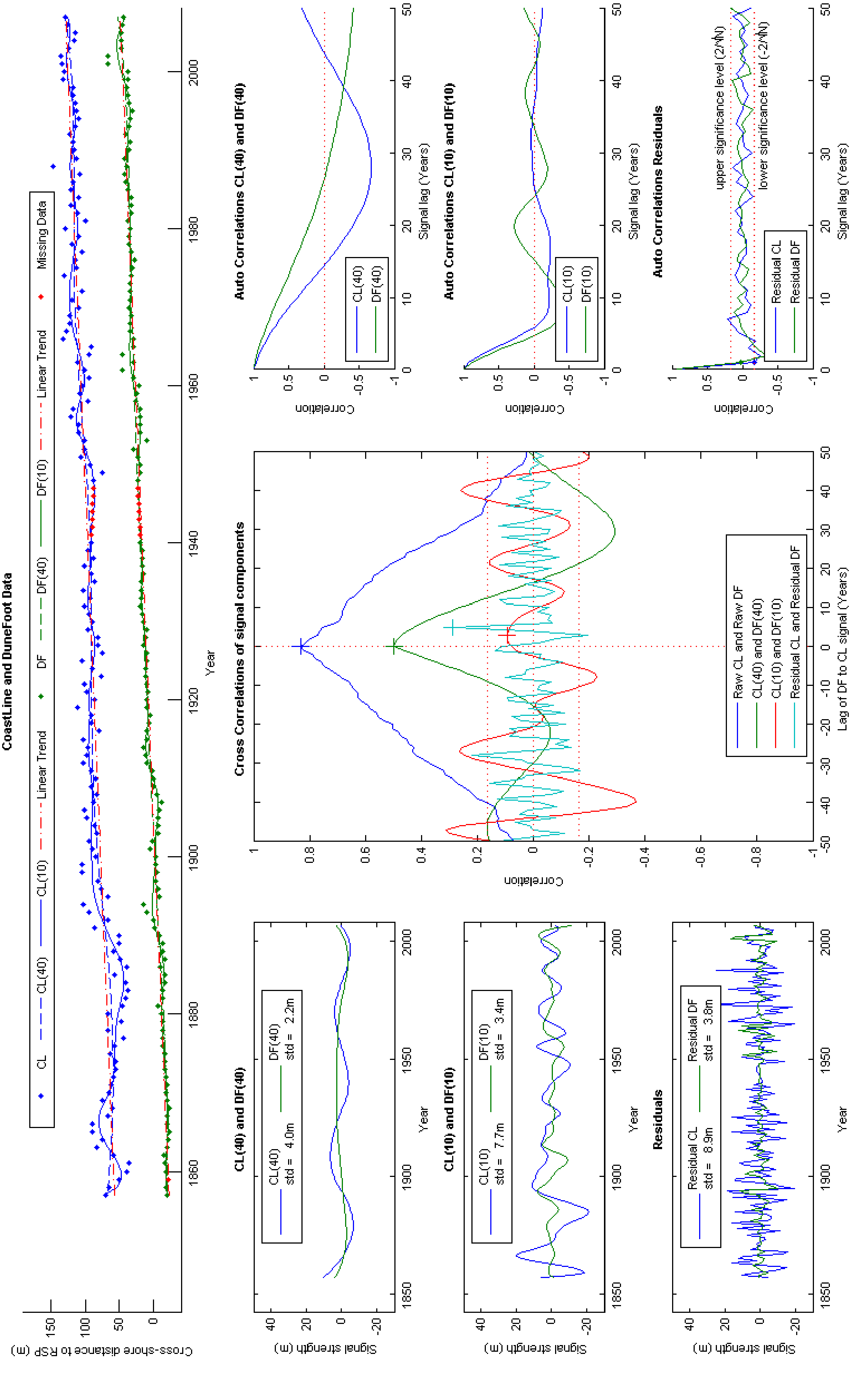

Figure 25. Correlation diagram for transect 8200

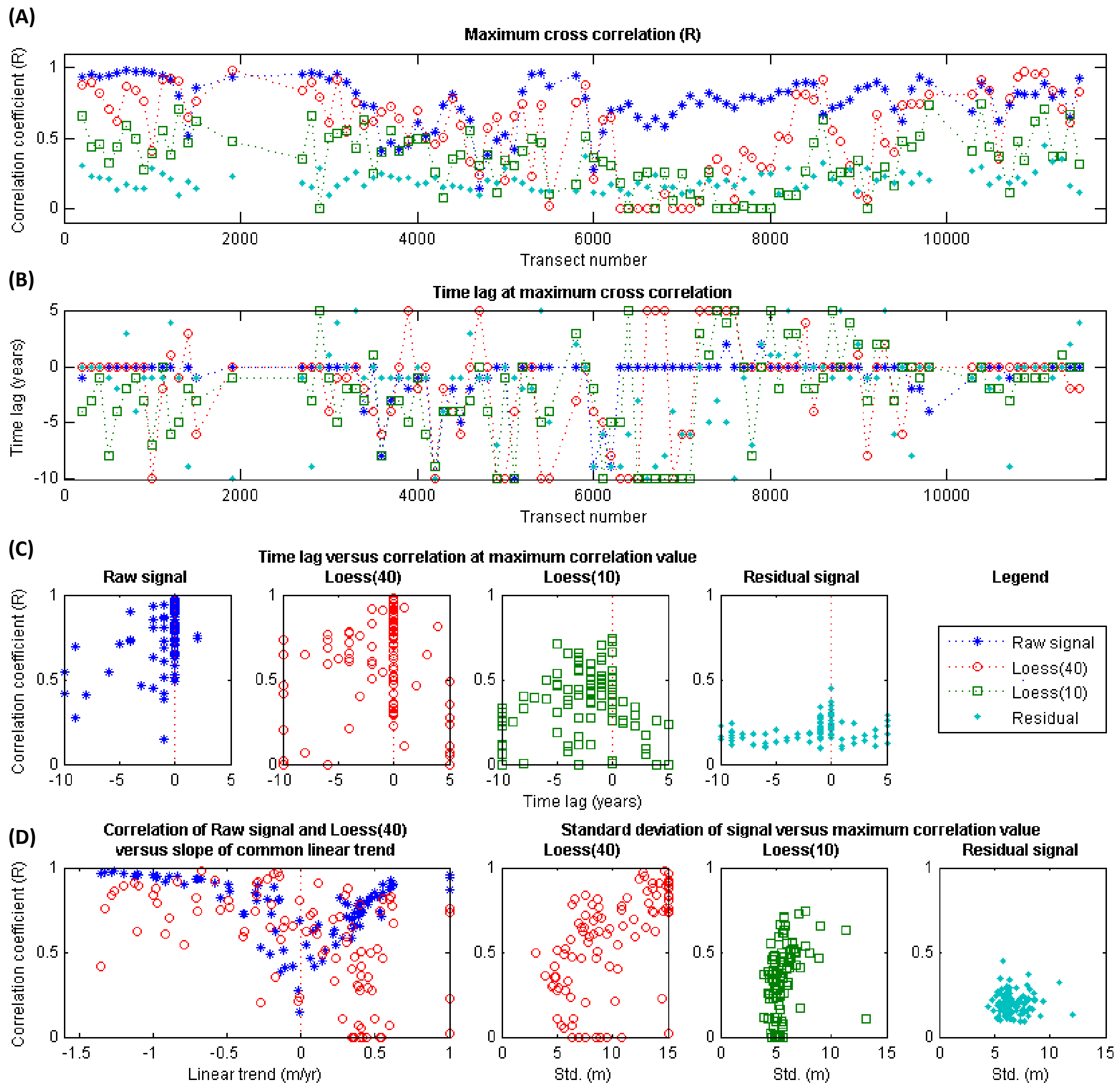

Figure 26. Local maxima (A) of correlations and corresponding time lags (B) for examined transects. (C) and (D) give more insight per signal component. Negative values for correlation are zeroed out. For (D) the standard deviation is the mean of the separately calculated values for DF() and CL(). Value is clipped at 15.

3.3.3 Discussion of results

When comparing the plots for all of the transects, it is apparent that there are great differences. Not all of these 109 plots for the different transects can be discussed, but as an illustration of these differences, the results for a selection of three transects are discussed in more detail below.

Transect 4600

In general the coastline and dunefoot have advanced some 40 m over the last 165 years in transect 4600 (Figure 23). The correlation of the raw signal is therefore reasonably high (0.7). There is some variation in the CL over the 40 year timescale, but the longer term component of the dunefoot is less pronounced. The correlation of the DF(40) and CL(40) components is rather weak.

The DF(10) and CL(10) components show more interesting similarities. The auto-correlation plot reveals that both signals are cyclic with the same period of about 17 years. The highest correlation for the DF(10) signal is found at a lag of two years to the CL(10) component. The standard deviation of the CL(10) signal is about twice as large as that of the DF(10) signal component. Medium term dunefoot movement is strongly influenced by coastline movement at this transect, although the amplitude is halved, and the phase is two years behind.

The residual signals do not have any relevant periodic behaviour, and the autocorrelation drops to within the significance boundaries at a time lag of one. This indicates that these components are (almost) random (white) noise.

Transect 4300

Only three kilometres to the north transect 4300 (Figure 24) shows a very different behaviour. The DF(40) and CL(40) signals are much stronger (higher standard deviations), but show little resemblance. Still, the calculated maximum correlation is a lot higher than in transect 4600 (0.5 versus 0.3). The time lag is 0 or 1 year (not very clear).

The DF(10) and CL(10) components show little resemblance to each other. The CL(10) signal has a period of some 14 years, the DF(10) shows only subtle signs of periodic behaviour, and with a period of 23 years.

The residual signals do not have any relevant periodic behaviour, and the autocorrelation drops to within the significance boundaries at a time lag of one. This indicates that these components are (almost) random (white) noise.

Transect 8200

Finally a transect in Zuid-Holland is examined (Figure 25). The raw signals correlate fairly well, because both have progressed some 50 m. The CL(40) movement appears to behave periodically at about 55-60 years. This is such a long period compared to the length of the dataset that this signal might have been created by the filter technique or just by chance rather than that it is actually there. Correlation of the signals at time lag 0 is 0.5, but as the signals are not very strong, the importance of this value can easily be overestimated.

The dunefoot shows some periodic behaviour in the DF(10) component, with a period of about 20 years. This period is absent in the CL(10) signal.

Again, the residual signals do not show any relevant periodic behaviour. The autocorrelation drops to within the significance boundaries at a time lag of one. This indicates that these components are (almost) random (white) noise.

General observations

When all local maxima in correlations are compared, the following can be observed:

- The raw signals of dunefoot and coastline movement generally correlate very well. As can be expected, the value of the correlation is strongly influenced by the slope of the shared linear component: the steeper it’s slope, the higher the correlation. It is interesting that the value of the correlation seems to be a little more sensitive to an erosive (negative) than to an accreting (positive) trend. This implies that an eroding coastline influences the dunefoot in a stronger way that an accreting coastline.
- Behaviour elements on 10 and 40 year time scales are very well correlated in some cases, but not at all in other. In general, the DF(40) and CL(40) correlate better than the DF(10) and CL(10) signals.
- The DF(40) and CL(40) signals usually correlate better when the standard deviation of these signals is higher. Also the correlation of these signals is generally higher for eroding than for accreting coasts. The values found are lowest at slightly accreting (0,5 m/yr) coasts.
- The residual signals seem to represent white noise for most transects. The residual signals for the dunefoot and coastline therefore appear to be completely unrelated.
- There is only little spatial coherence in the behaviour of different components. The maximum value of the raw signal correlation shows the highest spatial coherence (which is caused by the great dependency of the maximum correlation to the slope of the linear trend, which is spatially coherent).
- Strong periodic behaviour of the coastline is often accompanied by a strong periodic behaviour in dunefoot behaviour.
- There is no evidence of any specific lagged behaviour of the dunefoot movement to the coastline movement. The values do much more often tend to be negative than positive, a subtle indication that the dunefoot indeed follows the coastline movement (and not vice versa).

3.3.4 Conclusions

For a very few locations dunefoot movement can be neatly described as a reaction lagged response to periodic coastline behaviour. But because completely different behaviour is observed, even for neighbouring transects, no generally valid conclusions can be drawn from this analysis. The way that dunefoot movement responds to coastline movement greatly varies in time and space.

Dunefoot and coastline movement are generally related better at strongly eroding areas than at stable areas.

3.4 Spatial and temporal patterns

In a very stormy year, the dunefoot generally retreats, and in a quiet year it advances (or erodes less). As the storminess is roughly the same for all dune transects within a coastal section for a certain year, one can expect that part of the dunefoot behaviour is uniform along the coast. If this alongshore uniform movement is subtracted from the individual dunefoot movement, an alongshore non-uniform movement can be derived, as has been done by Ruessink and Jeuken (2002).

Along a large part of the Dutch coast patterns can be observed in the temporal and spatial variation of the coastline position (see Figure 27). These patterns are known as sand waves (Verhagen, 1989). The alongshore non-uniform component of dunefoot movement is organized in very similar patterns; therefore it is concluded that the dunefoot movement patterns are shoreward extensions of similar sand wave patterns in the beach position.

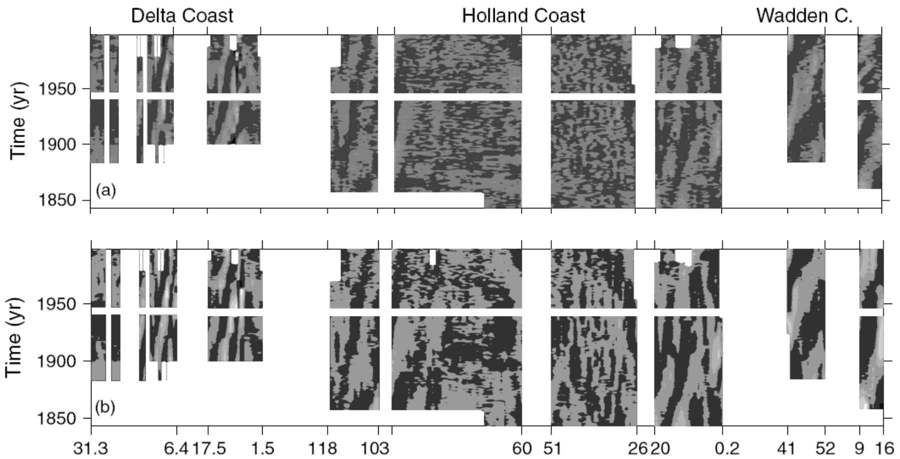

Figure 27. Space–time diagram of (a) alongshore non-uniform residual coastline position and (b) alongshore non-uniform residual dunefoot position. From left to right: coastal areas from southwest to southwest to northeast (differently from other plots). Dark grey values correspond to negative residuals (position is landward of linear trend), light grey values to positive values (position is seaward of linear trend). For increased readability, all sub-regions are separated by blank parts. Modified from Ruessink and Jeuken (2002).

As only about 20% of dunefoot movement can be explained as being alongshore uniform this leads to the (bold) conclusion that the vast majority (>80%) of the residual dunefoot movement along the Holland coast is controlled by temporal and spatial characteristics in beach width (Ruessink and Jeuken, 2002).

In the following analysis the alongshore non-uniform component of dunefoot movement will be further investigated using the JARKUS dataset. If it is true that the vast majority of the residual dunefoot movement along the Holland coast is controlled by temporal an spatial characteristics in beach width it should be very well possible to explain yearly variations in dunefront volume change in terms of beach width.

3.4.1 Method

For this analysis only the JARKUS dataset is used (see appendix A.3). Though this dataset is much shorter (since 1965) than the Dutch Beach Line dataset (since 1843), it has a four times higher alongshore resolution (250m intervals), and provides not only positions of a few contour lines but an entire cross-shore profile.

All available JARKUS transects are included in the routine, but the emphasis is on the Holland coast. Data are used from 1965 to 2007. For every year and every transect the values of several coastal indicators are determined, namely the DVC (Dunefront Volume Change), and the position and movement of the DF, DF_{MKL}, CL, and CL_{MKL} coastal indicators (see Appendix B).

Next to this, also the susceptibility of a transect to erosion is computed with a dune erosion model. This is done by calculating the DVC for a certain storm. The same storm is applied to all examined cross-shore profiles. The only variable in the input is thus the profile shape. If more erosion is predicted for one transect than for another, that transect is assumed to be more susceptible to erosion.

DUROSTA

To calculate the susceptibility to erosion a model is needed. The requirements for such a model are:

- It can predict dune erosion for the Dutch coast in general.
- It explicitly is able to calculate dune erosion as a function of the initial profile.
- It can calculate fast (the model will be run for all 2200+ measurement transects of the Dutch coast, for all measured years, for four different storms: total of 297,296 runs).

The only model that fits these requirements is the DUROSTA model. This model is well validated for the Holland Coast (and found to provide good results), is fully process-based (and thus responds to changes in the profile in a realistic way), and it requires very little computational time (typically 0.5-1.0 s). The workings of the model have been thoroughly examined and documented by van Baaren (2007).

Because it is not known a priori which values for the DUROSTA input parameters will yield the best results for predicting the DVC, 4 different input scenarios are used (Table 6).

Table 6. Input values for different storm scenario's

	Grain diameter D_{50} (μm)	*Storm surge level (m)*	*Wave height H_{sig} (m)*	*Peak period T_{Peak} (s)*	*Storm duration (H)*
DUROSTA 1	200	2	4	10	6
DUROSTA 2	200	2.5	5	10	6
DUROSTA 3	200	3	6	10	6
DUROSTA 4	200	4	8	10	6

Normalization

The absolute values of the coastal indicators are not relevant for this method, instead the emphasis is on their relative values. The question is not if the dunefront at a certain location erodes or not, but if it erodes more than at other locations in the same section (due to the same forcing).

To compare the coastal indicators they have all been normalized in a similar manner; as an example the procedure is explained for the dunefront volume change:

For all transects the volume change is determined for every year. Per year the mean and standard deviation are computed (over all transects). The mean value for the volume change is subtracted from this value for every transect, and this value is divided by the standard deviation. By normalizing the data in this way, year to year differences in storminess are filtered out. Not the absolute value of the erosion is important, but if a transect has eroded more/accreted less than its neighbouring transects.

$$\Delta V_{i,n}^{NORM} = \frac{\Delta V_{i,n} - \mu_{\Delta V i}^{*}}{\sigma_{\Delta V i}^{*}} \quad \mathbf{(0.4)}$$

In which:

$\Delta V_{i,n}$	= Volume change of dunefront for every year *i* and location *n*.
$\Delta V_{i,n}^{NORM}$	= Normalized volume change of dunefront for every year *i* and location *n*.
$\mu_{\Delta V i}$	= Mean volume change of the dunefront at all locations in a certain year *i*.
$\sigma_{\Delta V i}$	= Standard deviation of volume change of the dunefront at all locations in a certain year *i*.

To reduce the influence of outliers the 5% highest and 5% lowest values are not used to calculate the values of the standard deviation and the mean (indicated by the *).

Calculation requirements

Not all transect measurements include a clear dune row, therefore only transects with a highest value above NAP+8 and lowest below NAP-4 are used in calculations. Nonetheless DUROSTA calculations or the search routines for other coastal indicators sometimes fail. In the time-space diagrams these occurrences are marked grey. Also nourished areas (indicated in time and space by black lines) are greyed out, including the year before and after the nourishment is listed because the time of nourishment is about the same as the time of measurement (the nourishment could have taken place just before or after the measured result).

3.4.2 Results

Of the four different input sets for DUROSTA, the second gave the best results. In Table 7 to Table 9 R^2 is calculated for the normalized values of BW, BW_{MKL}, and the DUROSTA calculation, compared to the DF movement, the DF_{MKL} movement and the DVC, respectively.

The amount of variance explained by the different normalized coastal indicators is clearly highest for the DUROSTA calculations, although the value is generally low. Despite this low R^2 the general patterns of accretion and erosion are very well predicted by the DUROSTA calculations, as can be seen in Figure 28 to Figure 31.

Table 7. R^2 of normalized coastal indicators to normalized DF3 movement

	BW	*BW_{MKL}*	*CL movement*	*CL_{MKL} movement*	*DUROSTA 2*
Schiermonnikoog	0.00	0.00	0.01	0.01	0.01
Ameland	0.06	0.06	0.00	0.02	0.08
Terschelling	0.04	0.01	0.00	0.03	0.02
Vlieland	0.04	0.03	0.01	0.05	0.04
Texel	0.16	0.03	0.04	0.11	0.18
Noord-Holland	0.10	0.08	0.03	0.04	0.09
Rijnland&Delfland	0.06	0.04	0.02	0.05	0.03
Goeree	0.02	0.00	0.00	0.05	0.10
Schouwen	0.09	0.11	0.02	0.05	0.23
Walcheren	0.05	0.03	0.06	0.13	0.02
Zeeuws-Vlaanderen	0.03	0.01	0.07	0.14	0.05

Table 8. R^2 of normalized coastal indicators to normalized $DF3_{MKL}$ movement

	BW	*BW_{MKL}*	*CL movement*	*CL_{MKL} movement*	*DUROSTA 2*
Schiermonnikoog	0.01	0.01	0.00	0.02	0.00
Ameland	0.10	0.11	0.00	0.01	0.18
Terschelling	0.06	0.05	0.00	0.00	0.05
Vlieland	0.09	0.10	0.00	0.01	0.12
Texel	0.23	0.23	0.02	0.05	0.35
Noord-Holland	0.17	0.21	0.01	0.01	0.21
Rijnland&Delfland	0.11	0.13	0.01	0.03	0.13
Goeree	0.01	0.01	0.00	0.01	0.10
Schouwen	0.05	0.06	0.02	0.04	0.23
Walcheren	0.11	0.12	0.04	0.09	0.05
Zeeuws-Vlaanderen	0.02	0.02	0.04	0.09	0.11

Table 9. R^2 of normalized coastal indicators to normalized DVC

	BW	BW_{MKL}	*CL movement*	CL_{MKL} *movement*	*DUROSTA 2*
Schiermonnikoog	0.02	0.02	0.00	0.01	0.00
Ameland	0.04	0.05	0.01	0.02	0.08
Terschelling	0.00	0.00	0.00	0.01	0.01
Vlieland	0.10	0.11	0.01	0.04	0.11
Texel	0.19	0.14	0.02	0.04	0.34
Noord-Holland	0.09	0.11	0.01	0.01	0.14
Rijnland&Delfland	0.06	0.08	0.02	0.04	0.08
Goeree	0.00	0.00	0.00	0.01	0.05
Schouwen	0.04	0.05	0.02	0.04	0.21
Walcheren	0.06	0.06	0.04	0.09	0.04
Zeeuws-Vlaanderen	0.01	0.01	0.02	0.04	0.05

Patterns in time-space diagrams

In Figure 28 to Figure 31 the relative values are plotted for the beach width, the observed dunefront volume change and the DUROSTA predicted dunefront volume change, respectively. Also time and location of nourishments is indicated (thick black lines).

In the top plots, the deep red areas have a beach width that is wider by four standard deviations than other beaches in the same section in that particular year. Deep blue corresponds with a beach that is narrower by four standard deviations than other beaches in the same coastal section in that particular year. Whiter areas have a beach width close to the mean for that year. Similarly in the middle and bottom plot deep red (blue) corresponds to a volume gain (loss) that is higher by four standard deviations than the average volume gain (loss) in other transects in the same coastal section in that particular year.

For grey areas either there are no available measurements, or the calculations failed, or there is no suitable dune coast (e.g. there is a dyke, a seawall or an inlet).

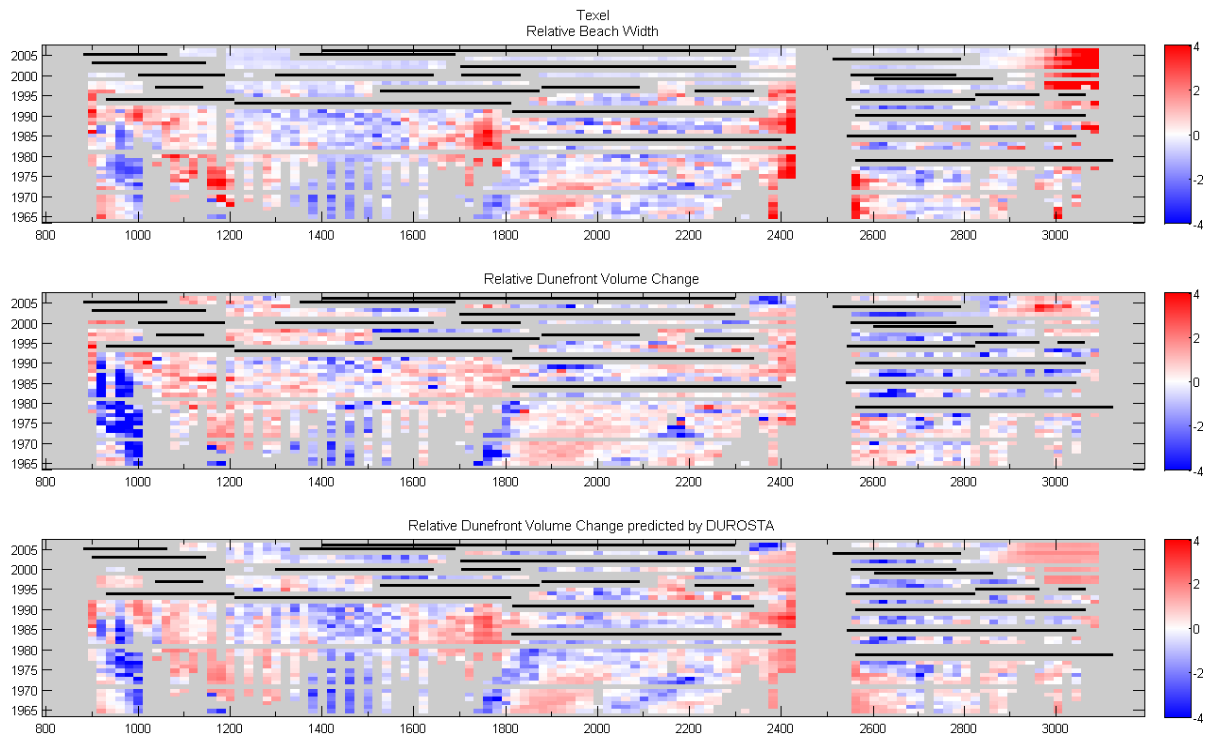

Figure 28. Results for Texel. Transects near the inlet in the Slufter at 2500 are disregarded. The general patterns of erosion and accretion are well predicted by both the beach width and DUROSTA calculations, but very high beach widths do not result in very large dunefoot accretion. Narrow beaches are accompanied by a lot of erosion, especially near transects 1000 and 2700.

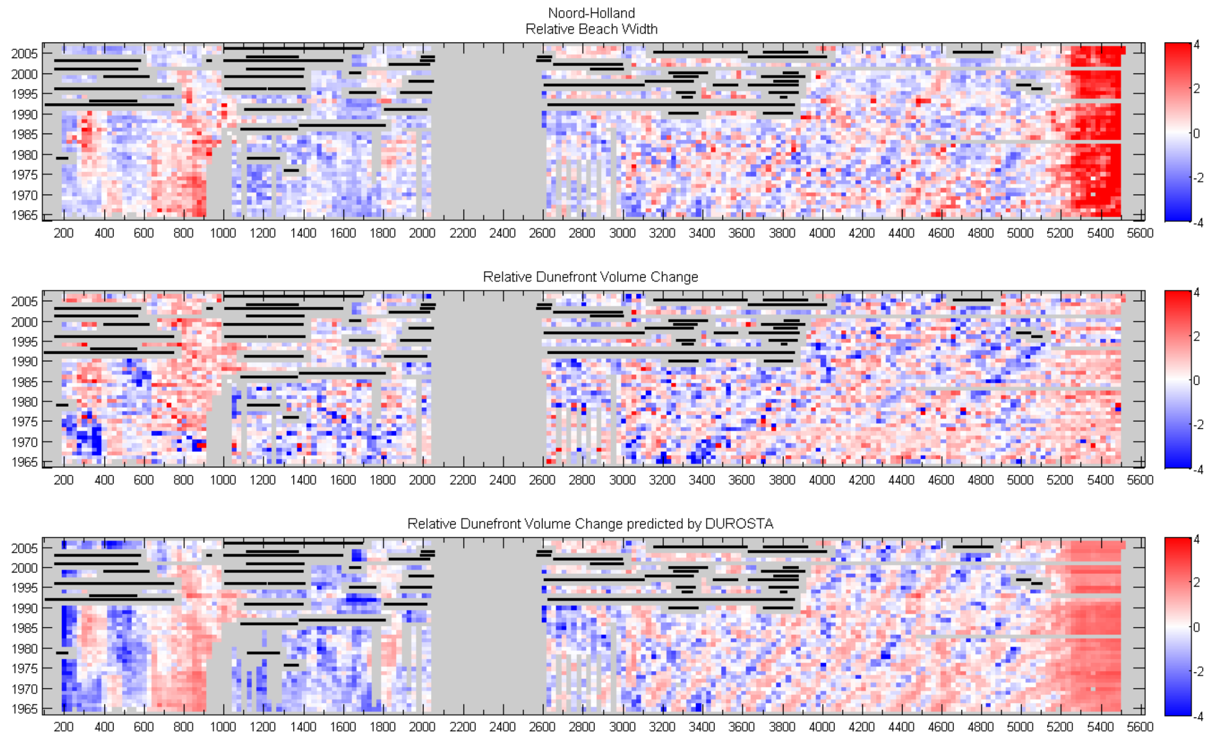

Figure 29. Results for Noord-Holland. The dyke between transects 2100 to 2600 is greyed out. DUROSTA predictions clearly represent the patterns in the relative DVC more accurately than the relative BW. Especially the very red areas (wide beach) just north of IJmuiden (transects 5200 through 5500) do not correspond with equally red areas (accreting dunes) in the middle plot.

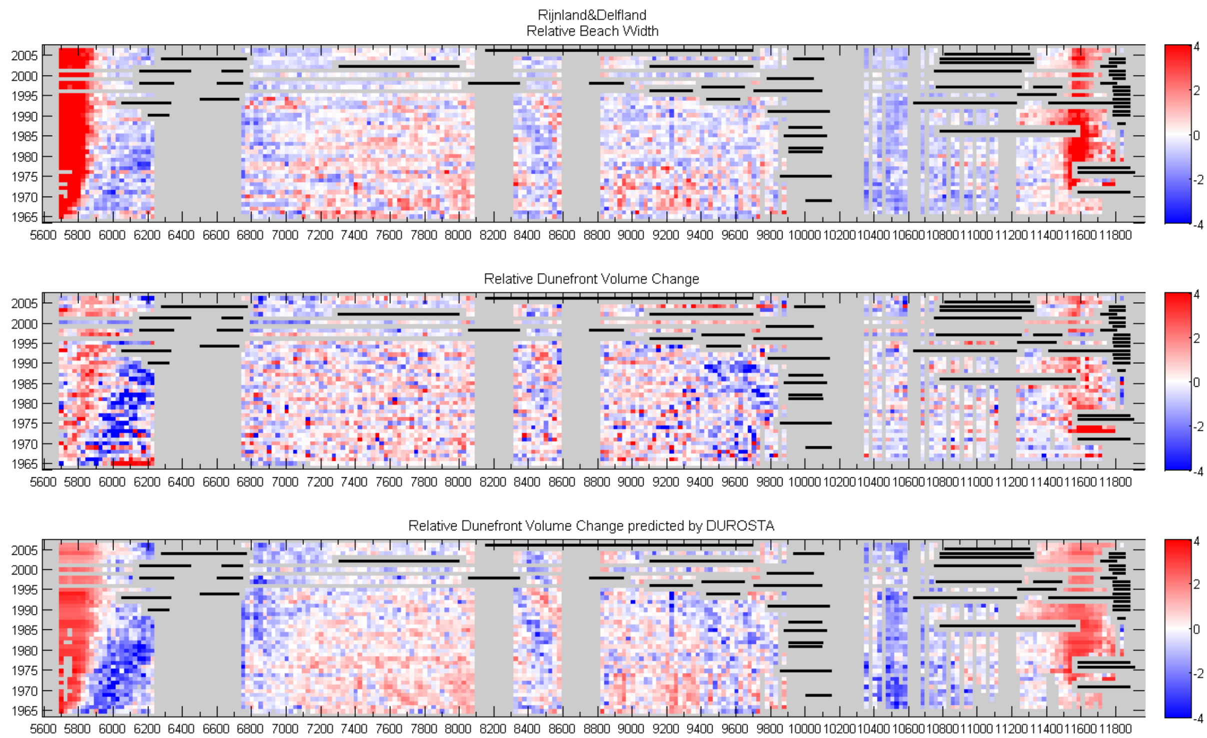

Figure 30. Results for Zuid-Holland. As the dunes are very artificial near all coastal settlements they are all greyed out. Near transect 10500 DUROSTA predicts a lot of erosion, due to the narrow beach width. This is not observed in real life however.

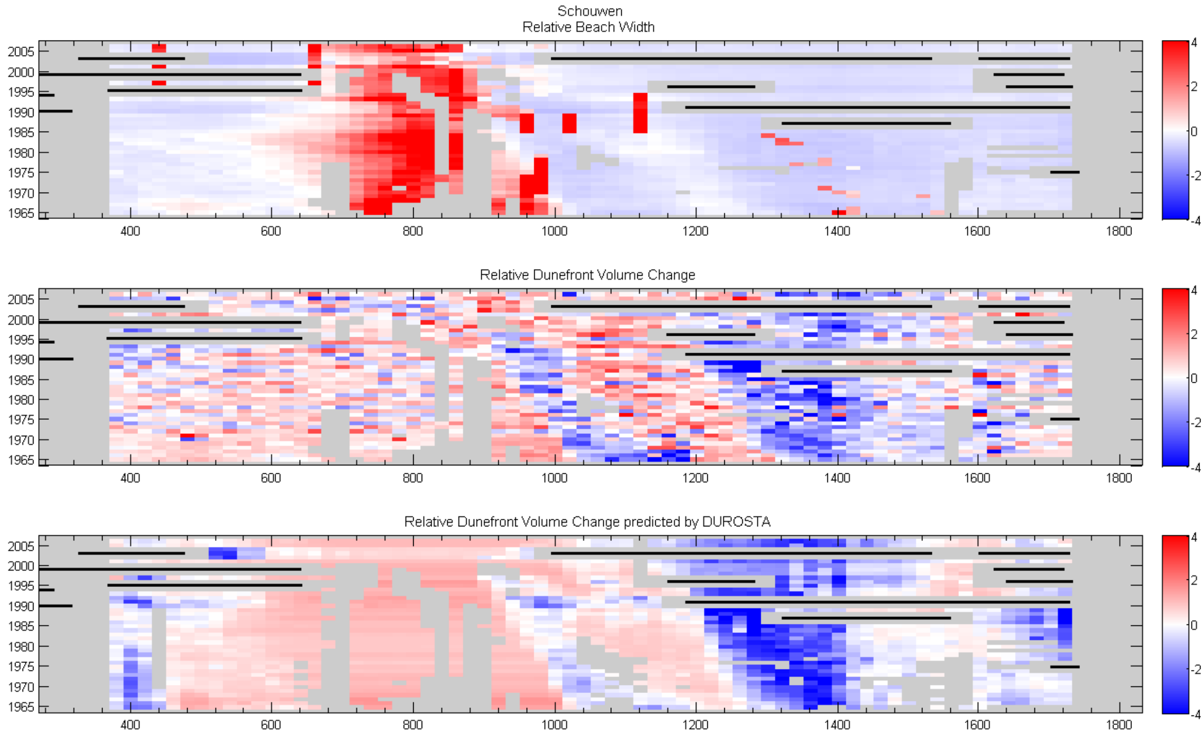

Figure 31. Results for Schouwen. It is very clear that the beach width is not a good indicator for the DVC. The very wide beaches near transect 800 are not accreting very fast, though the slightly narrower beaches near 1400 are eroding a lot. The DUROSTA predictions near transect 400 and 1700 are very poor however. The most probable reason for this is that these transects are protected from erosion due to their sheltered orientation.

3.4.3 Discussion of results

Similar patterns are observed in the relative plots for beach width, coastline movement, and susceptibility to erosion. As these indicators are physically related, this is not surprising (e.g. a passing sand wave shifts the coastline seaward, increasing the beach width and thereby reducing susceptibility to erosion.). But these parameters are not interchangeable, as they are calculated in different ways.

For each of these three indicators, its influence on the dunefoot can be explained in a physically reasonable way. To illustrate this, a hypothetical explanation is formulated for how dunefoot behaviour could be related to each of these coastal indicators.

- **Coastline**

  The strong relation between coastline and dunefoot behaviour can be understood by assuming that the time in which the dune system reaches its equilibrium is short (well within a year). The equilibrium is determined by the balance between the erosion and the accretion, both of which depend on beach width. In such a case a summer beach (beach width is measured in summer) is always in equilibrium, as it has had a lot of time to adjust since the last storm. Thus the measured beach width is always the same. If the coastline then moves, the beach must follow.

- **Beach width**

  Beach width and dunefoot behaviour will be strongly related if the time a beach needs to adjust to an equilibrium is (much) longer than a year (the measuring interval). In that case the movement to equilibrium caused by the same processes which link coastline and dunefoot behaviour, but because of the slow speed of adjustments, an annual observer will see the beach widen at first, and only then witness a dunefoot movement.

- **Susceptibility to erosion**

  A strong relation between the dunefoot volume change and its susceptibility to erosion would be explained if in the balance between erosion and accretion the latter were fairly constant. Different net effects are caused by varying erosion rates. The relation between beach width and susceptibility is not linear, as a wide beach might be completely resistant to erosion (at a certain forcing). An even wider beach is then equally resistant (also 100%) to dune erosion. But for narrow beaches, the susceptibility to erosion is very dependent on variations in beach width.

So there are three different indicators, which all have similar relative patterns in time and space, but each of them is thought to influence dunefoot behaviour in a different way.

In this research, beach width is only found to explain 0-16% of local non-uniformities. That value is much lower than Ruessink and Jeuken (2002) found; they concluded that the vast majority (>80%) of the residual dunefoot movement along the Holland coast is controlled by temporal an spatial characteristics in beach width. The susceptibility to erosion (as calculated by DUROSTA) explains local non-uniformities much better.

Because of the interlinking of the different coastal indicators, and because only annual data are available, it is not possible to determine the influence of each of these mechanisms independently with absolute certainty. However, as the parameter for susceptibility to erosion by far explains most of the variance in relative dunefoot volume change, this mechanism is argued to be the dominant one.

The direct correlation between the dunefront volume change and the susceptibility to erosion may not be very high, but the visual resemblance of the patterns is striking. Apparently dunefront volume change is also influenced by some highly variable local influences, among which may be vegetation levels. Maybe there is just a certain amount of (unpredictable) randomness involved, as a local, single wave can cause considrable erosion.

3.4.4 Conclusions

Local variations in dune erosion largely determined by variations in foreshore morphology. It appears that eroding mechanisms (storms), and not accreting ones (aeolian sand transport), are dominant. A well sheltered dunefoot with a wide beach shows little less accretion than an extremely well sheltered dunefoot with a very wide beach. Only after a very severe storm differences in rate of erosion will show.

In a less stormy year the dunefoot at the extra wide beach is not likely to accrete more than compared to the dunefoot at a wide beach. It seems that differences in rate of accretion are to be attributed to differences in other factors.

3.5 Synthesis and conclusions of data research

From literature four issues are identified into which more insight is needed. To do so, three different analyses have been performed on the JARKUS and DBL datasets. Per issue, the conclusions are as follows:

- Scale dependency of empirical relation for dune evolution.
  No evidence for the validity of the Roelvink's relation on the scale of the sand engine (10 years, 10 km) can be found in the data.
- Correlation between dunefoot and coastline position.
  The dunefoot and coastline movement correlate well on time scales >50 years. On shorter time scales, the behaviour of dunefoot and coastline seem to be independent.
- Existence of a time lag in dunefoot position compared to coastline movement.
  No evidence for the existence of a general lag in dunefoot behaviour to coastline behaviour could be identified.
- Observed patterns in dunefoot and coastline behaviour, and how these are related to aeolian accretion and hydrodynamic erosion.
  The relative susceptibility to erosion is found to be the best predictor of relative dunefront volume changes.

Next to these issues, a few general observations are made:

- When beaches are wide, the dunes generally do not erode. If and how much the dunes accrete, however, does not seem to be related to the exact width of the beach, so the only generally valid observation for very wide beaches is that they do not erode. For this reason, beach width and coastline movement are no good predictors of dunefoot movement. The susceptibility to erosion is a better indicator, because it is just null.
- When the beach is very narrow the behaviour of the dunefoot is strongly steered by coastal indicators such as the beach width, coastline movement, and susceptibility to erosion. As these coastal indicators are interdependent, several explanations are possible, but the most plausible one is that dunes at narrow beaches will erode, because they are susceptible to erosion. In other words: if a beach/foreshore offers little protection to a dunefront, it is very likely to erode significantly in the following year.

3.5.1 Implications for predicting dune development

Dunefoot migration is caused by both aeolian and hydrodynamic processes. Relatively wide beaches are generally associated with accreting dunes, and narrower beaches with eroding dunes. As most observations are annual the net sediment gain measured is a result of both accretion and erosion. To predict dunefoot migration rates it is essential to know the individual contribution of each of these mechanisms.

In literature the positive correlation observed between beach width and rate of aeolian deposition is often explained by taking into account only aeolian transport. The reasoning being quite straightforward: if more deposition is measured at a wide beach, a wider beach must cause more transport. This mechanism is theoretically substantiated by the fetch concept: the longer the beach stretch the wind can blow over, the more sand it can transport. Some remarks on this are already made in chapter 2, as the critical values which are associated with the fetch vary widely over different studies, but these differences are mostly unexplained.

The hypothesis that varying rates of aeolian transport are the main cause of spatial variability in dunefoot migration rates fails to explain the observation from chapter 3 why the dunefoot movement at narrower beaches correlates so much better to coastline development than at wide beaches. From Figure 3 (page 11) and Figure 12 (page 30) it appears that dunes at a 100 meter wide beach will typically erode fairly strong, while dunes at a beach with a width of 120 m will accrete. Even if the relation between aeolian transport and fetch would be linear, this seems a very strong reaction to a relatively small change in beach width.

As the relation between fetch length and transport is argued to be a power function, the highest sensitivity to changes in fetch length is at relatively short fetch lengths. Beach width of 100 meters are, when comparing to the range of typical values that are mentioned in literature, at the higher end of the fetch range. Therefore, moderate variations of fetch length at this range should have only a very small effect on transport rates in theory.

If beach width of 100 meters are actually well below the critical fetch length, this high sensitivity to variations of beach width at about 100 m can be explained, but then the question arises why beaches of 150m or wider seem to be completely insensitive to variations in beach width.

Also the year-to-year variance in the dunefoot position observed can not be explained satisfactorily by aeolian processes. The annual net rate of aeolian transport is suggested to be fairly constant because the total aeolian transport depends more on the moderate conditions than on the extreme conditions (Arens 1994).

Paradigm shift

Following the literature (chapter 2) and the data research (this chapter), a different approach to understanding variability is proposed, namely that variability in the amount of sediment deposited in the dunes is determined by the variability in the erosive (hydrodynamic) processes, not the variability in the accretive (aeolian) processes. This leads to the central hypothesis of this thesis:

"Variability in dunefoot migration rates is determined by variability in the erosive (hydrodynamic) processes, not by variability in the accretive (aeolian) processes."

This hypothesis is supported by several observations in the data:

- The susceptibility to erosion is a much better predictor for dune erosion/accretion than the beach width.
- The more direct response of dunes to coastline movement at narrow beaches than at wide beaches: Erosion at narrow beaches requires a smaller (more likely to occur) storm than at wide beaches. The frequency of storms that provide the link between dunefoot and coastline is therefore higher.
- Why dune growth seems to be independent of the beach width at very wide beaches. The erosion is simply zero, and cannot be lower. The rate of accretion is then only influenced by the variability in the rate of accretion, which apparently depend on other factors than the beach width (provided the beach is already very wide).

This theory can also be connected to the general observation in literature that rates of dune erosion are linked to the storminess. Because the storminess is highly variable on short time scales, but fairly constant over longer timescales this hypothesis provides an explanation for:

- Why Roelvink's relation only holds for longer terms.
- Why the coupling between dunefoot and coastline movement is strong only for long terms.

The fact that these relations do *not* hold for short (10 year) time scales is because the year to year variance in the dunefoot position observed cannot be explained satisfactorily by aeolian processes. This on itself is a strong indication that another mechanism (that *does* have a strong year to year variability) dominates the variance.

In literature only one study is found that explicitly supports the proposed hypothesis:

"*Our results show that aeolian transport and upper beach/dune evolution on this macrotidal beach is strongly controlled by the magnitude and frequency of occurrence of high water levels. [...] Erosion, due to storm events combined with high water levels, completely eliminated summer aeolian sand accumulation."* (Ruz and Meur-Ferec 2004)

Furthermore, the monthly dataset gathered by Quartel (see Figure 6 on page 18) provides strong supporting evidence for the hypothesis: the rate of dunefoot growth is almost constantly positive on a monthly basis, but very negative in a few stormy months. It is clear that the position of the dunefoot at any moment is influenced much more by the variability (magnitude and frequency) of storms than by variability in the rate of dune growth (as this is apparently almost constant on a monthly basis).

Finally, the variations in rates of aeolian deposition described in literature, and attributed to varying rates of aeolian transport, can also be explained by the different sensitivities to erosion. As an example, two papers are discussed in detail in Appendix C.

An observed (or desired) shift in the balance in the erosive and accretive processes that causes a net dune growth, is thus argued to be caused primarily by a reduction of the erosive processes, rather than by an increase of the accretive processes. The implication of the proposed paradigm shift is that dune *growth* must be studied from a dune *erosion* perspective.

4 A conceptual model for dunefoot migration

In the introduction of this thesis, the following question is posed: "*How will the coastal dunes develop in the ten years after the sand engine plan has been executed?"*. In this chapter, the findings of the previous chapters will be utilized in order to develop a conceptual model, as a first step in finding an answer to that question.

In chapter 2 it is concluded that no suitable model exists that can incorporate both the hydrodynamic and aeolian processes that play a role in dune evolution. Neither is an easy combination of existing models possible, as aeolian transport cannot be modelled on the appropriate scales.

An alternative to process based modelling can be to implement empirical relations. The existing empirical relationship found by Roelvink, however, is found to be unsuitable for the scale of the sand engine, and no other empirical relationship is found or could be derived that provides a valid alternative.

However, the hypothesis presented in chapter 3.5.1, that variability in dunefoot migration rates is determined by variability in the erosive (hydrodynamic) processes, not by variability in the accretive (aeolian) processes, does provide an opportunity for development of a dune evolution model.

4.1 Outline

In this paragraph the outline for the chosen model approach is discussed. Following this outline, the implementation of the model is discussed in paragraph 4.2. In paragraphs 4.3 and 4.4 test cases are performed. Based on observations from these test cases conclusions are drawn in paragraph 4.5.

4.1.1 Requirements for modelling

Based on the current understanding of the dunes and on the objective of predicting the influence of the sand engine, the minimum requirements for the dune model are the following:

- Inclusion of the two main driving forces of dune-beach interaction:
  - Wind driven dune growth
  - Storm driven dune erosion
- Potential to provide results on a scale of 10 years and 10 km (alongshore).

Because it is not feasible to develop new process based models, a third pragmatic requirement can be added:

- No complex new models must be needed

Literature suggests that the cycle of dune erosion and accretion can be simplified to two stages: fair weather and storms (see Figure 6). During fair weather, dunes generally accrete, and during storms they erode. Furthermore, three different zones are identified: the foreshore, the beach and the dunes. Models with different capabilities are needed for each of these zones, and for both fair an stormy weather, this is summarized in Table 10. For stormy conditions, only hydrodynamics are assumed to play a role.

Table 10. Models needed for dune evolution modelling

	Fair weather	*Storm*
Subaqueous (foreshore)	Hydrodynamic transport model	Dune erosion model
Intertidal area (lower beach)	Mix of aeolian and hydrodynamic transport model	Dune erosion model
Sub-aerial (upper beach, dunes)	Aeolian transport model	Dune erosion model

4.1.2 Available models

For an alongshore uniform 2D-profile and alongshore non-uniform 3D field model the models could be selected as in Table 11. For hydrodynamic sand transport the processes involved are sufficiently understood to make predictions, and models are available. For the aeolian and mixed aeolian/hydrodynamic processes, no models are available.

For longer term predictions, the capabilities of the fair weather models are of great importance. The storms causing dune erosion are occur only episodically, but within a short time span they can cause high rates of cross-shore transport. The alongshore redistribution of sediment after a storm is a much more gradual process. So the capabilities of the fair weather model largely determine the capabilities of the model to make predictions over a several year time scale.

For two of the conditions in Table 11 no suitable models exist. In the next paragraphs the findings from the previous chapters will be applied to be able to come up with a pragmatic solution for this.

Table 11. Possible selection of models for 2D and 3D (in italics)

	Fair weather	*Storm*
Subaqueous *(foreshore)*	UNIBEST-TC *Delft3D*	DUROSTA *XBeach*
Intertidal area *(lower beach)*	- -	DUROSTA *XBeach*
Sub-aerial *(upper beach, dunes)*	- -	DUROSTA *XBeach*

4.1.3 Fair weather dune modelling

During fair weather conditions, it is the aeolian processes that transport sand to the dunes. Before a suggestion is made how the aeolian processes can be modelled, the spatial and temporal variations in aeolian transport rates are discussed.

Spatial and temporal variations in aeolian transport rates

In chapter 2 it is concluded that accurate process based aeolian transport modelling is not feasible within the current state of the art. Highly varying rates of aeolian transport are observed on even the shortest time scales (seconds), and also spatial variability ids found to be very high. Also, no valid empirical relations could be found that can provide somewhat valid results.

In chapter 3.5.1 it argued that the variability in the rate of aeolian transport is not that important for modelling the annual variability in dunefoot migration. The assumption that the temporal and spatial variations in aeolian sand transport can be neglected on an annual scale, greatly improves the perspectives for modelling fair weather dune accretion: instead of a process based sand transport rate model that includes the forcing and the topography (which is impossible to do with the state of the art knowledge), the rate of fair weather dune accretion can be reduced to a single constant parameter: the total annual volume of sand transported from the beach to the dunes per meter of coast.

Implications for modelling

Fair weather dune accretion is represented by a constant parameter. In this conceptual model it is not necessary to determine the exact value of this parameter. An indication for a realistic order of magnitude can be found in the work of van der Wal. When corrected (removal of nourishment locations affected by erosion, see Appendix C), a typical value of 18 m^3/m of dune accretion is found (van der Wal, 2004). In a different study, Arens finds an annual deposition of 12 m^3/m for different sites that are planted with reed stems (Arens et al., 2001). A typical value of 0.05 m^3/m/day is therefore suggested.

4.1.4 Fair weather intertidal area modelling

The beach forms the connection between the foreshore and the dunes. Due to varying water levels, it is influenced by both aeolian and hydrodynamic processes. Modelling the exact interaction of wind, water and sand on the lower beach is very complicated (Aagaard et al., 2005; van Rijn et al., 2003), and probably not possible at all.

Because of the high amount of energy dissipated in this zone, the lower beach is probably in a dynamic equilibrium already after a relative short period of constant forcing. It was observed that the beach can be surprisingly resilient on an intra-storm time scale and the intertidal zone gradient can remain almost constant before and after storm events (Aagaard et al., 2005). Typical timescales of adjustment to fair weather conditions are in the order of days to weeks (List et al., 2006).

Because of the simplifications in aeolian transport, it is not necessary to know the exact beach profile during fair weather conditions. Only before a new storm arrives, the profile is needed as an input for the dune erosion model. It seems to be a safe assumption that in most cases the beach will have recovered to a more or less equilibrium state before a new storm occurs.

This is a simplification though, as observations by Quartel et al. (2008) indicate that in winter, when storms are frequent, the morphology antecedent to storm events varies due to differences in storm interval. For the conceptual phase of the model this will be ignored.

Implications for modelling

The beach forms the connection between the foreshore and the dunes. As the dunes and the foreshore are simulated, the beach (in a profile view) will be assumed to form the connection between these two. The cross-shore profile of this connection can be derived from observations of a summer beach.

4.1.5 3D Area model or 2D profile model

Before the model can be implemented, a decision between a 2D profile or 3D area model must be made. For both options there are models available.

The only way to accurately model the influence of a large-scale, alongshore non-uniform coastal intervention as the sand engine, is to use a 3D area model. However, for practicality it is favourable to start off with a 2D profile model: dune erosion calculations on a profile require much less computing power, and existing dune erosion profile models are better verified as large scale laboratory tests can be done only in wave flumes. So for exploring the capabilities of the conceptual model a profile model will be developed.

If further 3D devolvement is desired, a series of independent 2D profiles can be linked to provide an intermediate step between a 3D area model and 2D profiles. A model as UNIBEST-CL+ could be used to provide this linkage. Alternatively, if the conceptual model proposed works well, a similar approach in modelling as for the 2D situation can be applied in a 3D situation; the process based models involved have 3D counterparts and assumptions and simplifications for the 2D scenario can also be applied in 3D.

4.1.6 Modular approach

As two very different processes (different forcing, different time scale) are involved, the conceptual model will consist of different modules for stormy conditions and for fair weather conditions. For the fair weather conditions a seperate module will be used for each of the three zones indicated in Table 10. For the stormy weather, one dune erosion model is capable of covering all zones. In total four modules are needed to describe the full cycle of dune erosion and recovery.

4.2 Model implementation

Using the requirements and following the setup discussed previously, a working implementation of the model is coded in MATLAB. The model starts by obtaining a certain JARKUS transect, and then modifies that profile for every time step. The length of the time step has no physical meaning, but values are chosen such that a time step represents 24 hours.

If at a certain time step there is a storm, the profile evolution is calculated by feeding that storm (in parameters) to the *Dune erosion module*. If there is no storm, the dune grows with a certain amount. This is calculated with the *Dune accretion module*. The beach and underwater profiles are calculated with the *Underwater profile evolution module* and the *Beach evolution module,* respectively.

Each of these modules will be discussed in the next paragraphs.

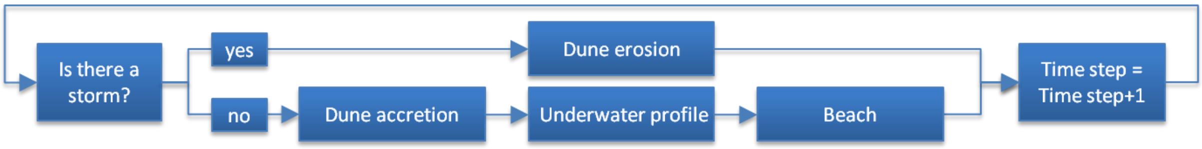

Figure 32. Scheme of model run. Model runs until maximum time step is reached.

4.2.1 Description of modules

Dune erosion module

The main requirement for the dunefoot module, therefore, is that it can predict the influence of initial profile shape on short-term dune erosion under storm conditions. Two models are available that fulfil that requirement: DUROSTA and XBeach. While the experimental XBeach is also capable of two and three dimensional dune evolution, the more tried and proven DUROSTA is chosen for this implementation. Additional benefit is that the code of DUROSTA is highly optimized, so calculation times are very short.

The module works as follows: The profile and the storm parameters are used to construct input for DUROSTA. After DUROSTA has calculated the output that is generated, it is then used to modify the profile. Therefore, the module is nothing more than an interface for DUROSTA.

Dune growth module

Because aeolian transport cannot be modelled in a process-based way, a simplification is suggested in paragraph 4.1.3. Following this suggestion, the total transport formula is reduced to one constant parameter: the *Aeolian transport to the dunes* in m^3/m/time step.

By far most of the sand that is blown to the dunes is observed to accumulate on the seaward side of the first dune row. The exact distribution along the slope varies, and depends both on the presence of sand trapping obstacles such as sand fences and vegetation and on the wind speed (See paragraph 2.1.4).

Though field observations indicate that the dunefoot is likely to attract more sand than the dune slope, deposition of sand is assumed to be distributed evenly over the dune slope in this conceptual approach aeolian.

The dune growth module is implemented as follows: all sand that is blown to the dune is equally (over the height) distributed over the face of the dune. If for example 1 m^2/m sand is blown to a ten meter high dune (dunefoot by definition at NAP +3 m, top at NAP +13 m), this is modelled by shifting each point along the seaside slope of the dune 10cm seaward.

If the dune front is too steep, the sand is transported down the slope until the steepness requirement is fulfilled. This requirement (maximum slope) is user definable. After a storm, a maximum slope of 1:1 is not unlikely (van de Graaff, 1986), but on the longer run dune faces along the Holland coast are rarely steeper than 1:2.

Finally, to fulfil the conservation of mass requirement, sand that is blown into the dune is extracted from the beach.

In summary, the dune growth module works as follows:

- Sand transport is defined by a single constant, the *Aeolian transport to the dunes (m^3/m/time step).* This means that there is no temporal variation in the modelled aeolian sand transport, and that the amount is independent of the beach width.
- Sand blown into the dunes is equally distributed between the dunefoot (+3 NAP) and the top of the dune, on the seaward side.
- The dune front is gentled where it is too steep
- Sand blow to the dunes is extracted from the beach.

Underwater profile evolution module

The underwater profile recovery of a storm is not the primary interest for this model. So even though process based models are available that can simulate underwater profile developments, it is decided not to implement such a model in this phase of the development because the state of the art of such models demands a lot of computer power. The modular approach of the model does allow a relatively easy implantation of a more advanced model to be made in the future.

Big storms that really cause a significant relocation of the dunefoot typically occur up to only a few times per year. Similar to beach recovery, time scales associated with bar recovery after a storm are in the same range as the interval between the bigger storms. More energetic conditions in winter do widen the beach and move the bars more offshore in winter compared to summer (Quartel et al., 2008). This effect will not be taken into account.

So because there is no fast computing stable model for day to day profile evolution readily available, and because the time scale associated with post-storm profile recovery is usually shorter than the interval between storms, the assumption is made that the underwater profile is adjusted to equilibrium very fast.

This near instant recovery of the profile to the equilibrium state will probably not influence calculations too much: The underwater profile does not influence the rate of dune growth, only the amount of erosion. Therefore the instant recovery will not give different results to a more gradual recovery, provided both models reach full recovery before the next storm occurs.

This is achieved by forcing the shape of the underwater profile (below NAP -1m) to the state it was in the initial profile (the assumed equilibrium profile) at every time step. However the (fixed shaped) underwater profile is allowed to shift in the cross-shore direction to fulfil the mass continuity requirement: when more sand is added to the underwater profile, this is 'absorbed' by moving the profile in offshore direction. Similarly, when sand is extracted from the foreshore, the entire profile moves in landward direction.

For every time step the difference between the current situation and the profile in equilibrium situation is calculated. That difference, multiplied by the 'profile recovery per time step fraction', is added to the current profile. A recovery fraction of 1 means full recovery in one time step. A fraction of .5 means that the difference between the current state and what is believed to be the equilibrium state is reduced by 50%.

The equilibrium profile is simply the initial profile (a JARKUS transect) that is fed to the model. JARKUS transects are measured in the non stormy season, so a good representation of the equilibrium profile is likely.

Beach evolution module

Between the dunefoot (NAP +3) and the equilibrium profile (NAP -1) is the beach. Full process based modelling of the beach is not possible, but in this context not necessary either.

The beach is represented by an interpolated curve that visually resembles the beach profile of the initial transect. As the cross-shore location of entire equilibrium profile shifts, the beach width is altered. Because the beach is generated by a curve it can easily be stretched and condensed.

Overview of modules

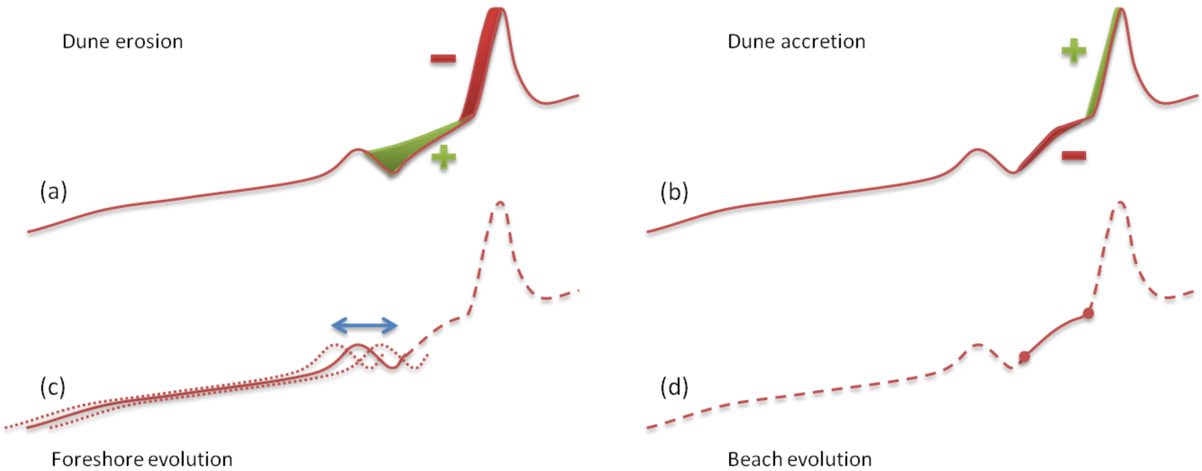

Figure 33. Schematization of different modules. (a) Dune erosion takes sand from the dunefront and deposits it on the beach and foreshore. (b) under fair weather conditions, sand is taken from the beach and transported to the dunes. (c) the entire underwater profile is shifted landward or seaward in such a way that, together with the connection between foreshore and dunes formed by the beach (d), the amount of sediment remains constant.

4.2.2 Input & output

Input

For the model to run, the following input is needed:

- Calculation length: The total number of time steps for which to calculate.
- Initial profile: The model starts with a profile, this profile is then adjusted during the run.

- Dune growth parameter.
- Storm parameters.
    - Interval: Storms occur either on a fixed interval, a random interval or on predefined time steps.
    - Parameters: The storm parameters are also either predetermined or a random pick from a statistical distribution. The parameters are:
        - Significant wave height
        - Water level
        - Peak period
        - Grain diameter
- Profile recovery speed: The speed at which the profile recovers from a storm. The input is the fraction of the difference between the occurring profile and the equilibrium profile that is added to the occurring profile. A setting of 1.00 completely updates the profile to the equilibrium profile, a fraction of 0.20 only updates the profile for 20% per time step.

Some additional input parameters include seasonal variation to the equilibrium profile (bar amplitude and location), but these will not be discussed here.

Output

The output provided by the model is profile data at every time step, and the values of the DF, CL and BW coastal indicators, as defined in Appendix B. For easy inspection of these results a simple graphical interface is included. A screenshot of the result viewer is given in Figure 34.

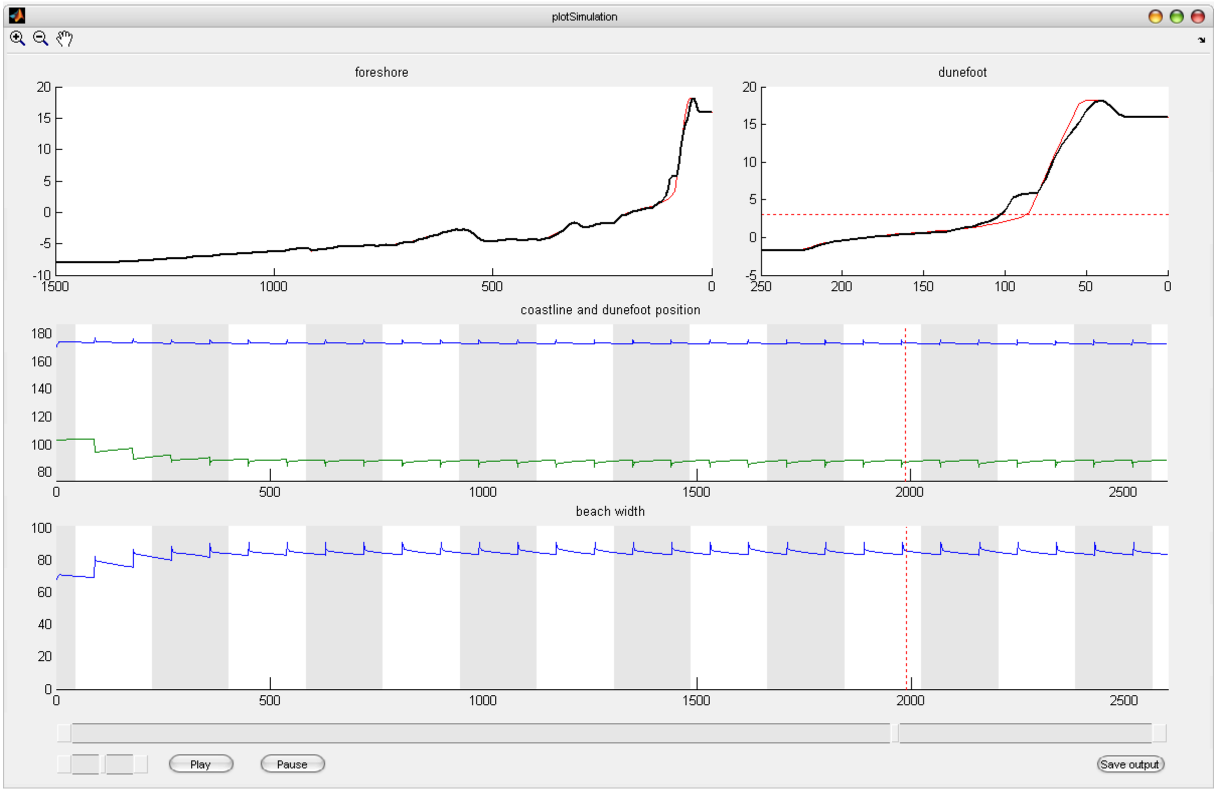

Figure 34. Screenshot of result viewer. Top left shows the foreshore. The red line is the current profile, the black line the initial profile. The top right gives a close up of the dunefoot. The middle plot gives the DF (green) and CL (blue) location per time step. The bottom chart gives the BW. The dotted red line indicates which result is being viewed, in this case a time step just under 2000. The storms have a regular interval and intensity, so the model reaches a dynamic equilibrium at a beach width of about 84 m, after some 500 time steps. The grey and white bands are spaced 180 time steps apart, indicating a 360 time step period (and with one time step per day, that is about a year).

Each peak in the bottom graph represents a storm. Directly after the storm the beach is widened because that is what DUROSTA provides. Quickly after the storm the width of the beach is reduced, because the foreshore is forced to the equilibrium profile. This only takes a few time steps as the factor that determines the recovery speed is set very high. After the initial reduction of the beach, further sediment is taken from the beach and put in the dunes. Because of the equilibrium profile assumption, the results in a landward movement of the underwater profile: the beach width is slowly reduced.

4.3 Test case 1: sensitivity analysis

The first question, after the model is implemented, is if it works. Several test runs are made, all with credible results given the simplifications of the model. The second important question is what the sensitivity is to variation of the input parameters. Nine runs are done, between which only the storm intensity and the daily dune accretion rates are varied.

4.3.1 Model Input

A distinction is made between the shared input (equal for all runs), and the varying input.

Shared input

The input which is the same for each run is summarized in Table 12.

Table 12. input parameters

Variables	*Value*
Simulation length	2600 time steps (days)
Profile recovery fraction per day	0.5
Initial transect	Transect 8400 (Rijnland), 1999. (Slightly modified)
Storm frequency	1 per 90 days
Storm duration	6 hours
Grain diameter	200 µm
Wave period	10 s

Varying input

To adjust the sensitivity of the model to different input scenarios, both the aeolian transport component and the storminess are varied. The aeolian transport is varied between 0 and 0.20 m^2/m of sand that is transported to the dunes per day. For storms the wave height is assumed to be twice the water level elevation height. The water level is varied between 2 and 3 meters NAP, consequently the wave height is varied between 4 and 6 meters.

4.3.2 Results

The BW coastal indicator (as defined in Appendix B) is used to compare the calculations for the different input scenarios. All but two runs reach a dynamic equilibrium after 2600 calculation time steps. In Table 13 the BW at time step 2600, just before a storm, is presented. In Figure 35 and Figure 36 the output of the two extreme scenarios (c and g) is presented.

Table 13. Sensitivity analysis of storminess and aeolian transport rate, BW in meters.

Water level η (m)	*Aeolian transport to the dunes ($m^3/m/day$)*		
Wave height H (m)	0.00	0.05	0.20
η = 2 *H = 4*	88 (a)	79 (b)	56 (c)
η = 2.5 *H = 5*	118* (d)	107 (e)	84 (f)
η = 3 *H = 6*	162** (g)	150 (h)	120 (i)

* equilibrium only reached after about 6000 time steps, at 135 m.

** no equilibrium, dunefoot slowly retreats to model boundary after +/- 8000 time steps

Example runs

To give insight into the results for two cases the output is presented in Figure 35 and Figure 36.

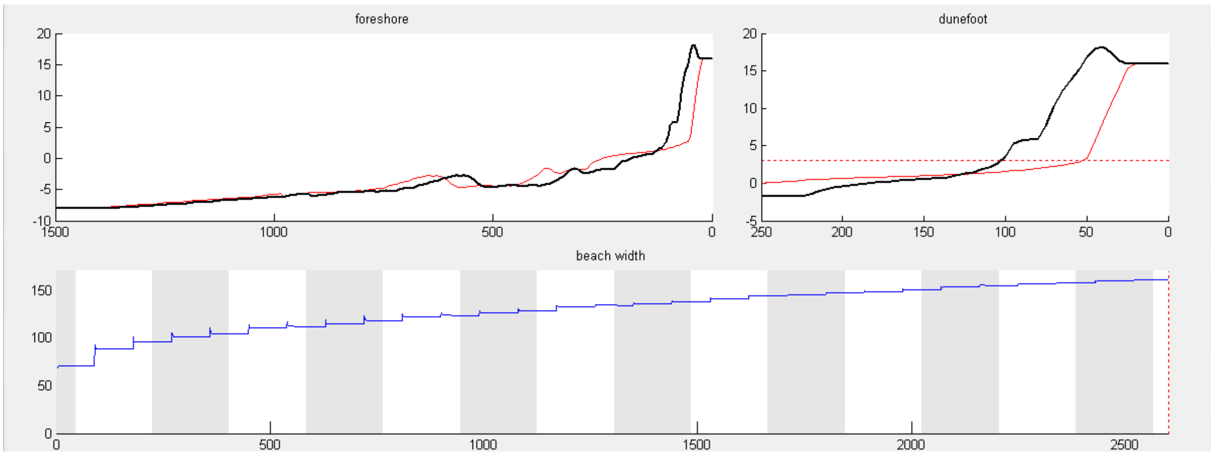

Figure 35. Beach width evolution and profile after 2600 time steps for case (g): no aeolian transport and high storminess

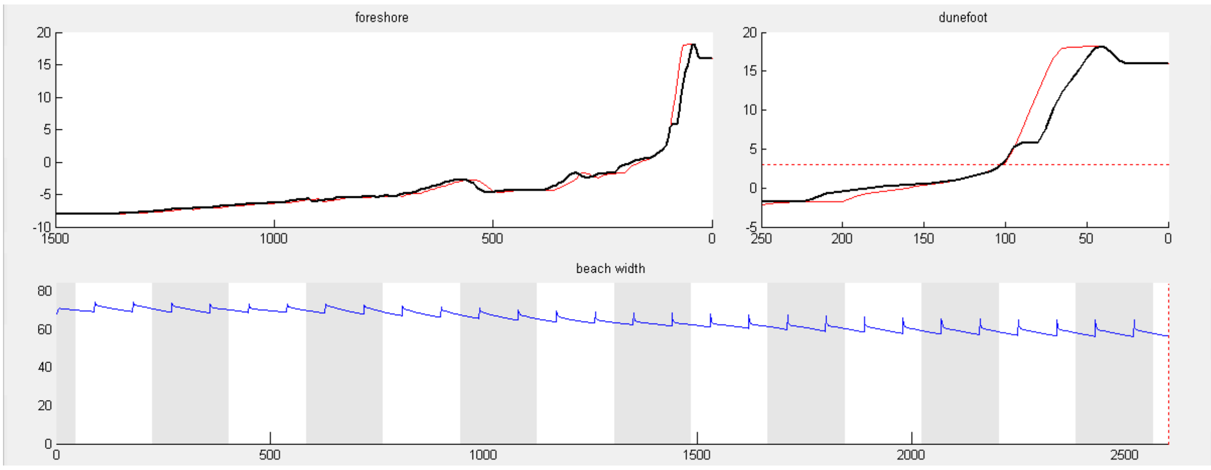

Figure 36. Beach width evolution and profile after 2600 time steps for case (c): high aeolian transport and low storminess

4.3.3 Discussion of results

A striking result is that even dunes with no aeolian transport feeding them remain intact. This is because the model simulates a near direct beach recovery and there is a conservation of sand. After a certain amount of erosion the beach is so wide that the erosion does not reach the dunefoot anymore, but only affects the beach. The dune is then in an absolute equilibrium, it is neither eroded nor nourished. However, it is probable that these extreme situations fall out of the validity region for DUROSTA results, but this is not further looked into.

Another result is that the equilibrium beach width seems much more determined by the variations in storminess than in the aeolian transport rate. Compared to the middle case, the water level and wave height is varied by 20% in both directions. Compared to the middle scenario, the aeolian transport is reduced by 100% and increased by 300%. The model is clearly much more sensitive to the variations in storminess than the variations in aeolian transport rates.

The equilibrium beach width is determined by how much protection a dune needs to be able to cope with the erosion by storms. Wider beaches are therefore associated with higher storminess and lower aeolian transport rates, narrower beaches with lower storminess and increased aeolian transport. This is in line with observations by Quartel et al. (2008).

4.4 Test case 2: a large scale intervention

4.4.1 Model Input

For this analysis the input is taken from two of the previously discussed scenarios:

(b): medium aeolian transport (0.05 m^2/m/day) and low storminess (η = 2 m, H = 4 m)

(f): high aeolian transport (0.20 m^2/m/day) and medium storminess (η = 2.5 m, H = 5 m)

At time step = 1000, a foreshore nourishment of 250 m^3/m is added two both runs. This is implemented by adding sediment to the underwater profile. As the Profile recovery speed is set very high, this nourishment is (unrealistically) almost instantly redistributed over the entire underwater profile (making it shift seaward). This results in a widening of the beach. After a certain time, the beach will have returned to its original equilibrium width, but the entire profile will have shifted seaward: the sand is redistributed over the profile.

4.4.2 Results

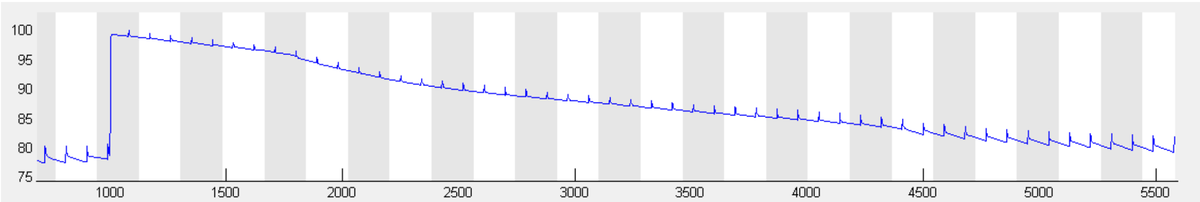

Figure 37. evolution of beach width for (b). Equilibrium beach width is reached again at time step 5000 ($T_{adjustment}$ = 4000)

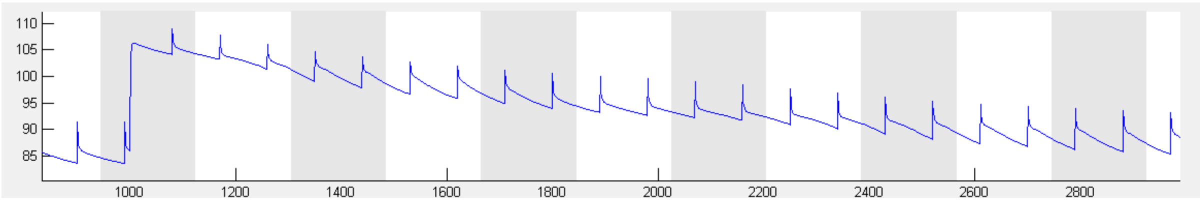

Figure 38. evolution of beach width for (f). Equilibrium beach width is reached again at time step 2500 ($T_{adjustment}$ = 1500)

4.4.3 Discussion of results

The results clearly show that the ability of the model to adjust to changing circumstances is determined by the dynamics of the system, not the (dynamic) equilibrium. Both scenario (b) and (f) have roughly the same dynamic equilibrium (the equilibrium beach width is respectively 79 and 84 metres), but the time it takes to adjust to varying circumstances is determined by the dynamics (erosion and accretion) of the system.

For quantifying and qualifying the effect of large scale interventions along the Holland coast on dune evolution, this implies that it is very important to have insight into the variability of the dune front on an intra-yearly basis. Not the annual net effect of wind and water is important, but the total amount of sand transported back and forth.

4.5 Conclusions

The conceptual model and its successful implementation presented here make clear that the chosen model concept is capable of fulfilling the requirements stated in paragraph 4.1.1: The model clearly distinguishes aeolian dune growth and storm driven dune erosion, the model is capable of predictions on timescales of several years, and no complex new knowledge has been developed to do so.

Because a lot of simplifications are made, the conceptual model is essentially not much more than a batch run of DUROSTA. The new element is that this model explains dune accretion variations in terms of erosion, and not only in terms of aeolian sand transport.

The first results of the implementation of the conceptual model are encouraging. Based on this conceptual model, already some interesting conclusions can be drawn, proving its usefulness:

- The beach widths the model predicts depend to a much larger degree on the dominating storm conditions, than on the aeolian sand transport capability. This implies that dune growth depends on storminess and bathymetry. Variations in dune growth thus depend on temporal (decadal/annual/seasonal) variations in storminess, and spatial and temporal variations in bathymetry.
- To widen a beach, the dunes must not be strengthened (e.g. by planting marram grass) and protected (e.g. by offshore breakwaters). On the contrary, the more storms have influence on a beach, and the lesser the amount of sand trapped in dunes by aeolian processes, the wider a beach is.
- The ability of a system to adjust to changes on the foreshore is determined by the dynamics of the system, not on the (dynamic) equilibrium.
- The dunefoot development of a nourished beach will only stand out to that of a non nourished beach during storms. If no storms occur, both nourished and non nourished dunes experience similar growth. The net accretion of the nourished beach is only differentiated from the non nourished beach during an erosion event that hits the non nourished beach harder.

The current implementation of the model is only capable of modelling a 2D cross-shore profile and not a 3D area. To make this concept applicable for the case of the sand engine, a three dimensional counterpart must be developed. But both for underwater profile evolution and storm induced dune erosion existing models could be used Delft3D and XBeach, respectively, but maybe also others can be applied.

But before such a model is made, it seems very wise to do some validation of the model first, as the current implementation is not yet validated in its conceptual state. However, the most important part of the model, the DUROSTA model, is validated. And because of the way the model is implemented, most errors will be damped out, instead of amplified: if erosion in one year is over-predicted, the extra sand on the foreshore will reduce erosion during the next storm.

5 Conclusions

The development of a coastal dune is the result of both aeolian and hydrodynamic processes. The common assumption that variability in dune growth is dominated by the aeolian processes is disputed; research of literature and data in this thesis has lead to the following hypothesis:

"Variability in dunefoot migration rates is determined by variability in the erosive (hydrodynamic) processes, not by variability in the accretive (aeolian) processes."

This hypothesis cannot be confirmed with absolute certainty, but strong circumstantial evidence is found in both data and literature. A conceptual model is developed based on this hypothesis. Being capable of qualitatively explaining observed phenomena in the data, the model results are encouraging.

Next to support for the main hypothesis, the following conclusions are drawn:

- Aeolian processes that influence the dunes cannot be adequately modelled with the state of the art knowledge.
- Therefore development of a fully process-based model that includes both the foreshore as well as the beach and the dunes is not feasible with current knowledge.
- For the time and space scale of the sand engine (10 years and 10 kilometres) the empirical Roelvink relation is not valid.
- Analysis of periodic components in dunefoot and coastline behaviour is shown to provide appealing results for only some specific locations, but such an analysis is shown to be unable to provide universally valid results.

5.1 Implications for the sand engine pilot project

The question posed in the beginning of this thesis is "*How will the coastal dunes develop in the ten years after the sand engine plan has been executed?"*. No quantitative answer can be provided yet, but the conceptual model presented in this thesis provide a promising starting point for development of a dune evolution model.

The findings in this thesis do allow for some qualitative statements:

- A maximum beneficial effect of a beach or foreshore nourishment on dune evolution can be expected for a nourishment design that minimizes dune erosion.
- Dune evolution prediction for the sand engine presents some kind of paradox: maximum dune growth can be expected if no more storms will occur, but the more storms occur, the more influence the sand engine will have: During fair conditions the rate of dune growth at the sand engine and non-nourished locations is expected to be comparable. The protection a large scale nourishment provides against dune erosion will only clearly differentiate dune development at the sand engine location from that at unprotected locations during a (sufficiently powerful) storm.
- Dune development strongly depends on the extreme conditions, much less on the moderate conditions. Dune evolution over periods up to 10 years can therefore not be modelled by average conditions, it must be assessed by a probabilistic approach because storms may or may not occur. Only on a longer timescale fluctuations in storminess can be aggregated.

The conceptual model is not capable of quantitative predictions, but following measurements described in literature a cautious suggestion is made for the dune growth that can be expected in the area fully protected from erosion by the sand engine pilot project: 12 – 18 m^3/m/year (paragraph 4.1.3).

6 Recommendations

Several recommendations follow from this thesis.

Dune evolution prediction for the sand engine

No quantitative predictions for dune evolution can be made yet, but the insights this thesis provides do allow for a qualitative comparison of alternative designs for the sand engine. A sand engine design that limits dune erosion the most can be expected to invoke the highest increase in dune volume. The relative reduction of the susceptibility to erosion can be calculated using state of the art knowledge.

Measurements

The sand engine pilot project will be intensively monitored. It is strongly recommended to apply the insights from this study to this program. If surface elevation measurements are timed right, the sand engine pilot project provides the opportunity to create a dataset in which the individual influence of aeolian and hydrodynamic processes can be determined explicitly and unambiguously. This would require measurements to be taken directly before and after each storm, and not at a fixed interval.

Conceptual model

As the results of the conceptual model are encouraging, it is recommended to develop this concept further. As a first step a validation study should be performed using wave and water level records, and the JARKUS data. Results of such a study could be used to refine the model. Extra attention should be given to the following aspects:

- The model assumes that there is no sub-aerial alongshore transport, and that there is no influence of variability in aeolian transport rates for yearly net transports. Both of these assumptions should be refined.
- Improvement of the dune accretion module in such a way that it includes sand accumulations at the dunefoot.
- Inclusion of a near-shore coastal evolution model.

When the model is validated, the model could be expanded to the third dimension.

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Appendix A Datasets of the Dutch coast

The Dutch coast is one of the best measured coasts in the world. Two datasets are of particular importance for dune research: the Dutch Beach Line and the JARKUS datasets. As these datasets form the basis of many of the studies that are mentioned in this thesis and also for the research done within this thesis, an introduction to these datasets is provided in this paragraph.

A.1 Coordinate System

In 1840 the first oakwood pole was driven in the beach of Huisduinen (2 km west of Den Helder), after the idea of Jan Blanken (1755-1838), a renowned Dutch coastal engineer. Until 1843 another 123 'Rijksstrandpalen' (RSP) were placed, one for every kilometre from Den Helder in the North to Hoek van Holland in the South.

The imaginary line connecting them is known as the RSP-line, and is used as a baseline for measurements of the Dutch coast. Orthogonal to this base line transects are defined over which yearly measurements have been made, usually at the locations of the beach poles.

In later years the system was expanded to the entire Dutch North Sea coast. Where beach poles have become covered with sand in the course of time extra poles were placed on the beach (at the same alongshore position). From 1963 to 1967 the RSP coordinate system underwent a major revision. New measurement transects were defined to reduce their alongshore spacing to about 250 m. In the seventies the number of measurement transects near the Wadden island heads was greatly reduced. The coordinate system has also been updated where major coastal changes have taken place, for instance near the Maasvlakte and the Oosterschelde (Kalf et al., 1993).

For the Holland coast these measuring transects are identified by their distance (in decametres) from the first beach pole, following the baseline; e.g. transect 3800 corresponds to the transect 38 km South of Den Helder, which is in Egmond aan Zee. In all of the 17 costal sections transects are numbered from the North East to the South West.

From the RSP line seaward is defined as the positive x direction, landward is the negative x direction. Height measurements are all made with respect to NAP (Nieuw Amsterdams Peil), the Dutch ordnance level. 0 m NAP roughly corresponds to the mean sea level.

A.2 Dutch Beach Lines

From 1843 till 1980 the positions of the mean low water (MLW), mean high water (MHW) and dunefoot (DF) have been recorded annually at the locations of the beach poles during the calm weather season (April to October), using the RSP-line as a base line.

The DF position was visually determined as the location of the sharp bend in the profile, usually where the vegetation starts, however the exact criteria could not be retrieved. For the MHW and MLW it is assumed that these where determined using the sea as a reference height, introducing some vertical errors estimated at ± 0.5 m.

- as the position of the DF is relatively easy to measure, the accuracy (σ) is estimated at 2 m.
- the position of the MLW and MLW was probably determined using the sea level as reference. Vertical variations are estimated at ± 0.5 m and a beach slope of 1:20 leads to horizontal accuracy (σ) of 10 m.
- the definition of the dunefoot is a bit ambiguous, but it is assumed the dunefoot in the Dutch Beach Line measurements corresponds to the +3 NAP reference height, as is done in many other studies on the Dutch coast, e.g. de Vriend and Roelvink (1989), Jeuken et al. (2001) and Ruessink and Jeuken (2002) .

A.3 JARKUS

In 1963 Rijkswaterstaat (the Dutch Department of Public Works) started the JARKUS (JAaRlijkse KUStmeting, annual coastal measurement) program in the southern part of Holland (km 99 – km 118), and the next year the rest of the Holland coast (km 0 – km 99) was included. In this monitoring program profiles of the coast are measured.

The transects are measured at all the locations the Dutch Beach Lines are measured, but also in between these locations, usually at an interval of 250 m. In areas with groins, the alongshore resolution varies between 110 and 310 meters, as the measurements are taken in between the groins. (Kalf et al., 1993)

The cross-shore resolution for measurements ranges from 5 to 20 meters, but is usually 5 meters at the dunefoot and the waterline and less further offshore. A transect usually includes at least the area from the dunefoot to the -5 m contour line, and often also the top of the first dune row to the -10 m contour line. In the beginning transects were measured from about 200 landwards from the shoreline to 800 seawards. Since 1985 the seaward boundary has been expanded, locally to some 2000 m seaward of the RSP line. Every five years extra measurements have been made till about 5 km offshore on one transect per km (usually the same transects as the Dutch Beach Line dataset). These transects are designated as so called 'doorlodingsraai' (Kalf et al., 1993).

Underwater measurements have been made with echo sounding, for the above water part of the transect various in-situ (levelling, GPS) or remote sensing (stereo photogrammetry, LiDAR) techniques have been used. Ideally the underwater part of the transect is measured at high water and the dry part is measured at low water, resulting in an overlap so both parts can easily be merged together in post processing. Both parts should also be measured at about the same time. As these requirements significantly reduce measurement efficiency, this unfortunately has often not been the case; measurements are known to be taken several months apart and the wet and dry part do not always overlap.

Next to the errors discussed below also data errors can exist, due to failing technology (e.g. punch card errors) or human error.

Sub-aqueous JARKUS transect

When measuring the water depth at a given location, many errors can accumulate. The most common error sources are due to:

- Positioning (xy)
- Instrument to bottom measurement (measured depth)
- Instrument to reference level determination
- Presentation (Interpolation)

In all of these fields significant improvements have been made in the past years. Because of the gentle slopes under water and the coarse grid in which the data are stored (5 m), errors in xy positioning are of less importance than errors in bed level.

To determine the bed level the vertical distance from the instrument to the bottom is measured, and corrected with position of the instrument with respect to the reference level. Until the introduction LRK-GPS (Long range kinematic – global positioning system) system, with a vertical accuracy in the order of centimetres in 2000, vertical referencing was done with respect to the water level. The water level at any given point is not exactly known however, some potential uncertainties are the water model accuracy, the tides, the wind and wave set up and flow contraction near piers and groins

The position of the sounder with respect to the water level also varies, some common sources of error:

- Pitch, roll and heave (The ship draft varies with its pitch, roll and heave. Furthermore, the distance measured by the sounder needs to be corrected to find the vertical distance to the bottom)
- Squat (the draft of a vessel depends on its speed)
- Varying ship tonnage (fuel consumption)

Finally, there is an error introduced by the (single or multibeam) echo sounder itself

- Correction for acoustic zero point
- Sound speed model
  - Varying salinity
  - Varying temperature

The total error is divided in a systematic and relative part. Systematic errors are of importance when comparing two separate transect measurements. Relative errors are within one transect measurement. The cumulative effect of the different error sources is estimated in Table 14.

Table 14. Variable and systematic errors in underwater JARKUS measurements (Wiegman et al., 2002)

	Variable	*Systematic*
Water level + single beam echo sounding (before 2000)	0.09 cm	0.25 cm
LRK-GPS + multi beam echo sounding (after 2000)	0.09 cm	0.05 cm

Sub-aerial JARKUS transect

For the survey of the dry part of the JARKUS traditionally levelling techniques were used. In 1977 stereo photogrammetry was introduced, and since 1996 mostly LiDAR (Light Detection and Ranging) is used. However, some terrestrial techniques are also still used, usually an RTK-GPS (Real Time Kinematic – Global Positioning System) receiver mounted to a measuring pole for use on foot or a small all terrain vehicle.

For levelling an accuracy of individual points is mentioned (but not thoroughly investigated) in the order of one centimetre (Oosterwijk and Ettema, 1987), as cited by Wijnberg (1995). For levelling (or RTK-GPS) it is required for the surveyor to physically be at point that is to be measured. Because this made it hard (or impossible) to measure the area from the dunefoot to the first dune crest, this part was often not measured.

With the introduction of remote sensing in the form of stereo photogrammetry it became possible to measure a larger part of the dune area. The accuracy (σ) of this technique for individual data points is estimated in the order of 9 cm in the dunes and 6 cm on the beach. Main source of error is the accuracy in orientation of the measured heights with respect to the reference system, and for the dunes also vegetation. Systematic errors (σ) for both beach and dunes are estimated at 7 cm (Veugen, 1984).

From 1996 onwards laser altimetry (LiDAR) techniques are used. Typically one point is measured for every 1-6 m2 of terrain covered. In post processing a transect is computed from these points, reducing sensitivity to local undulations in the profile. It is no extra work to also include the first dune rows, however LiDAR is sensitive to vegetation. The accuracy (σ) is estimated at 10 to 15 centimetres (de Graaf et al., 2003).

Data of all different methods are stored in the same 5 meter JARKUS grid. This is too coarse to accurately represent the undulations in profile, especially the dunefoot where there is a sharp bend in the profile. The accompanying errors can be much greater than those introduced by the measurements alone: 10 to 60 centimetres (de Graaf et al., 2003)

A.4 Data accessibility

The JARKUS and DBL datasets are very valuable datasets. However, very often the usability of data is limited by the accessibility. To overcome problems with accessibility and consistency the UCIT (Universal Coastal Intelligence Toolkit) has been developed within Deltares. UCIT is developed within the McTools environment (software tools in the area of Marine and Coastal science and technology). McTools has proved a valuable resource for discovering and sharing MATLAB routines for handling of data. The toolkit is described by van Koningsveld et al. (2005), van Koningsveld and Lescinski (2007) and van Koningsveld et al. (2007).

During the course of this work, ongoing developments on the (for internal use only) McTools toolbox have culminated in the development of the OpenEarth toolbox. OpenEarth is fully open source, and therefore free (as in beer and as in speech). A quote from the website:

> *"The sustainable interaction between mankind and the dynamic natural system provides a great number of hydraulic and environmental engineering challenges. The paradigm to confront these challenges one-project-at-a-time, while attractive from a budget management perspective, results in grave inefficiencies in the development and maintenance of the basic elements that are invariably involved: data, models and tools.*
>
> *Hardly any project is by itself of sufficient scale to comprehensively develop easy accessible high quality data archives, state-of-the-art model systems and well tested practical analysis tools under version control. As a result research and consultancy projects commonly spend a significant part of their budget to set-up some basic infrastructure, most of which dissipates again once the project is finished.*
>
> *OpenEarth is the open source initiative to archive, host and disseminate Data, Models and Tools for marine & coastal scientist and engineers. It aims to remedy the above-described inefficiencies by providing a project-superseding approach.*
>
> *To facilitate steady and continuous development and growth of these building blocks even beyond the man-made boundaries of projects Subversion repositories are utilised for storage, back-up and version control of raw data, scripts and source code. Products are shared freely via various web based tools. As a result research and consultancy projects no longer need to waste valuable resources by repeatedly starting from scratch. Rather they can build on the preserved efforts from countless projects before them.*
>
> *OpenEarth is, amongst others, supported by the concerted effort of professionals from Deltares (formerly Delft Hydraulics), Delft University of Technology's Hydraulic Engineering and Environmental Fluid Mechanics sections and UNESCO-IHE. It is currently the central platform for data and knowledge management in the research programmes Delft Cluster - Northsea and Coast, Building with Nature and MICORE."*
>
> *http://openearth.deltares.nl/*

Appendix B Coastal Indicators

To compare data in different years several coastal indicators are used in this thesis. Many other studies of the Dutch coast have used the same or similar coastal indicators. The differences between these are more a matter of definition than fundamental. The indicators used are either the cross-shore locations of contour lines (DF, MHW, MLW and CL), volume based cross-shore positions (MKL, DF_{MKL}, CL_{MKL}), or a difference between these lines (BW, BW_{MKL}). For the development of the frontal dune a volume based parameter is defined.

Dunefoot line (DF)

Until the beginning of the JARKUS measurements (1965), the position of the dunefoot was determined visually as the position with a break in slope between the beach and the foredune, roughly corresponding to about 3 m above MSL. For later years the position is defined as the most seaward crossing of the NAP + 3 m, in accordance with van der Burgh et al. (2007) , Ruessink and Jeuken (2002), and Quartel et al. (2008). In literature also other definitions are used for the dunefoot position, e.g. based on the intersection of the steepest part of the dune slope with the + 1 m NAP plain (Guillen et al., 1999), or more generally the transition between the beach and the mainland (van de Graaff, 1990).

Mean high water line (MHW) and Mean low water line (MLW)

The mean high and low water contour lines are the most seaward crossings of the local mean low water and mean water levels. The tidal range varies strongly along the Dutch Coast (1.38 to 3.88 m, along respectively Holland coast and Zeeland coast), so the MHW and MLW levels are not constant along the Dutch coast. The MHW height varies between NAP +0.55 (Holland) and NAP +2.09 (Zeeland), the MLW varies between NAP -0.64 (Holland) and NAP -1.79 (Zeeland).

Coastline (CL)

The coastline (or shoreline) is defined as the mean of the MHW and MLW positions. By levelling between these two highly variable parameters the variance is somewhat reduced.

Beach width (BW)

In literature various definitions for beach width exist, all of them the difference between the dunefoot position on the landward side, and a contour line on the seaward side. This can be the MHW (de Vriend and Roelvink, 1989), the MLW (Jeuken et al., 2001; Quartel et al., 2008), or the + 0 NAP contour line (Brière et al., 2008). Sometimes different definitions are analysed separately, e.g. the wet and the dry beach width (with respectively the MLW and MHW as seaward boundary) , (van Koningsveld and Lescinski, 2007; Roelse, 2002).

In this study the CL is used as the seaward boundary of the beach (BW = CL - DF), consistent with Ruessink and Jeuken (2002) and Verhagen (1989).

MKL

The MHW and MLW positions are very sensitive to temporary phenomena as for instance swash bars because of the shallow beach slope. To get better insight in the coastal state a procedure to extract a better coastal indicator from the JARKUS data was adopted in the Dutch coastline preservation policy of 1990: the momentary coastline position. This parameter is referred to in this report by its Dutch abbreviation (Momentane KustLijn). The MKL volume, per (longshore) linear metre (Figure 39), is bounded by (i) two horizontal planes at equal distances above and below the MLW datum plane (this distance being that from the level of the DF (+3 NAP) to the MLW plane), by (ii) the profile and by (iii) an arbitrary vertical reference line landward of the DF (and also landward enough not to be reached by future possible retreat of the DF position). Dividing the volume by its height gives the position of the coastline relative to the reference line (MKL position). In practice, it will be close to the MLW line, albeit showing less scatter over relatively short periods (weeks) (Hamm et al., 2002).

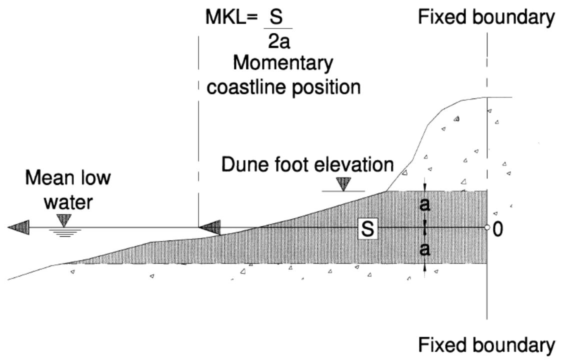

Figure 39. MKL definition, taken from Hamm et al. (2002)

DF_{MKL}

Analogous to the MKL position a volume based parameter for the dunefoot position is defined. The upper and lower boundaries for the calculation are 7 and 3 metres, respectively. Using the volume of sand instead of just a crossing of a plain make the parameter less sensitive to small insignificant disturbances, while the response to significant changes will be about the same as for the DF parameter.

CL_{MKL}

The CL_{MKL} calculation boundaries are 3 and -3 metres, respectively. On average this is very near to the CL position, but because of the wide area over which the position is calculated the indicator is insensitive to swash bars and less sensitive to near-shore bar movement than the CL.

BW_{MKL}

Analogous to the BW, this is the difference between the DF_{MKL} and CL_{MKL} positions.

DVC

The Dunefront Volume Change is defined as the volume difference of the first dune row in a JARKUS transect in two consecutive years. The seaside boundary of this zone is defined by the most seaward crossing of the +3 m NAP line, the landward boundary as 100 m landwards from the seaward crossing, consistent with Koster (2006)

Appendix C Storm erosion and measured aeolian transport rates

Many papers are found that try to measure the rates of aeolian deposition. As often only annual measurement data are used, the total deposition might be influenced by hydrodynamic forces. Hypothetically this might lead to a situation where an alongshore non-uniform erosion partially washes away an alongshore uniform deposition. If only the net rate of deposition is measured, this might lead to the false conclusion that the rate of deposition was alongshore non-uniform. As an example two papers are discussed.

C.1 Measurement and prediction of long-term sediment supply to coastal foredunes, Davidson-Arnott and Law (1996)

In this paper dune growth is evaluated on a spit in Lake Erie, Canada. Measured annual net deposition is compared to potential transport calculated by a simple transport formula based solely on wind speed and wind angle, integrated over an hourly wind dataset. Locally averaged aeolian deposition is found to be just a fraction (25-50%) of the potential yearly transport rate, with much higher local variations. The correlation with the beach width was found to be much greater:

"A comparison of measured sediment deposition with variations in beach width at the three sites suggests that beach width is a much better predictor of the spatial and temporal patterns of deposition than is potential transport due to wind alone. The highest deposition recorded at each of the sites is associated with the greatest beach width."

An explanation for this is found in the following:

"...it is evident that beach width influences the total volume of sediment transport into the foredune/embryo dune zone in three ways: 1) together with wind direction, it determines the source width and thus the instantaneous rate of sediment transport for a given wind speed; 2) together with the thickness of sediment above the beach water table, it determines the total volume of sediment available for transportation under a given set of conditions; and 3) it indirectly influences sediment transport through its effect on beach form and slope."

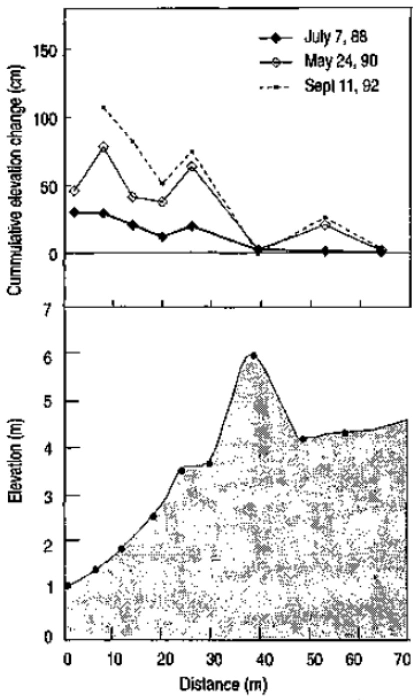

Figure 40. Measured cumulative depositon rates (above), and profile shape (below) for one of the profiles

Discussion

The influence of erosion is ignored in this work, while the relatively small increase of the dunes bordering the narrow beach might be because most of the aeolian deposited sand is simply washed away.

It is stated that extensive dune scarping occurred in the winter before the measuring campaign started, but there is no mention of it afterwards. Highest rates of deposition are measured at elevations of only 1-3 m above the lake level.

"Typical storm waves have a period of 3-5 seconds and a significant wave height of 1-2 m, while intense storms can produce waves with periods exceeding 6 seconds and significant wave heights over 2.5 m. [..] surges at the end of Long Point are on the order of 1-1.5 m."

Considering these surge levels and wave heights, it seems highly unlikely that there was *no* direct influence of hydrodynamic forces on the 'aeolian' deposition rates, but this is not looked into. The only mention of offshore is the following:

"Because of the extensive vegetation cover in the foredune and embryo dune zones, there is limited offshore transport of sediment back onto the beach in this part of the spit."

The authors interpretation of the observed variance in net deposition rates is that *aeolian* transport is very much dependant on the beach width. Another interpretation could be that erosion rates are significantly less at the wider beaches. Which conclusion is closer to the truth is not known, as only the net effect of the aeolian and hydrodynamic forces has been measured.

C.2 Beach-dune interactions in nourishment areas along the Dutch coast, van der Wal (2004)

In a study of the impact of beach nourishment on the development of coastal dunes along the Dutch coast, the JARKUS dataset (see appendix A.3) was used to derive volumetric changes associated with aeolian and hydrodynamic processes. Volumetric changes occurring on the selected sites were statistically related to the number of years following nourishment. A substantial part of nourished sand was observed to be blown to the foredunes:

"One year after nourishment, this amount increased significantly. At the same time, the supratidal beach was eroded more. In the second and third year after nourishment, the erosion of the higher parts of the nourishment decreased. In the foredune, dune toe erosion due to storm surges was usually negligible until the fourth year following beach nourishment. Thus, beach nourishment temporarily protected the adjacent foredunes from being eroded by periodic wave attack, and also temporarily enlarged the aeolian sand transport rate to the dunes."

Discussion

To draw conclusions for aeolian and hydrodynamic influences individually, a distinction between these influences must be made. As only yearly data are available, this is achieved by splitting the profiles into several zones (Figure 41).

For every year analyzed the landward limit of storm surge erosion is determined. All volume change landward of this zone (and landward of the nourishment), can only be caused by aeolian processes.

From year to year these zones are determined, and volume change is compared for nourished years and reference years. Significantly higher values of the accretion in this 'aeolian zone' is found for the first year after a nourishment compared to the reference situation. It is therefore concluded that a nourishment increases the aeolian transport in the year after the nourishment.

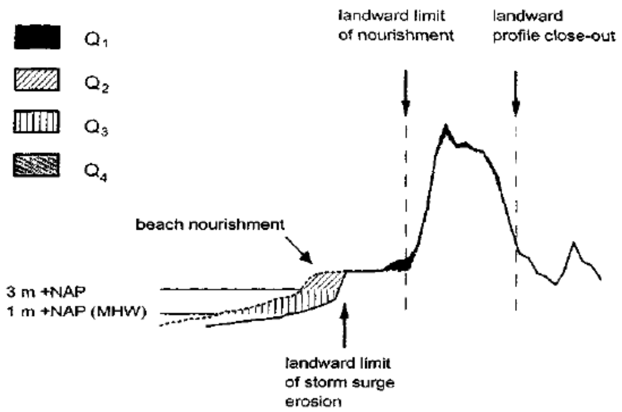

Figure 41. Distinction of profile in four different zones: Q_1 is the mean volumetric change of the zone above the 3 m level, landward of the limit of storm surge erosion, excluding direct nourishment. Volume gain in this zone is exclusively caused by aeolian processes. Adapted from van der Wal (2004).

There is something wrong with this reasoning, however, as the landward limit for erosion is significantly influenced by a nourishment. Where for the unnourished reference year the limit of storm surge erosion is often the dune foot, the limit for the nourished site is only somewhere halfway down the beach, as the nourishment protects the dune and upper beach from erosion. And as the area that typically receives the most aeolian deposition is the are directly in front of the dune foot, this introduces a significant bias. For a nourished site, accretion at the dune toe is included, but for an unnourished it is usually not.

A closer look at the paper learns that five out of the twelve sites examined have eroded in the year following the nourishment above the +3 m NAP level, between the landward limit of the nourishment and seaward of the limit of storm surge erosion. So only for these five sites the storm surge erosion may have been at or landward of the dunefoot position. These sites are also five of the six sites at which the lowest gain in aeolian transport is measured in the year following the nourishment. Three of these five sites have even accreted less in the first year after the nourishment than in their reference years.

While hydrodynamic forces have no direct influence the area landward of storm surge limit, the observed increase of accretion in the 'aeolian zone' in the year following a nourishment can be caused by an increased aeolian transport or a reduction of hydrodynamic erosion, or some combination of both. When only annual measurements are available, it seems impossible to correctly distinguish between the aeolian and hydrodynamic components.

Appendix D Dunefoot and coastline correlation found by Guillen

For the Holland coast, separately examined in four different zones, Guillen et al. (1999) found that the correlation between the position of the dunefoot in the profile and of the +1 m NAP is in the range 0.90-0.97. This implies that at a certain timescale the dunefoot closely mimics the coastline behaviour, and can thus be used for predictions of dune evolution.

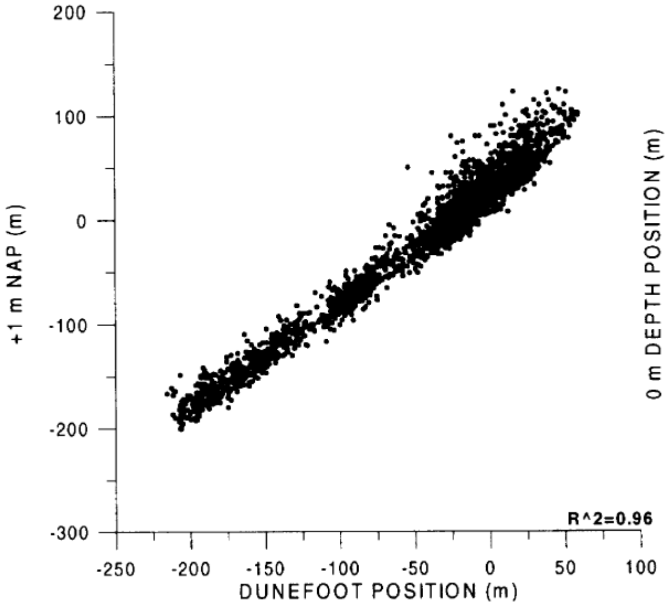

Figure 42. Relationships between dunefoot position and +1 m NAP for the Holland coast from 2600 (Hondsbossche Zeewering) to 5500 (IJmuiden), adapted from Guillen et al. (1999)

Closer examination, however, learns that all cross-shore locations in Figure 42 are plotted relative to the RSP line, which closely corresponds to the 1843 dunefoot line position. So even though only 28 years of data are examined, information of a much larger period is encapsulated in the coordinates, making it impossible to judge a timescale for the correlation found.

An example for clarification: Up to 28 points are plotted of every alongshore location (one point for every measurement from 1964 to 1992). All these points lie within a certain range with respect to the RSP baseline, which corresponds roughly to the 1843 coastline. If the coast (dunes and +1 NAP) at that specific location would have retreated 100 m in the period from 1843 to 1964, and be fairly stable for the period from 1964 to 1992, all points thus lie near each other in the plot. For an area that has accreted 100 meters the same applies. The correlation between the dunefoot and +1 NAP locations would have little correlation for each transect separately, but two condensed clouds of points spaced well apart in both x and y direction by definition have a very high correlation.

The established correlations are therefore hardly a measure for year to year correlations in dunefoot and +1 m depth contour positions. If anything, the established coefficients are a measure for the variance in net coastline movement in the period from 1843 to the analysed period (1964 to 1992), which has no useful application.

Appendix E Data visualization in GoogleEarth

The large amounts of data used for this report where visualized in the GoogleEarth™ software. Though no direct results of these visualizations are used, the visualization enabled an easy insight into the data, by linking the measured profiles directly with aerial photographs. Many apparent artefacts in measurement records could be understood by comparing them to their location.

In Figure 43 an example of JARKUS transects is presented, but also the Dutch Beach Line dataset has been prepared for viewing in GoogleEarth.

The visualizations where made by extracting data from the UCIT database and transforming them to *.kml (keyhole markup language) files using MATLAB™. The results of this effort are made publicly available in the OpenEarth project (See paragraph A.4)

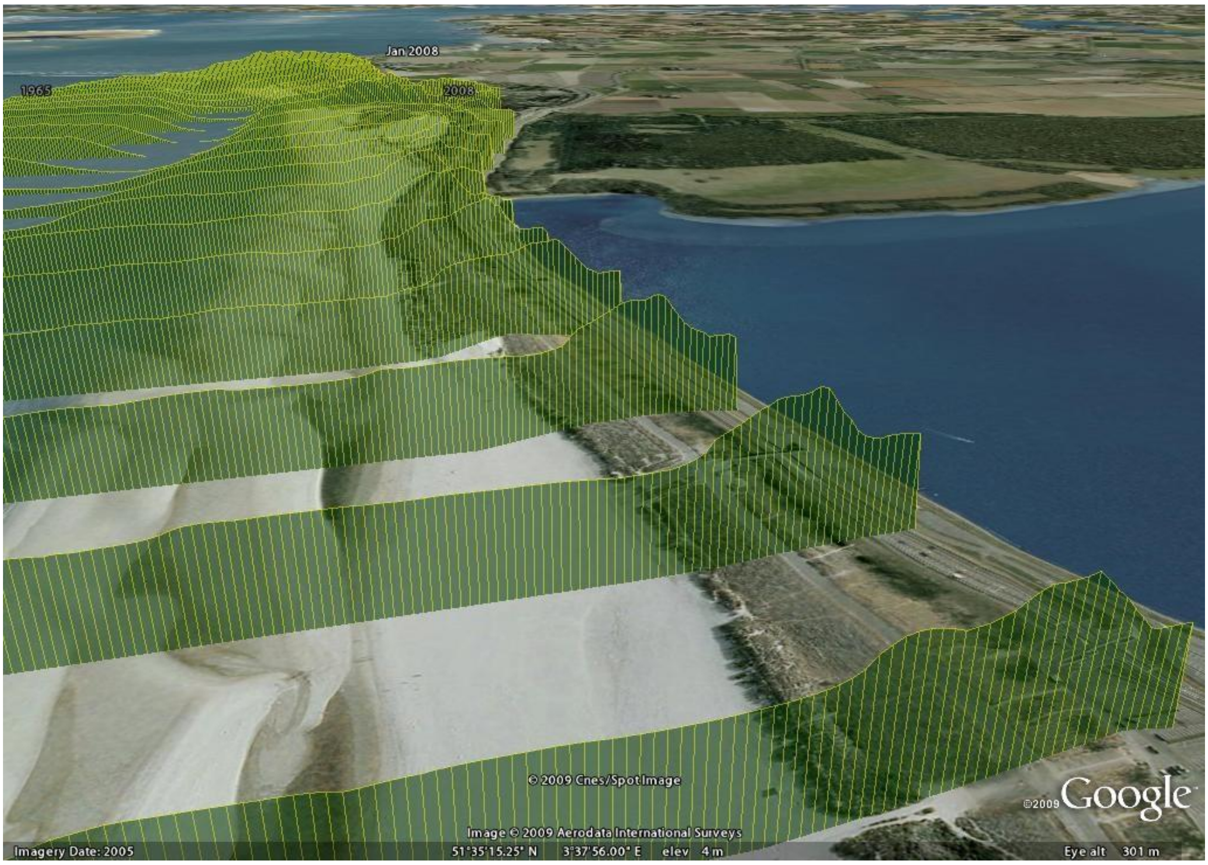

Figure 43. Example of JARKUS data visualized in GoogleEarth