AEOLIAN TRANSPORT OF NOURISHMENT SAND IN BEACH-DUNE ENVIRONMENTS

Daphne van der Wal

UBA003000240

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STELLINGEN

behorende bij het proefschrift
Aeolian transport of nourishment sand in beach-dune environments
door Daphne van der Wal
in het openbaar te verdedigen op 9 december 1999 te Amsterdam

1. Een niet-verwaarloosbaar deel van het zand van Nederlandse strandsuppleties verstuift.

2. De gemiddelde korrelgrootte van het zand van veel Nederlandse suppletiestranden is van ondergeschikt belang voor de stuifgevoeligheid van dat zand.

3. Onder andere door eolische aanvoer van sediment vanuit het intergetijdegebied leidt een schelpenvloer op het strand niet tot stopzetting van het eolisch sedimenttransport.

4. Er moet rekening mee worden gehouden dat strandsuppletie met schelphoudend zand de vegetatie van aangrenzende kalkarme duinen kan beïnvloeden.

5. Dat de invloed van vocht op het eolisch zandtransport complex is, blijkt uit de grote variatie in uitkomsten van empirisch onderzoek en van theoretisch afgeleide vergelijkingen over dit onderwerp.

6. Bij het beschrijven van het eolisch zandtransport over geaccidenteerd onbegroeid terrein mag het effect van topografie op turbulentie niet worden veronachtzaamd.

7. Het deterministisch zandtransport- en luchtstromingsmodel SAFE-HILL beschrijft de plaats van verandering door eolische processen in een strand-duinsysteem wel redelijk, maar de grootte van die verandering niet.

8. Leonard *et al.* menen ten onrechte dat de urgentie van suppletie ten behoeve van kustverdediging geheel is af te lezen aan de breedte van het strand.

   L.A. Leonard, K.L. Dixon & O.H. Pilkey (1990). A comparison of beach replenishment on the U.S. Atlantic, Pacific, and Gulf coasts. Journal of Coastal Research, Special Issue 6 (Artificial beaches), pp. 127-140.

9. De gangbare term 'borrow area' voor winlokatie van sediment suggereert veelal ten onrechte een teruggave van sediment aan dit gebied.

10. De uitdrukking 'naar de vaantjes' heeft tijdens het veldwerk voor dit onderzoek een extra dimensie gekregen.

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AEOLIAN TRANSPORT OF NOURISHMENT SAND IN BEACH-DUNE ENVIRONMENTS

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus prof.dr. J.J.M. Franse
ten overstaan van een door het college voor promoties ingestelde commissie
in het openbaar te verdedigen in de Aula der Universiteit

op donderdag 9 december 1999, te 10.00 uur

door Daphne van der Wal

geboren te Alkmaar

Promotor:
prof. dr. P.D. Jungerius

Co-promotor:
dr. ir. J.H. van Boxel

Aeolian transport of nourishment sand in beach-dune environments /
Verstuiving van suppletiezand / Daphne van der Wal
Thesis Universiteit van Amsterdam
With ref. / With summary in English and Dutch
ISBN 90-6787-053-6
NUGI 816
Subject headings: beach nourishment, aeolian sand transport, foredunes

This study was carried out in the Laboratory of Physical Geography and Soil Science (Nieuwe Prinsengracht 130, 1018 VZ Amsterdam, the Netherlands), Faculty of Social and Behavioural Sciences, University of Amsterdam, within the framework of the Netherlands Centre for Geo-ecological Research (ICG).

Parts of the research have been funded by the dr. ir. Cornelis Lely Stichting, by the National Institute for Coastal and Marine Management (RIKZ) and the Road and Hydraulic Engineering Division (RWS-DWW) of Rijkswaterstaat on behalf of the Technical Advisory Committee for Water Defences, and by the North Holland Directorate of Rijkswaterstaat.

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Caja van der Woude, Jean Melounou, Stéphane Rognon en Robert Colombo are acknowledged for grain-size and carbonate analysis of many samples. I also greatly appreciate the assistance of Caja during the first field work on Ameland. Eugene Farrell and Doug Sherman provided help and company during the second field work on Ameland.

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CHAPTER 1

INTRODUCTION

SCOPE

Beach nourishment is used worldwide as a method for restoring and maintaining coastal areas threatened by structural marine erosion. Beaches are nourished either for recreational use or as a means of protecting the coastline by absorbing wave energy and so counteracting further erosion of the original beach and dune and preventing damage to coastal property. Beach nourishment implies a direct supply of sand to the beach. In recent years the primary source of sand for beach nourishment has been offshore deposits. These are dredged from the seabed, transported to the beach, and either dumped or pumped into the littoral zone (Komar, 1998). The fill is redistributed over the coastal profile during the lifetime of the nourishment by ambient marine and aeolian processes. Most sand will eventually be lost from the considered coastal stretch, as the basic cause of erosion and the negative sand budget often continue to exist after nourishment. Periodic replenishment is, therefore, often necessary. Yet, beach nourishment is often preferred to coastal protection schemes that use hard structures, because so many of these have resulted in subsequent loss of the beach by reflection scour (National Research Council, 1995; Bird, 1996).

In the Netherlands, nourishment appears to be an effective and economical measure, to be carried out flexibly at places with highest urgency (Rijkswaterstaat, 1988; Davison *et al.*, 1992). More than 130 nourishment projects have been executed at about 50 coastal stretches (see Appendix). The coast has been nourished for various reasons, but the main reason was to safeguard the low-lying hinterland against flooding from the sea (Hillen & Roelse, 1995). A large part of the Dutch coastline consists of beaches bordered by shore-parallel foredunes of 10 to 20 m in height, which form the principal sea defence. More than half of this coastline is subject to erosion (De Ruig & Hillen, 1997).

Since the early fifties, weak dune areas were strengthened by artificial nourishment of type a, b and c in Fig. 1.1, to bring the dunes in line with the safety standard, as laid down under the Delta Act of 1953 (Deltacommissie, 1961). Since 1992, dunes along the Dutch coast all fulfil the safety

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The planned life span of nourishments varies between three and ten years. Especially at locations where short-term morphological effects are unpredictable, frequent small-sized nourishments are preferred to nourishments with a long life span (Hillen & Roelse, 1995). In general, the nourishment sand is derived from the nearshore zone of the North Sea, as near as possible to the location to be nourished, but with the proviso that the source area is located seawards of the contour line of 20 m of depth, or more than 20 km offshore (Rijkswaterstaat, 1988).

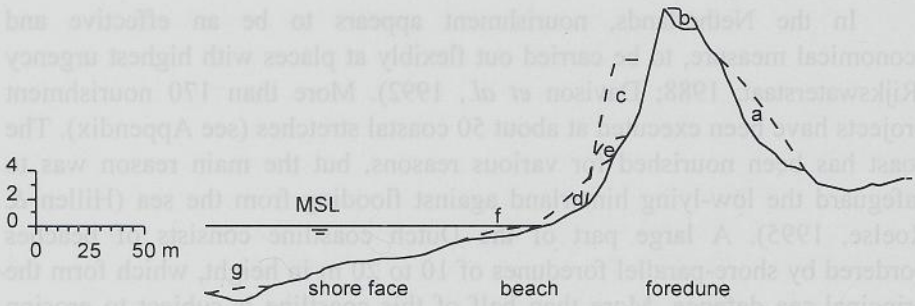

Figure 1.1. *Cross section with fill placing (a) at the landward side of the foredune, (b) on top of the foredune, (c) against the seaward front of the dunes, (d) on (the upper part of) the beach, often combined with (e) a high buffer ('banquet'), (f) on the foreshore, and (g) on the shore face.*

Various methods are used to win, transport and emplace the fill material. Usually, the sand is extracted by a dredge and transported to a discharge location in the vicinity of the beach to be nourished. Then, the material is brought ashore by a dredge and spread out over the beach (Van Oorschot & Van Raalte, 1991). Bulldozers and cranes are used to remodel the fill.

An understanding of coastal geomorphology is an essential background for planning beach nourishment, and indeed for any modification of the coastline (Bird, 1996). The behaviour of the fill has to be studied to evaluate the effectiveness of beach nourishment and to justify additional inputs of sediment to the coastal system (Psuty & Moreira, 1992). One aspect that has to be studied is the response of aeolian activity to nourishment. Part of the nourishment sand will be subject to aeolian processes, and will be trapped in the (fore)dunes, where it is stored to be available during storm events. The aeolian sediment exchange rate between the beach and dunes may, however, change after nourishment. Changes in the rate of aeolian sand transport after nourishment are likely to depend on several factors, such as the techniques that are used for nourishment, properties of the nourishment sand and nourishment design (Fig. 1.2). For example, the fill may differ in grain-size distribution from the native beach sand, resulting in a different erodibility of the surface (Draga, 1983; Nordstrom *et al.*, 1986; Olij, 1993; Van der Wal *et al.*, 1995). Depending on nourishment design, the beach may be widened by nourishment, altering the availability (source) of sand for onshore transport.

Beach nourishment has become a condition for the dynamic preservation policy in the Netherlands; when the safety is guaranteed by means of beach nourishment, there are opportunities to allow for natural dynamics, such as sand drift (Arens & Van der Wal, 1998). Sand drift is a steering factor controlling development and dynamics of vegetated coastal foredunes (Sarre, 1989b; Arens, 1994). In the Dutch foredunes, the dominant plant species is marram grass (*Ammophila arenaria*). The plants stabilize trapped wind-blown sand with their root system, and promote dune building by upward growth. The plants are stimulated when they are regularly buried by beach sand; they can escape from their harmful soil organisms by upward growth, avoiding damage of the roots (Van der Putten, 1989).

However, anomalous wind-borne sand transport may have adverse impacts. Too much deposition of sand leads to suffocation of plants. The composition of sand (*e.g.*, the mineral content) is also an important factor for vegetation; it largely explains the differences in plant species in the Dutch dunes (Rozema *et al.*, 1985). Since offshore dredged material may differ in composition from native beach sand, aeolian transport of this nourishment sand to the dunes can alter the characteristics of dune sand, and may subsequently affect vegetation. Apart from ecological impacts on vegetated foredunes, excessive sand-drift has other potentially adverse effects (Sherman & Nordstrom, 1994), *e.g.* on recreation, construction and drinking water abstraction, both on the beaches and dunes and on the (agricultural) hinterland. Anomalous wind-borne sand transport may also affect the efficiency of the nourishment.

AIMS AND OBJECTIVES

The aim of the study is to assess the impact of beach nourishment on aeolian sand transport and morphological development of the beach-dune system. The study focuses on the role of properties of the nourishment sand (*e.g.* grain-size distribution and shell content) and nourishment design parameters (*e.g.* beach width and shape of the nourishment) in:

(1) the erodibility of the surface,
(2) the availability of sand for aeolian sand transport, and
(3) the erosivity of the wind,

as is schematized in Fig. 1.2.

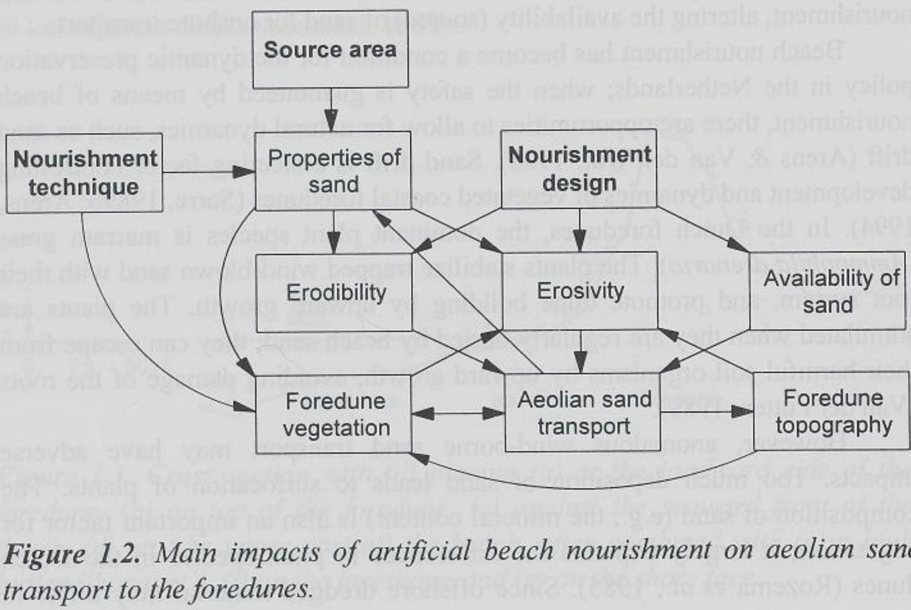

***Figure 1.2.** Main impacts of artificial beach nourishment on aeolian sand transport to the foredunes.*

APPROACH AND OUTLINE

The thesis has been compiled from a number of research papers dealing with wind-borne sand transport on beach nourishments along the Dutch North Sea coast. The text of some of the submitted and published papers has been slightly adapted to avoid overlap in this thesis.

In Chapter 2, the DONAR data base of Rijkswaterstaat, which comprises annual profile measurements of the coast, is used to assess the impact of beach nourishment on the development of the supratidal beach and dune. The study is conducted on several nourishment sites on a time scale of years.

In Chapter 3, wind tunnel experiments are presented. The study aims to asses the impact of the properties of the fill on aeolian sand transport. The grain-size distributions of samples collected at nourishment sites and nearby control sites are related to the erodibility of the surface, as determined in a wind tunnel.

Chapters 4 and 5 deal with field measurements. The measurements were carried out on two beaches, referred to as the Ameland site (located at 53°28'N, 5°43'E) and the Den Helder site (located at 52°55'N, 4°43'E). Aeolian sand transport, and factors that affect sand transport, such as wind conditions, beach width and sediment characteristics were measured in the field in the spring of 1996 for one month at each site. The two beaches were nourished in the summer of 1996. Then, in the autumn of 1996, the field measurements were repeated. The study focuses on the measurements on the nourished beaches, but data collected before and after nourishment are also compared. Deposition of nourishment sand was determined by mapping the colours of native and nourishment wind-blown sand (in the spring of 1998). In Chapter 4, the grain-size-selective processes of the fill material, and their effects on vegetated foredunes are elucidated for the Ameland site. Chapter 5 shows how the aeolian sand transport is affected by the fetch of wind over beach sand, a factor that is altered by nourishment due to enlargement of the beach.

Chapter 6 presents a model application. The development of the two sites was monitored by measuring topography and vegetation half-yearly between the spring of 1996 and the autumn of 1998. These data were the main input for the SAFE-HILL model system developed by Van Dijk *et al.* (1999) and Van Boxel *et al.* (1999). The models were applied to evaluate the impact of the properties of the fill and nourishment design.

Chapter 7 is a synthesis of the studied aspects of aeolian activity on beach nourishments and contains recommendations to optimize nourishment measures from a geomorphological and ecological point of view, and recommendations for further research. Finally, a summary of the thesis is presented.

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CHAPTER 2

BEACH-DUNE INTERACTIONS IN NOURISHMENT AREAS ALONG THE DUTCH COAST

ABSTRACT

The impact of beach nourishment on the development of coastal dunes has been studied. A database of annual cross-shore profiles of the Dutch North Sea coast over a period of 15 years has been analysed. The database has been used to derive volumetric changes associated with aeolian and hydrodynamic processes. The changes were statistically related to the number of years following nourishment. By considering nourishments that were carried out arbitrary within the time-span used for analysis, it was possible to study the mere effect of nourishment on foredune development. There is an overall negative sand budget of the supratidal zone of the nourishment sites, which does not significantly change after nourishment. A substantial part of the sand is 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, changes seawards of the limit of storm surge erosion were usually negligible until the fourth year following beach nourishment. Beach nourishment thus temporarily protects the adjacent foredunes from being eroded by periodic wave attack, and temporarily enlarges the aeolian sand transport rate to the dunes.

KEY WORDS

Beach nourishment, sediment budget, aeolian sand transport, marine sand transport, supratidal beach, foredune, the Netherlands.

Paper by D. van der Wal

submitted to ***Journal of Coastal Research***

INTRODUCTION

Beach nourishment is the artificial supply of sediment to a coast. It aims to counteract marine erosion or to provide a wide beach for recreational uses (Davison *et al.*, 1992). The behaviour of the fill must be studied to evaluate the effectiveness of beach nourishment and to justify additional inputs of sediment to the coastal system (Psuty & Moreira, 1992). One aspect to be studied is the impact of beach nourishment on the development of coastal foredunes.

Dune building is governed by aeolian and hydrodynamic processes, which are subject to complex feedback mechanisms. Artificial beach nourishment interferes with these processes. Nourishments are planned to be reworked by waves and currents (Draga, 1983). The enlarged beach diminishes the frequency of dune toe erosion by waves, and, therefore, promotes dune growth (Nordstrom *et al.*, 1986). The effect is often temporary. The basic cause of erosion and the inherent negative sediment budget may continue to exist after nourishment, and most sediment will eventually be lost from the coastal zone of the considered coastal stretch by hydrodynamic processes.

A part of the nourishment sand is subject to aeolian processes (Draga, 1983; Nordstrom *et al.*, 1986; Erchinger & Knaack, 1995; Van der Wal, 1998b). In many locations, aeolian processes produce a net input of sand into the dunes. Sand transported onshore is trapped at the dune toe by sand fences (Philips & Willetts, 1978; Nordstrom & McCluskey, 1985) or in the foredunes by vegetation (Hesp, 1989; Sarre, 1989b; Carter & Wilson, 1990; Arens & Wiersma, 1994). Dune scarping by periodic wave attack causes sand transport back to the beach (Van de Graaff, 1977; Nickling & Davidson-Arnott, 1990), after which the foredune is restored (Thom & Hall, 1991; Tsoar & Blumberg, 1991; Morton *et al.*, 1994). The rate of sediment exchange between the beach and the dunes due to aeolian processes may be altered after nourishment. Such a change depends on fill placing, size and form of the nourishment, characteristics of the fill material, and on the techniques that are used for nourishment (Van der Wal, 1999c; Chapter 6), and changes may vary with time after nourishment.

This paper aims to assess the impact of beach nourishment on the development of the beach-dune system. A number of beach nourishment sites along the Dutch North Sea coast was selected. The annual volumetric changes of the beach and dunes were calculated separately by analysing sequential cross-shore profiles over a period of 15 years. The changes were statistically related to the number of successive years after nourishment.

METHODS

DATA COLLECTION

Since 1963, annual elevation measurements of the entire Dutch coast have been performed by the Dutch Ministry of Transport and Public Works (De Ruig & Louise, 1991), providing a valuable database for coastal research. They include measurements in a fixed framework of cross-shore sections of about 1 km in length with a section interval of 200 m to 250 m, and records of elevation along the sections at every 5 m. The measurements consist of two types of data: data of the supratidal beach and dunes and data of the intertidal beach and shoreface. As this paper focuses on supratidal processes, the former data have been used for this study. They are derived from the photogrammetric analysis of aerial photographs, taken during periods with suitable weather conditions between April and October. The height measurements are related to the fixed Dutch Ordnance Datum (DOD), which is about mean sea level. The accuracy (standard deviation) of the height measurements is about 0.1 m (Veugen, 1984). This error is reduced by removing accidental and systematic errors from the data set. A visual validation was performed on the selected data set by plotting all profiles of a section and eliminating the profiles that contained unreliable data.

DATA SELECTION

Coastal stretches that were first nourished before 1995 were selected. A number of these sites were discarded:

(1) sites with (additional) dune front and dune nourishments (but beach nourishments accomplished with a banquet or a small dune front nourishment were not discarded),

(2) sites with beaches bordered by hard structures, such as boulevards or dikes, and

(3) sites that were near cross-shore structures, such as harbour moles.

After discarding these sites, 12 sites remained for analysis (Fig. 2.1), some of which have been nourished more than once. Table 2.1 lists the specifications of the nourishments carried out at these sites. Cross-shore sections have been selected within each of the 12 sites. The sections that were close to the borders of the nourishment (*i.e.* within about 200 m) and the sections of dune areas that were disturbed (*e.g.* by the presence of beach entrances) were discarded.

Table 2.1. *Specifications of the nourishments taken into account in this study. The main fill placing is indicated, with f is foreshore, b is beach, bq is banquet, and df is dune front (see Fig. 1.1). Sources are Rijkswaterstaat (1988), Roelse (1996) and unpublished data of Rijkswaterstaat. See Appendix for more information on these nourishments.*

Site		Year	Volume ($\times 10^6$ m^3)	Length alongshore (km)	Type
1	Texel, Eierland	1979	3.05	4.8	b, bq
		1985	2.85	5.0	b, bq
		1990	2.54	5.2	b, bq
2	Texel, De Koog	1984	3.02	6.0	b, bq
		1991	2.00	5.1	b, bq
3	Texel, Zuidwest Texel	1993-1994	2.26	8.6	b
4	North Holland, Den Helder	1992-1993	0.89	6.5	b
5	North Holland, Callantsoog	1986	1.32	2.9	b, bq
		1991	0.54	3.0	b, bq
6	North Holland, Zwanenwater	1987	1.92	4.3	b, bq
7	North Holland, Petten	1991	0.37	2.2	b
		1995	0.67	3.0	b
8	North Holland, Hargen	1992	1.47	12.3	b, bq
9	Rijnland, Meijendel	1994	0.70	2.0	b
10	Goeree, Kop van Goeree	1984-1985	0.86	3.0	b
11	Schouwen, Kop van Schouwen	1987	1.83	1.7	f, b
12	Walcheren, Domburg	1986	0.23	0.8	b, df
		1989	0.21	1.1	b, df
		1990	0.41	2.7	b, df
		1992	0.64	4.7	b, bq, df
		1993	0.32	1.6	b
		1994	0.45	1.5	b
		1995	0.55	2.0	b

The study comprises a period of 15 years, from 1981 up to 1996. However, for a number of sites, a limited time series has been used. Data up to 1994 were used for Eierland, due to the construction of a dam in 1994. Kop van Schouwen was studied up to 1991, due to a large dune front nourishment carried out in 1991. At three sites in North Holland (*viz.* Callantsoog,

Figure 2.1. *The study sites along the Dutch North Sea coast.*

Zwanenwater and Petten) data up to 1987 of a number of sections are discarded, because these sections were shifted in 1987. The remaining data set is comprised of 8 to 34 cross-shore sections per site, yielding a total of 2861 profiles.

SAND BUDGET CALCULATION

The profile data are analysed by comparing the heights of a section for two successive years to determine changes over the intervening time. The area between the two profiles represents the volumetric change per unit of shoreline length during that period. Profile data that showed reshaping of the dune area by earth-moving equipment were used for comparison with the subsequent profile, but not with the previous profile in time.

Annual volumetric changes of the supratidal beach and dune caused by hydrodynamic processes, aeolian processes and nourishment have been distinguished separately, by defining several (system) boundaries, which are illustrated in Fig. 2.2. The seaward boundary of a profile is the point at which it intersects the level of 1 m +DOD, which approaches the high water level at most places. The sand of most beach nourishments was partly deposited below the high water level. A level of 3 m +DOD is chosen to separate the beach and the dunes. These definitions are in accordance with sediment budget studies of the Dutch coast of, among others, Van Vessem & Stolk

(1990), Wijnberg & Terwindt (1995), Roelse (1996) and Van Rijn (1997). However, many fills exceeded the 3 m +DOD level. Therefore, the two compartments have been termed 'zone above 3 m +DOD', comprising the

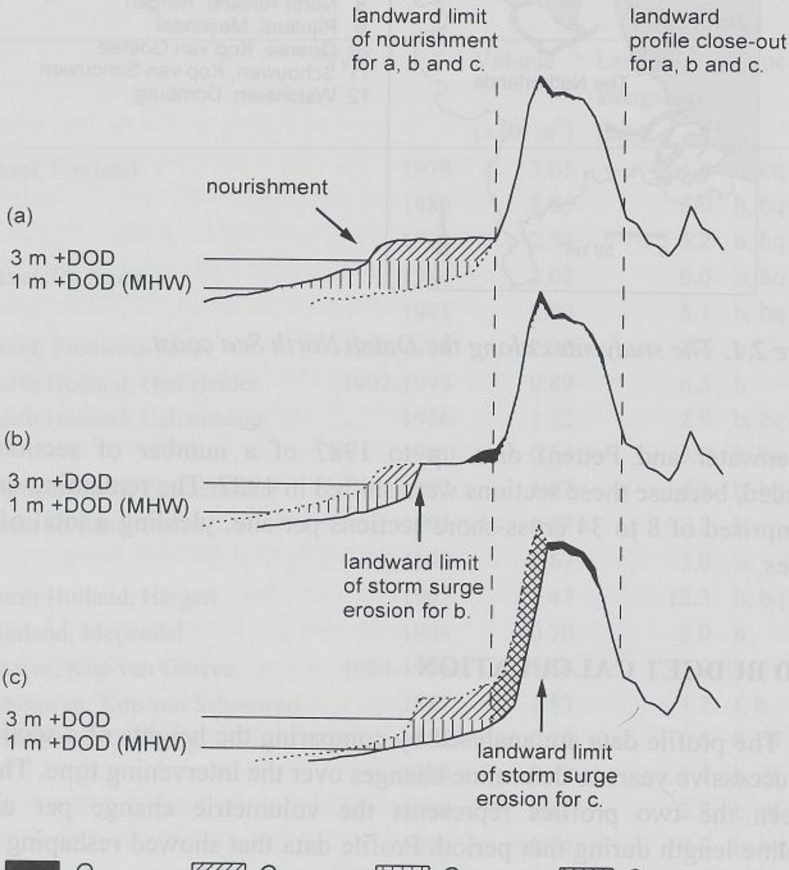

Figure 2.2. *Calculation of volumetric changes. Subsequent examples show (a) nourishment, (b) net erosion of this nourishment and (c) net erosion of both the nourishment and the foredune, with aeolian deposition in all examples.* Q_1 *is the mean volumetric change of the zone above 3 m +DOD, landward of the limit of storm surge erosion, excluding direct nourishment.* Q_2 *is the mean volumetric change above the 3 m +DOD level and seaward of the limit of storm surge erosion.* Q_3 *is the mean volumetric change between the 1 and 3 m +DOD level.* Q_4 *is the mean volumetric change above the 3 m +DOD level, landward of the nourishment and seaward of the limit of storm surge erosion. Note that* Q_4 *is part of* Q_2.

(fore)dune and the higher parts of the nourishment, and 'zone between 1 and 3 m +DOD', comprising the supratidal beach, respectively. The landward boundary of a section is the point of profile close-out; beyond this point volumetric changes are negligible, *i.e.* they can not be measured. Usually, this point is situated between the foredune crest and the landward toe of the foredune. In addition, the limit of storm surge erosion (resulting in a cliff) is determined by visual comparison of every subsequent profile. Finally, the apparent limit of nourishment is determined; this limit is fixed after nourishment, until the next nourishment is carried out.

Volumetric changes have been calculated from several compartments. An attempt has been made to separate aeolian and hydrodynamic sediment transport. However, most parts of the supratidal coast develop by the combination of the waves and the wind. Only in one compartment, changes are entirely due to aeolian processes. This is Q_1, which includes the profile changes above the 3 m +DOD level, landward of the limit of storm surge erosion, but excluding changes due to direct nourishment (Fig. 2.2). Profile changes in dune valleys (*i.e.* areas below the 3 m +DOD level that are situated in between the landward system boundary and the foredune crest) are included in Q_1. Other volumetric changes in the zone above 3 m +DOD (*i.e.*, nourishment or the changes that take place seawards of the limit of storm surge erosion due to hydrodynamic and aeolian sediment transport and mass movement) are calculated separately (Q_2). The volumetric changes of the supratidal beach (Q_3) are comprised of the profile changes between the 1 and 3 m +DOD level, but seaward of the foredune crest. The changes in this zone can be due to beach nourishment as well as due to hydrodynamic and aeolian sediment transport.

Q_2 includes changes in the volume of the nourishment, where the fill exceeds the 3 m +DOD level, and is therefore not a good measure to study the development of the foredune. Therefore, an additional measure, Q_4, was calculated. This is the volumetric change above the 3 m +DOD level resulting from sediment transport that takes place landward of the limit of nourishment (*i.e.*, in the foredune), but seaward of the limit of storm surge erosion (cliff).

STATISTICAL ANALYSIS

The annual volumetric changes were related to nourishment events. The change from a profile established two years before nourishment and a profile established prior to nourishment was assigned -1 years after nourishment, the change from profiles without and with nourishment was assigned 0 years, and so on, up until 3 years after nourishment. All other data were assigned 'control'. Thus, this group, which is assumed to represent a control situation, includes both changes more than one year before nourishment and changes more than three years after nourishment. Mean values of the annual volumetric changes were calculated for every site, averaging Q_1, Q_2 and Q_3, respectively, of all profiles for -1 to 3 years after nourishment and for the control years. For Q_4, this calculation was performed for 0 to ≥4 years after nourishment. In this case ≥4 years after nourishment was reserved for 4 or more years after nourishment, thus excluding years before a nourishment event.

A non-parametric statistical test, the two-tailed Wilcoxon matched-pairs signed-rank test (Burt & Barber, 1996), was performed to test whether the differences in volumetric changes were related to the number of years following nourishment, applying a level of significance $\alpha=0.05$. The hypothesis that two variables (for instance, Q_1 at $t=0$ and Q_1 at $t=1$) have the same distribution is tested, regardless of the shape of these distributions. The test gives more weight to pairs (*i.e.*, values from the same sites) that show large differences than to pairs that show small differences.

The volumetric changes are not merely caused by effects of beach nourishment. Other factors, such as meteorological and hydraulic factors and local conditions also infer variations in sediment transport, and therefore in volumetric changes. The impact of other factors than beach nourishment was excluded by ensuring that nourishment occurred arbitrary within the time-series used for analysis.

RESULTS

Fig. 2.3 shows the volumetric changes for control years, illustrating the natural temporal fluctuations and spatial variation in sediment transport. In control years, the mean changes due to aeolian processes (Q_1) are all positive, indicating deposition, and range from 3.32 (Domburg) to 16.78 $m^3m^{-1}y^{-1}$ (Kop van Schouwen), with 9.05 $m^3m^{-1}y^{-1}$, on average. These values illustrate the variations between sites. The associated standard deviations (*i.e.*, the standard deviations per site of the changes of all profiles in control years) of the aeolian sand transport rate range from 4.16 (Callantsoog) to 14.25 $m^3m^{-1}y^{-1}$ (Eierland), illustrating the temporal and spatial variation within sites.

Table 2.2 lists the mean volumetric changes due to aeolian processes (Q_1), sorted by time after nourishment. Paired tests were performed on these data, in order to address the variation within sites, rather than between sites.

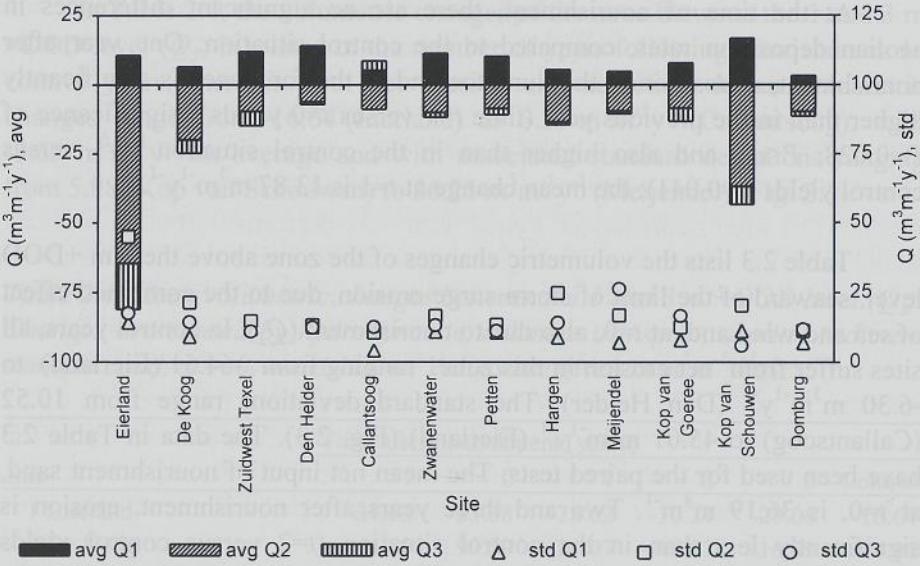

Figure 2.3. *Mean volumetric changes (avg) of Q_1, Q_2, and Q_3 with standard deviations (std) of all sites in control years.*

Table 2.2. *Mean volumetric changes above the 3 m +DOD level and landward of the limit of storm surge erosion (Q_1). Changes are due to aeolian processes. Changes due to nourishment, at t=0, are excluded. Values are given in $m^3 m^{-1} y^{-1}$.*

	Time after nourishment (years)					
Site	-1	0	1	2	3	Control
1 Eierland	12.34	14.03	18.43	10.86	12.36	10.70
2 De Koog	6.76	13.63	16.22	14.65	18.06	6.61
3 Zuidwest Texel	1.11	6.59	22.95	8.84	—	12.06
4 Den Helder	17.87	2.43	18.41	16.02	4.82	14.12
5 Callantsoog	6.18	6.61	15.02	12.86	6.45	5.16
6 Zwanenwater	9.58	3.64	23.93	8.59	4.08	11.36
7 Petten	2.26	2.62	8.03	4.27	—	10.26
8 Hargen	3.08	11.13	3.84	4.78	4.18	5.48
9 Meijendel		2.99	13.42	—		4.86
10 Kop van Goeree	11.22	12.13	6.96	12.97	5.13	7.93
11 Kop van Schouwen	5.68	6.70	17.87	14.08	13.68	16.78
12 Domburg	1.59	2.68	1.39	3.86	—	3.32

At the time of nourishment, there are no significant differences in aeolian deposition rates, compared to the control situation. One year after nourishment, deposition at the dune toe and in the foredunes is significantly higher than in the previous year (time t=1 versus t=0 yields a significance of P=0.028; $P<\alpha$), and also higher than in the control situation (t=1 versus control yields P=0.041); the mean change at t=1 is 13.87 $m^3m^{-1}y^{-1}$.

Table 2.3 lists the volumetric changes of the zone above the 3 m +DOD level, seaward of the limit of storm surge erosion, due to the combined effect of sea and wind and, at t=0, also due to nourishment (Q_2). In control years, all sites suffer from net erosion in this zone, ranging from -64.51 (Eierland) to -6.30 $m^3m^{-1}y^{-1}$ (Den Helder). The standard deviations range from 10.52 (Callantsoog) to 45.01 $m^3m^{-1}y^{-1}$ (Eierland) (Fig. 2.3). The data in Table 2.3 have been used for the paired tests. The mean net input of nourishment sand, at t=0, is 36.19 m^3m^{-1}. Two and three years after nourishment, erosion is significantly less than in the control situation (t=2 versus control yields P=0.041 and t=3 versus control yields P=0.050, respectively), with mean changes of -9.78 at t=2 and -8.89 $m^3m^{-1}y^{-1}$ at t=3, respectively.

Table 2.3. *Mean volumetric changes above the 3 m +DOD level and seaward of the limit of storm surge erosion (Q_2). Changes are caused by hydrodynamic and aeolian processes, and, at time t=0, nourishment. Values are given in* $m^3m^{-1}y^{-1}$.

	Time after nourishment (years)					
Site	-1	0	1	2	3	Control
1 Eierland	-74.30	61.71	-18.33	-26.78	-24.69	-64.51
2 De Koog	-6.71	80.07	-21.99	-7.95	-6.88	-19.98
3 Zuidwest Texel	-35.29	72.57	-6.90	-0.02	—	-9.65
4 Den Helder	-17.97	7.81	-1.83	-0.25	-0.55	-6.30
5 Callantsoog	-1.66	19.68	-6.18	-6.64	-16.47	-9.06
6 Zwanenwater	-4.48	38.26	-14.00	-23.65	-1.34	-10.12
7 Petten	-2.05	12.82	-13.19	-8.88	—	-8.69
8 Hargen	-20.84	8.51	-14.45	-11.71	-5.75	-13.53
9 Meijendel	—	31.02	0.14	—	—	-9.54
10 Kop van Goeree	-5.62	17.80	-3.85	-1.35	-10.48	-8.56
11 Kop van Schouwen	-40.72	24.57	-4.71	-13.53	-4.93	-37.06
12 Domburg	-15.17	59.44	-23.78	-6.84	—	-9.78

In Table 2.4, the volumetric changes of the zone between the 1 and 3 m +DOD level (Q_3) is related to the number of years following nourishment. In control years, there is both net erosion and accretion. Mean volumetric changes range from -16.64 (Eierland) to 3.51 $m^3m^{-1}y^{-1}$ (Callantsoog), with -3.65 $m^3m^{-1}y^{-1}$ on average and with associated standard deviations ranging from 5.98 (Kop van Schouwen) to 26.25 $m^3m^{-1}y^{-1}$ (Meijendel) (Fig. 2.3).

Table 2.4. *Mean volumetric changes between the 1 and 3 m +DOD level (Q_3). Changes are caused by hydrodynamic sediment transport, aeolian sediment transport and, at t=0, nourishment. Values are given in $m^3m^{-1}y^{-1}$.*

	Time after nourishment (years)					
Site	-1	0	1	2	3	Control
1 Eierland	-31.62	83.38	-28.02	-30.21	-29.06	-16.64
2 De Koog	-4.69	99.59	-21.07	-19.67	-16.59	-4.98
3 Zuidwest Texel	-10.49	91.33	-22.08	10.63	—	-5.32
4 Den Helder	-1.88	38.94	-16.58	-1.30	-4.19	-0.98
5 Callantsoog	-6.41	21.70	-18.33	-7.53	-13.45	3.51
6 Zwanenwater	-9.25	40.42	0.66	-18.62	2.58	-1.70
7 Petten	-4.62	30.84	-14.30	-3.52	—	-2.28
8 Hargen	-3.49	15.14	-10.53	2.28	-4.12	-1.11
9 Meijendel	—	59.95	-6.24	—	—	-1.18
10 Kop van Goeree	-7.31	29.35	-18.91	-5.57	-17.34	-4.86
11 Kop van Schouwen	-5.84	73.81	-8.76	-8.19	-25.99	-6.50
12 Domburg	-1.74	29.23	-12.21	-4.76	—	-1.79

The data in Table 2.4 are also used for the paired tests. Nourishment is most apparent; the mean net input of nourishment sand to the beach at t=0 is 51.14 m^3m^{-1}. A year before nourishment, there is significantly more erosion than in control years (t=-1 versus control yields P=0.016); the mean change at t=-1 is -7.94 $m^3m^{-1}y^{-1}$. The year after nourishment, there is also significantly more erosion than in control years (t=1 versus control yields P=0.004); the mean change at t=1 is -14.70 $m^3m^{-1}y^{-1}$. The erosion three years after nourishment is also more severe than in control years (t=3 versus control yields P=0.036); the mean change at t=3 equals -13.52 $m^3m^{-1}y^{-1}$.

The sum of Q_1, Q_2 and Q_3 represents the changes of the entire supratidal coast. In all years but the year of nourishment, there is a negative sand budget, which does not significantly change after nourishment. In control years, the mean change is -11.83 $m^3m^{-1}y^{-1}$. In the year of nourishment (t=0), the mean net input of sand is 94.43 m^3m^{-1}.

Table 2.5 presents the mean volumetric changes of the foredune, landward of the nourishment zone, but seaward of the limit of storm surge erosion (Q_4), after nourishment. Paired tests were performed in order to focus on the variation within sites. The results show that the erosion of the foredune (Q_4) is only a fraction of the erosion of the zone above the 3 m +DOD level (Q_2 in Table 2.3); the mean value of Q_4 is -1.33 $m^3m^{-1}y^{-1}$. At two sites with relatively small beach nourishments (*viz.* Hargen and Petten), erosion of the foredune is substantial. In the year of nourishment (t=0), the foredune could have been eroded either prior to nourishment and after nourishment. From the fourth year following nourishment onwards, erosion of the foredune increases, illustrating the buffering function of nourishment; the volumetric change at $t \geq 4$ differs significantly from the change at t=0 (t=0 versus control yields P=0.043), t=1 (t=1 versus control yields P=0.046) and t=2 (t=2 versus control yields P=0.043), respectively. However, even at $t \geq 4$ the mean change is only -4.02 $m^3m^{-1}y^{-1}$.

Table 2.5. *Mean volumetric changes above the 3 m +DOD level, landward of the nourishment and seaward of the limit of storm surge erosion (Q_4). Values are given in $m^3m^{-1}y^{-1}$.*

	Time after nourishment (years)				
Site	0	1	2	3	≥4
1 Eierland	-2.25	0.00	0.00	-0.73	-5.97
2 De Koog	-0.31	-0.22	0.00	0.00	-4.72
3 Zuidwest Texel	0.00	0.00	0.00	—	—
4 Den Helder	0.00	0.00	0.00	0.00	—
5 Callantsoog	0.00	-0.02	0.00	-0.58	0.00
6 Zwanenwater	0.00	0.00	0.00	0.00	-0.24
7 Petten	-0.63	-3.01	-3.43	-1.78	—
8 Hargen	0.00	-5.88	-9.69	-4.77	—
9 Meijendel	-1.71	0.00		—	—
10 Kop van Goeree	0.00	0.00	0.00	0.00	-3.98
11 Kop van Schouwen	-6.45	0.00	0.00	0.00	—
12 Domburg	-0.34	-0.93	-1.10	0.00	-9.21

DISCUSSION

The effects of beach nourishment on the sediment budget of the beach-dune system were established by considering a group of nourishment sites. Evaluating a group of nourishments rather than individual nourishments offers possibilities, but has also limitations. Many factors that determine the development of the coastal system have to be disentangled to evaluate an individual beach nourishment project (Hansen & Byrnes, 1991). Autonomous coastal behaviour is different at each site. In addition, year-to-year variability in the sand volume caused by variations in meteorological and hydrodynamic conditions is apparent (Van Vessem & Stolk, 1990; De Ruig & Louisse, 1991; Psuty & Namikas, 1991). Any effect of beach nourishment on the development of the beach-dune system is superimposed on this variability. By considering nourishments that were carried out arbitrary within the time-span used for analysis, it was possible to study the mere effect of nourishment. The response of sediment transport to beach nourishment may not be the same for each nourishment, as beach nourishments differ in design and fill characteristics. Especially the aeolian sand transport may increase or decrease after beach nourishment, depending on, for instance, the susceptibility of the sand to wind erosion (Van der Wal, 1998b; Chapter 3). The present method merely allows for an evaluation of overall effects of nourishment.

The rate of aeolian sand transport increased one year after the fill is placed. Van der Wal *et al.* (1995) came to the same conclusion for another set of nourishments. They found no explanation for this effect in the susceptibility of the sand to wind erosion, indicating the importance of other factors. Such factors may be related to the input of sediment by nourishment that widens the beach. An enlarged beach increases the source of sediment for onshore winds, resulting in an overall increase of the aeolian sediment flux (*e.g.*, Davidson-Arnott & Law, 1990; Van der Wal, 1998a; Chapter 5). The raised beach may also be more susceptible to wind erosion as its moisture content is lower and, therefore, more favourable for aeolian sand transport (Draga, 1983). Aeolian sand transport (Q_1) increased one year after beach nourishment; no change was found in the year of nourishment. In the year of nourishment, aeolian sand transport within the nourished area, including the accumulation of sand at the dune toe, was assigned to Q_2, and did not contribute to Q_1, resulting in an underestimation of Q_1. Any change in the rate of aeolian sand transport directly after nourishment could, therefore, not be established properly. Apart from this, the timing of nourishment and the timing of profile measurements may be of importance here. However, beach nourishments have usually already been exposed to aeolian processes for almost a year at t=0, and they experienced the storms of autumn and spring.

The supratidal beach provides a source of sediment for inland aeolian transfer, suggesting that the increase in beach erosion (Q_3) is related to the increase in sand blown to the foredunes (Q_1), one year after nourishment. However, this relation can not be proven by the present method.

The sediment budget of the considered beach-dune environment is not closed. As is illustrated for other locations, sediment input and output includes longshore sediment transport (*e.g.* Clayton, 1980; Psuty, 1993; Nordstrom *et al.*, 1986) and cross-shore sediment transport exchange with the intertidal beach and upper shoreface (*e.g.* Eitner & Ragutzki, 1994; Eleveld, 1999). In addition, substantial part of the fill is often deposited on the intertidal beach and upper shoreface. The present study shows a negative sediment budget for the entire supratidal coast, for all years but the year of nourishment. Part of this net sediment output is related to hydrodynamic processes. After nourishment, these processes rework the fill. The constructed nourishment profile is, for technical reasons, often too steep to be in balance with the processes acting on it (De Ruig & Hillen, 1997). Marine sediment transport reshapes the beach to adjust it more closely to the prevailing wave and current regimes, leading to initial losses of sediment in the active zone (Psuty & Namikas, 1991; Verhagen, 1996; Roelse, 1996). This is followed by a more gradual depletion (Stive *et al.*, 1991), although the rates depend on, for instance, storm activity (Leonard *et al.*, 1990). The present method does not allow for an assessment of the initial losses from the supratidal part of the coast. The study does show that there is no increased erosion of the entire supratidal zone after nourishment.

Beach nourishments prevent the dunes from being eroded by periodic wave attack. The present study shows a decrease of erosion of especially the higher parts of the nourishment (Q_2), as compared to the erosion of the dune in the control situation, in the second and third year after nourishment. The foredune zone between the limit of nourishment and storm surge erosion (Q_4), in which hydrodynamic processes play an important role, changed on average only -1.33 $m^3m^{-1}y^{-1}$ after nourishment. From the fourth year following nourishment onwards, the erosion of the foredune increased, as the nourishment buffer is weakened.

The present study shows that the rate of aeolian sand transport is substantial. The overall aeolian deposition to the dune toe and foredunes is about 9 $m^3m^{-1}y^{-1}$ ($\sim 14 \times 10^3$ kg m^{-1} y^{-1}), augmenting to about 14 $m^3m^{-1}y^{-1}$

($\sim 22 \times 10^3$ kg m^{-1} y^{-1}) one year after nourishment. A part of this deposited sand is subsequently returned to the beach during storm surges. Several long-term (on a time-scale of decades) sediment budget studies of the Dutch coast report the net effect of aeolian sediment transport and storm surge erosion. De Ruig & Louisse (1991) reported an average sand gain of the zone above 0 m +DOD of 3 to 3.5 $m^3 m^{-1} y^{-1}$ for the central Dutch coast (including the sites in North Holland and Rijnland), amounting to 10 $m^3 m^{-1} y^{-1}$ in depositional areas; the dunes acted as a sink. Van Rijn (1997) estimated the averaged onshore wind-blown sand for this part of the Netherlands between the 3 and 10 m +DOD level at 2.4 $m^3 m^{-1} y^{-1}$, using data of Van Vessem & Stolk (1990). On smaller spatio-temporal scales, values of aeolian deposition into the foredunes may be much higher, ranging from 25 $m^3 m^{-1} y^{-1}$ at an accretional site in North Holland, 50 $m^3 m^{-1} y^{-1}$ at an erosive site at Texel (Arens & Wiersma, 1994) and about 75 $m^3 m^{-1} y^{-1}$ at a site on Goeree (Kroon & Hoekstra, 1990).

Apart from the volumetric input of sand to the foredunes, the increase in height due to deposition of sand is of importance, especially to vegetation (Sykes & Wilson, 1990; De Rooij-Van der Goes *et al.*, 1995). As the average length of the Q_l compartment (measured horizontally along the transect) is 73 m at t=1, and 67 m in control years, the average amount of deposition is about 0.19 m y^{-1} one year after nourishment, versus 0.13 m y^{-1} in the control situation. However, the sand is often not uniformly deposited within the compartment; large amounts of sand are deposited behind sand fences at the dune toe rather than being blown over the foredune crest. Further research could focus on the extent of burial of foredune vegetation by wind-blown nourishment sand.

CONCLUSIONS

The impact of beach nourishment on the development of the supratidal beach and dune is established. An attempt was made to distinguish between aeolian and hydrodynamic processes, which provided insight into the development. Volumetric changes measured in a number of sites were statistically related to the number of years after beach nourishment, and to a control situation, consisting of data more than one year before nourishment and more than three years after nourishment.

The present study shows an overall negative sand budget of the supratidal zone, which does not significantly change after nourishment (as compared to the 12 $m^3 m^{-1} y^{-1}$ eroded in the control situation). In nourishment years, on average a net amount of 94 $m^3 m^{-1}$ of sand is added to the supratidal zone. The present method does not properly account for losses by aeolian and hydrodynamic processes in this year.

One year after nourishment, the erosion of the beach between the 1 and 3 m +DOD level is more than in the control situation. The foredune acts as a sink for wind-blown sand. One year after nourishment, the rate of aeolian sand transport to the dunes significantly increased to about 14 $m^3m^{-1}y^{-1}$, as compared to about 9 $m^3m^{-1}y^{-1}$ in the control situation, despite the large variation in aeolian sand transport.

In the second and third year following nourishment, the rates of aeolian sand transport did not differ from the control situation. In this period, the zone above the 3 m +DOD level and seaward from the limit of storm surge erosion (which changes due to the combined effect of wind and waves) eroded less than in the control situation. The sand was eroded from the nourishment emplaced above the 3 m +DOD level, rather than from the dunes. The foredune was barely eroded after nourishment, demonstrating the protective function of the beach nourishment to especially wave erosion.

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CHAPTER 3

THE IMPACT OF THE GRAIN-SIZE DISTRIBUTION OF NOURISHMENT SAND ON AEOLIAN SAND TRANSPORT

ABSTRACT

An investigation was carried out in the Netherlands to assess the impact of the properties of the sand from various beach and dune nourishments on the rate of aeolian sand transport. Samples from nourished beaches and dunes and nearby unnourished beaches were collected. The grain-size distribution of these samples were related to the 'susceptibility' of the sediments to mobilize under controlled wind tunnel conditions. In all cases, the nourishment sand corresponded to lower transport rates than the sand from nearby unnourished beaches. Large amounts of shell fragments, poor sorting and suitability for compaction resulted in low rates of aeolian transport of the nourishment sand compared to the ambient sand.

KEY WORDS

Beach nourishment, dune nourishment, fill material, ambient sand, grain-size distribution, aeolian sand transport, wind tunnel experiments, the Netherlands

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INTRODUCTION

Beach nourishment is the artificial addition of sediment to a beach area. The method is mainly used to restore and maintain sandy coastal areas with a sediment deficiency (Davison *et al.*, 1992; Delft Hydraulics, 1987). Nourishment implies a direct supply of sand to the beach-dune system, but it may also affect the sediment exchange rate between the beach and the dune (Van der Wal, 1999a; Chapter 2). Changes in the rate of aeolian sand transport after nourishment are likely to be dependent on fill placing, size and form of the nourishment and on the way the sand is supplied. Changes can also be expected as a result of a different composition of source material compared to the ambient beach sand.

In the Netherlands, sediment is usually derived from offshore locations. The sand in the source area is often characterized by a variety in material properties in both vertical (temporal) and horizontal (spatial) direction (Van der Wal *et al.*, 1995). This is because the source area exhibits different geological formations, supplied by rivers, land ice and sea. Moreover, currents and waves interact with sedimentological processes, such as the formation of sand banks, ripples and ridges, which have different sediment characteristics (Eisma, 1968; Van Alphen & Damoiseaux, 1989). The nourishment sand represents a mixture of this source sediment. In addition, the nourishment sand has not been subject to the sorting processes in the surf zone, like the sand that normally reaches the beach. The fill may therefore differ in composition from the ambient beach sand. This will result in a change in the threshold wind velocity and eventually this may lead to a change in the rate of wind-borne sand transport.

Sand-drift is a steering factor controlling development and dynamics of vegetated coastal foredunes (*e.g.* Arens, 1994) and their flora and fauna. It is essential for the growth of healthy marram grass (*Ammophila arenaria*), which is the dominant plant species in the Dutch foredunes (Van der Putten *et al.*, 1989). Yet, too much deposition of sand will lead to suffocation of these and other plants. Apart from impact on vegetated foredunes, excessive sand-drift has other potential adverse effects, *e.g.* on recreation, construction and drinking water abstraction, both on the beaches and dunes and on the (agricultural) hinterland. With respect to coastal defence, the effect of nourishment is both direct and indirect. The increased amount of sand on the beach acts as a direct buffer against wave energy, but part will be blown into the foredunes, where it is stored to be available in times of very high floods or erosion (Van der Wal, 1999a; Chapter 2). However, an extreme rate of aeolian sand transport may diminish the efficiency of the nourishment.

An investigation has been carried out in the Netherlands on changes in aeolian sand transport and foredune vegetation response as a result of artificial nourishment (Van der Wal *et al.*, 1995). One of the objectives of this study is to assess the impact of the fill material on aeolian sand transport, *i.e.*:

(1) to determine the textural parameters influencing the rate of aeolian sand transport, and

(2) to assess the differences between the rates of aeolian transport of nourishment sand and native beach sand as a result of differences in these textural parameters.

In this paper, results of grain-size analysis of samples from nourished beaches and dunes and adjacent unnourished beaches, and results of wind tunnel experiments to determine the 'susceptibility' of the sediments to mobilize, are compared and discussed. The results of the study are discussed with reference to actual aeolian sand transport on nourished beaches.

METHODS

FIELD SITES

From the locations nourished after 1990, five sites were chosen, with different corresponding source areas and various frequencies and ages of nourishments and fill placing (Fig. 3.1). Besides, reference sites at adjacent unnourished beaches were selected.

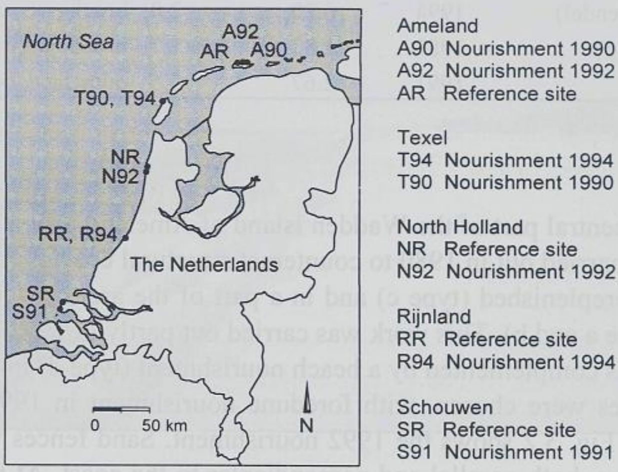

Figure 3.1. *Location of sites.*

The sites were selected from a rather limited number of coastal sections with both a nourished site and a nearby unnourished beach. Furthermore, the sites were chosen such that other management activities were restricted, both on the beach and in the foredunes. The prefill sand on the nourished beaches is assumed to be comparable to the sand from the unnourished beaches. This assumption is confirmed by previous studies of beach and dune sand (*e.g.* Eisma, 1968; Depuydt, 1972; Technical Advisory Committee on Water Defences, 1984). A general overview of the sites and fill placing as indicated in Fig. 1.1 is given here (see also Table 3.1).

Table 3.1. *Some characteristics of the nourishments on the investigated sites (data from Roelse & Hillen, 1993 and De Ruig, 1995).*

Site	Year	Volume ($\times 10^6$ m^3)	Length alongshore (km)	Type
Ameland (Central part)	1980	2.20	5.6	dune face
	1990	0.97	4.6	dune and dune face
	1992	1.67	8.1	dune and beach
Texel (Eierland)	1979	3.05	4.8	beach and banquet
	1985	2.85	5.0	beach and banquet
	1990	2.54	5.2	beach and banquet
	1994	1.33	3.3	beach and banquet
North Holland (Bergen)	1990	0.45	1.5	beach and banquet
	1992	1.47	12.3	beach and banquet
Rijnland (Meijendel)	1994	0.70	2.0	beach
Schouwen (Kop)	1987	1.83	1.7	beach and foreshore
	1991	2.67	5.5	dune face, beach, banquet

Ameland

In the central part of the Wadden island of Ameland a first nourishment (type c) was carried out in 1980 to counteract structural coastal erosion. Later, the area was replenished (type c) and in a part of the area, the foredune was enlarged (type a and b). This work was carried out partly in 1990 and partly in 1992, and was complemented by a beach nourishment (type d) in 1992. In this area, two sites were chosen, with foredune nourishment in 1990 and 1992, respectively. Fig. 3.2 shows the 1992 nourishment. Sand fences were erected at the dune toe, both parallel and perpendicular to the coast. At the west side of the area, a reference site was investigated.

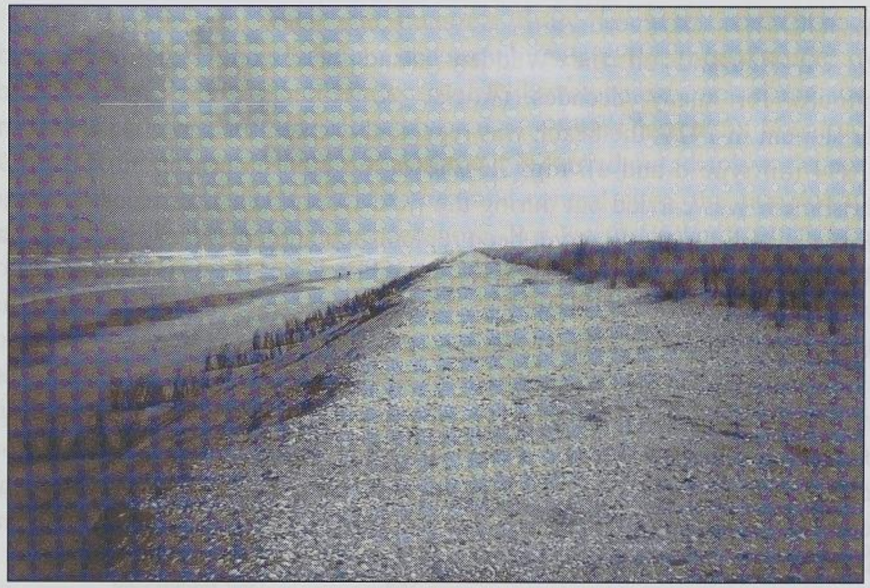

Figure 3.2. *The Ameland dune nourishment of 1992. (Photograph taken on 12 August 1994.)*

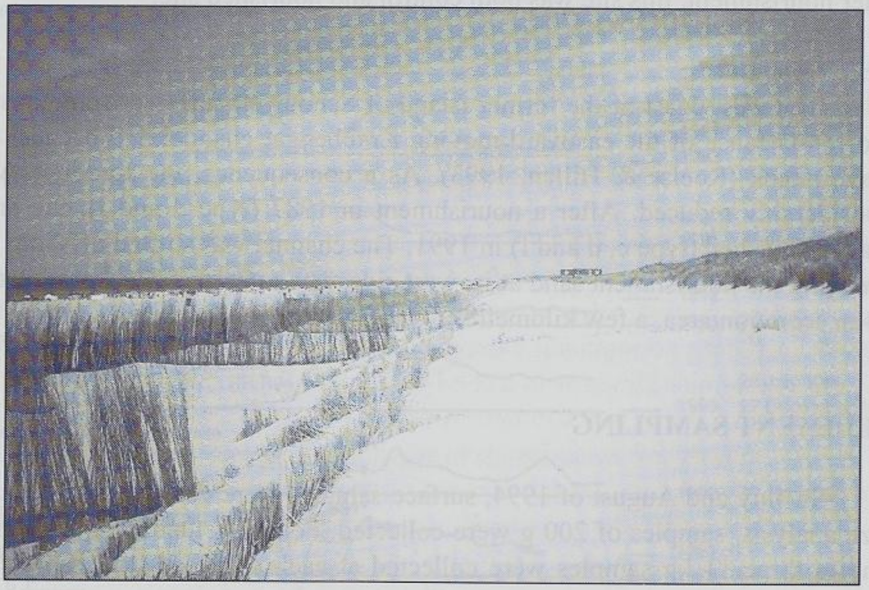

Figure 3.3. *The Texel beach nourishment of 1994. (Photograph taken on 20 July 1994.)*

Texel

On Eierland on the Wadden island of Texel, structural erosion continues for many decades (Roelse & Hillen, 1993). After a first nourishment in 1979, the beach was repeatedly replenished in 1985, 1990 and in 1994 (all type d and e). Fig. 3.3 shows the 1994 nourishment. The 1994 nourishment was carried out during the field work. Two sites were chosen: a site at a stretch that had not yet been replenished and one at a stretch that had just been nourished. Sand fences were placed on top of the 'banquet'.

North Holland

The area near Bergen, along the mainland coast of Holland, is subject to persistent erosion. In 1990, a first nourishment was carried out, followed by a replenishment in 1992 (type d and e). Although nourishment was carried out over a length of more than 10 km along the coast, some areas within this stretch were not supplied, neither in 1990 nor in 1992. The reference site was situated in one of these windows.

Rijnland

In 1994, a first beach nourishment (type d) was executed along the rather stable coast of Rijnland. Since the beach was sampled both before and after nourishment, this site was both control and nourished site.

Schouwen

The west coast of the former island of Schouwen suffered from coastal erosion because of the eastward moving Krabbengat channel and because of wave attack (Roelse & Hillen, 1993). As a consequence, the foredune was considerably reduced. After a nourishment in 1987 (type d and f), the area was replenished (type c, d and f) in 1991. The channel was shifted offshore by dredging the nourishment sand at its west side. The reference site was situated in an accretion area, a few kilometres to the north of the nourished site.

SEDIMENT SAMPLING

In July and August of 1994, surface samples were collected. For grain-size analysis, samples of 200 g were collected. For wind tunnel experiments, one to three 11 kg samples were collected at each site. For each sample, a layer of 0.05 m in depth was scraped from the surface.

In Fig. 3.4, for each site transects from beach to inner dune are displayed, with sampling locations and sampling date. Records of height were obtained from the JARKUS data base of Rijkswaterstaat, comprising yearly profile measurements (see De Ruig & Louisse, 1991; Chapter 2). Usually, the profile from the year in which a nourishment is carried out, displays the prefill topography. At beach nourishment sites and control sites, the samples were derived from the surface of the backshore. For North Holland, fill from the nourishment carried out in 1992 was sampled at the dune face, in the remnants of the eroded banquet. On Ameland, nourishment sand was collected on top of the dune nourishment and on Schouwen on top of the dune face nourishment. Fill material of the beach nourishment carried out in Rijnland in autumn of 1994 was obtained in December of that year.

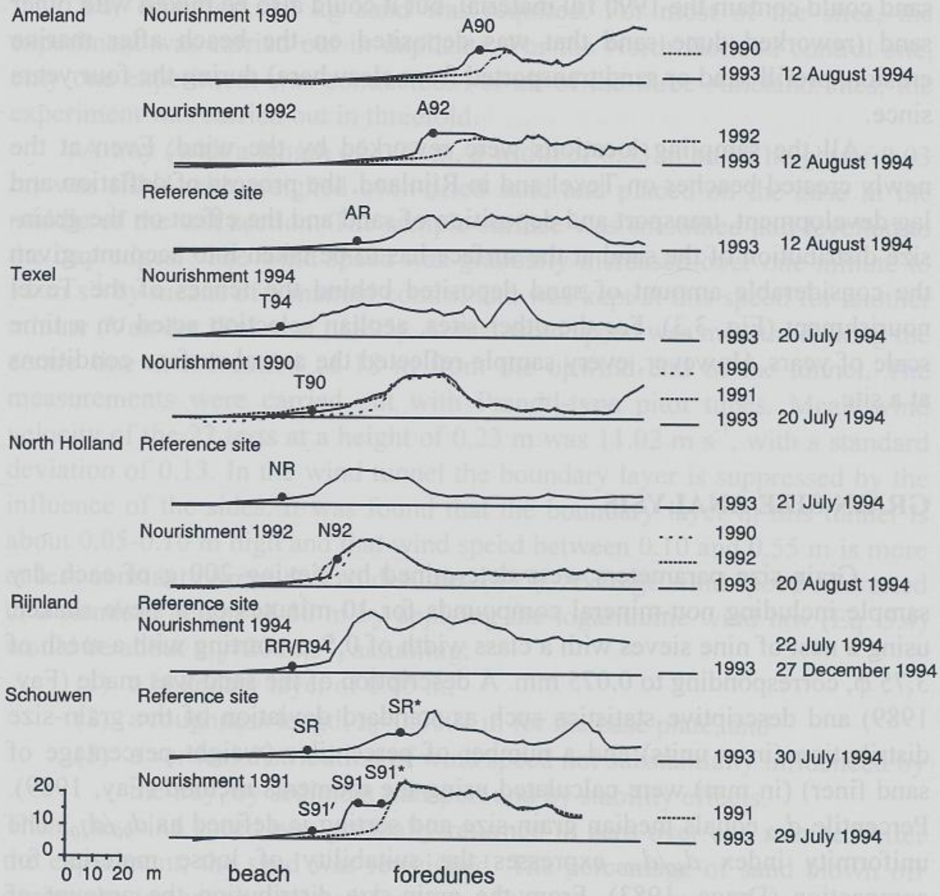

Figure 3.4. Transects of each site with sampling location and date.

At a number of sites, additional samples were taken alongshore (about 200 m apart) at comparable locations (*i.e.*, at a specific distance to the sea) to gain insight in the spatial variability of the properties of the sand. Furthermore, samples of wind-blown nourishment sand and wind-blown native sand (*i.e.*, sand that was trapped by marram grass) were collected on Schouwen.

Except for the Rijnland site, it can not be excluded that the control sites were indirectly influenced by nourishment. This applies especially to the reference site in North Holland. Nourishment sand, however, was not mixed with ambient sand or with nourishment sand transported from elsewhere. This was assured by sampling fill that was not reworked by the sea. An exception is the material collected at the backshore on the Wadden island of Texel (sample T90), at the stretch of coast that had not yet been replenished. This sand could contain the 1990 fill material, but it could also be mixed with other sand (reworked dune sand that was deposited on the beach after marine erosion, prefill sand or sand transported from elsewhere) during the four years since.

All the sampling locations were reworked by the wind. Even at the newly created beaches on Texel and in Rijnland, the process of deflation and lag development, transport and deposition of sand and the effect on the grain-size distribution of the sand at the surface has to be taken into account, given the considerable amount of sand deposited behind the fences of the Texel nourishment (Fig. 3.3). For the other sites, aeolian selection acted on a time scale of years. However, every sample reflected the actual surface conditions at a site.

GRAIN-SIZE ANALYSIS

Grain-size parameters were determined by sieving 200 g of each dry sample including non-mineral compounds for 10 minutes on a sieve shaker, using a nest of nine sieves with a class width of 0.5 φ, starting with a mesh of 3.75 φ, corresponding to 0.075 mm. A description of the sand was made (Fay, 1989) and descriptive statistics such as standard deviation of the grain-size distribution (in φ units) and a number of percentiles (weight percentage of sand finer) (in mm) were calculated using the moments method (Fay, 1989). Percentile d_{50} equals median grain-size and sorting is defined as d_{90}/d_{10}. The uniformity index d_{60}/d_{10} expresses the suitability of loose material for compaction (Draga, 1983). From the grain-size distribution the amount of fines (<0.075 mm) consisting of fine sand, silts, clays and organic matter and the amount of coarse material (>2 mm), containing shell fragments and at one location (Texel) shell fragments, gravel and stones, was calculated as a weight percentage of the total dry weight of the sample.

WIND TUNNEL EXPERIMENTS

Experiments with 22 samples of nourishment sand and native sand were carried out in a closed-circuit wind tunnel. The tunnel has an observation section of 19.5 m in length with a cross section of 0.75 by 0.75 m^2. The wind speed in the tunnel can be adjusted continuously by opening or closing the blinds in front of the fan that sucks the air through the tunnel. Knottnerus (1976) described the wind tunnel in detail.

For each test, 11 kg sand was required. For most of the sites, the experiment was carried out in duplicate. For the North Holland control site, only one experiment was conducted. For all of the three Ameland sites, the experiment was carried out in threefold.

A tray (with a length of 1.22 m, a width of 0.33 m and a height of 0.03 m) was filled with weighed oven-dried sand and placed on the base in the middle of the test section. The sample surface was smoothed and levelled to the tray edges. The wind speed was gradually increased over one minute to 11 m s^{-1} by means of a manual control and was kept at this speed for another minute (Van der Wal *et al.*, 1995). Actual wind speed was measured along the centre line at a location of 18 m from the upwind end of the tunnel. The measurements were carried out with Prandtl-type pitot tubes. Mean wind velocity of the 22 tests at a height of 0.23 m was 11.02 m s^{-1}, with a standard deviation of 0.13. In the wind tunnel the boundary layer is suppressed by the influence of the sides. It was found that the boundary layer in this tunnel is about 0.05-0.10 m high and that wind speed between 0.10 and 0.55 m is more or less constant (Arens & Van der Lee, 1995). Average wind speed converted to a standard height of 10 m by applying the logarithmic wind law (Eq. 5.4) would be about u_{10}=20 m s^{-1}, assuming:

(1) a boundary layer of 0.05 m,
(2) a roughness length z_0=0.0001 m for the base plate, and
(3) a vertical distribution of wind speed not substantially influenced by the tray, by sediment transport and by stability effects.

Then, the wind speed was gradually returned to zero over one minute. After the experiment, the sand was reweighed. The percentage of sand blown off during the test was calculated for each of the experiments and was averaged for each site.

Because of a limited amount of available sand for each test, the steady state with a fully loaded saltation layer was not reached. Nevertheless, this method was preferred to measurement of the critical wind velocity for aeolian entrainment as a measure for erodibility. This was because for natural sands (both ambient beach sand and nourishment sand) critical wind velocity is usually not a definite value but a threshold range, which is a function of grain-size composition (Nickling, 1988). Moreover, the composition of sand is time dependent as a result of aeolian selection, especially when shells are involved.

RESULTS

The rate of aeolian sand transport was expressed as the percentage of sand removed at the end of the wind tunnel experiment, averaged for each site (Table 3.2). This variable was plotted against a number of parameters derived from the grain-size analysis of the samples (Fig. 3.6).

Deviations in grain-size distribution between the samples collected at one site at different locations at a given distance from the sea, were small for native sand (*cf.* samples from Schouwen in Fig. 3.7). In case of nourishment sand containing a considerable amount of shell fragments, there was a larger variability in grain-size distribution between samples (*cf.* samples in Fig. 3.5). As a result, the variation in the amount of sand blown off during the wind tunnel experiments was larger for these nourished sites (Table 3.2).

Table 3.2. *Weight percentages of sand blown off during wind tunnel experiments and average percentages (see text for explanation).*

Site		Sample	Experiment (1)	(2)	(3)	avg
Ameland	Nourishment 1990	A90	12	14	11	12
	Nourishment 1992	A92	24	13	14	17
	Reference site	AR	59	63	64	62
Texel	Nourishment 1994	T94	82	61	—	72
	Nourishment 1990	T90	19	21	—	20
North Holland	Reference site	NR	68	—	—	68
	Nourishment 1992	N92	56	56	—	56
Rijnland	Reference site	RR	53	49	—	51
	Nourishment 1994	R94	—	—	—	—
Schouwen	Reference site	SR	53	55	—	54
	Nourishment 1991	S91	36	45	—	41

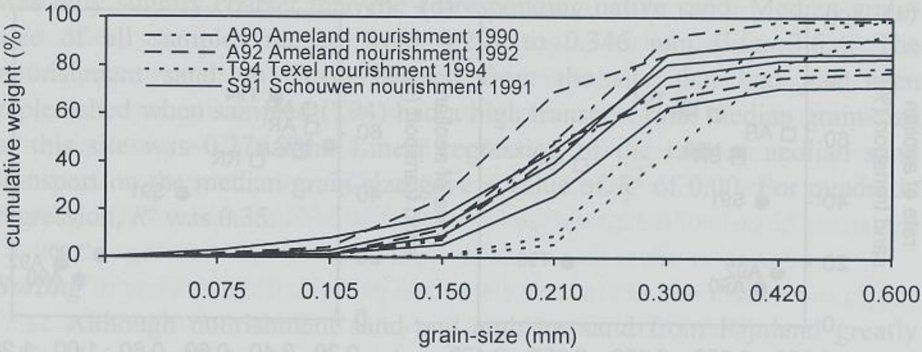

Figure 3.5. *Cumulative curves of grain-sizes, showing variation in grain-size distribution within some nourished sites.*

Median grain-size

Table 3.3 reveals, that at three sites (North Holland, Rijnland and Schouwen), median grain-sizes of fill material were smaller than the values obtained for samples from their former or nearby natural beach. In Rijnland, median grain-size of nourishment sand is more than 0.1 mm smaller than the median of the sand that was sampled at the same location before nourishment was carried out. Material on top of the dune face nourishments on Ameland

Table 3.3. *Median grain-size (d50), uniformity index (d60/d10), sorting (d90/d10) and standard deviation (σ) for the nourished sites and nearby control sites showed in Fig. 3.1.*

Site	Sample	*d50* (mm)	*d50* (φ)	*d60/d10* (mm/mm)	*d90/d10* (mm/mm)	σ (φ)
Ameland	A90	0.227	2.14	1.70	—	1.00
	A92	0.217	2.20	1.88	—	1.05
	AR	0.211	2.24	1.44	1.77	0.29
Texel	T94	0.276	1.86	1.40	1.91	0.40
	T90	0.346	1.53	1.93	—	0.93
North Holland	NR	0.256	1.97	1.31	1.73	0.29
	N92	0.242	2.05	1.40	1.59	0.23
Rijnland	RR	0.338	1.56	1.63	2.26	0.45
	R94	0.232	2.11	1.58	2.25	0.52
Schouwen	SR	0.242	2.05	1.51	1.88	0.32
	S91	0.227	2.14	1.85	3.15	0.68

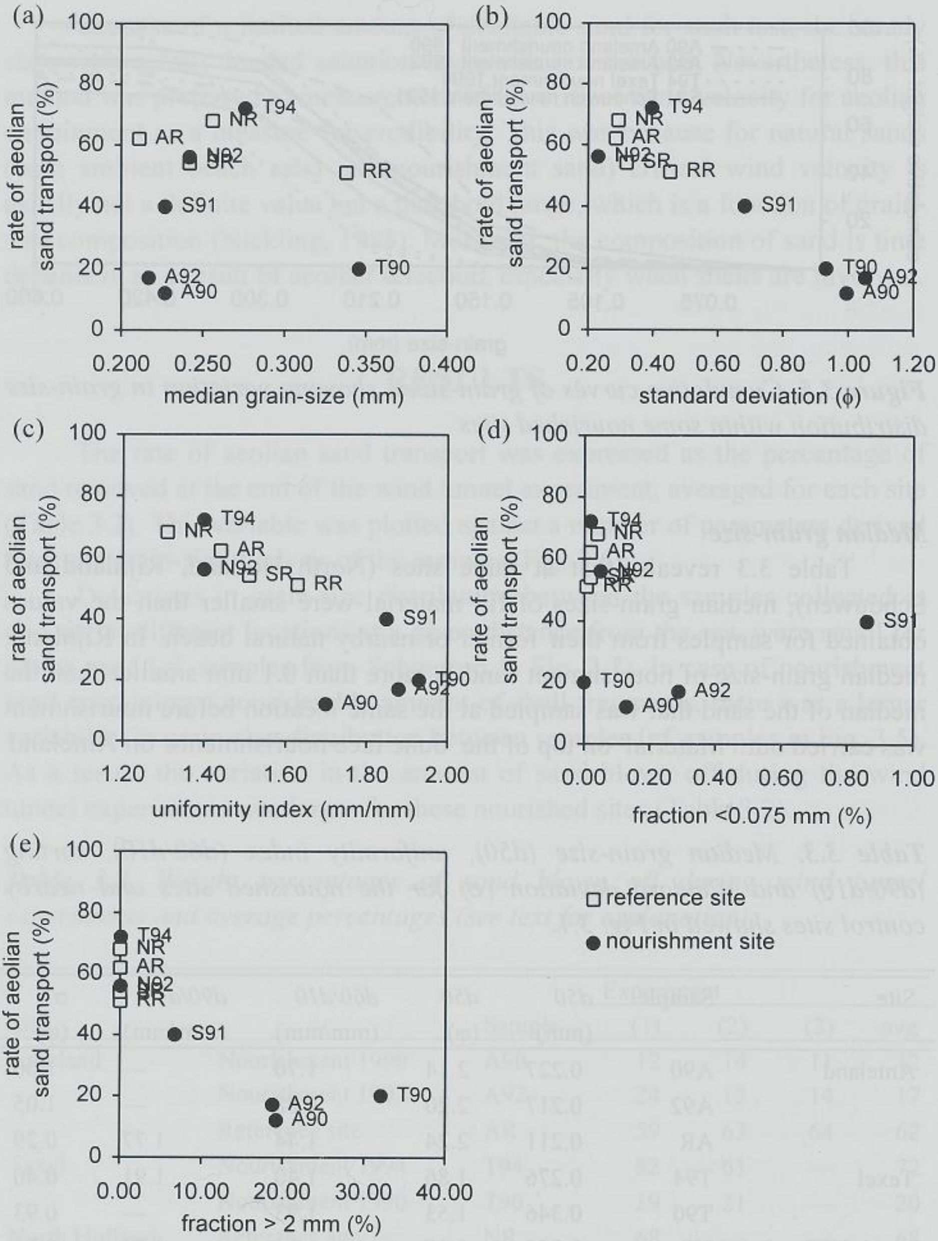

Figure 3.6. *The rate of aeolian sand transport versus several textural parameters of the samples shown in Fig. 3.4: (a) median grain-size, (b) sorting, (c) uniformity index, (d) fraction <0.075 mm and (e) fraction >2 mm.*

was only slightly coarser than the corresponding native sand. Median grain-size of all samples ranged from 0.211 to 0.346 mm (Fig. 3.6a). The nourishment sand on Texel derived from the site that had just been replenished when sampled (T94) had a high transport rate; median grain-size at this site was 0.276 mm. Linear regression of the rate of aeolian sand transport on the median grain-size gave a value of R^2 of 0.00. For quadratic regression, R^2 was 0.35.

Sorting

Although nourishment sand and ambient sand from Rijnland greatly differed in median grain-size, they had almost identical sorting, as was expressed by d_{90}/d_{10} (Table 3.3). Very well sorted replenishment sand was found at the nourished beach in North Holland (standard deviation of the grain-size distribution was 0.23 φ units) and sorting of fill materials on Ameland was only moderate (standard deviation of 1.00 and 1.05, respectively) (Fig. 3.6b). The former was rather compatible with corresponding native sand whereas on Ameland, fills differed highly in sorting from sand sampled at their adjacent control site. Native sand was well or even very well sorted and values for standard deviation of the grain-size distribution ranged from 0.29 to 0.45 (φ units). For moderately well sorted to moderately sorted nourishment sand (*i.e.*, sand with a standard deviation exceeding 0.5 φ units), the rate of aeolian sand transport decreased with standard deviation. R^2 of linear regression was 0.89.

Uniformity index

Regarding to uniformity index, again, Rijnland fill and to a lesser extent sand from the nourishment in North Holland were compatible with corresponding ambient sand (Table 3.3). As these sands were well or very well sorted, they were not suitable for compaction. Sand sampled at the nourishments on Ameland (in particular the nourishment carried out in 1992) and on Schouwen was suitable for compaction: uniformity indices up to 1.88 were found, whereas at adjacent control sites values did not exceed 1.51. The rate of aeolian sand transport decreased with the uniformity index (Fig. 3.6c). A value of $U > 1.7$ was associated with low transport rates (<45% of the sand was blown off after the wind tunnel experiment). Linear regression of the rate of aeolian sand transport on the uniformity index gave a value of R^2 of 0.74.

Fraction <0.075 mm

The fraction <0.075 mm (>3.75 φ) primarily consisted of mineral grains. Organic material of this size was too rare to be of any importance at the research areas. In Schouwen and Ameland sand, the fraction <0.075 mm contained material up to a weight percentage of 0.86% (Fig. 3.6d). The corresponding amount of sand transported during the wind tunnel experiments did not exceed 45% (Table 3.2). Both on Ameland and Schouwen, clayey sediment layers were exposed in the locally clear cut dune (face) nourishment. A sample taken from such a layer in the 1992 nourishment on Ameland contained 22.06% of material <0.075 mm and 80.95% of material <0.150 mm.

For the other sites, the amount of particles <0.075 mm was less than 0.05% and the amount of silt- and clay-sized particles did not relate to the rate of aeolian sediment transport. Linear regression of the rate of aeolian sand transport on the fraction <0.075 mm gave a value of R^2 of 0.08.

Fraction >2 mm

The role of shells and shell fragments in forming a lag surface and preventing the underlying sand from blowing away was apparent. Especially in nourishment sand from Ameland and Schouwen, shell pavements were formed during the wind tunnel experiments, limiting the supply of sand (Table 3.2). Sand from Texel contained very coarse sand, gravel and stones, which also proved to be effective in reducing deflation (T90 in Fig. 3.6e). A content of more than 6% of coarse material resulted in a rate of aeolian sand transport of less than 45% during wind tunnel experiments, whereas all samples exhibiting sand-drift over 50% during the experiments were associated with shell contents of less than 0.15%. Linear regression of the rate of aeolian sand transport on the fraction >2 mm (<-1.00 φ) gave a value of R^2 of 0.78. The relationship between the results of the grain-size analysis and the wind tunnel experiments of the sand from Ameland illustrates that more sand was blown off during the experiments (Table 3.2) when shell fragments were smaller (fraction 0.6-2 mm versus fraction >2 mm), even with a slightly higher total weight percentage of particles >0.600 mm (22.4% in the 1992 nourishment versus 20.7% in the 1990 nourishment).

In natural circumstances, the shells on the beach will be reworked by the sea, re-exposing the sand beneath the shell pavement. Especially in case of fill placing normally inaccessible to the sea, semi-persistent pavements may play a role in the aeolian sand budget, which was confirmed by observations on Ameland and Schouwen. This is illustrated by the results of the analysis of the Schouwen samples. Samples were taken from the 1991 beach nourishment, from the 1991 dune face nourishment and from a nearby unnourished beach (Fig. 3.7). Furthermore, samples of wind-blown sand (*i.e.*, sand that was trapped by marram grass) of both the nourishment site and the control site were collected (Fig. 3.8). The samples collected at the dune face nourishment where not reworked by the sea and contained 6.7 to 24.7% of material larger than 2 mm. The material sampled at the beach nourished in 1991 was reworked by the sea. No shell pavements were observed and the weight percentage of material larger than 2 mm ranged from 0 to 0.1%, which is comparable to the ambient sand on the unnourished beach (0%). Wind-blown nourishment sand also contained very few shell fragments (0 to 0.65%), whereas none of the samples of wind-blown ambient sand contained material larger than 2 mm.

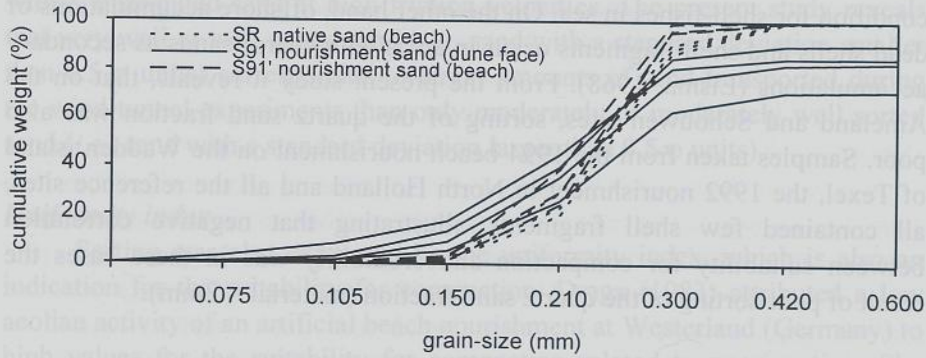

Figure 3.7. Cumulative curves of grain-sizes of three samples of sand from a natural beach, collected at the backshore (SR), four samples from the dune face nourishment on Schouwen (S91), and three samples from the beach nourishment on Schouwen, collected at the backshore (S91').

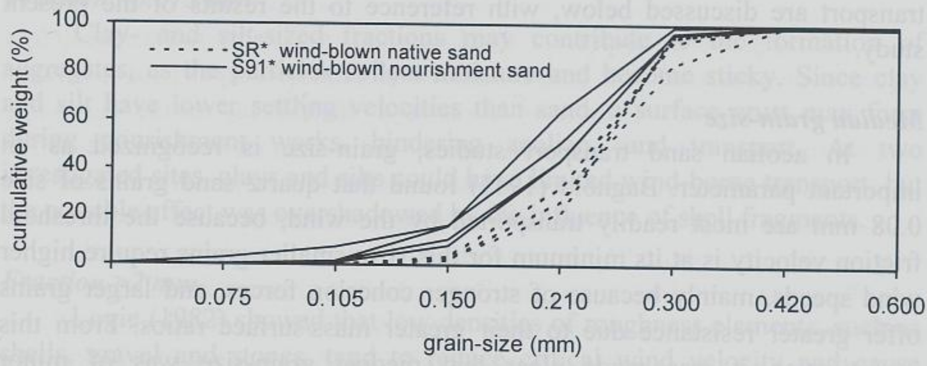

Figure 3.8. Cumulative curves of grain-sizes of five samples of wind-blown native sand and four samples of wind-blown nourishment sand from Schouwen.

Shell pavements may not only develop from aeolian selection. On both Ameland and Schouwen, concentrations and layers of shells were exposed in a cliff (that was formed locally by marine erosion) of the dune (face) nourishment.

Together, the factors mentioned in the previous paragraphs affect the rate of aeolian sand transport. On Ameland and on Schouwen for example, nourishment sand was not only rich in shell fragments, but it also contained large amounts of clay- and silt-sized particles. The joint presence of shells and fines is not unexpected since the presence of fine sediment is a favourable condition for shell-fishes in sea. On the other hand, offshore accumulations of dead shells and shell fragments occur in areas with coarse sands as secondary accumulations (Eisma, 1968). From the present study it reveals, that on the Ameland and Schouwen sites, sorting of the quartz sand fraction was also poor. Samples taken from the 1994 beach nourishment on the Wadden island of Texel, the 1992 nourishment in North Holland and all the reference sites, all contained few shell fragments, illustrating that negative correlation between suitability for compaction and erodibility was in these cases the result of poor sorting of the quartz sand fraction (material < 2mm).

DISCUSSION

To assess the impact of artificial beach nourishment on the beach dune system, the factors affecting wind-borne transport of nourishment sand have to be studied. Several textural parameters influencing the rate of aeolian sand transport are discussed below, with reference to the results of the present study.

Median grain-size

In aeolian sand transport studies, grain-size is recognized as an important parameter. Bagnold (1941) found that quartz sand grains of size 0.08 mm are most readily transported by the wind, because the threshold friction velocity is at its minimum for this size; smaller grains require higher wind speeds, mainly because of stronger cohesion forces, and larger grains offer greater resistance due to their greater mass/surface ratios. From this investigation it was made clear that median grain-size was of minor importance in determining the rate of aeolian sand transport, as the median value is largely affected by the grain-size distribution of the sand.

Sorting

Bagnold (1941) suggested that with a fixed average diameter, the transport rate of a sand widely distributed in grain-size is greater than that of a well-sorted sand under the same friction velocity, which was confirmed by studies conducted by Horikawa *et al.* (1983). Nickling (1988) found that critical friction velocities were smaller for more widely distributed sands. The smaller or more exposed surface grains were entrained at low friction velocities and set in motion a rapidly increasing number of grains by imparting momentum as wind velocity continued to rise. Willetts *et al.* (1982) however, found higher transport rates for well sorted sand than for a more widely distributed sand at high friction velocities. The present study reveals that very well or well sorted sand (*i.e.*, sand with a standard deviation smaller than 0.5 φ units) corresponded to larger amounts of sand transported during the wind tunnel experiments than only moderately or moderately well sorted sand (*i.e.*, sand with a standard deviation larger than 0.5 φ units).

Uniformity index

Sorting was also expressed by the uniformity index, which is also an indication for the suitability for compaction. Draga (1983) attributed a low aeolian activity of an artificial beach nourishment at Westerland (Germany) to high values for the suitability for compaction related to poor sorting. She suggested that dredging, bulldozing and other methods used in fill transporting and placing would have increased compaction. These findings were confirmed by the results of this study, although values found for *U* in the present study were much lower.

Fraction <0.075 mm

Clay- and silt-sized fractions may contribute to the formation of aggregates, as the particles collect moisture and become sticky. Since clay and silt have lower settling velocities than sand, a surface crust may form during nourishment works, hindering aeolian sand transport. At two investigated sites, clays and silts could have limited wind-borne transport, but the possible effect was overshadowed by the influence of shell fragments.

Fraction >2 mm

Logie (1982) showed that low densities of roughness elements, such as shells, gravel and stones, tend to reduce critical wind velocity and cause increased erosion because of wind acceleration along the obstacles and development of turbulent eddies. An increase in non-erodible particles however raises the threshold (Nickling & McKenna Neuman, 1995). Semipermanent lag deposits may develop, which eventually prevent sand beneath from drifting, but sand transport may be re-activated after disturbance of such a pavement (Carter, 1976).

During the wind tunnel experiments described in this paper, large amounts of shell fragments considerably decreased the amount of sand blown off. Field observations confirmed that shell pavements can form within weeks, *e.g.* on the beach nourished in 1994 on the Wadden island of Texel. They may be semi-persistent in areas that are not periodically flooded by the sea, especially on top of dune face nourishments (nourishment types b and c in Fig. 1.1), *e.g.* on Schouwen. They may also form on top of the banquets (type e in Fig. 1.1) and on the upper part of the beach (type d in Fig. 1.1). On natural beaches, these extensive shell pavements were not encountered during the field work.

Other factors

A factor not yet investigated is the mineralogical composition of nourishment sand, especially the amount of sand-sized shell fragments and calcite grains and admixtures of heavy minerals, such as magnetite (Van der Wal *et al.*, 1995). Since Olij (1993) found hardly any differences between mineral grain roundness of natural beach and dune sand compared to nourishment sand in North Holland, particle shape (Williams, 1964; Willetts *et al.*, 1982), seems to be an insignificant factor affecting rates of sediment movement after nourishment in the Netherlands. In further studies, other factors than textural parameters, such as the influence of bonding agents (Nickling & Ecclestone, 1981) on threshold friction velocity and rates of transport have to be taken into account (Van der Wal *et al.*, 1995).

Although from the present wind tunnel experiments it becomes clear that nourishment sand and native sand differ considerably in the measured rate of aeolian sand transport as a result of differences in the grain-size distribution of the sands, the influence of the fill properties on the actual aeolian sand transport rates and foredune development is not yet assessed. Spatial and temporal variability in grain-size distribution and surface roughness, such as initial aeolian selection of fine sand and the formation and disturbance of shell pavements, have to be studied in more detail. The aeolian mobility of surface materials may decrease with time because of the development of a lag surface. High rates of mobilization could be temporally restricted, but strong winds may disturb the pavement and remobilize the sand. The heterogeneity of the fill material (*f.i.*, the occurrence of layers of shells and shell fragments within the nourishment) may also play a role in this sequence. Therefore, the interaction between surface conditions and aeolian sand transport has to be studied over the whole longevity of the fill, *i.e.*, 5 to 10 years.

As already pointed out, many other factors may be involved in altering aeolian sand transport rates after nourishment. Moisture conditions for example, are likely to increase potential of sand movement due to a raised beach level after nourishment. Beach nourishment may also affect beach width, altering the fetch of onshore winds. In addition, a decrease in marine erosion of the foredune may change the transfer of sand within the beach dune system. The changes are superimposed on the natural variability in sand transport rates to the foredunes (for instance due to meteorological conditions) (Van der Wal, 1999a; Chapter 2). Assessing the impact of nourishment on foredune development necessitates an exact method to determine the causes of small scale variation in aeolian sand transport from nourished beaches. A further study should comprise the whole longevity of the fill and should start before fill placement. Especially when linking the results to vegetation development, field monitoring techniques are required (Roelse *et al.*, 1991; Van der Wal *et al.*, 1995). A field-based monitoring study has already been carried out (*e.g.*, Van der Wal, 1999c; Chapter 6).

CONCLUSIONS

This research focused on the different rates of aeolian transport of sand from beach and dune nourishments in the Netherlands, as a result of different properties of fill material compared to ambient beach sand. The rates of aeolian transport of sand as determined in a wind tunnel was found to be highly dependent on:

(1) the grain-size distribution of sand, and
(2) the amount of shell fragments in the sand.

Beach sand with high rates of transport during wind tunnel experiments was well to very well sorted with a very small positive skewness (fine tail) or a symmetrical, often leptokurtic grain-size distribution. Samples of native sand all exhibited these properties. Fill was moderate to moderately well sorted with a negative skewness caused by shell fragments, and an often platykurtic grain-size distribution, resulting in low rates of sand transport during wind tunnel experiments. At two nourished sites however, sand was well or very well sorted, and samples from these nourishments exhibited high transport rates.

By choosing appropriate fill material, it is therefore recommended not only to take into account medium grain-size, but also the whole grain-size distribution and the spatial variability of sand properties, since even well sorted sand in the source area exhibiting spatial variability in mean grain-size may result in poor sorting of fill due to mixture. For the Dutch situation, well sorted sand with a minimum of shell fragments is suitable.

In order to optimize beach nourishment measures from a geomorphological point of view, many aspects related to the source area, fill material, nourishment design, and execution method and their impacts on the (local) coastal system have to be assessed. A choice for compatible material (with fill placing preferably below the high water level), is one of the conditions to minimize the impact of nourishment on the beach dune system.

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CHAPTER 4

GRAIN-SIZE-SELECTIVE AEOLIAN SAND TRANSPORT ON A NOURISHED BEACH

ABSTRACT

The grain-size-selective aeolian processes that take place after a beach nourishment were studied on the island of Ameland in the Netherlands. The beach and foredunes were sampled both before and after nourishment. Grain-size distributions of surface and subsurface sand, wind-laid sand and sand in transport were analysed. The unreworked fill is only moderately sorted and exhibits a large spatial variation. Marine reworking results in a decrease of shell fragments and a decrease in fines on the foreshore, with the exception of the swash mark. During aeolian sand transport, aeolian decoupling results in a backshore with surface lag deposits with moderately sorted sand containing a substantial amount of shell fragments and silt, and patches of sand with less shell fragments. Wind-laid nourishment sand, *i.e.* the nourishment sand that is blown to the dunes, contains only small amounts of these shell fragments and the sand is finer and better sorted than the nourishment beach sand. However, the nourishment sand that is blown to the foredunes still deviates from the wind-laid native sand; it is more poorly sorted and more negatively skewed. Furthermore, the wind-laid nourishment sand contains significantly more coarse material, *i.e.*, shell fragments, than the wind-laid native sand, which will lead to an increase in calcium carbonate content in the foredunes.

KEY WORDS

Beach nourishment, grain-size distribution, aeolian decoupling, marine reworking, shell pavement, carbonate, foredunes, the Netherlands.

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INTRODUCTION

Beach nourishment is often used to counteract marine erosion in sandy coastal areas. An amount of sand is added to the beach, where the sand acts as a buffer against wave energy or provides a wide beach for recreational uses (Davison *et al.*, 1992). Preferably, fill material of approximately the same size as the native beach material, or slightly coarser, is used for nourishment (Dean, 1983). However, in many cases it is not feasible to use compatible fill. This has important geomorphological and ecological consequences.

Worldwide, an important source for beach nourishment has been offshore deposits. This material is dredged from the seabed, transported to the beach, and either dumped or pumped into the littoral zone (Komar, 1998). In the Netherlands, source areas are situated either 20 km offshore or seaward from the 20 m line of depth (*i.e.*, safely beyond the closure depth of nearshore profile changes but as near as possible to the location to be nourished). Sea sand in this area can differ considerably in texture from native beach sand (Eisma, 1968; Draga, 1983; Van der Wal, 1998b; Chapter 3). This is due to the history of the sands and the recent conditions of transport.

The sand frequently contains admixtures of gravel, silt, shells, or organic matter, which are insubstantial in the ambient beach sand. In addition, spatial variability in sediment properties in the source area may result in polymodal size distributions on the beach to be nourished, since the nourishment sand is mixed when brought ashore (Van der Wal *et al.*, 1995).

The fill material has not been subject to marine and aeolian sorting to the same extent as the sand that normally reaches the beach. The beach environment will select out the grain-sizes that are appropriate for its particular conditions (Komar, 1998). Wave action, beach drift, currents and wind action determine the characteristics of sediments on a natural beach, as is shown by several studies (*e.g.*, Depuydt, 1972; Bauer, 1991; Lee, 1997). These sorting processes can rework the fill as soon as the nourishment sand is placed on the beach. Eitner (1996) and Hoekstra *et al.* (1996) show that the grain-size distribution of the fill tends to match the grain-size distribution of native sediments as a result of these sorting processes on the foreshore and shore face. The finer fractions will be lost offshore, while the coarser material remains on the beach (Swart, 1991). For the backshore, where aeolian processes dominate, a similar tendency can be expected. Aeolian selection may result in sediment decoupling, *i.e.* the sorting of a source population into two or more subpopulations that have distinctly different size distributions (Bauer, 1991). The grain-size distribution of the surface sand is important for the aeolian sand transport rate.

For the Netherlands, there is another aspect to changes in sediment properties. There are two primary sources of sand to the Dutch North Sea beaches: glacial sand of the Saalian age dominate the beaches north of Bergen (North Holland), whereas deposits of the Pleistocene Rhine River dominate the beaches south of this location. Due to the different origin of the sands, the beach and dune sands in the north contain, *e.g.*, less aluminium, iron, calcium, and magnesium than the sands in the south (Eisma, 1968). The mineral content is an important factor for vegetation and largely explains the differences in plant species found in the dunes north and south of Bergen, respectively (Rozema *et al.*, 1985). Offshore, the geographical distribution of sands is more complex (Eisma, 1968). Therefore, offshore dredged sand may differ in mineral content from native beach sand. Consequently, aeolian transport of this nourishment sand to the dunes may alter the composition of dune sand. These changes affect vegetation. Vegetation effects due to a changed carbonate content can also be expected in case of nourishment sand containing more shells and shell fragments than the native sand.

The objective of this paper is to assess the grain-size-selective aeolian processes on a nourished beach. Grain-size distributions were determined of:

(1) surface and subsurface sand,
(2) wind-laid sand, and
(3) sand in transport.

The sand was sampled both before and after nourishment. In addition, the carbonate content of the surface sand was analysed. The study addresses:

(1) the differences in grain-size between native and nourishment sand,
(2) the aeolian selection of grain-size,
(3) the vertical distribution of grain-size in air, and
(4) the differences in carbonate content between native and nourishment sand.

The implications of the differences in grain-size distribution and carbonate content of the samples for the aeolian selection process and foredune ecology are discussed.

STUDY SITE

The study site is situated on the North Sea side of the Wadden island of Ameland, near the village of Ballum in the Netherlands (Fig. 4.1). There is a semi-diurnal tidal range of 2.2 m. The coast has an east-west orientation; northerly winds blow perpendicular onshore. A first beach nourishment was carried out in 1996: 1.56×10^6 m^3 of sand were deposited on the beach along

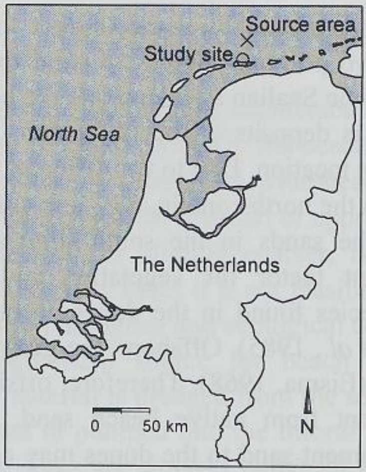

Figure 4.1. Location of the study site on the Wadden island of Ameland and the source area that provided the nourishment sand.

a 4 km stretch of coast. The work started in May and was completed by September 1996. The sand was dredged from an area about 15 km offshore (Fig. 4.1), transported by ship to a location about 5 km offshore, from which it was pumped to the beach. Here, it was remodelled using cranes and bulldozers. Cross-shore profiles were measured before and after nourishment with EDM (laser Electronic Distance Measurement) equipment (Fig. 4.2).

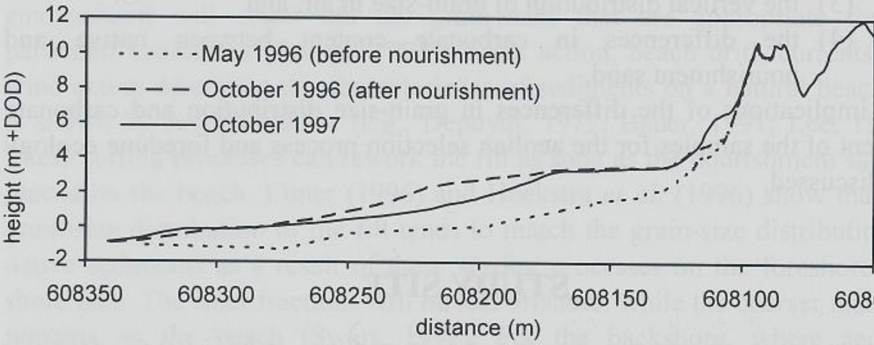

Figure 4.2. Cross-shore profiles of the site before and after nourishment. The profile of October 1997 shows erosion of the beach and deposition landward of the sand fence at the dune toe and in the foredunes. Height (m) is relative to DOD (Dutch Ordnance Datum), which is about mean sea level. Distances (m) refer to the Dutch rectangular co-ordinate system.

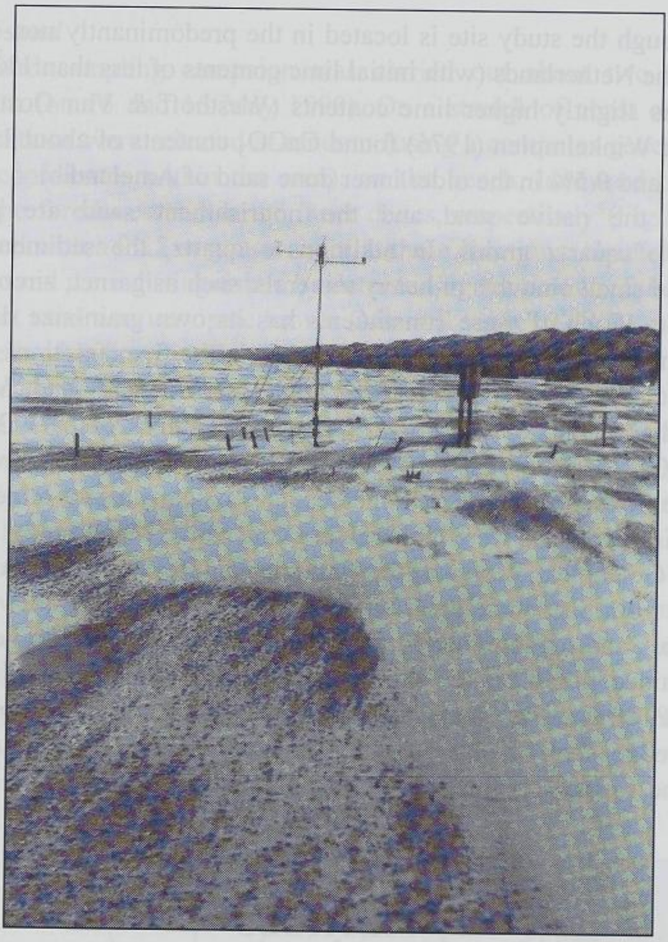

Figure 4.3. *The nourished beach on Ameland, after a period with strong onshore winds. (Photograph taken on 30 October 1996.)*

There is a foredune ridge of about 10 m above the Dutch Ordnance Datum adjacent to the beach (Figs 4.2 and 4.3). A sand fence was erected at the dune toe before nourishment; it was buried by the 1996 nourishment. A new fence was erected in November 1996, thus after nourishment. Nourishment sand then accumulated landward of this sand fence. The foredune is dominated by marram grass (*Ammophila arenaria*) and baltic marram grass (*Calammophila baltica*) and the inner dunes are covered by mosses and sea buckthorn (*Hippophaë rhamnoides*).

Although the study site is located in the predominantly non-calcareous district of the Netherlands (with initial lime contents of less than 1%), the area in study has slightly higher lime contents (Westhoff & Van Oosten, 1991). Veenstra & Winkelmolen (1976) found $CaCO_3$ contents of about 1.3% in the beach sand and 0.5% in the older inner dune sand of Ameland.

Both the native sand and the nourishment sand are principally composed of quartz grains. In addition to quartz, the sediment contains feldspar and small amounts of heavy minerals, such as garnet, zircon, epidote, and ilmenite. Each of these constituents has its own grain-size distribution, although the heavy minerals are concentrated in the finer fractions (Schuiling *et al.*, 1985; Tánczos, 1996). In their study on Ameland sand, Veenstra & Winkelmolen (1976) locally found garnet percentages of over 30% in the fraction 3.00 to 3.25 φ (105 to 125 mm), but garnet percentages were under 1% for the bulk of the sand. The percentages of dark heavy minerals in the 1996 nourishment sand were higher than in the native beach sand.

The Geological Survey of the Netherlands (1996) analysed a number of drill cores from the source area; sand occasionally contained thin laminae of silt and clay, and organic matter was included sporadically. Furthermore, the sand contained finely broken shell fragments and relatively hard shells and coarse shell fragments, mainly consisting of through shell (*Spisula sp.*), banded wedge shell (*Donax vittatus*) and common cockle (*Cerastoderma edule*). The (quartz) grains in the nourishment sand have ferric hydroxide coatings.

METHODS

SEDIMENT SAMPLING

Surface and subsurface sand

The surface was sampled along 1 m spaced transects from the low water line to the dune toe, both before (11 May 1996) and after (17 October 1996) nourishment (Fig. 4.4). There were 4 transects with 16 samples on each transect.

Subsurface samples were collected at the nourishment sites only. The subsurface samples were taken at 0.10 m and 0.20 m below the surface, respectively, at the same locations as the surface samples. All samples were taken from a 0.5 cm layer and weighed about 100 g each.

Wind-laid sand

A third sampling campaign was carried out about two years after nourishment (on 15 and 16 May 1998). On a stretch of coast of 50 m, 60 sample locations were selected at random (using a computer-generated set of *X*- and *Y*-coordinates within the area), on the beach, landward of the sand fence, in the foredunes and in the inner dunes, respectively (Fig. 4.4). Sand was sampled with a 0.25 m gouge auger at these locations. Nourishment sand and native sand were distinguished by determining the colour of the sand. The nourishment sand was very pale brown (Munsell scale 10YR7/3 or 10YR7/4) or light yellowish brown (Munsell scale 10YR6/4) due to ferric hydroxide coatings on the grains, whereas native sand was light grey (Munsell scale 10YR7/1 or 10YR7/2). Where the deposition of nourishment sand was less than 0.25 m, both wind-laid native and wind-laid nourishment sand were sampled at the same sample point. The non-organic samples were used for further analysis. They were divided into:

(1) sand from the nourished beach (16 samples),
(2) wind-laid nourishment sand behind the sand fence (9 samples),
(3) wind-laid nourishment sand in the foredunes and inner dunes (17 samples),
(4) wind-laid native sand in the foredunes and inner dunes (9 samples).

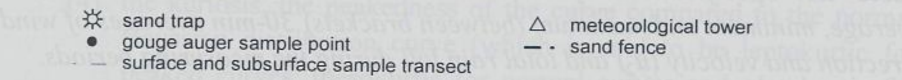

Figure 4.4. *Sampling scheme. The contours display the situation of October 1996, after nourishment. A sand fence was present before nourishment (i.e., there was a sand fence during sampling of the native beach), buried by nourishment (i.e., there was no sand fence during sampling of the nourished beach) and renewed in November 1996 (i.e., there was a sand fence during gouge auger sampling). Co-ordinates (m) refer to the Dutch rectangular co-ordinate system. Height (m) is relative to DOD (Dutch Ordnance Datum), which is about mean sea level. Contour interval is 1 m.*

Sand in transport

Sand traps were used to collect sand in transport, both before and after nourishment, during a period of one month. The omnidirectional vertical distribution-type sand traps, described by Arens & Van der Lee (1995), were installed on the beach (trap T1, T2 and T3 in Fig. 4.4) and at the seaward side of the foredune (trap T4 in Fig. 4.4). The traps collected material up to 0.30 m above the surface in 0.05 m high compartments (trays). For the measurements prior to nourishment, sand traps were exposed for several hours; the period with sand transport was determined using a continuously registrating saltiphone, described by Spaan & Van den Abeele (1991). Measurements on the nourished beach were conducted during sand transport events only; the exposure time was 30 minutes for each run. For this study, the sand trapped during onshore winds was analysed; 26 samples of native sand and 73 samples of nourishment sand were selected. The trap efficiency (which is about 15% for moderate wind speeds) is only slightly dependent on the grain-size distribution of the sand (Arens & Van der Lee, 1995). The creep mode has a lower trap efficiency, especially when the base of a sand trap is not level with the surface, for instance when using long exposure times.

A meteorological tower with rotating cup anemometers was erected on the beach, approximately 50 m from the foredune. Wind speeds were recorded at 2 m elevation (u_2). The tower was topped by a wind vane. The instruments were sampled at 5-sec intervals. The data were automatically recorded and stored in a datalogger; they were averaged over 30-min intervals, corresponding with the sand trap exposure. Specifications of the meteorological conditions during the selected events are listed in Table 4.1.

Table 4.1. *Specifications of selected onshore wind erosion events, with average, minimum and maximum (between brackets) 30-min averages of wind direction and velocity (u_2) and total rain fall during the measuring periods.*

Date	Period (h:min)	Trap exposure	Wind direction (°)		Wind velocity (m s^{-1})		Rain (mm)
Before nourishment							
7 May 1996	02:30-23:00	total period	69	(50-82)	8.34	(6.37-10.00)	0.0
14 May 1996	13:00-23:00	total period	2	(358-9)	7.14	(6.16-8.23)	0.0
After nourishment							
21 Oct 1996	09:30-18:00	30-mins	296	(290-300)	10.08	(8.63-10.96)	0.0
29 Oct 1996	10:00-17:30	30-mins	297	(285-311)	15.08	(13.89-15.90)	2.2

GRAIN-SIZE ANALYSIS

All samples were dried in an oven at 40 °C for 24 hours. The sizes of the surface and subsurface samples and the samples of wind-laid sand were all about 100 g, and all the material was used for grain-size analysis. The sand trap samples were unequal in weight, as sample size depends on aeolian sand transport. Sample size influences the sieving results: large samples tend to give coarser grain-sizes due to shielding of the sieves, and splitting the samples repeatedly in subsamples introduces a splitting error (Socci & Tanner, 1980). Preferably, 50 g of sand trap sample was used. Samples smaller than 15 g were excluded from analysis. Samples larger than 100 g were split once in eight equal subsamples using a splitting-machine with rotating jar containers. If necessary, these subsamples were combined to obtain samples of the target weight of 50 g. Tests with a number of samples proved that each subsample yielded a similar grain-size distribution.

The samples were sieved for 10 minutes on a mechanical sieve shaker. Breakdown of shells and aggregates during sieving was avoided. A nest of nine calibrated sieves was used with a class width of 0.50 φ, starting with a mesh of 3.75 φ (0.075 mm). A sieve with mesh -1.00 φ (2 mm) was added to discriminate between sand and gravel-sized material.

The frequency distributions of grain-size were expressed in mass weight percentages. The frequency distributions of the sand trap samples were also numerically integrated per trap and reconverted to percentages, taking into account the amount of sand that was trapped in every tray.

Four statistical measures of the grain-size distribution can be calculated:

(1) the mean, a measure of central tendency,
(2) the sorting or standard deviation of the distribution,
(3) the skewness, which defines the asymmetry of the frequency distribution,
(4) the kurtosis, the peakedness of the curve compared to the normal Gaussian distribution curve (which is said to be leptokurtic for peaked curves, mesokurtic for normal curves and platykurtic for flat curves).

The measures can be derived either by the moment method, yielding moment measures, and by the percentile-intercept method, yielding graphic measures (Folk, 1966; Depuydt, 1972). In this study, moment measures of every grain-size distribution were calculated using the GAPP computer program (Fay, 1989), and the measures were classified according to Larson *et al.* (1997). Although the moment measure is often recommended, it also has some drawbacks compared to the percentile-intercept method (Folk, 1966; Depuydt, 1972; Larson *et al.*, 1997). For this study, the most important drawback of this method is that curves may be open-ended, in that they contain a large proportion of unanalysed coarse material (shells and coarse shell fragments). It is necessary to make some arbitrary assumptions about the grain-size in the tails of the distribution, because the method of moments includes the entire distribution. In this case, the fraction <-1.00 φ (>2 mm) is considered to be centred around -2.25 φ, and the fraction >3.75 φ (<0.075 mm) is considered to be centred around 4.00 φ.

The amount of fines (>3.75 φ) and the amount of coarse material (<0.75 φ and <-1.00 φ, respectively) were calculated from the grain-size distribution as a weight percentage of the total dry weight of the sample. The grain-size distribution as a whole was also taken into account, because the mixture of quartz and shell fragments may combine to give non-Gaussian size frequency distributions (Carter, 1982). In addition, the moment measures of the sand >0.75 φ were calculated to exclude the bulk of the shells and shell fragments. Kurtosis -3 was calculated to centre the kurtosis values around 0.

CARBONATE CONTENT ANALYSIS

Carbonate content analysis was performed on all surface and subsurface samples. The carbonate content was determined following the Wesemael (1955) method from the three following fractions: >3.25 φ (<0.106 mm), 1.25-3.25 φ (0.106-0.425 mm) and <1.25 φ (>0.425 mm). From each fraction of a sample, 2 to 5 g of homogenized crushed material was forced to react with an excess of HCl, and the weight loss after 26 hours was measured. This weight loss was used to calculate the percentage of CO_2. A blank test, a test with pure calcium carbonate, and a test with pure shell material (whole valves and coarse fragments) from the area were carried out to provide a reference. All tests were performed in duplicate. When the differences between the two measurements were larger than 10%, the test was repeated twice. Percentages of $CaCO_3$ were calculated assuming that all carbonates were present in $CaCO_3$ form. This assumption is not justified as, for instance, the shells are also made out of other carbonates. Therefore, the absolute values have to be interpreted with caution. Furthermore, shells may be made out of substances that do not react. Indeed, the samples of the pure shell only gave a mean percentage of 87.1%.

STATISTICAL ANALYSIS

Non-parametric statistical tests were applied to compare the grain-size parameters of the samples. A Wilcoxon matched-pairs, signed-ranks test was performed to determine the relationship between two dependent samples (for instance, a specific textural parameter on a specific location before and after nourishment). The hypothesis that values of the parameter are equal for the two groups was tested against the alternative hypothesis that these were not equal. Mann Whitney *U* tests were performed to test two independent groups. A level of significance $\alpha=0.05$ was applied.

RESULTS

SURFACE AND SUBSURFACE SAND

Grain-size of native sand and nourishment sand

The textural parameters of nourishment sand and native sand sampled at the surface of the beach, have been compared for every sample location. The samples proved to be significantly different for a number of parameters. Compared to native sand at the surface, nourishment sand at the surface:

(1) is coarser (with respect to mean grain-size),
(2) is more poorly sorted (with respect to the standard deviation),
(3) contains more material < 0.75 φ and <-1.00 φ, and
(4) contains more material >3.75 φ.

Aeolian selection of grain-size

The aeolian selection process was elucidated by comparing the textural parameters of surface nourishment sand (which was exposed for a few months) to those of (unreworked) subsurface nourishment sand collected at 0.10 m below the surface, for every location. There were a number of significant differences. When comparing the surface nourishment sand and the subsurface nourishment sand, the former:

(1) is coarser (with respect to the mean grain-size),
(2) is more poorly sorted,
(3) contains more material <0.75 φ and <-1.00 φ, and
(4) contains more material >3.75 φ.

There were no significant differences in textural parameters of nourishment sand from 0.10 m and 0.20 m below the surface, respectively. There were also no significant differences when the total group of nourishment surface samples was related to the group of -0.10 m samples, due to the large spatial variation in grain-size in the fill.

Hydraulic selection of grain-size in the intertidal zone

To gain insight in the hydraulic selection process, the surface nourishment sand collected at the supratidal beach or backshore (*i.e.* the sand mainly reworked by the wind for a few months) was compared to the sand collected at the intertidal beach or foreshore (*i.e.* the sand mainly reworked by the sea for a few months). Application of the Mann Whitney test yielded the following significant results. Compared to the sand collected at the backshore, the surface nourishment sand collected at the foreshore:

(1) is better sorted,
(2) contains less material $<0.75\ \varphi$, and
(3) contains less material $>3.75\ \varphi$.

Carbonate content of native sand and nourishment sand

The $CaCO_3$ content of the native and nourishment surface sand is determined along a cross-shore transect (Fig. 4.5). On the native beach $CaCO_3$

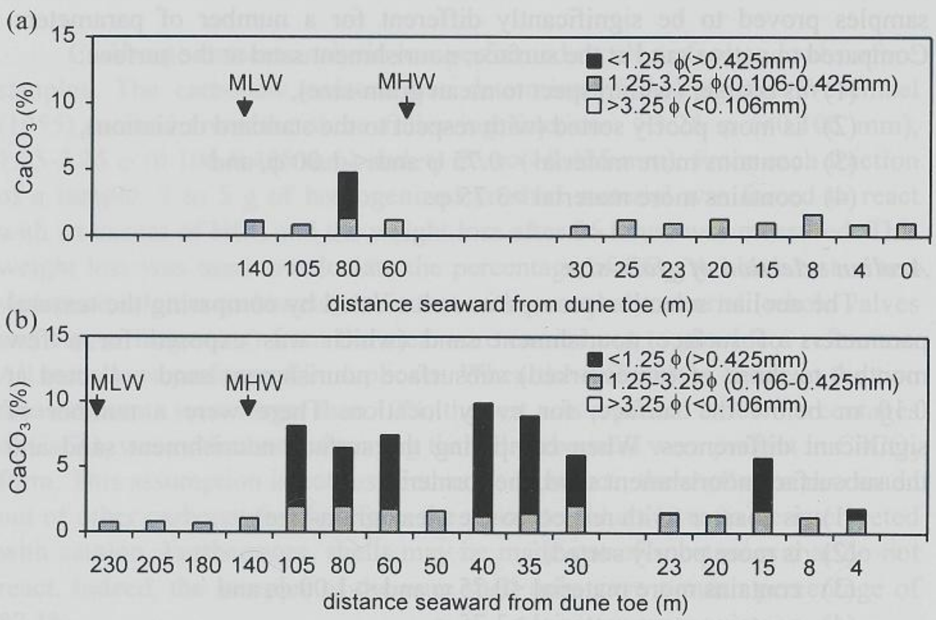

Figure 4.5. *$CaCO_3$ content (%) of (a) native and (b) nourishment surface sand along a cross-shore transect on the beach. The distance from the dune toe is not to scale.*

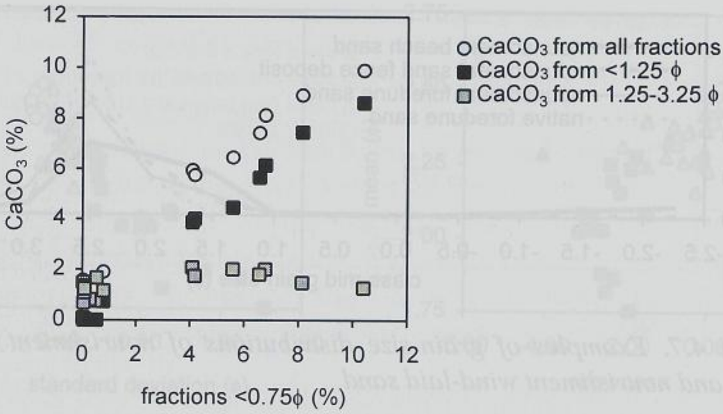

Figure 4.6. *Fractions <0.75 φ (>0.600 mm) versus $CaCO_3$ content for the nourishment sand samples displayed in Fig. 4.5.*

values are under 2%, except for the swash mark, which has much higher values due to the presence of shells. The nourishment beach exhibits more spatial variation, with lag deposits locally containing over 10% of $CaCO_3$ and patches of wind-blown sand deposited on top of the lag with lower $CaCO_3$ contents. $CaCO_3$ contents of nourishment sand are significantly higher than $CaCO_3$ contents of native sand, both in the fraction 1.25-3.25 φ (0.106-0.425 mm) and in the fraction <1.25 φ (>0.425 mm).

The coarse material (<1.25 φ) determines the $CaCO_3$ of the total sample. The finer fractions (>1.25 φ) also contain carbonate, but they do not contribute much to the total amount of $CaCO_3$. The $CaCO_3$ content of both the total sample and the coarse material (<1.25 φ) is thus proportional to the amount of material <0.75 φ, but the $CaCO_3$ content of medium-grained material (1.25-3.25 φ) is not (Fig. 4.6). A plot of the $CaCO_3$ content of native sand would show the same trends.

WIND-LAID SAND

Grain-size of native sand and nourishment sand

The wind-laid nourishment foredune sand differs from the native foredune sand (Fig. 4.7). The nourishment foredune sand contains more sand in the fraction 1.75-2.25 φ and, especially, in the fraction 1.25-1.75 φ.

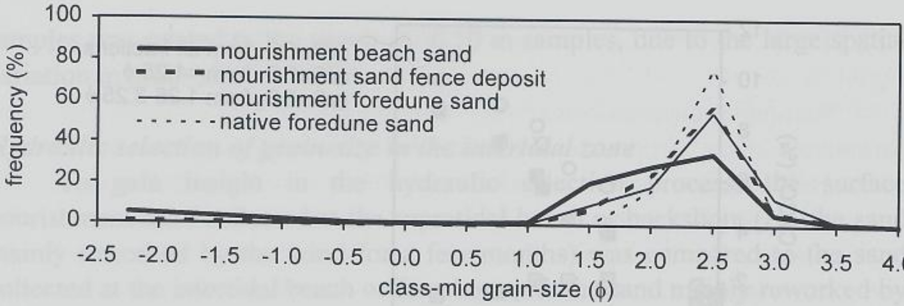

Figure 4.7. *Examples of grain-size distributions of nourishment sand and native and nourishment wind-laid sand.*

A Wilcoxon matched-pairs signed-ranks test performed on wind-laid nourishment and native sand sampled on the same locations in the foredunes reveals the following significant results. Compared to wind-laid native sand, wind-laid nourishment sand from the foredune:

(1) is coarser (with respect to the mean grain-size),
(2) is more poorly sorted,
(3) has a more negatively skewed grain-size distribution, and
(4) contains more material <0.75 φ but not more material <-1.00 φ.

The differences are shown in Fig. 4.8. In addition, moment measures have been calculated for sand >0.75 φ (<0.600 mm), comprising the entire quartz component of the sand. The grain-size distribution of the fractions >0.75 φ is leptokurtic (*i.e.* large kurtosis values) for native wind-laid sand and less leptokurtic or mesokurtic for wind-laid nourishment sand.

Aeolian selection of grain-size

Nourishment sand was traced in the entire area of Fig. 4.4. The amount of nourishment sand that was deposited during two years gradually decreased with distance inland (Fig. 4.9). Behind the sand fence, more than 0.25 m sand was deposited. At the seaward side of the foredune, 0.15 to over 0.25 m of sand was found. At the crest and landward side of the foredune, 0.003 to 0.10 m of sand accumulated. Landward of the foredune, up to 0.005 m of nourishment sand was detected. The examples of grain-size distributions (Fig. 4.7) show that the nourishment beach sand contains coarse material, but mainly material sized 1.25 to 2.75 φ. The sand fence deposits of nourishment sand have a distinct peak at the fraction 2.25-2.75 φ and contain less coarse material. The nourishment foredune sand resembles the sand fence deposit, apart from the absence of the coarse fraction.

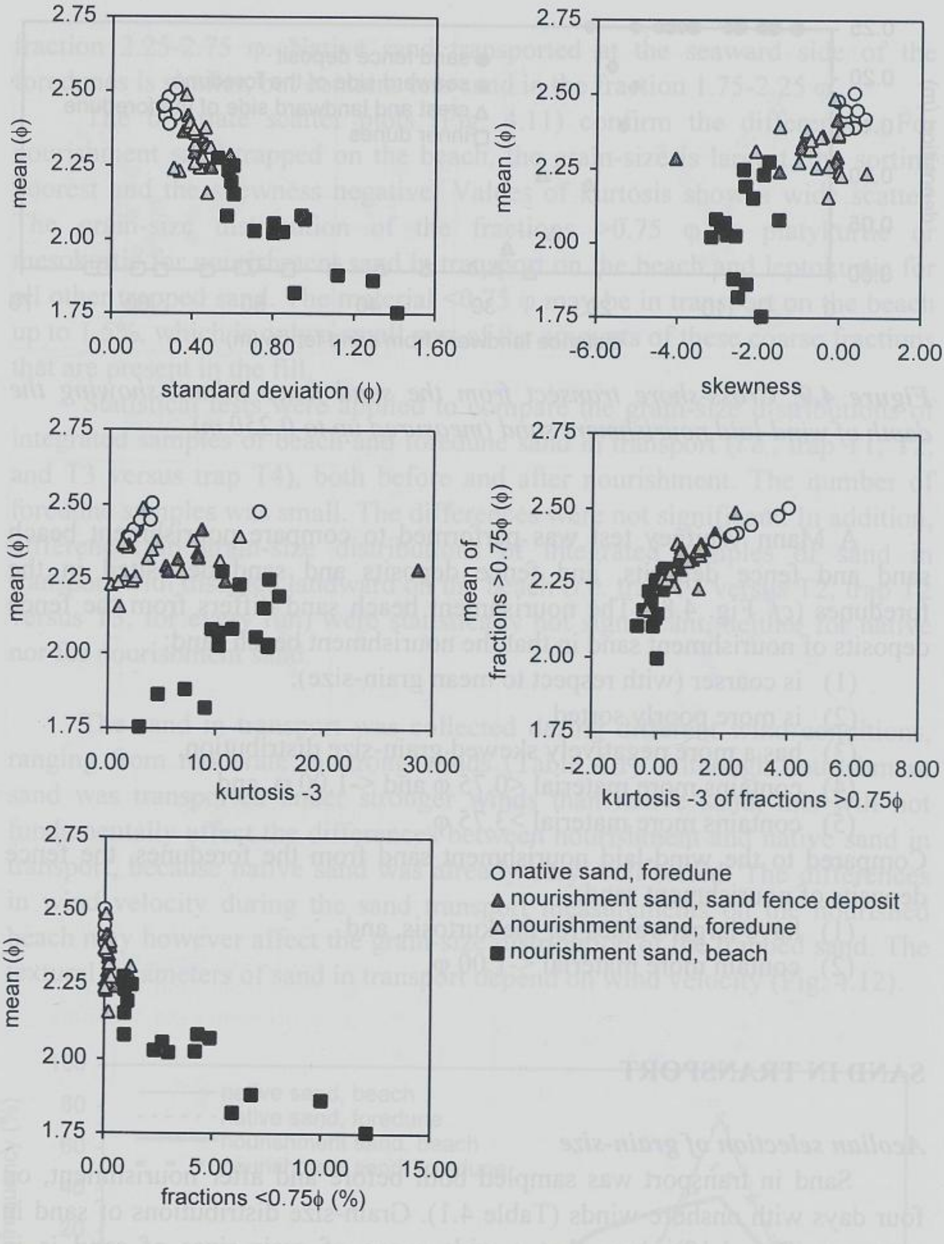

Figure 4.8. *Bivariate scatter plots of nourishment sand and native and nourishment wind-laid sand.*

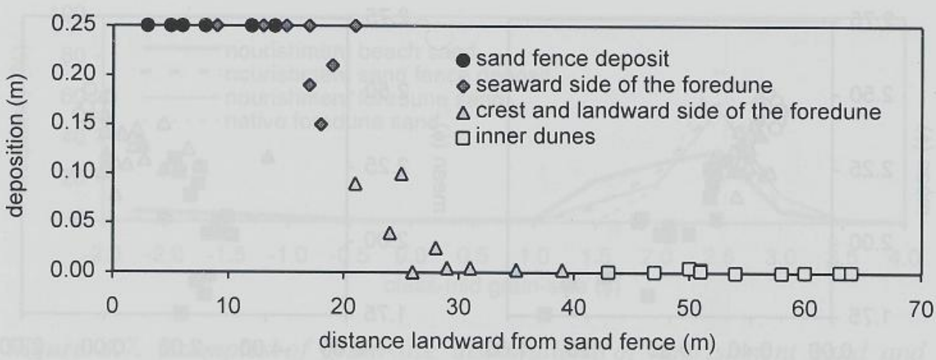

Figure 4.9. *Cross-shore transect from the sand fence inland showing the depth of wind-laid nourishment sand (measured up to 0.250 m).*

A Mann Whitney test was performed to compare nourishment beach sand and fence deposits, and fence deposits and sand deposited in the foredunes (*cf.* Fig. 4.8). The nourishment beach sand differs from the fence deposits of nourishment sand in that the nourishment beach sand:

(1) is coarser (with respect to mean grain-size),
(2) is more poorly sorted,
(3) has a more negatively skewed grain-size distribution,
(4) contains more material <0.75 φ and <-1.00 φ, and
(5) contains more material >3.75 φ.

Compared to the wind-laid nourishment sand from the foredunes, the fence deposits of nourishment sand:

(1) have larger values for the kurtosis, and
(2) contain more material <-1.00 φ.

SAND IN TRANSPORT

Aeolian selection of grain-size

Sand in transport was sampled both before and after nourishment, on four days with onshore winds (Table 4.1). Grain-size distributions of sand in transport (Fig. 4.10) show that a wide range of grain-sizes of sand is in transport on the nourished beach, with most material sized 1.25 to 2.75 φ (0.150 to 0.425 mm). At the seaward side of the foredunes, nourishment sand in the fraction 2.25-2.75 φ is abundant, with admixtures of sand in the fractions 1.75-2.25 φ and 2.75-3.25 φ and only small amounts of fraction 1.25-1.75 φ. The native sand transported on the beach shows a distinct peak at fraction 2.25-2.75 φ. Native sand transported at the seaward side of the foredunes is similar, but contains less sand in the fraction 1.75-2.25 φ.

The bivariate scatter plots (Fig. 4.11) confirm the differences. For nourishment sand trapped on the beach, the grain-size is largest, the sorting poorest and the skewness negative. Values of kurtosis show a wide scatter. The grain-size distribution of the fractions >0.75 φ is platykurtic or mesokurtic for nourishment sand in transport on the beach and leptokurtic for all other trapped sand. The material <0.75 φ may be in transport on the beach up to 1.5%, which is only a small part of the amounts of these coarse fractions that are present in the fill.

Statistical tests were applied to compare the grain-size distributions of integrated samples of beach and foredune sand in transport (*i.e.*, trap T1, T2, and T3 versus trap T4), both before and after nourishment. The number of foredune samples was small. The differences were not significant. In addition, differences in grain-size distributions of integrated samples of sand in transport with distance landward on the beach (*i.e.* trap T1 versus T2, trap T2 versus T3, for every run) were statistically not significant, neither for native nor for nourishment sand.

The sand in transport was collected during different wind conditions, ranging from moderate to strong winds (Table 4.1). Although nourishment sand was transported under stronger winds than native sand, this will not fundamentally affect the differences between nourishment and native sand in transport, because native sand was already very well sorted. The differences in wind velocity during the sand transport measurements on the nourished beach may however affect the grain-size distribution of the trapped sand. The textural parameters of sand in transport depend on wind velocity (Fig. 4.12).

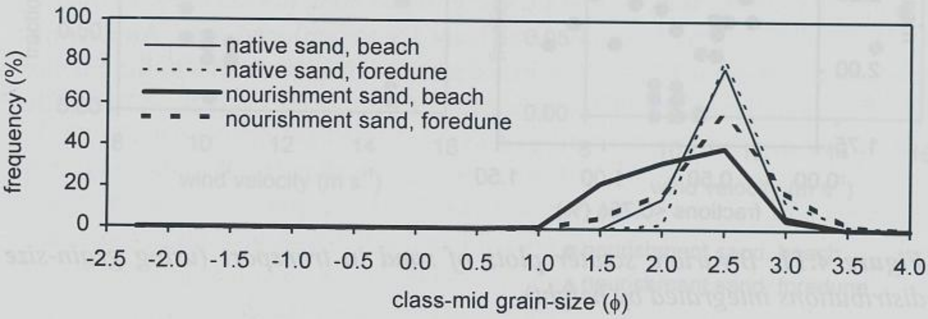

Figure 4.10. *Examples of grain-size distributions of sand in transport, integrated by height.*

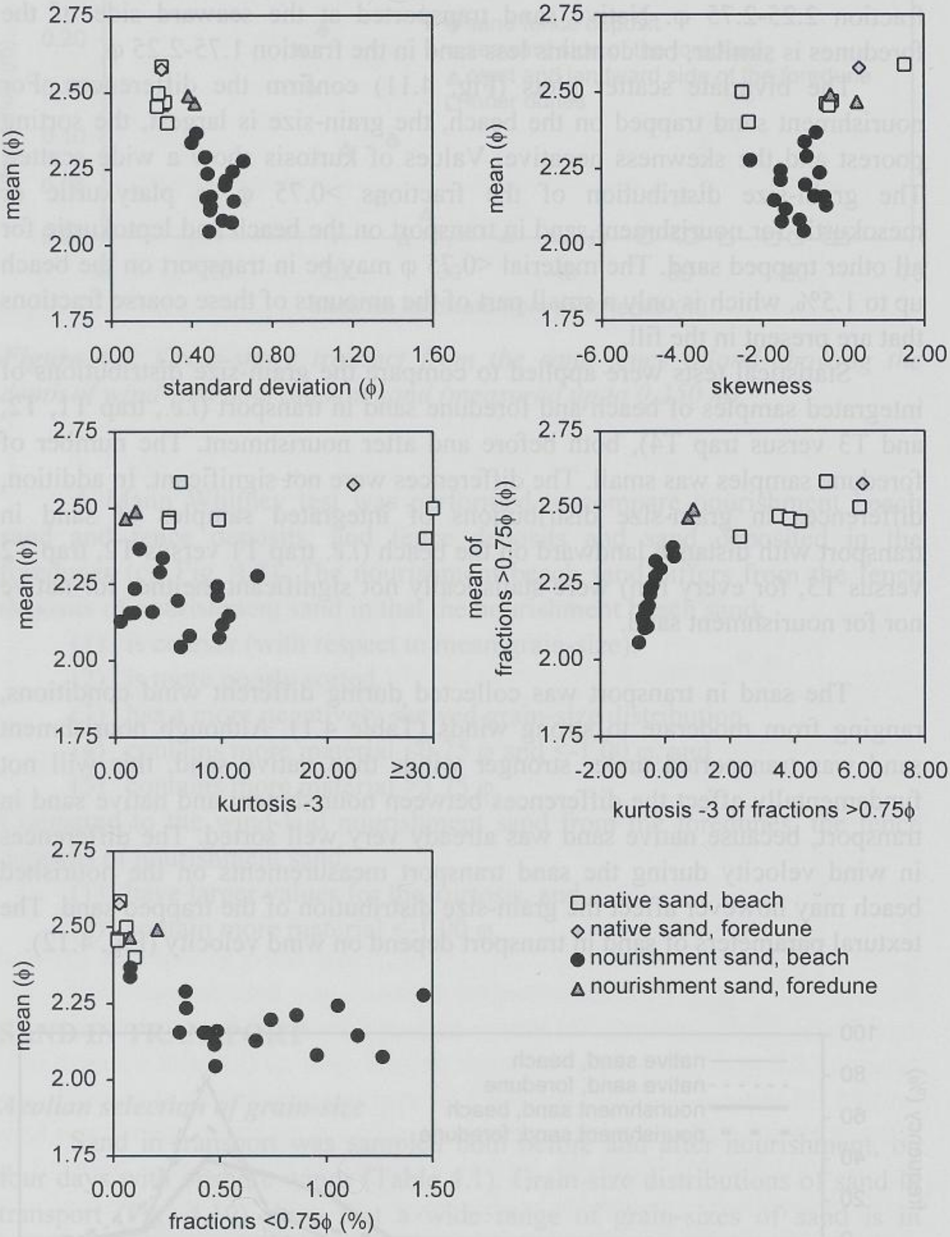

***Figure 4.11.** Bivariate scatter plots of sand in transport (using grain-size distributions integrated by height).*

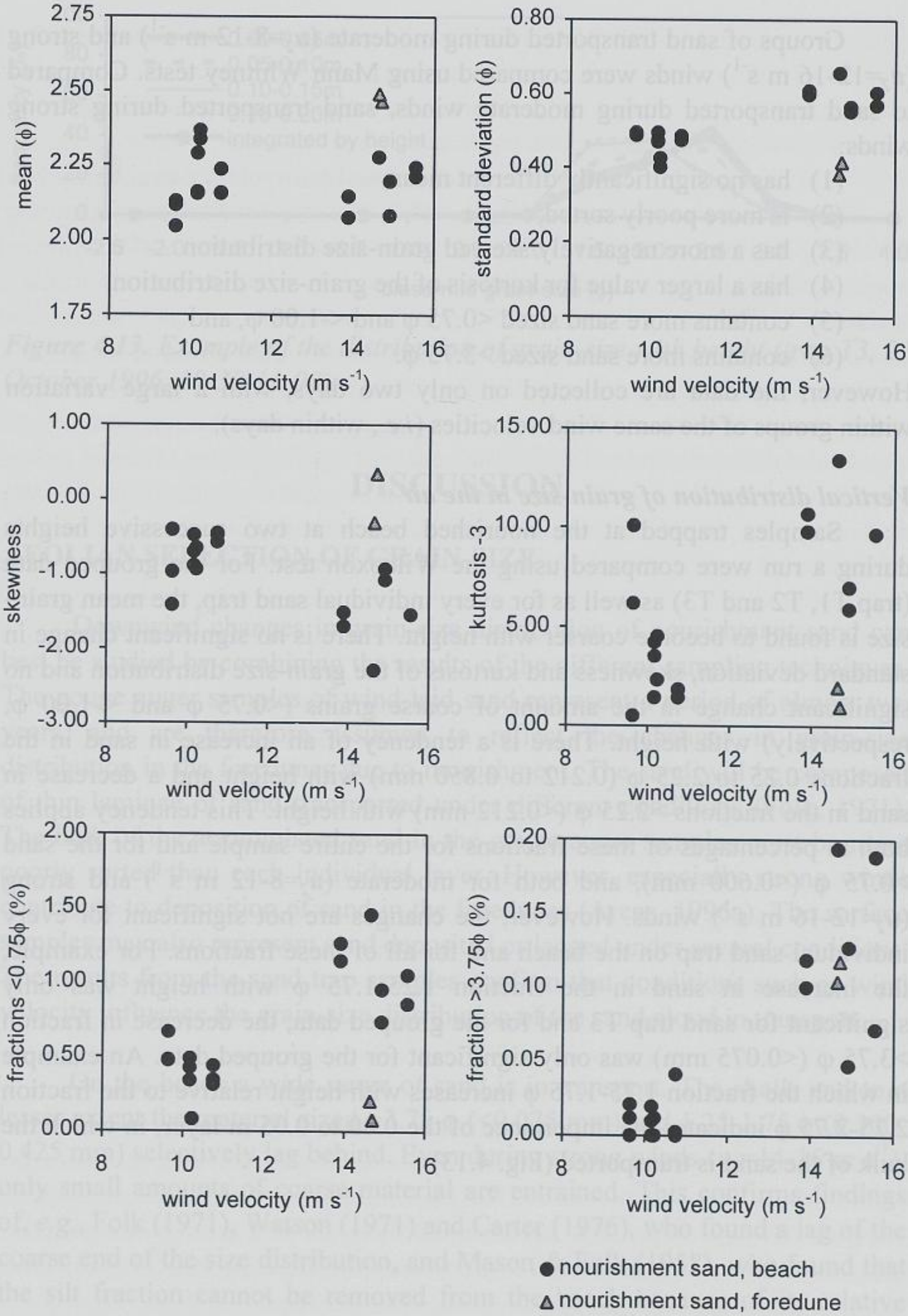

Figure 4.12. *Some textural parameters of sand in transport versus wind velocity (using grain-size distributions integrated by height).*

Groups of sand transported during moderate (u_2=8-12 m s^{-1}) and strong (u_2=12-16 m s^{-1}) winds were compared using Mann Whitney tests. Compared to sand transported during moderate winds, sand transported during strong winds:

(1) has no significantly different mean,
(2) is more poorly sorted,
(3) has a more negatively skewed grain-size distribution
(4) has a larger value for kurtosis of the grain-size distribution
(5) contains more sand sized <0.75 φ and <-1.00 φ, and
(6) contains more sand sized >3.75 φ.

However, the data are collected on only two days, with a large variation within groups of the same wind velocities (*i.e.*, within days).

Vertical distribution of grain-size in the air

Samples trapped at the nourished beach at two successive heights during a run were compared using the Wilcoxon test. For the grouped data (trap T1, T2 and T3) as well as for every individual sand trap, the mean grain-size is found to become coarser with height. There is no significant change in standard deviation, skewness and kurtosis of the grain-size distribution and no significant change in the amount of coarse grains (<0.75 φ and <-1.00 φ, respectively) with height. There is a tendency of an increase in sand in the fractions 0.25 to 2.25 φ (0.212 to 0.850 mm) with height and a decrease in sand in the fractions >2.25 φ (<0.212 mm) with height. This tendency applies both to percentages of these fractions for the entire sample and for the sand >0.75 φ (<0.600 mm), and both for moderate (u_2=8-12 m s^{-1}) and strong (u_2=12-16 m s^{-1}) winds. However, the changes are not significant for every individual sand trap on the beach and for all of these fractions. For example, the increase in sand in the fraction 1.25-1.75 φ with height was only significant for sand trap T3 and for the grouped data, the decrease in fraction >3.75 φ (<0.075 mm) was only significant for the grouped data. An example in which the fraction 1.25-1.75 φ increases with height relative to the fraction 2.25-2.75 φ indicates the importance of the 0.00 to 0.05 m layer, in which the bulk of the sand is transported (Fig. 4.13).

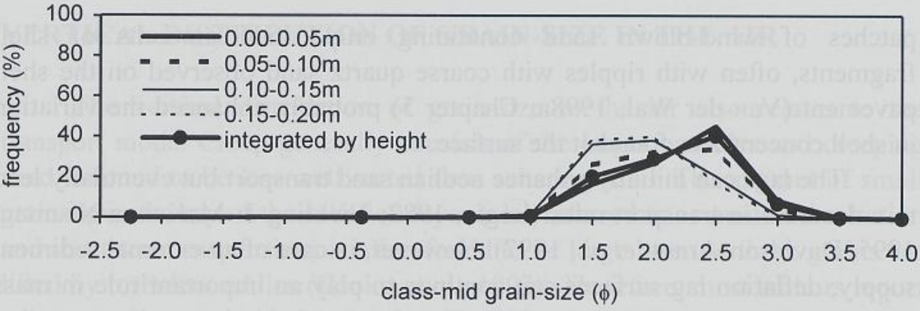

Figure 4.13. *Example of the distribution of grain-size with height (trap T3, 21 October 1996, 10:30-11:00).*

DISCUSSION

AEOLIAN SELECTION OF GRAIN-SIZE

Downwind changes in grain-size distribution of nourishment sand can best be studied by combining the results of the different sampling techniques. The gouge auger samples of wind-laid sand represent a period of almost two years, and are therefore assumed to reflect the changes in grain-size distribution in the foredunes due to nourishment. The sand will be composed of thin laminae of sand transported under different conditions (Folk, 1971). The bulk of the accumulated sand in the gouge auger samples must be more poorly sorted than each individual layer. However, especially strong winds contribute to deposition of sand in the foredunes (Arens, 1996a). The surface samples may also represent sand deposited or lagged under several conditions. The results from the sand trap samples confirm that conditions such as wind velocity influence the grain-size distribution of the sand cloud in transport.

On the beach a wide range of sand is in transport. The shells and to a lesser extent the material sized >3.75 φ (<0.075 mm) and 1.25-1.75 φ (0.300-0.425 mm) selectively lag behind. Even during strong winds (u_2=14-16 m s^{-1}), only small amounts of coarse material are entrained. This confirms findings of, *e.g.*, Folk (1971), Watson (1971) and Carter (1976), who found a lag of the coarse end of the size distribution, and Mason & Folk (1958), who found that the silt fraction cannot be removed from the beach because of its relative inaccessibility to wind erosion. The shells formed a non-uniform shell pavement at the surface. The variation in subsurface concentrates of shells, the wind-blown sand trapped within the shell pavement and, especially, the patches of wind-blown sand containing only small amounts of shell fragments, often with ripples with coarse quartz sand observed on the shell pavement (Van der Wal, 1998a; Chapter 5) probably enhanced the variation in shell concentrates found at the surface.

The lags can initially enhance aeolian sand transport but eventually lead to a decrease in transport rates (Logie, 1982; Nickling & McKenna Neuman, 1995; Davidson-Arnott *et al.*, 1997). However, in case of an external sediment supply, deflation lag surfaces can continue to play an important role in mass transport (McKenna Neuman, 1998). For the Ameland site, such an upwind sediment supply is provided by the intertidal zone, which was illustrated by sand transport measurements by Van der Wal (1998a; Chapter 5). The present study shows that the modification of the grain-size distribution of the sand due to the different rates of hydraulic response and breakage of shells makes the nourishment sand itself more susceptible to wind erosion. There are only low densities of shells on the foreshore, with the exception of shells concentrated within the high-energy breaker zone (swash mark). There are also less fine (>3.75 φ) particles on the intertidal beach than on the supratidal beach, as the finest material is transported offshore due to turbulence and swell of the sea (Depuydt, 1972).

From the beach landward to the foredunes, the grain-size distribution of the wind-blown nourishment sand became finer, better sorted, less negatively and eventually positively skewed and leptokurtic. This supports findings of, *e.g.*, Bagnold (1941), Folk & Ward (1957), Shephard & Young (1961) and McLaren & Bowles (1985) in natural beach, desert, and river environments. The wind-laid nourishment sand in the foredunes contains 4.9% of the material <0.75 φ (>0.600 mm) and only 0.6% of the material <-1.00 φ (>2 mm) of those in the nourishment sand on the beach, on average. However, this still means a significant increase in absolute amounts of these fractions in the foredune sand due to beach nourishment.

There are three main modes of transport: creep, saltation, and suspension (Bagnold, 1941). According to Bauer (1991), downwind grading of sediments is not necessarily gradual because these different transport modes infer non-gradual changes. The non-linearity in the landward decerase in deposition (Fig. 4.9) confirmed findings of Arens (1996a), who atttributed a rapid decrease in deposition between the dune toe and crest to the saltation process and a more gradual decrease between the foredune crest and the inner dunes to the suspension process.

VERTICAL DISTRIBUTION OF GRAIN-SIZE IN THE AIR

The vertical distribution of grain-size in the air also relates to the transport mode. Creep generally consists of the larger particles and creeping sand is found to be less well sorted than saltating sand. The amount of small grains near the top of the saltation layer (also referred to as modified saltation and short-term suspension) is often found to be large because these grains are lifted by turbulent eddies (Cooke *et al.*, 1993). Therefore, most authors report a decrease in mean grain-size and an increase in sorting with height above the surface (Gerety & Slingerland, 1983; Weihan *et al.*, 1995). However, some authors (Bagnold, 1941; Sharp, 1964) found that average rebound heights are larger for larger particles, providing they are <3.00 φ (>0.125 mm) in size. Large particles may rise high into the saltation layer because they have lower specific surface areas and therefore have proportionally less vertical drag (Cooke *et al.*, 1993). Van Dijk (1990) and Arens (1994) also found an increase in grain-size with height on the beach and Williams (1964) found both increases and decreases in grain-size with height. De Ploey (1978) and Draga (1983) found an increase in mean grain-size and sorting with height due to a concentration of both very coarse sand and silt near the ground surface, although some gravel-sized grains bounced to a height of up to 0.5 m. Because small grains receive their energy supply from the turbulent fluctuations of the fluid, the grains may also damp out these fluctuations (Raudkivi, 1967). Draga (1983) suggested that this phenomenon may especially be important during high wind velocities. A number of authors suggest that the grain-size distribution of the eroding sediment directly affects the percentage of sediment transported in each mode (Nickling & Davidson-Arnott, 1990). There does not seem to be a prerequisite of grain-size for a given mode of transport. Perfect separation of different sizes of particles does not occur, because aeolian sediment transport is a stochastic process in which the trajectories of individual grains are affected to varying degrees by random turbulent fluctuations of wind, and also by considerable natural variability in the nature of grain-bed collisions (Ungar & Haff, 1987; Anderson, 1987).

The separation between the transport modes in the field is virtually impossible. The lowest compartment of the sand traps used in this study catches sand up to 0.05 m, which comprises the bulk of the sand in transport, including the underscored creep mode and a substantial part of the saltation load. Applying a different trap efficiency for the lowest tray and the upper trays will only partly improve the approach to calculate an integrated grain-size. The shift in grain-size from predominantly 2.25-2.75 to 1.25-1.75 φ with height and the absence of such a trend for the fractions <0.75 φ (*i.e.* the shell fragments) found in trap T3 on the beach suggests that there is a tendency of some larger quartz grains to rebound to greater heights. Possibly, the effect is amplified by the presence of the hard shell pavement (especially found near trap T3), which, according to Bagnold (1941), results in higher rebound heights of saltating grains. In addition, both Williams (1964) and Willetts *et al.* (1982) observed that grains of low sphericity, such as shell fragments, have flatter trajectories than the more spherical (quartz) grains. Preferential blow-out of the 2.25-2.75 φ fraction from the higher compartments of the sand traps was refuted by Arens (1994).

The small quantities of sand transported to the foredunes do not resemble the load transported near the top of the saltation layer, but rather resemble a further selection from the grain-sizes of the entire load in transport that was selected from the surface.

CARBONATE CONTENT OF SAND

$CaCO_3$ contents of the native sand were small. The values were below 2% on the beach. Additional surface samples from the foredunes collected before nourishment show that the small fractions in the sand (>3.25 φ) contain up to 0.7% $CaCO_3$ (which is 0.0% of the total sample), and the sand sized 1.25 to 3.25 φ contains 1.2% $CaCO_3$ at most (which is 1.2% of the total sample). The $CaCO_3$ content of beach sand was significantly higher after nourishment. The $CaCO_3$ contents of the separate fractions in the wind-blown nourishment sand were not studied. However, the coarse fraction of the sand (<0.75 φ) (which almost entirely consists of shell fragments), that is blown to the foredunes, significantly increased after nourishment. This study also shows that the nourishment sand is transported far into the dune area, in which initial lime contents can be small. From this point of view, vegetation effects due to nourishing lime-rich fill in lime-poor districts are therefore probable. Further research could focus on this issue.

CONCLUSIONS

As soon as the beach is nourished, marine and aeolian selection processes alter the surface texture of the beach. Marine reworking results in a decrease in shell fragments and silt below the low water line, with the exception of the swash mark. Lag deposits form above the high water line, as the amount of shells and shell fragments taken into transport by wind is small.

Furthermore, the silt fraction is left behind. The nourishment sand in transport reaching the foredune is therefore finer and better sorted, and also contains less coarse quartz (1.25-1.75 φ fraction) than the beach sand.

The nourishment sand that is blown to the foredunes deviates from the wind-laid native sand in that it is coarser, more poorly sorted and more negatively skewed. Although coarse material (*i.e.,* material <0.75 φ (>0.600 mm) selectively lag behind, wind-laid nourishment sand contains more coarse material than the native beach sand and the wind-laid native sand found in the foredunes. Because a good correlation was found between the amount of this coarse material and carbonate content, this suggests that vegetation effects may be expected.

ACKNOWLEDGEMENTS

Part of this work was financially supported by the Cornelis Lely Stichting. Rijkswaterstaat Ameland is thanked for logistic support. Caja van der Woude assisted in the field and performed the carbonate analyses. Jean Melounou, Stéphane Rognon and Robert Colombo helped with the sieving. Bas Arens, John van Boxel, Pim Jungerius, Aart Kroon and Norbert Psuty are acknowledged for their critical comments on the manuscript.

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CHAPTER 5

EFFECTS OF FETCH AND SURFACE TEXTURE ON AEOLIAN SAND TRANSPORT ON TWO NOURISHED BEACHES

ABSTRACT

On two nourished beaches aeolian sand transport was related to fetch of wind over beach sand and surface characteristics. Meteorological and hydrological conditions were recorded for two months. The fetch of wind over beach sand was estimated from wind direction, water level, wave height and beach topography. Aeolian sand transport was determined with sand traps. Sediment flux was found to increase with fetch, although this relation was especially affected by the variability in surface characteristics. On one of the beaches, sediment supply was limited as a result of shells, forming a lag deposit.

KEY WORDS

Aeolian sediment flux, fetch, shell pavements, beach nourishment, field measurements, the Netherlands.

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INTRODUCTION

Beach nourishment is often used as a method to compensate for marine erosion in sandy coastal areas (Davison *et al.*, 1992). The method implies a direct supply of sand to a beach, where the sand acts as a buffer against wave energy during extreme events. Besides, it affects the sediment exchange rate between the beach and dunes by aeolian processes. Changes in the rate of aeolian sand transport depend on location, size and shape of the nourishment and fill material. In particular, sediment flux may be affected by fetch of wind over beach sand and characteristics of the sand at the surface.

When loose sand is transported over a dry surface and the saltation population is in equilibrium with the local flow field, the rate of transport of sand by wind can be described by (Bagnold, 1941):

$$q = C\sqrt{\frac{d}{D}}\,\frac{\rho_a}{g}\,u_*^3 \qquad \textbf{\textit{(Equation 5.1)}}$$

where q is the sediment flux (kg m^{-1} s^{-1}), C is an empirical coefficient (varying from 1.5 for a nearly uniform sand to 2.8 for a sand with a very wide range of grain-size, to more than 3.5 for a relatively immobile surface), d is the grain diameter of the sand (μm), D is the grain diameter of a standard sand (250 μm), ρ_a is the air density (taken as 1.22 kg m^{-3}), g is the gravitational acceleration (taken as 9.81 m s^{-2}) and u_* is the friction velocity (m s^{-1}). Kawamura (1951) expressed sediment flux as:

$$q = K\frac{\rho_a}{g}(u_* + u_{*_t})^2(u_* - u_{*_t}) \qquad \textbf{\textit{(Equation 5.2)}}$$

where K is an empirical coefficient of about 2.78 in field experiments, and u_{*_t} is the threshold friction velocity (m s^{-1}) at which dry and non-cohesive sand starts to move. Bagnold (1941) described this threshold by:

$$u_{*_t} = A\sqrt{\frac{(\rho_s - \rho_a)}{\rho_a}gd} \qquad \textbf{\textit{(Equation 5.3)}}$$

where A is a constant (with a value of 0.1 at the initiation of motion (fluid threshold), dropping to 0.08 once active saltation begins (impact threshold)), ρ_s is the grain density (for quartz, 2650 kg m^{-3}) and d is the mean grain diameter (m). For moist sand, the threshold friction velocity term can be replaced with a wet surface equivalent (Namikas & Sherman, 1995).

In a steady wind above the threshold for wind erosion, saltation develops with distance downwind from a leading edge of a saltating surface (Bagnold, 1941). The distance required to achieve a fully developed saltation layer is known as critical fetch (Gillette *et al.*, 1996). On a beach, the minimum available fetch is delimited by the beach width from the limit of run-up to the edge of the dunes (Nickling & Davidson-Arnott, 1990). Several studies report that beach width can restrict sediment transport (*e.g.* Svasek & Terwindt, 1974; Davidson-Arnott & Law, 1990; Nordstrom & Jackson, 1992; Arens, 1996b). Nourishment usually enlarges the beach. This increases the fetch of wind over beach sand during the lifetime of the nourishment. To predict changes in the rate of aeolian sand transport due to beach nourishment, the role of fetch in aeolian sand transport has to be understood.

Fill material may differ from native material in grain-size and sorting (Draga, 1983; Van der Wal, 1998b; Chapter 3). This is because sand in offshore source areas is usually not sorted in the same way by marine and aeolian processes as the sand that normally reaches the beach. Besides, the nourishment sand, often containing sand deposited under various sedimentological conditions, is mixed when transported to the beach on which it is deposited. In the Netherlands, for example, the nourishment sand may contain considerable amounts of shells and clay, in contrast to well sorted native beach sand. A change in grain-size or sorting of sand induces a change in the rate of aeolian sand transport on a beach (see Eqs 5.1, 5.2 and 5.3).

The research presented here is part of a study on aeolian transport of nourishment sand, studied on two nourished beaches along the Dutch coast. The aim of this paper is to relate aeolian sand flux to fetch of wind over beach sand and textural characteristics of sand on these beaches. The paper reports measurements of aeolian sand transport and meteorological and hydrological conditions and estimations of fetch of wind over beach sand. Relations between aeolian sand transport and wind velocity, fetch and surface characteristics are discussed.

STUDY SITES

Two sites along the Dutch coast were selected from coastal sections in which a beach nourishment was carried out in the summer of 1996. The sites were located on the Wadden island of Ameland, and along the Holland coast near Den Helder, respectively (Fig. 5.1).

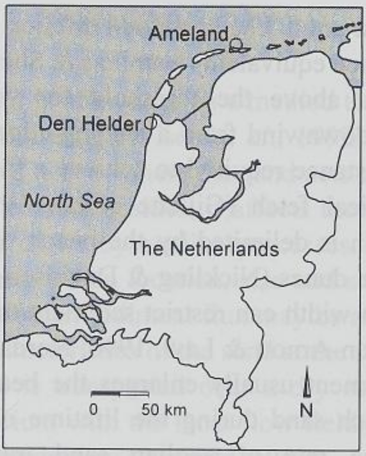

Figure 5.1. Location of field sites.

Ameland

The study site referred to as Ameland is situated on the North Sea side of the barrier island of Ameland, near the village of Ballum. The aspect of the coast is 0°; northerly winds blow perpendicular onshore. In general, the barred beach has an intermediate hydrodynamic regime (Short, 1991). The site has a semi-diurnal tide with a mean tidal range of just over 2 m (mesotidal).

The beach on Ameland was nourished in the late spring and summer of 1996. An amount of 1.56×10^6 m^3 of sand was deposited on the beach, along a stretch of coast of 4 km. The width of beach that was situated above the Dutch Ordnance Datum (DOD), which is about mean sea level, increased from about 90 m before nourishment to 175 m after nourishment. The slope of the backshore ranges from 0° to 4°. Adjacent to the beach, there is a vegetated foredune ridge of over 10 m +DOD, aligned parallel to the shore (Fig. 5.2).

Table 5.1 presents the characteristics of the beach sand. The native beach sand was composed of fine-grained very well sorted quartz sand. Samples of the unreworked nourishment sand collected at 0.1 m beneath the surface of the nourishment were well to only moderately well sorted. The nourishment sand contained up to 0.6% very fine material (fraction <75 μm). There was an admixture of heavy minerals to the quartz in the fine fractions, comprising, for instance, epidote, garnet, and rutile (Schuiling *et al.*, 1985). At the surface of the nourishment, the average mean grain-size of the sediment was 1.63 φ (323 μm), with an average sorting of 1.35 φ. Lag deposits of poorly sorted sand with shell fragments and small deposition

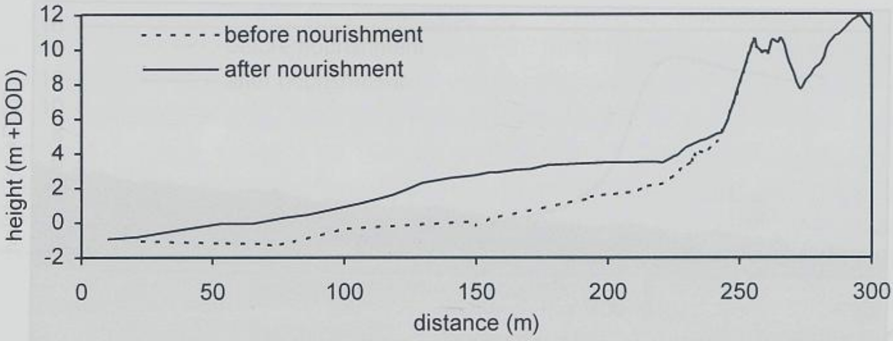

Figure 5.2. *Cross-shore profile of the Ameland site before (6 May 1996) and after (8 October 1996) beach nourishment. Distance is relative to an arbitrary benchmark on the transect. Height is relative to DOD, which is about mean sea level.*

Table 5.1. *Average and minimum and maximum (between brackets) mean grain-size and sorting of Ameland sand, using moment measures.*

	Mean grain-size (mm)	(φ)		Sorting (φ)		No. of samples
Before nourishment						
Surface sample	0.202	2.31	(1.95-2.49)	0.35	(0.27-0.82)	10
After nourishment						
Surface samples	0.323	1.63	(0.94-2.33)	1.35	(0.34-2.04)	9
Depth samples	0.247	2.02	(1.54-2.33)	0.73	(0.38-1.45)	9

patches of very well sorted sand formed after some aeolian activity (Fig. 5.3). Due to wave action, sediment at the foreshore contained few shell fragments and was well sorted.

Den Helder

The research area referred to as Den Helder is situated on the North Sea coast of North-Holland, about 3 km from the town of Den Helder. The aspect of the coast is 272°; westerly winds blow perpendicular onshore. In general, the barred beach has an intermediate hydrodynamic regime (Short, 1991). The tide is semi-diurnal and the mean tidal range is 1.4 m (microtidal). Cross-shore groynes are constructed approximately 200 m apart. They are awash at high tide.

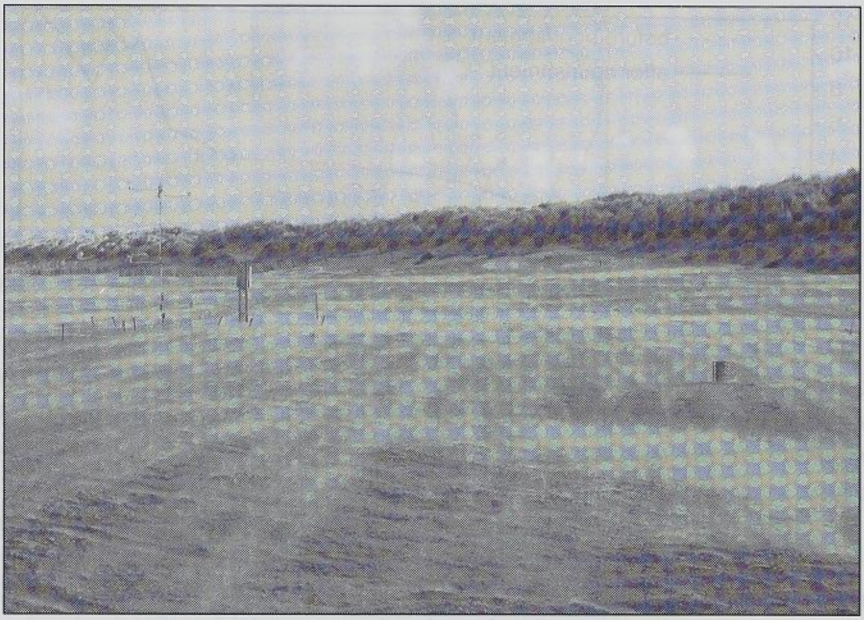

Figure 5.3. The study site on Ameland with aeolian sand transport during onshore winds. (Photograph taken on 21 October 1996.)

Figure 5.4. The study site near Den Helder. (Photograph taken on 30 November 1996.)

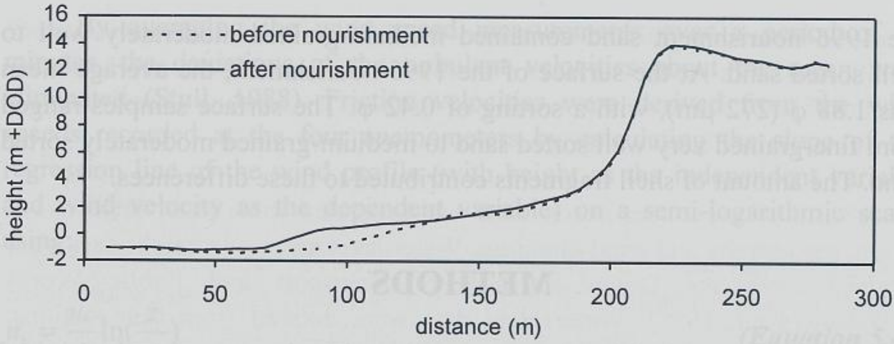

Figure 5.5. *Cross-shore profile of the Den Helder site before (8 June 1996) and after (20 December 1996) beach nourishment. Distance is relative to an arbitrary benchmark on the transect. Height is relative to DOD, which is about mean sea level.*

The beach near Den Helder was first nourished between the summers of 1992 and 1993. A second nourishment was carried out in the summer of 1996, when about 0.85×10^6 m^3 of sand was placed along a stretch of coast of approximately 5.5 km. Most of the 1996 nourishment sand was deposited on the foreshore, in between the groynes (Figs 5.4 and 5.5). As a result, the width of beach above DOD increased from about 90 m to 110 m after the 1996 nourishment. The beach slope is between 0° and 4°. The beach is bordered by a foredune ridge of 14 m +DOD (Fig. 5.5).

Table 5.2 presents the characteristics of the beach sand. Sand that was sampled prior to the 1996 nourishment was composed of medium-grained very well to well sorted sand containing some shell fragments. Samples collected at 0.1 m beneath the surface of the 1996 nourishment showed that

Table 5.2. *Average and minimum and maximum (between brackets) mean grain-size and sorting of Den Helder sand, using moment measures.*

	Mean grain-size (mm)	(φ)		Sorting (φ)		No. of samples
Before nourishment						
Surface sample	0.332	1.59	(1.41-1.83)	0.39	(0.34-0.49)	5
After nourishment						
Surface samples	0.272	1.88	(1.54-2.13)	0.42	(0.32-0.61)	6
Depth samples	0.354	1.50	(1.24-1.73)	0.58	(0.44-0.67)	6

the 1996 nourishment sand contained medium-grained moderately well to well sorted sand. At the surface of the 1996 nourishment, the average mean was 1.88 φ (272 μm), with a sorting of 0.42 φ. The surface samples ranged from fine-grained very well sorted sand to medium-grained moderately sorted sand. The amount of shell fragments contributed to these differences.

METHODS

The data used in this paper were collected in the autumn and winter of 1996. Fig. 5.6 gives an overview of the locations where the equipment was installed. On the beach, approximately 50 m from the foredune, a meteorological tower was erected. Four rotating cup anemometers were mounted at 0.5, 1, 2 and 4 m elevation, respectively. The tower was topped by a wind vane. Due to instrument failure of the vane on the beach a wind vane in the inner dune had to be used at the Den Helder site. The rain intensity was measured using a tipping bucket rain gauge. The data were automatically recorded and stored in a datalogger. The instruments were sampled at 5-second intervals. The statistical data output (minimum, maximum, mean and standard deviation) over 30-minute intervals was used for further analysis. The amount of precipitation was integrated over 30-minute intervals.

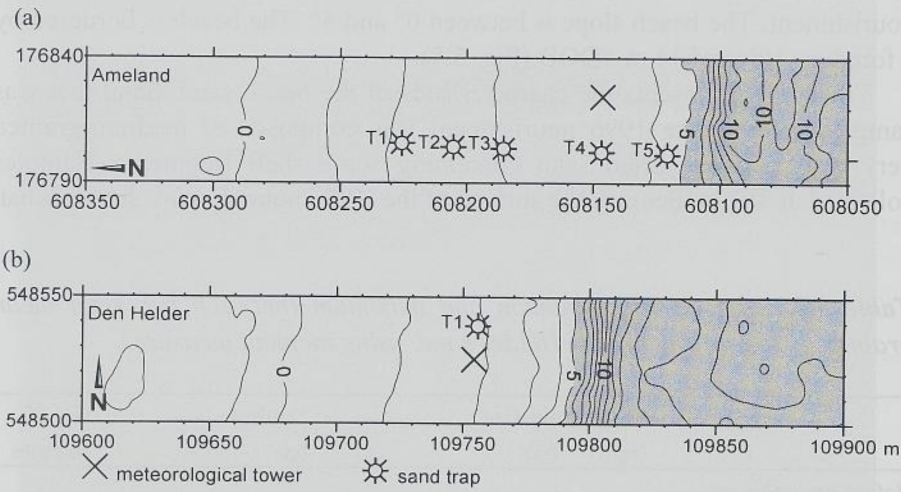

__Figure 5.6.__ Plan view of (a) the Ameland site and (b) the Den Helder site with the location of the equipment. Co-ordinates (m) refer to the Dutch rectangular co-ordinate system. Contour interval is 1 m. Height is relative to DOD, which is about mean sea level.

By averaging the wind speed measurements over a period of 30 minutes, the deviations of the turbulent velocities about the mean were eliminated (Stull, 1988). Friction velocities were derived from the wind speeds recorded at the four anemometers by calculating the slope of the regression line of the wind profile (with height as the independent variable and wind velocity as the dependent variable) on a semi-logarithmic scale, using:

$$u_z = \frac{u_*}{\kappa} \ln(\frac{z}{z_0}) \qquad \textbf{\textit{(Equation 5.4)}}$$

where u_z is the wind velocity (m s^{-1}) at height z (m) , u_* is the friction velocity (m s^{-1}), κ is the Von Kármán constant (taken as 0.4) and z_0 is the aerodynamic roughness length (m) (Von Kármán, 1934). Eq. 5.4 applies to neutral atmospheric conditions and uniform flow (Stull, 1988; Bauer *et al.*, 1992). For large friction velocities (u_*>0.4 m s^{-1}) these conditions were satisfied. The aerodynamic roughness length appeared to be fairly constant during periods with sand transport (z_0=0.001 m). For lower friction velocities, either non-uniform wind flow during offshore winds or unstability of the atmosphere on days with high solar radiation lead to underestimations of roughness length and, hence, of friction velocity for some periods. However, for the range of heights which is used for regression (0.5 to 4 m), only small errors were made (Arens *et al.*, 1995).

During sand-blowing events, omnidirectional vertical distribution-type traps were exposed to the wind to determine the rate of aeolian sand transport. The traps collected material from 0 to 0.3 m above the surface. The exposure time was 30 minutes, coinciding with the automatic measurements. For 19 October 1996, exposure time was 2 hours. The sand traps were placed in a cross-shore array from the beach to the foredune. In this study, a selection of these traps was used (Fig. 5.6). On the photograph of the Ameland site (Fig. 5.3), a trap (T4) is shown at the right. Arens & Van der Lee (1995) described the sand traps in detail. They also tested the traps in a wind tunnel under different conditions. Trap efficiencies were calculated given an effective trap width of 0.1 m. For moderate wind speeds, efficiencies of 14% to 19% were found. The efficiency depends on the grain-size distribution of the blown sand. There is also a pronounced effect of the moisture content of the sand on trap efficiency. Under moist conditions less sand blows out of the trap due to cohesion of the sand, especially during strong aeolian sand transport. Arens & Van der Lee (1995) report an increase in trap efficiency of about 10% for these conditions. In the present study a trap efficiency of 15% was assumed for all data. The transport rates presented in this paper are the total dry weights of collected material normalized by the exposure time (30 minutes for most runs), the efficiency (15%) and the trap width (0.1 m).

Fetch of wind over beach sand was estimated from water level, wave height, topography and wind direction. Water level and wave height data were obtained from the Dutch Ministry of Transport and Public Works (Rijkswaterstaat, 1996). Water level data were derived from four stations: Terschelling Noordzee and Wierumergronden for the Ameland site, and Den Helder and Petten Zuid for the study site near Den Helder (Fig. 5.7). First, the 10-minute water level averages (m +DOD) from the two stations for each site were set in phase. Then, for the Ameland site an average of every pair of water level data was calculated. For the Den Helder site a weighted average was made, using a factor of 0.8 for the water level at the Den Helder station and a factor of 0.2 for the water level at the Petten Zuid station. The factors were estimated from the proximity of the stations to the study sites and from the shape of the tidal curve. The phase difference in the tide between the stations and the factors mentioned above were used to shift the calculated data to coincide with the phase of the tide at the study sites. Finally, the data were converted to 30-minute values, corresponding to wind and sediment flux data.

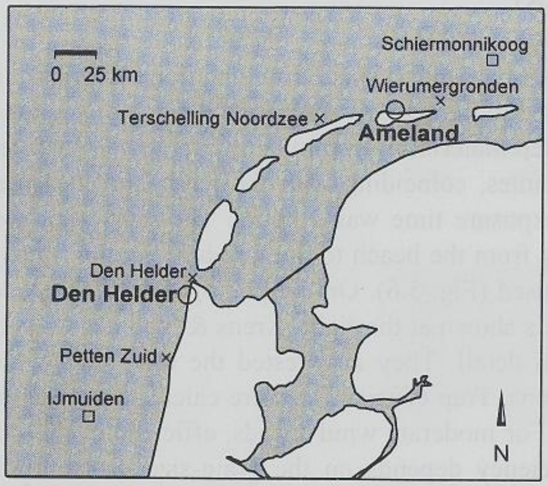

Figure 5.7. Locations and names of the stations that provided water level (marked with crosses) and wave height data (marked with squares) for the sites on Ameland and Den Helder (marked with circles).

Wave set-up (during onshore winds) was estimated using (Bowen *et al.*, 1968; Plant & Holman, 1997):

$$\eta \approx \frac{3}{8}\gamma\frac{H_s}{\sqrt{2}}$$ ***(Equation 5.5)***

where η is the total set-up (m) at the still water level, γ is the ratio of the wave height to water depth (taken as 0.42 (Guza & Thornton, 1981, in Plant & Holman, 1997)) and H_s is the deep water significant wave height (m) measured at the nearest offshore wave gauges. For Ameland, 60-minute data from station Schiermonnikoog were used and for Den Helder, 60-minute data from station IJmuiden were used, respectively (Fig. 5.7). The data of wave set-up were converted to 30-minute data by interpolation and added to the values of water level.

Topography was surveyed employing laser electronic distance measurement (EDM) equipment. This method yields values of height (expressed in m +DOD) with an accuracy of better than 0.01 m. The distance between points measured along the shore-normal transects (Figs 5.2 and 5.5) was 5 m at most, depending on the complexity of the morphology of the terrain.

The water level values were graphically related to the cross-shore EDM profile to estimate positions of the water's edge. These heights were converted to values of the width of the beach (*i.e.*, the shortest distance from the water's edge to the dune toe), using the profile data. At both study areas, an intertidal swashbar was formed after nourishment. On Ameland water stayed in the runnel with falling tide. In Den Helder the bar was interrupted by small rip channels which drained the runnel. In both cases, the runnel determined the seaward boundary for aeolian sand transport during these conditions.

The fetch of wind over beach sand is defined as the length of beach from the water's edge to the dune toe, measured along the direction of the wind. It was calculated using:

$$f = \frac{w_c}{\cos\alpha}$$ ***(Equation 5.6)***

where f is the fetch (m), w_c is the calculated width of subaerial beach (m) and α is the angle (°) between the wind direction and a line normal to the coast. The fetch was also related to the trap locations. The fetch of wind over beach sand associated with a sand trap is either the length of beach from the water

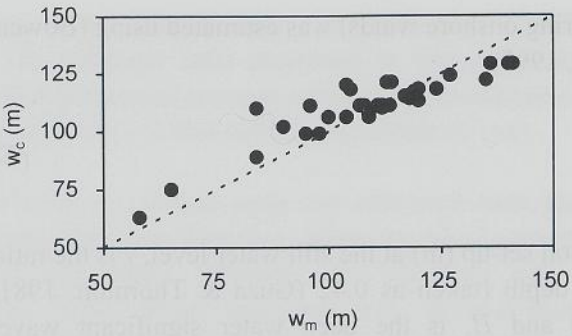

Figure 5.8. *Beach width calculated from water level, wave height and beach topography (w_c) versus measured beach width (w_m) for the Den Helder site. Measurements were made between 6 and 18 December 1996. The dotted line represents the one-to-one relationship.*

front to that sand trap (during onshore winds) or the length of beach from the dune toe to that sand trap (during offshore winds), measured along the direction of the wind.

To validate the method to calculate beach width from water level, wave height, topography and wind direction, beach width was also measured in the field. Fig. 5.8 shows the results from the site near Den Helder. Beach width was measured over 12 days, under different wind and tidal conditions. Linear regression of the calculated beach width on the measured beach width yielded a value of the coefficient of explanation R^2=0.88. The mean difference between the calculated and measured values was 0.5 m, with a standard deviation of 6.8 m. The mean of the absolute differences between the calculated and measured values was 5.2 m, with a standard deviation of 4.3 m. From Fig. 5.8 it can be seen that the width of a broad beach is underestimated, whereas the width of a narrow beach is overestimated by the procedure to calculate the beach width. The measurements are assumed to be representative for the study period. For Ameland, good correspondence was found between the measured and calculated beach width during one day with weak offshore winds.

RESULTS

Aeolian sand transport was measured on several days. For Ameland, the events are listed in Table 5.3, and the measurements are plotted in Fig. 5.9.

Table 5.3. Average, minimum and maximum (between brackets) 30-min average wind direction and wind velocity (u_2) and total rain fall for selected wind erosion events at the Ameland site.

Date	Period (h:min)	Wind direction (°)			Wind velocity (m s⁻¹)		Rain (mm)
19 Oct 1996	10:30-18:30	261	(257-266)	parallel	8.55	(6.87-9.83)	0.0
21 Oct 1996	09:30-18:00	296	(290-300)	onshore	10.08	(8.63-10.96)	0.0
24 Oct 1996	11:00-14:30	111	(108-114)	offshore	5.21	(4.90-5.56)	0.0
26 Oct 1996	14:00-18:00	219	(212-225)	offshore	3.77	(3.06-4.12)	0.0
28 Oct 1996	10:00-15:30	208	(200-214)	offshore	5.36	(4.89-5.85)	<0.2
29 Oct 1996	10:00-17:30	297	(285-311)	onshore	15.08	(13.89-15.90)	2.2
30 Oct 1996	13:00-15:30	256	(253-262)	offshore	8.03	(7.44-8.61)	0.2

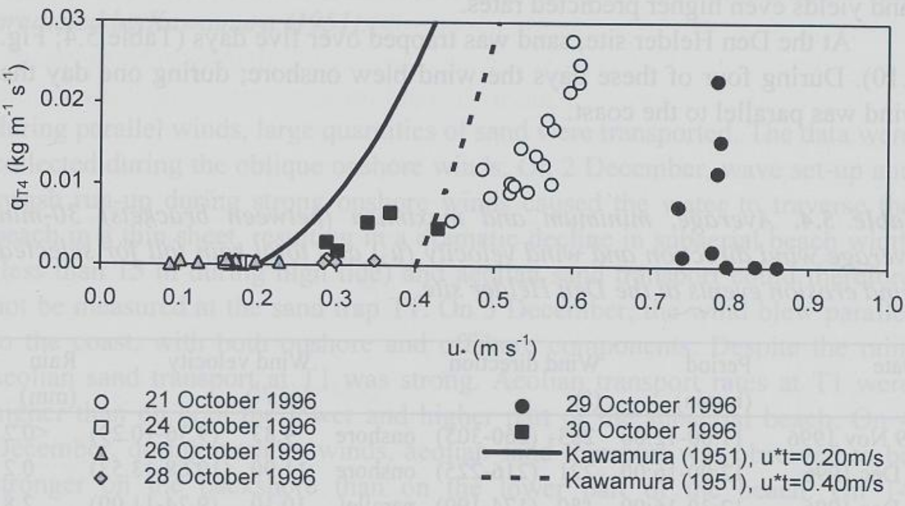

***Figure 5.9.** Aeolian sand transport at sand trap T4 (q_{T4}) versus friction velocity (u_*) at the Ameland site. The lines represent the transport rate predicted by Kawamura (1951).*

For low friction velocities (u_*<0.4 m s^{-1}), associated with offshore winds, mainly creep and (intermittent) streamers of sand were observed at sand trap T4 (24, 26, 28 and 30 October 1996) (see Fig. 5.6 for trap locations). On 19 October 1996, higher friction velocities resulted in higher transport rates during parallel winds. On 21 October 1996, aeolian sand transport during onshore winds was in the form of streamers. Sediment flux was found to be proportional to the cube of the friction velocity. On 9 October 1996, the threshold friction velocity strongly increased (u_{*t}> 0.7 m s^{-1}). Rain may have attributed to this increase by wetting the beach sand, but the highest transport rates were found during rain. However, rates are probably overestimated on this day, due to underestimation of the trap efficiency. Maximum wind velocities measured at 2 m elevation exceeded 21m s^{-1} during gusts. Aeolian sand transport was limited on the beach and intense transport from the backshore to the dunes was observed.

In Fig. 5.9, the aeolian sand transport predicted by Eq. 5.2 is plotted for Ameland, assuming well sorted dry sand with a mean grain-size of 323 μm (impact threshold u_{*t}=0.21 m s^{-1}). On 21 October 1996, the threshold friction velocity was found to be u_{*t}=0.4 m s^{-1}. Using this value in Eq. 5.2 instead of u_{*t}=0.21 m s^{-1} still yields a deviation of the actual rates from the predicted rates. Eq. 5.1 with C=3 to account for the moderate sorting and shells in the sand yields even higher predicted rates.

At the Den Helder site, sand was trapped over five days (Table 5.4; Fig. 5.10). During four of these days the wind blew onshore; during one day the wind was parallel to the coast.

Table 5.4. *Average, minimum and maximum (between brackets) 30-min average wind direction and wind velocity (u_2) and total rain fall for selected wind erosion events at the Den Helder site.*

Date	Period (h:min)	Wind direction (°)			Wind velocity (m s^{-1})		Rain (mm)
29 Nov 1996	11:00-12:00	283	(260-305)	onshore	9.83	(9.36-10.29)	<0.2
1 Dec 1996	12:00-16:00	221	(216-225)	onshore	11.90	(10.68-13.53)	0.2
3 Dec 1996	12:30-16:00	180	(174-190)	parallel	10.10	(9.24-11.00)	2.8
4 Dec 1996	12:00-16:30	230	(220-241)	onshore	10.91	(10.63-11.55)	0.0
14 Dec 1996	13:30-16:00	272	(269-275)	onshore	9.17	(8.92-9.34)	0.0

On 29 November and 4 and 14 December 1996, rain fell prior to the measurements. On 1 December, a number of short showers occurred. On 3 December, it rained continuously. The threshold friction velocities appear to vary both between and within days (roughly 0.25< u_{*t}< 0.50 m s^{-1}). There is no distinction in threshold conditions for events with and without rain, even when uncertainties in trap efficiency are considered. On 29 November, a front passed and the wind veered from parallel to oblique onshore. Especially

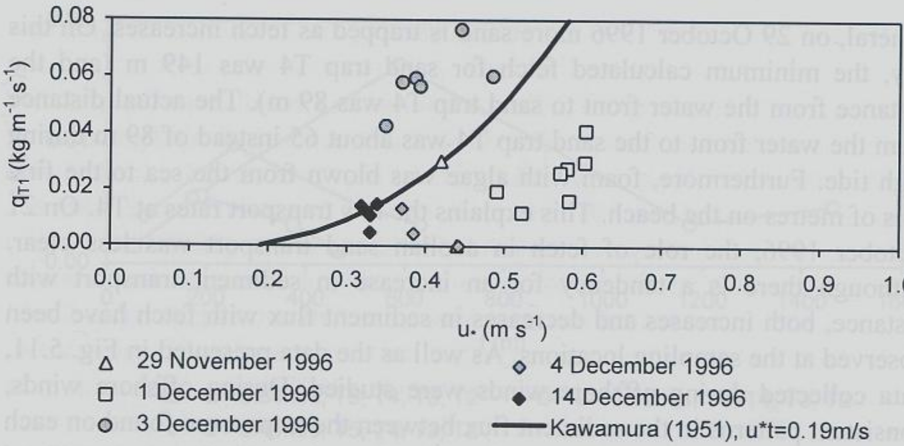

Figure 5.10. *Aeolian sand transport at sand trap T1 (q_{T1}) versus friction velocity (u_*) at the Den Helder site. The line represents the transport rate predicted by Kawamura (1951).*

during parallel winds, large quantities of sand were transported. The data were collected during the oblique onshore winds. On 2 December, wave set-up and swash run-up during strong onshore winds caused the water to traverse the beach in a thin sheet, resulting in a dramatic decline in subaerial beach width (less than 15 m during high tide) and aeolian sand transport could therefore not be measured at the sand trap T1. On 3 December, the wind blew parallel to the coast, with both onshore and offshore components. Despite the rain, aeolian sand transport at T1 was strong. Aeolian transport rates at T1 were higher than on both the lower and higher part of the subaerial beach. On 4 December, during onshore winds, aeolian sand transport was observed to be stronger on the backshore than on the lower part of the beach. On 14 December, the high tide inundated the beach up to 6 m from T1 (subaerial beach width was 51 m). About two hours after high tide, aeolian sand transport was observed at T1.

Fig. 5.10 shows the aeolian sand transport predicted with Eq. 5.2 for the Den Helder site, assuming well sorted dry sand with a mean grain-size of 272 μm (impact threshold u_{*t}=0.19 m s^{-1}).

Fig. 5.11 shows the variability in sediment flux over a shore-normal transect at the Ameland site during onshore winds. For every 30-minute interval, the fetch was calculated for each of the exposed sand traps. The data from two days with onshore winds (21 and 29 October 1996) are displayed. In general, on 29 October 1996 more sand is trapped as fetch increases. On this day, the minimum calculated fetch for sand trap T4 was 149 m (and the distance from the water front to sand trap T4 was 89 m). The actual distance from the water front to the sand trap T4 was about 65 instead of 89 m during high tide. Furthermore, foam with algae was blown from the sea to the first tens of metres on the beach. This explains the low transport rates at T4. On 21 October 1996, the role of fetch in aeolian sand transport was less clear. Although there is a tendency for an increase in sediment transport with distance, both increases and decreases in sediment flux with fetch have been observed at the sampling locations. As well as the data presented in Fig. 5.11, data collected during offshore winds were studied. During offshore winds, consistent patterns in the sediment flux between the traps were found on each day. The sediment flux increased with increasing wind velocity. Sand transport at sand trap T5 was small because the trap was in the lee of the dunes. The sediment flux at traps T1, T2, T3 and T4 did not systematically increase with fetch for a specific event: the largest rates were found at T4 during all runs. Fig. 5.12 gives the results for parallel, slightly offshore winds. The figure shows consistent patterns in sand transport rates over time on the beach, but no increase of sand transport with fetch.

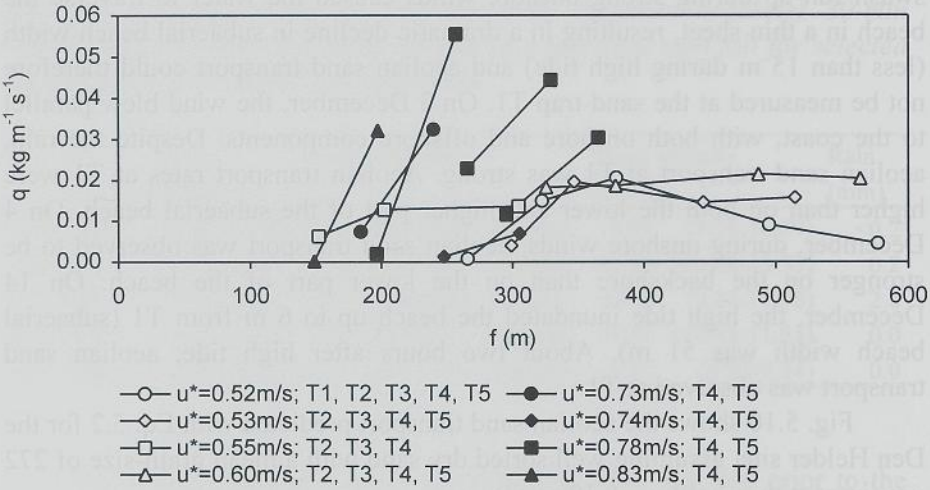

Figure 5.11. *Effect of fetch (f) on aeolian sand transport (q) during onshore winds at the Ameland site. T1, T2, T3, T4 and T5 refer to the sand traps as indicated in Fig. 5.6. The data from a specific 30-minute interval are interconnected. Open symbols refer to data collected on 21 October and closed symbols refer to data collected on 29 October 1996.*

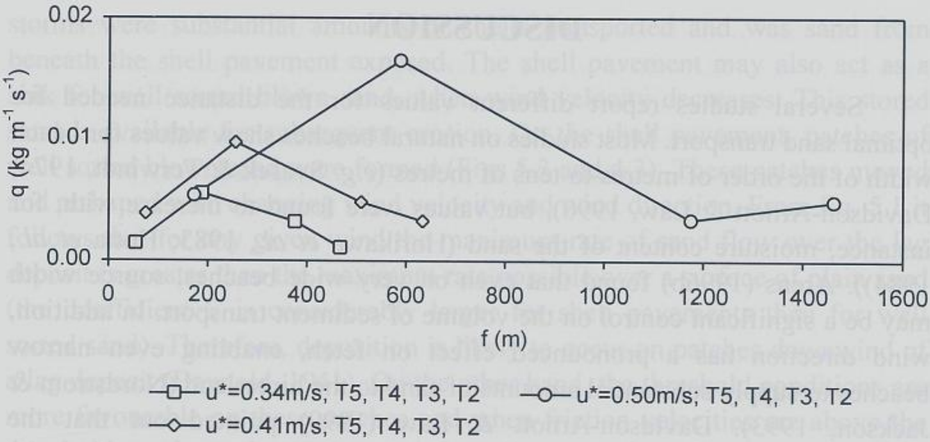

Figure 5.12. *Effect of fetch (f) on aeolian sand transport (q) during parallel and offshore winds at the Ameland site, on 19 October 1996. T2, T3, T4 and T5 refer to the sand traps as indicated in Fig. 5.6. The data from a specific run are interconnected.*

At the Den Helder site, the smallest fetch length for sand trap T1 calculated for the events was 31 m (onshore winds) and the maximum calculated fetch was over 2 km (parallel winds). Fig. 5.13 shows the tendency of an increase in sediment flux with fetch up until a distance of over 100 m. The largest transport rates corresponded to the vast fetches, even when friction velocities were low.

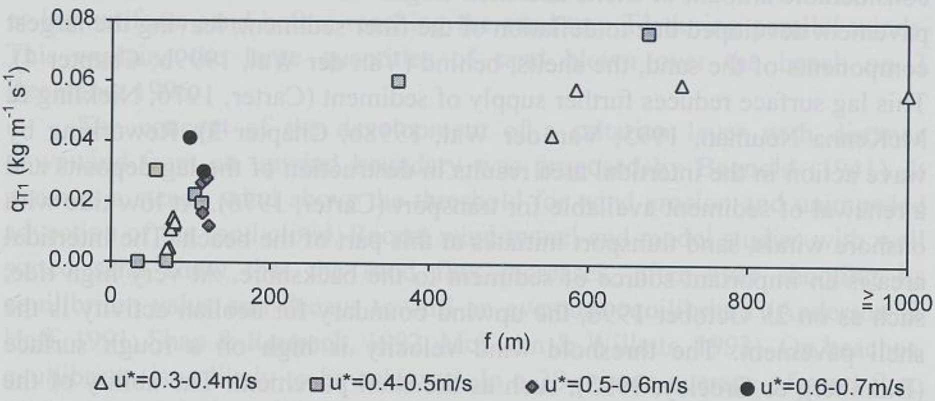

Figure 5.13. *Effect of fetch (f) on aeolian sand transport at sand trap T1 (q_{T1}) during onshore winds at the Den Helder site.*

DISCUSSION

Several studies report different values for the distance needed for optimal sand transport. Most studies on natural beaches show values for beach width of the order of metres to tens of metres (*e.g.* Svasek & Terwindt, 1974; Davidson-Arnott & Law, 1990), but values were found to increase with, for instance, moisture content of the sand (Horikawa *et al.*, 1983; Hotta *et al.*, 1984)). Arens (1996b) found that even on very wide beaches, source width may be a significant control on the volume of sediment transport. In addition, wind direction has a pronounced effect on fetch, enabling even narrow beaches to supply substantial amounts of sand to the hinterland (Nordstrom & Jackson, 1993). Davidson-Arnott & Law (1990) pointed out that the importance of higher wind velocities for aeolian sand transport may be reduced in favour of the significance of moderate wind speeds. This is because of the beach width reduction due to storm surge height, wave set-up and swash run-up during strong onshore winds. The results presented in this paper confirm the decline in fetch and little aeolian sand transport on the first tens of metres of subaerial beach, but transport on higher parts of the beach was found to be intense during these conditions. For the sediment flux to (high) foredunes, the stronger onshore winds are important since they can carry the sand, either from the beach or from the dune toe, into the foredunes.

This study also shows that despite a wide beach, the potential sand transport (as predicted by Eq. 5.1) may not be reached. This is because the characteristics of the surface can control the ability of the surface to supply sand to the air. At the Ameland site the nourishment sand comprised a considerable amount of shells and shell fragments. After nourishment, a shell pavement developed due to deflation of the finer sediment, leaving the largest components of the sand, the shells, behind (Van der Wal, 1999b; Chapter 4). This lag surface reduces further supply of sediment (Carter, 1976; Nickling & McKenna Neuman, 1995; Van der Wal, 1998b; Chapter 3). Reworking by wave action in the intertidal area results in destruction of the lag deposits and a renewal of sediment available for transport (Carter, 1976). At low tide with onshore winds, sand transport initiates at this part of the beach. The intertidal area is an important source of sediment to the backshore. At very high tide, such as on 29 October 1996, the upwind boundary for aeolian activity is the shell pavement. The threshold wind velocity is high on a rough surface (Blumberg & Greeley, 1993), such as the shell pavement. The ability of the surface to supply sand depends on the amount and distribution of the shells at the surface. The silt-sized material in the nourishment sand that is able to retain moisture could have caused even higher threshold values. Only during storms were substantial amounts of shells transported and was sand from beneath the shell pavement exposed. The shell pavement may also act as a sink for well sorted blown sand, when wind velocity decreases. This stored sand is available for subsequent erosion. On the shell pavement, patches of well sorted blown sand were formed (Figs 5.3 and 4.3). These patches moved and reshaped with changing wind velocity and wind direction. From Eq. 5.1 it follows that for any given wind the maximum rate of sand flow over the lag deposit is greater than the maximum rate possible over a surface of plain sand (the coefficient C is considerably larger for shell pavements than for well sorted sand). Therefore, deposition is likely to occur on patches downwind of a lag deposit (Bagnold, 1941). On the other hand, the threshold conditions are more favourable on these patches and when friction velocities are above the threshold sand can be transported from these patches (Gares *et al.*, 1996; Lancaster, 1996). The variability in erosive and depositional areas also implies that the variability in surface characteristics inhibits a constant sediment flux and, thus, spatial equilibrium of saltation. At the Den Helder site, shell pavements were less extensive and less dense. The sand trap T1 was placed just landward of the intertidal zone. So, shells did not play a role in the sand transport to T1 during onshore winds. In this case, the surface was wet due to the rain and due to the sea-water during falling tide. Threshold friction velocities will be higher on a moist beach than on a dry beach (Namikas & Sherman, 1995). However, when the water content is not too high, the wind enhances the surface grains to dry and to be entrained subsequently (Hotta *et al.*, 1984). Sarre (1988), for example, found that transport rates are similar to those over dry sand, once movement has been initiated at some point on a moist beach. At the Den Helder site, the wind passes over a vast fetch of more or less uniform sand before reaching the sand trap T1 during parallel winds. This explains the large quantities of sand blown over the beach on 3 December 1996.

The concept of the development of a saltation layer with distance downwind from an upwind boundary was proposed by Bagnold (1941). It assumes a steady wind above the threshold for wind erosion and unimpeded advection of the sand cloud. Recent wind tunnel and model studies with well sorted sand show that the sand flux increases, after over shooting its equilibrium value and decays toward an eventual equilibrium (Anderson & Haff, 1991; Shao & Raupach, 1992; McEwan & Willetts, 1993). On beaches, equilibrium is unlikely to be achieved. In a 30-minute average of sand flux, many states of disequilibria will be represented. Air flow over beaches is more complicated; wind, for example, is often gusty. In addition, variability in surface characteristics imposes constant adaptations in, for instance, the threshold wind velocity and the transport capacity of the wind. The consistent patterns in sand transport over the beach suggest that surface characteristics may play an important role in sand transport. However, in many cases sediment flux can be found to increase with fetch, resulting in erosion of the beach, due to the tendency of the wind to reach its transport capacity.

CONCLUSIONS

Aeolian sand transport appeared to relate both to fetch of wind over beach sand and characteristics of the sand. Especially at the Den Helder site, measured transport rates increased with fetch. Since beach width (and fetch) is enhanced by beach nourishment, this suggests that larger sediment fluxes (and more erosion) as compared to before nourishment can be expected. The effect will be largest just after nourishment and will gradually decrease as the size and width of the nourishment diminishes as a result of marine and aeolian processes. However, the relation between aeolian sand transport and fetch was seriously affected by other factors, such as the variability in surface characteristics.

Fill of the studied nourished beaches contained considerable amounts of shells. At the Ameland site, shell pavements developed after aeolian activity. The aeolian sand transport on the beach was reduced, but the transport did not cease. During different wind conditions either the input of sand from the intertidal area (where the sand had been reworked by the sea), the sand supply from the shell pavement or superimposed patches of dry well sorted blown sand provided a source for aeolian sand transport. The large variability in surface characteristics probably enhanced variation in aeolian sand transport over the beach.

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CHAPTER 6

MODELLING AEOLIAN SAND TRANSPORT AND MORPHOLOGICAL DEVELOPMENT IN TWO BEACH NOURISHMENT AREAS

ABSTRACT

The aeolian sand transport model SAFE and the air flow and turbulence model HILL were applied to evaluate cross-shore changes at two nourished beaches and adjacent dunes and to identify the response of aeolian sand transport and morphology to several nourishment design parameters and fill characteristics. The main input of the model consisted of data on the sediment, tide and meteorological conditions, and of half-yearly measured characteristics of topography, vegetation and sand fences. The cross-shore profiles generated by SAFE-HILL were compared to measured cross-shore profiles. The patterns of erosion and deposition, and the morphological development corresponded. In general, the rates of aeolian sand transport were overestimated. The impact of parameters that are related to beach nourishment (*viz.* grain-size, adaptation length and beach topography), on profile development was evaluated. Grain-size affected the aeolian sand transport rate to the foredunes, and therefore the morphology. Adaptation length, which is a measure of the distance over which sediment transport adapts to a new equilibrium condition, affected the topography of the beach in particular. The topography of a beach nourishment had a limited impact on both aeolian sand transport rate and morphology.

KEY WORDS

Aeolian sand transport, air flow, topography, beach nourishment, modelling, foredunes, the Netherlands.

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INTRODUCTION

Beach nourishment is the artificial supply of sediment to a coast. In a sandy coast, the sediment provides both a buffer against marine erosion (and therefore prevents dune erosion) and a wide beach for recreational purposes. A side-effect of beach nourishment is that the aeolian sediment transport rate can be altered, which can have geomorphological and ecological consequences. Such a change in the rate of sediment transport may be the result of, for example, a change in the availability of sediment or sediment characteristics, and the air flow over the new topography.

The impact of such factors on entrainment, transport and deposition of sand by wind has been studied. Examples are the wind and the turbulent characteristics of air flow (*e.g.* Butterfield, 1998 and Wiggs, 1993), availability of sediment (Nickling & Davidson-Arnott, 1990), sediment characteristics (Bagnold, 1941), moisture conditions (Hotta *et al.*, 1984) and slope angle (Iversen & Rasmussen, 1994). However, research conditions did not specifically apply to beach nourishment areas, as previous studies were carried out on natural beaches, desert environments or under wind tunnel conditions. So far, there are no tools to evaluate the effects of beach nourishment on the rate of aeolian sand transport. A model that addresses the impact and interaction of multiple factors has to be applied in order to evaluate the changes in aeolian sand transport due to individual factors changed by beach nourishment. Examples of these models are reported by *e.g.* Chapman (1990), Sherman & Lyons (1994), Stam (1997), Namikas & Sherman (1998) and Van Dijk *et al.* (1999). Most models have not been validated with field data, although some models incorporate components that are derived under field conditions. In addition, the models were not applied to beach nourishment areas. Models designed or applied to evaluate impacts of beach nourishment (*e.g.* Hansen & Byrnes, 1991) merely focus on maximizing beach longevity and minimizing storm impact, excluding any aeolian component.

This paper is focused on aeolian sand transport and cross-shore profile changes in beach nourishment areas. Data from two beach nourishment areas along the Dutch North Sea coast (Fig. 6.2) were used as an input for the aeolian sediment transport model SAFE of Van Dijk *et al.* (1999), which is dynamically linked to the air flow model HILL of Van Boxel *et al.* (1999). The models were applied to evaluate the aeolian sand transport and cross-shore profile changes at the two sites on a time scale of months. In addition, the models were used to identify the response of aeolian sand transport and morphology to parameters that are influenced by fill material and nourishment design, *viz.* grain-size, adaptation length (which is a measure of the distance over which sediment transport adapts to a new equilibrium condition, and which is assumed to depend on surface conditions), and topography. The performance of the models is discussed and suggestions for refinement are given to meet the needs of model application in beach nourishment environments on a time scale of months.

DESCRIPTION OF THE MODELS

In this section, a brief overview of the computer simulation models HILL and SAFE is given. Specifications of the models and the incorporated relationships taken from the literature are given by Van Boxel *et al.* (1999) and Van Dijk *et al.* (1999). Fig. 6.1 lists the main interactions of parameters and variables used in the models.

HILL is a two-dimensional second order closure model by Van Boxel *et al.* (1999), based on the model of Zeman & Jensen (1987). The model simulates air flow (including its turbulent characteristics) across linear ridges, using forward integration along streamlines. HILL calculates friction velocity along a topographic profile, using a given undisturbed (reference) friction velocity and a profile with roughness data created by SAFE, and returns the results to SAFE. In case of a bare surface, HILL yields a surface friction velocity. Over a vegetated surface, model output relates to the friction velocity immediately above the vegetation cover.

The aeolian sand transport model SAFE has been developed by Van Dijk *et al.* (1999). It uses established relationships to calculate sand transport along the height profile and calculates resulting surface height changes, which are converted to new height profiles. Aeolian sand transport basically depends on threshold friction velocity and surface friction velocity. In SAFE, local threshold friction velocity depends on the mean grain diameter of the sand (Bagnold, 1941), local slope angle (Iversen & Rasmussen, 1994), rainfall and relative humidity of the air (Arens, 1996b). Roughness characteristics are calculated from the aerodynamic roughness length of the sandy surface, and local vegetation characteristics (vegetation height and cover along the profile, and stem diameter of the plants) using a formula of Hagen & Armbrust (1994). A profile with roughness data is exported to HILL, which calculates friction velocities along the profile. From the friction velocities, SAFE calculates effective surface friction velocities, which incorporate vegetation effects (Raupach, 1992; Hagen & Armbrust, 1994). These values are used to calculate aeolian sand transport, using the transport formula of Kawamura

(1951), with a transport constant of 2.61, as proposed by White (1979).

In SAFE, the upwind edge of sediment transport is the water line, which is calculated dynamically; water level is described by a sine shaped curve with a 12-hour periodicity and an amplitude of half the tidal range. The mean sea level (0 m +DOD, *i.e.* Dutch Ordnance Datum) was set as deflation limit to account for sea water moisture during low tide.

An adaptation length, relating to the distance over which sediment transport adapts to a new equilibrium condition, according to a negatively exponential curve, is incorporated both for increasing and decreasing sediment transport in downwind direction (Van Dijk *et al.*, 1999). The new condition is associated with a change in surface and vegetation characteristics

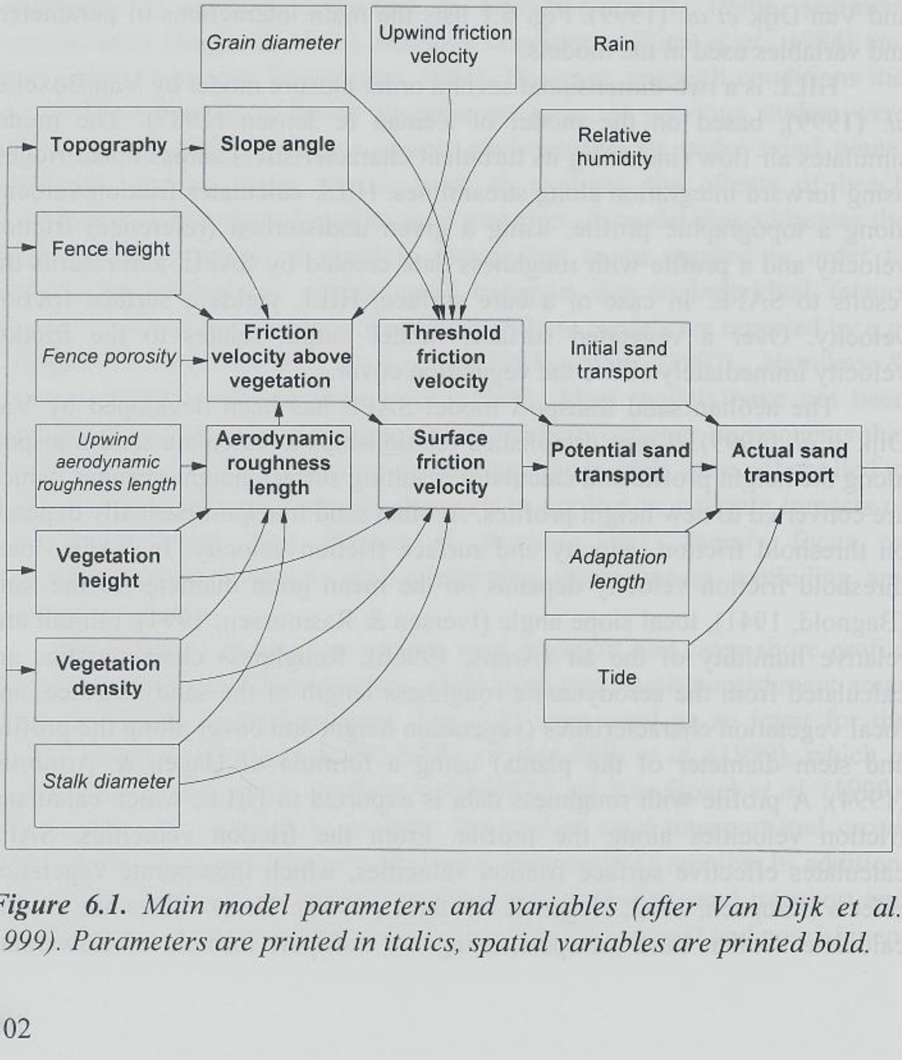

Figure 6.1. *Main model parameters and variables (after Van Dijk et al., 1999). Parameters are printed in italics, spatial variables are printed bold.*

or wind velocity, for instance. A similar concept has been used by Butterfield (1991) and Anderson (1988). The values for adaptation length used in SAFE are 20 m for increasing transport and 3 m for decreasing transport.

Additionally, a slip face routine is implemented (not in Fig. 6.1). Sand is redistributed on leeward and windward slopes exceeding an angle of yield of 37° until an angle of repose of 34° is reached (Van Dijk *et al.*, 1999). On steep slopes, flow separation occurs (Oke, 1987). HILL cannot deal with the recirculation vortex resulting from this flow separation (Van Boxel *et al.*, 1999). Instead, SAFE accounts for these processes in a simple way. If a leeward slope exceeds 15°, a downwind zone is defined, in which friction velocities are 20% of the reference friction velocity (Van Dijk *et al.*, 1999).

Input for SAFE and HILL include timing information (*viz.* time step interval and run duration) and a specification of the grid node spacing. SAFE and HILL interact dynamically. HILL is activated whenever a given change in height along the profile is exceeded. The output of HILL is then used as input for SAFE and vice versa.

For this study, the models are adapted to meet the requirements of the sites to be simulated. For example, procedures to simulate the effect of sand fences are added (Fig. 6.1). The effect of sand fences on the wind flow is calculated in HILL (using position, height and porosity of the fences), since the sand fences extract momentum from the air (Wilson & Shaw, 1977). SAFE adjusts the fence height after deposition or erosion and passes the new fence characteristics to HILL.

APPLICATION OF THE MODELS

STUDY SITES

The study was conducted on two sites along the Dutch North Sea coast (Fig. 6.2). The study site referred to as Ameland is situated on the North Sea side of the barrier island of Ameland, near the village of Ballum. The aspect of the coast is 0°. The beach was nourished in the spring and summer of 1996, with 1.56×10^6 m^3 of sand deposited along a stretch of coast of 4 km.

The study area referred to as Den Helder is situated on the coast of North-Holland, about 3 km from the town of Den Helder. The aspect of the coast is 272°. A first nourishment was carried out between the summers of 1992 and 1993. A second beach nourishment was carried out in the summer of 1996, when 0.85×10^6 m^3 of sand was placed along a stretch of coast of 5.5 km. Most of the 1996 nourishment sand was deposited on the foreshore.

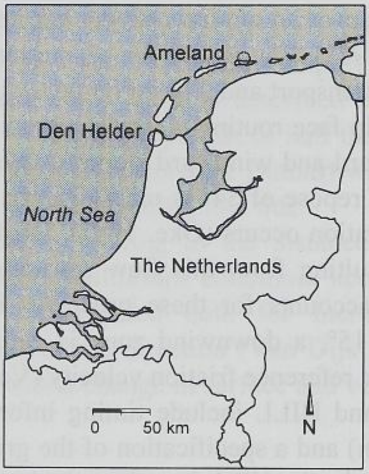

Figure 6.2. The study areas Ameland and Den Helder in the Netherlands.

MODEL INPUT

Time series

Data on the topography, vegetation and sand fences have been collected at approximately half-yearly intervals between the spring of 1996 and the autumn of 1997 at both locations. The data set of spring 1996 represented the situation just before nourishment. Three sets of data were collected after nourishment (*i.e.*, autumn 1996, spring 1997 and autumn 1997). Table 6.1 lists the exact data collection dates.

Table 6.1. Data collection dates.

	Ameland		Den Helder	
Time series	Topography	Vegetation	Topography	Vegetation
Spring 1996	7 May 1996	5 May 1996	15 Jun 1996	16 Jun 1996
Autumn 1996	9 Oct 1996	10 Oct 1996	21 Dec 1996	12 Dec 1996
Spring 1997	9 May 1997	10 May 1997	13 Jun 1997	14 Jun 1997
Autumn 1997	18 Oct 1997	19 Oct 1997	8 Nov 1997	15 Nov 1997

Topography

At the Ameland site, there is a vegetated foredune ridge of over 10 m +DOD adjacent to the beach, aligned parallel to the shore, and a second ridge more inland. The beach at the Den Helder site is bordered by a foredune of 14 m +DOD. The study sites were selected because of their two-dimensional character; shore-parallel variations in topography are small.

The models require cross-shore height profiles. Laser electronic distance measurement (EDM) equipment was used to measure the height along transects that were marked in the field. A transect that spanned the beach, the foredunes and the inner dunes was used for this study. The accuracy of EDM is better than 0.01 m in the vertical. Established benchmarks, of which the exact position was known, were also surveyed. They were used to express the heights in m +DOD, which is about mean sea level. Distances along the transect were expressed relative to an arbitrary benchmark. Fig. 6.3 gives the selected cross-shore profiles.

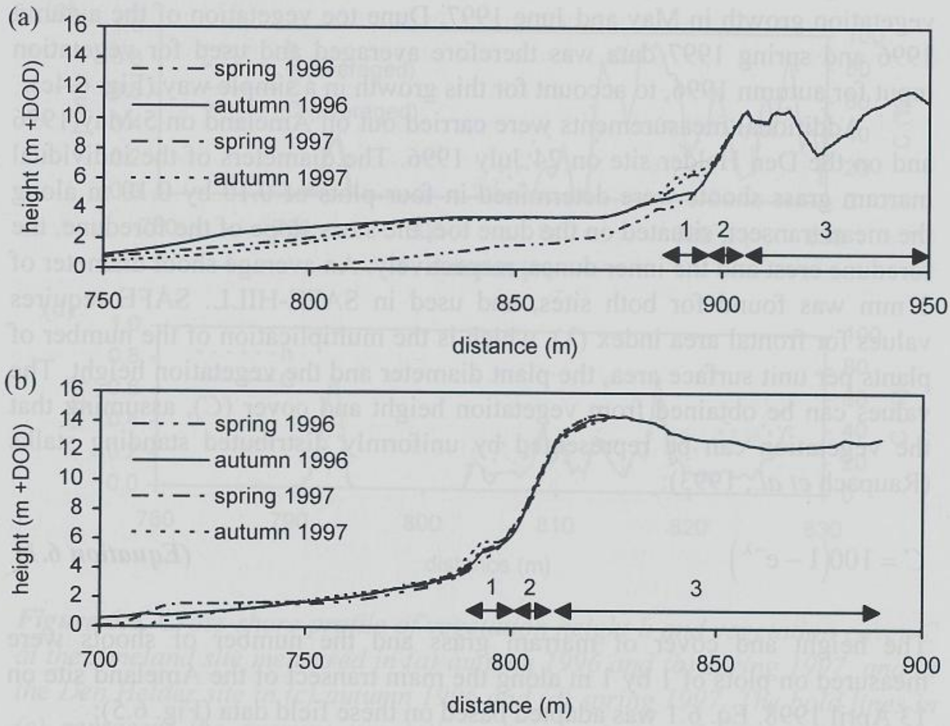

Figure 6.3. *Measured topographical development for (a) Ameland and (b) Den Helder. The numbers refer to geomorphological zones, i.e. (1) dune toe, (2) stoss slope of the foredune and (3) foredune crest.*

Vegetation

At the Ameland site, vegetation on the foredune consists of marram grass (*Ammophila arenaria)* and baltic marram grass (*Calammophila baltica*). The inner dunes are completely covered with mosses and sea buckthorn (*Hippophaë rhamnoides*). At the Den Helder site, the dune toe is dominated by the grass sand couch (*Elymus farctus*), and the foredunes and inner dunes are dominated by marram grass (*Ammophila arenaria)* and baltic marram grass (*Calammophila baltica*).

Vegetation input for SAFE-HILL mainly consists of cross-shore profiles with information on vegetation height and cover. Each EDM transect was divided in 0.10 m segments of 0.10 m in width. Mean vegetation height and cover (as seen from above) were recorded in each 0.10 by 0.10 m plot at half-yearly intervals. Cross-shore profiles of vegetation height and cover were constructed by applying a moving average over 1 m intervals (Fig 6.4). For the Den Helder site, the height and cover of the grass sand couch at the dune toe changed considerably between autumn of 1996 and spring of 1997, due to vegetation growth in May and June 1997. Dune toe vegetation of the autumn 1996 and spring 1997 data was therefore averaged and used for vegetation input for autumn 1996, to account for this growth in a simple way (Fig. 6.4c).

Additional measurements were carried out on Ameland on 5 May 1996 and on the Den Helder site on 24 July 1996. The diameters of the individual marram grass shoots were determined in four plots of 0.10 by 0.10 m along the mean transect, situated on the dune toe, the stoss slope of the foredune, the foredune crest and the inner dunes, respectively. An average shoot diameter of 3 mm was found for both sites, and used in SAFE-HILL. SAFE requires values for frontal area index (λ), which is the multiplication of the number of plants per unit surface area, the plant diameter and the vegetation height. The values can be obtained from vegetation height and cover (C), assuming that the vegetation can be represented by uniformly distributed standing stalks (Raupach *et al.*, 1993):

$$C = 100\left(1 - e^{-\lambda}\right) \qquad \textbf{\textit{(Equation 6.1)}}$$

The height and cover of marram grass and the number of shoots were measured on plots of 1 by 1 m along the main transect of the Ameland site on 13 April 1998. Eq. 6.1 was adapted based on these field data (Fig. 6.5):

$$C = 100\left(1 - e^{-0.4\lambda}\right) \qquad \textbf{\textit{(Equation 6.2)}}$$

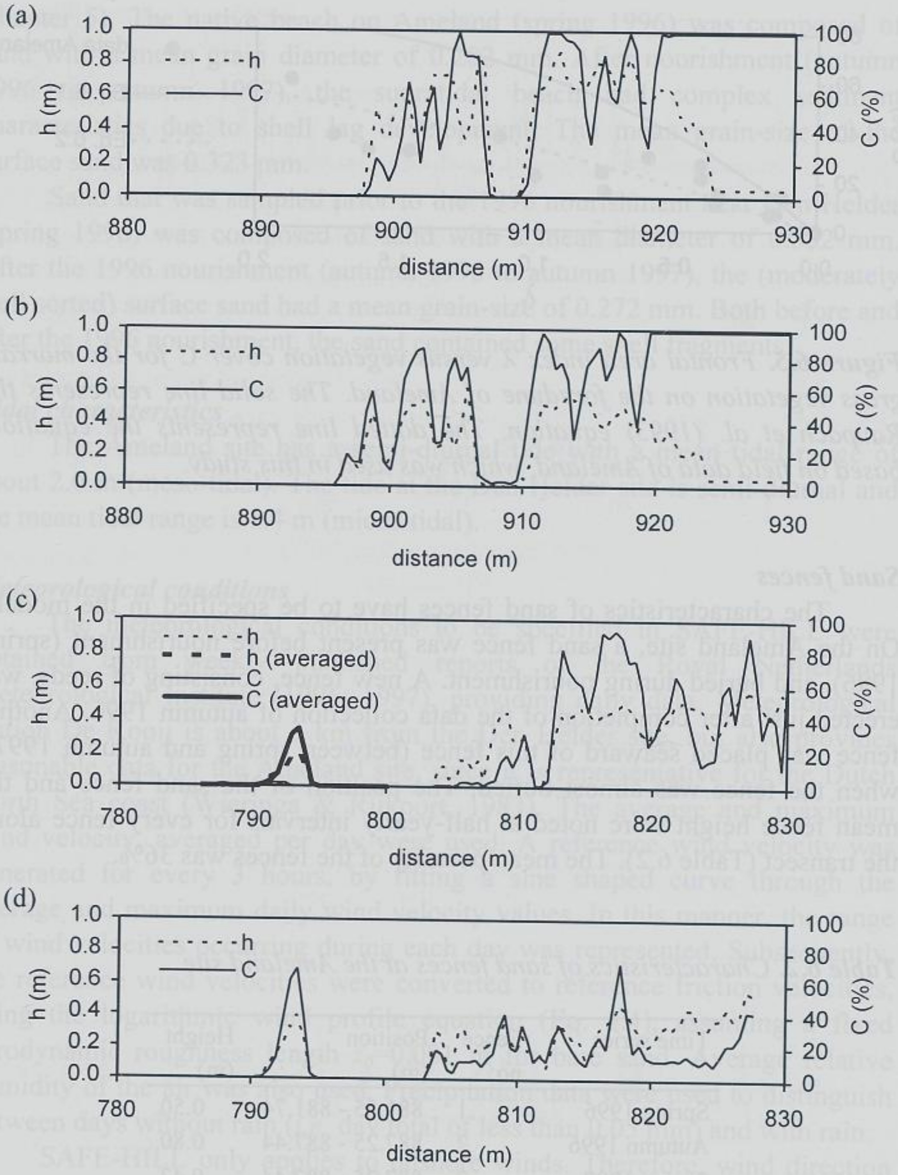

Figure 6.4. *Cross-shore profile of vegetation height h and vegetation cover C at the Ameland site measured in (a) autumn 1996 and (b) spring 1997, and at the Den Helder site in (c) autumn 1996 and (d) spring 1997. The bold lines in (c) represent the average vegetation characteristics of autumn 1996 and spring 1997 used in SAFE-HILL to account for vegetation growth in the period between autumn 1996 and spring 1997.*

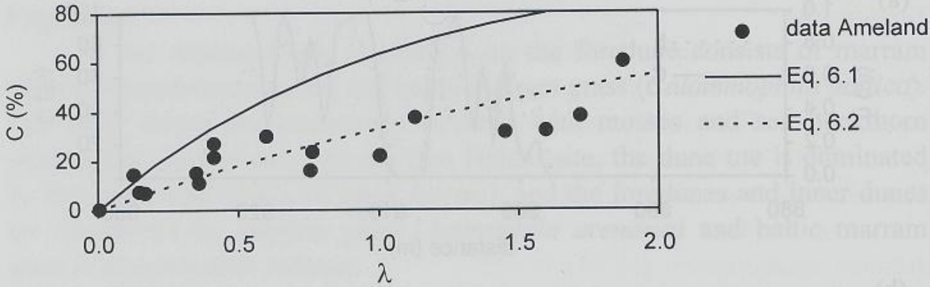

Figure 6.5. *Frontal area index λ versus vegetation cover C for the marram grass vegetation on the foredune of Ameland. The solid line represents the Raupach et al. (1993) equation. The dotted line represents the equation, based on field data of Ameland, which was used in this study.*

Sand fences

The characteristics of sand fences have to be specified in the models. On the Ameland site, a sand fence was present before nourishment (spring 1996), and buried during nourishment. A new fence, consisting of reeds, was erected just after completion of the data collection of autumn 1996. Another fence was placed seaward of this fence (between spring and autumn 1997), when the fence was almost buried. The position of the sand fence and the mean fence height were noted at half-yearly intervals for every fence along the transect (Table 6.2). The mean porosity of the fences was 36%.

Table 6.2. *Characteristics of sand fences at the Ameland site.*

Time series	Fence no.	Position (m)	Height (m)
Spring 1996	1	881.55 - 881.74	0.50
Autumn 1996	2	887.25 - 887.44	0.80
Spring 1997	2	887.25 - 887.44	0.42
	3	884.40 - 884.59	0.80
Autumn 1997	3	884.40 - 884.59	0.70

Sediment characteristics

SAFE uses a mean grain-size of the sand to characterize the sediment. Therefore, the surface of the beach was sampled (Van der Wal, 1998a;

Chapter 5). The native beach on Ameland (spring 1996) was composed of sand with a mean grain diameter of 0.202 mm. After nourishment (autumn 1996 to autumn 1997), the supratidal beach had complex sediment characteristics due to shell lag development. The mean grain-size of the surface sand was 0.323 mm.

Sand that was sampled prior to the 1996 nourishment near Den Helder (spring 1996) was composed of sand with a mean diameter of 0.332 mm. After the 1996 nourishment (autumn 1996 to autumn 1997), the (moderately well sorted) surface sand had a mean grain-size of 0.272 mm. Both before and after the 1996 nourishment, the sand contained some shell fragments.

Tidal characteristics

The Ameland site has a semi-diurnal tide with a mean tidal range of about 2.0 m (meso-tidal). The tide at the Den Helder site is semi-diurnal and the mean tidal range is 1.4 m (micro-tidal).

Meteorological conditions

The meteorological conditions to be specified in SAFE-HILL were obtained from weekly published reports of the Royal Netherlands Meteorological Institute (1996; 1997), providing daily data. Meteorological station De Kooij is about 3 km from the Den Helder site, but also provides reasonable data for the Ameland site, since it is representative for the Dutch North Sea coast (Wieringa & Rijkoort, 1983). The average and maximum wind velocity, averaged per day were used. A reference wind velocity was generated for every 3 hours, by fitting a sine shaped curve through the average and maximum daily wind velocity values. In this manner, the range of wind velocities occurring during each day was represented. Subsequently, the reference wind velocities were converted to reference friction velocities, using the logarithmic wind profile equation (Eq. 5.4), assuming a fixed aerodynamic roughness length z_0=0.001 m for bare sand. Average relative humidity of the air was also used. Precipitation data were used to distinguish between days without rain (*i.e.* day total of less than 0.05 mm) and with rain.

SAFE-HILL only applies to onshore winds. Therefore, wind direction data (from station De Bilt) were used to distinguish between onshore, shore-parallel and offshore winds. Days with onshore winds had winds with a westerly component (SW, W and NW) for the Den Helder site and winds with a northerly component (NW, N and NE) for the Ameland site, respectively. Days with shore-parallel winds and offshore winds, occurring for 50 to 70% of the observed period, were discarded. Fig. 6.6 lists the meteorological conditions for selected periods.

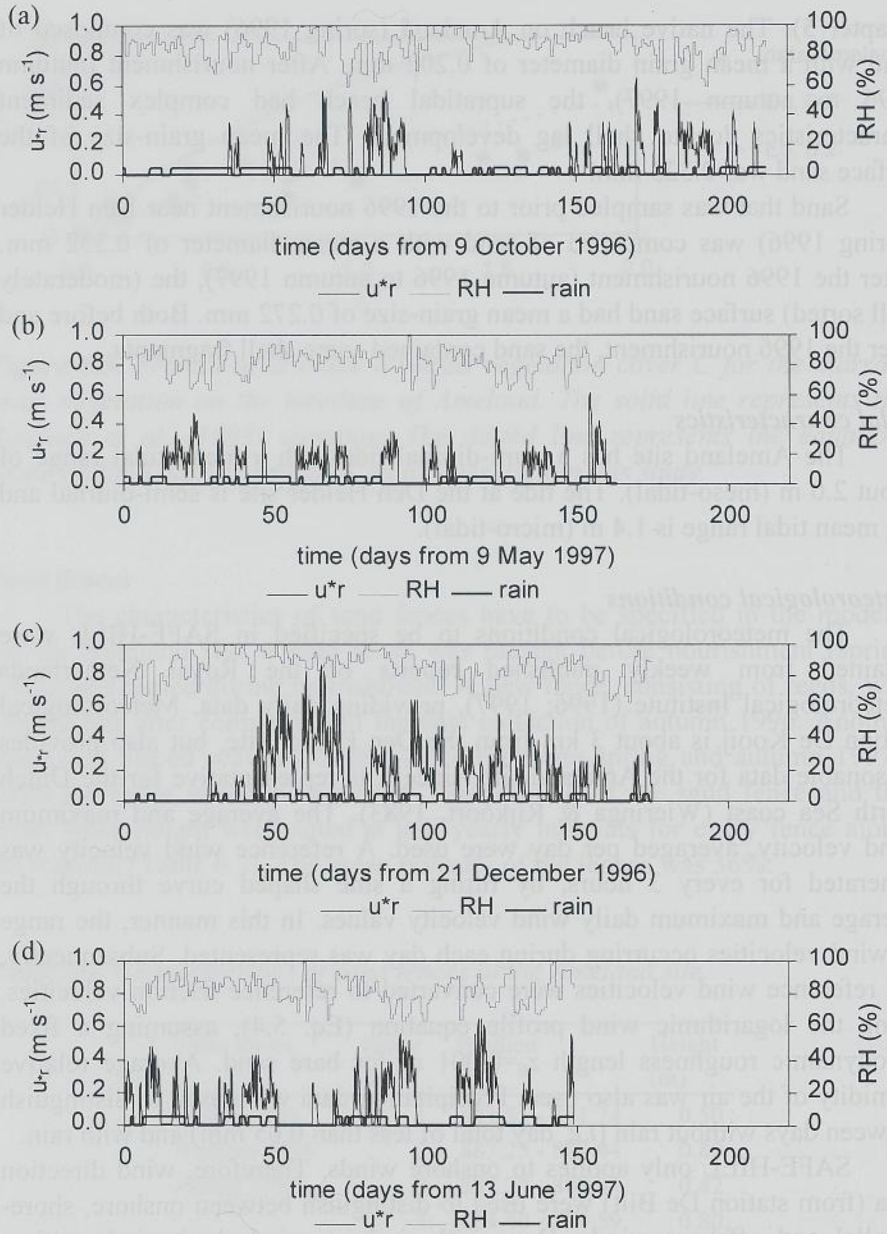

Figure 6.6. *Reference friction velocity u_{*r}, relative humidity RH and rain for Ameland, for (a) autumn 1996 to spring 1997 and (b) spring 1997 to autumn 1997, and for Den Helder, for (c) autumn 1996 to spring 1997 and (d) spring 1997 to autumn 1997. Rain is displayed as a boolean, with 'no rain' values set to 0. Friction velocities during onshore winds are displayed, friction velocities during offshore and shore-parallel winds are set to 0.01 m s^{-1}.*

MODEL EVALUATION

Measured and simulated changes

The topographic profiles generated by the model system were related to measured topographic profiles for two data series, as is represented in Fig. 6.7. The pattern of deposition and erosion reflected in the topographical development, and volumetric changes are compared. The profiles measured in spring 1996 cannot be used, since the development due to aeolian processes is obscured by the direct impact of nourishment.

Simulated changes for several cases

A number of cases were simulated to identify the response of aeolian sand transport and morphology to parameters that can be influenced by beach nourishment. Simulation runs with different values for grain-size (*e.g.*, the grain-size of the pre-nourishment sand and the nourishment sand) and for adaptation length (for increasing sand transport in downwind direction), which is assumed to depend on surface conditions (*e.g.*, Davidson-Arnott & Law, 1990) were evaluated to illustrate the effect of fill material. Simulations with a pre-nourishment profile, a post-nourishment profile and two beach fill design template geometries were run to assess the effect of topography on aeolian sand transport and morphology. The data collected in autumn 1996 at the Ameland site were used for these cases. Both a reference friction velocity of $u_{*,r}$=0.35 m s^{-1} during 20 days and the meteorological input during 213 days (*i.e.* the number of days between the autumn 1996 and spring 1997 series) were applied. For all runs, a time step interval of 0.005 days and a grid node spacing of 1 m were selected.

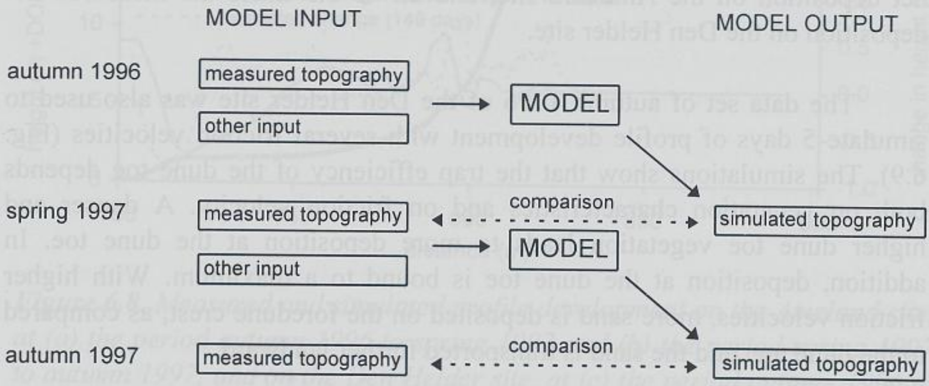

Figure 6.7. *Schematic representation of model evaluation.*

RESULTS

MEASURED AND SIMULATED CHANGES

Fig. 6.8a gives the simulated profile development for the autumn 1996 to spring 1997 period at the Ameland site. Both the actual and simulated situation show largest deposition just behind the sand fence. The simulated sand influx at the stoss slope of the foredune is overestimated. The simulation shows dune development due to convexities in the beach profile: the convex slopes propagate and grow higher. The simulated change for the period spring to autumn 1997 (Fig. 6.8b) corresponds well with the actual change, but the sand influx is slightly underestimated.

At the Den Helder site, equal amounts of sand were trapped at the dune toe and the foredune crest in the period of autumn 1996 to spring 1997 (Fig. 6.8c). The simulation shows extreme deposition at the foredune crest. This is the result of a period of strong winds (occurring between 51 and 71 days after the start of simulation, as can be seen in Fig. 6.8c). During the subsequent period with lower friction velocities, the accumulated sand migrates downwind. In the period of spring to autumn 1997, almost all sand was trapped at the dune toe (Fig. 6.8d). The simulated distribution of deposition at the dune toe and foredune crest, respectively, does not correspond with this measured distribution. Again, the rates are overestimated. The swashbar that was measured in spring 1997 develops similarly as the convexities in the beach profile of the Ameland site.

Table 6.3 summarizes volumetric changes for three geomorphological zones, calculated from the measured and simulated profiles of the Ameland and Den Helder site. Simulated net deposition is 0.8 to 1.4 times the measured net deposition on the Ameland site, and 2.9 to 5.5 times the measured net deposition on the Den Helder site.

The data set of autumn 1996 of the Den Helder site was also used to simulate 5 days of profile development with several friction velocities (Fig. 6.9). The simulations show that the trap efficiency of the dune toe depends both on vegetation characteristics and on friction velocity. A denser and higher dune toe vegetation leads to more deposition at the dune toe. In addition, deposition at the dune toe is bound to a maximum. With higher friction velocities, more sand is deposited on the foredune crest, as compared to the dune toe, and the sand is transported further landward.

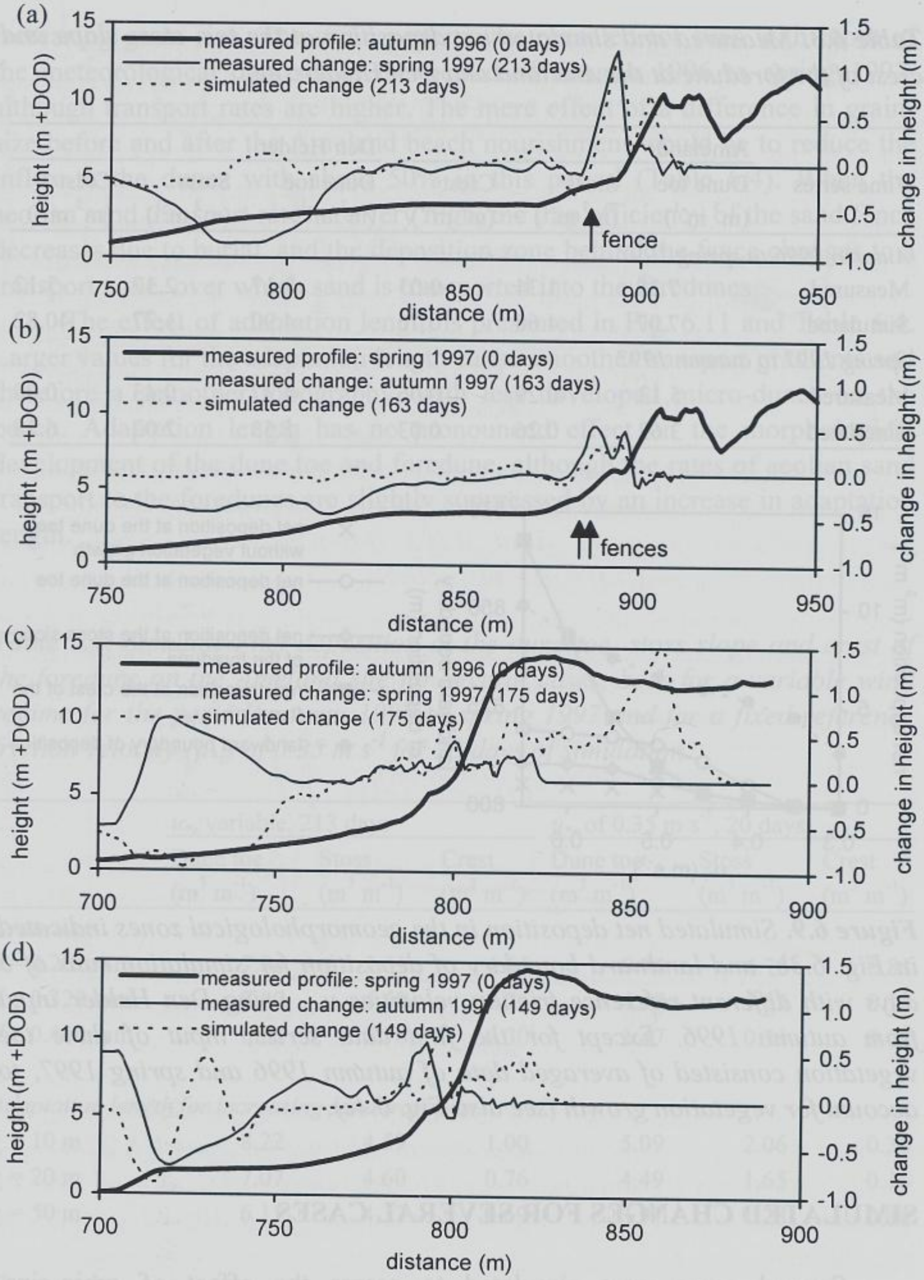

Figure 6.8. *Measured and simulated profile development on the Ameland site, at (a) the period autumn 1996 to spring 1997 and (b) the period spring 1997 to autumn 1997, and on the Den Helder site, at (c) the period autumn 1996 to spring 1997 and (d) the period spring 1997 to autumn 1997.*

Table 6.3. Measured and simulated net deposition at the toe, stoss slope and crest of the foredune at the Ameland and Den Helder site.

Time series	Ameland			Den Helder		
	Dune toe ($m^3 m^{-1}$)	Stoss ($m^3 m^{-1}$)	Crest ($m^3 m^{-1}$)	Dune toe ($m^3 m^{-1}$)	Stoss ($m^3 m^{-1}$)	Crest ($m^3 m^{-1}$)
Autumn 1996 to spring 1997						
Measured	7.38	1.34	-0.03	3.17	2.37	3.12
Simulated	7.07	4.60	0.76	4.90	1.77	40.82
Spring 1997 to autumn 1997						
Measured	5.13	-0.29	0.06	4.37	0.43	0.00
Simulated	3.62	0.26	0.03	5.53	2.02	6.18

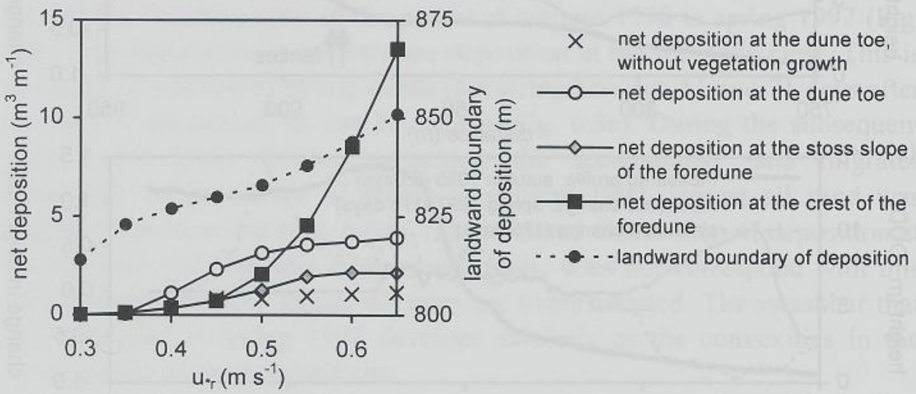

Figure 6.9. *Simulated net deposition in the geomorphological zones indicated in Fig. 6.3b, and landward boundary of deposition for simulation runs of 5 days with different reference friction velocities u_{*r}, using Den Helder input from autumn 1996. Except for the first data series, input of dune toe vegetation consisted of averaged data of autumn 1996 and spring 1997, to account for vegetation growth (see also Fig. 6.4c).*

SIMULATED CHANGES FOR SEVERAL CASES

Several cases were simulated to assess the effect of grain-size, adaptation length and topography, respectively. Fig. 6.10 and Table 6.4 show the effect of grain diameter on aeolian sand transport and cross-shore profile changes during a simulation run of 20 days with u_{*r}=0.35 m s^{-1}. The rates of sand transport, and thus the morphological stage after 20 days, decrease with increasing grain-size. The same patterns are revealed for runs with input of the meteorological data set of the period of autumn 1996 to spring 1997, although transport rates are higher. The mere effect of a difference in grain-size before and after the Ameland beach nourishment would be to reduce the influx to the dunes with about 50% in this period (Table 6.4). When the aeolian sand transport rates are very high, the trap efficiency of the sand fence decreases due to burial, and the deposition zone behind the fence changes to a transport zone, over which sand is transported into the foredunes.

The effect of adaptation length is presented in Fig. 6.11 and Table 6.4. Larger values for the adaptation length cause smoother transport gradients and therefore a smoother topography, with less developed micro-dunes on the beach. Adaptation length has no pronounced effect on the morphological development of the dune toe and foredune, although the rates of aeolian sand transport to the foredunes are slightly suppressed by an increase in adaptation length.

Table 6.4. *Simulated net deposition at the dune toe, stoss slope and crest of the foredune on the Ameland site for several cases, both for a variable wind regime for the period autumn 1996 to spring 1997 and for a fixed reference friction velocity (u_{*r}) of 0.35 m s^{-1} for 20 days of simulation.*

	u_{*r} variable, 213 days			u_{*r} of 0.35 m s^{-1}, 20 days		
	Dune toe (m^3 m^{-1})	Stoss (m^3 m^{-1})	Crest (m^3 m^{-1})	Dune toe (m^3 m^{-1})	Stoss (m^3 m^{-1})	Crest (m^3 m^{-1})
Grain-size						
d = 0.202 mm	7.84	5.61	4.65	6.94	4.73	0.81
d = 0.323 mm	7.07	4.60	0.76	4.49	1.65	0.16
d = 0.400 mm	6.52	2.76	0.30	1.47	0.31	0.04
Adaptation length for increasing sand transport						
χ = 10 m	8.22	4.59	1.00	5.09	2.06	0.36
χ = 20 m	7.07	4.60	0.76	4.49	1.65	0.16
χ = 50 m	6.15	4.37	0.69	3.97	1.28	0.10
Topography						
Pre-nourishment beach				1.83	4.35	1.11
1996 Beach nourishment				2.05	3.87	0.61
Beach nourishment				1.39	4.26	1.08
Beach nourishment and banquet				7.33	2.77	0.38

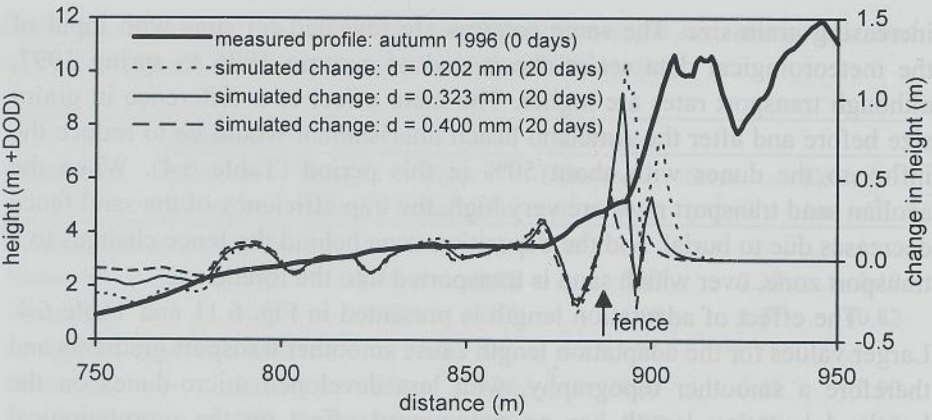

Figure 6.10. *Effect of grain-size on profile development. The model simulated 20 days of profile development, with a reference friction velocity of 0.35 m s*$^{-1}$ *and a sediment grain-size d of 0.202 (pre-nourishment sand), 0.323 (nourishment sand) and 0.400 mm, respectively.*

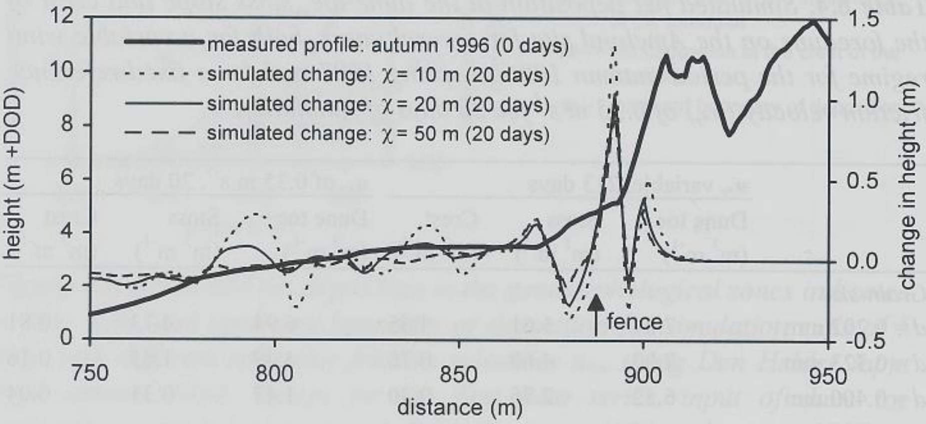

Figure 6.11. *Effect of adaptation length (of increasing sand transport with distance downwind) on profile development. The model simulated 20 days of profile development, with a reference friction velocity of 0.35 m s*$^{-1}$ *and an adaptation length for increasing sand transport* χ *of 10, 20 and 50 m, respectively.*

Fig. 6.12 shows the effect of topography on aeolian sand transport and morphology, after 20 days of simulation with u_{*r}=0.35 m s^{-1}. Note that no sand fence was applied for these runs. The ridge at the dune toe of the pre-nourishment profile, formed by a former sand fence, will erode and the sand will eventually be transported over the stoss slope of the foredune, to increase the foredune crest by 0.7 m (Fig. 6.12a). In the profile of the 1996 beach nourishment (Fig. 6.12b), there is some redistribution of sand on the beach and at the dune toe. Sand is deposited at the dune toe and the stoss slope of the foredune, rather than on the foredune crest. The development with a beach nourishment with a 1:50 slope (Fig. 6.12c) approaches the development without nourishment. A combination of a beach nourishment and a so-called banquet, *i.e.* a sand buffer at the dune toe (Fig. 6.12d), results in less growth of the foredune crest, but there is a dramatic adaptation of the banquet shape.

Differences in total net deposition landward of the dune toe between the profiles were small (Table 6.4). The largest total net deposition was found for the profile without nourishment. The total rates of the profile with both a beach nourishment and a banquet were also high. This is because the erosion of the banquet took place seaward of the 'dune toe', and was therefore not taken into account.

DISCUSSION

MEASURED AND SIMULATED CHANGES

Aeolian processes in the two beach nourishment areas can be simulated using SAFE-HILL. The model system indicates the location of deposition and erosion. The sand fence dramatically affects the morphology on the Ameland site; most sand was trapped behind the fence. At the Den Helder site, sand is deposited at the dune toe and crest. The morphological development is defined by the vegetation at the dune toe, and by the wind velocity, which determines the landward boundary of deposition.

In general, the rates of sand transport simulated by the model system are overestimated, compared to the rates of sand transport in the field. This is in correspondence with findings of most authors who used sediment transport equations and meteorological data to predict volumes of sediment transported from the beach to the dunes, and compared this with measured accumulation (*e.g.* Sarre, 1989a; Davidson-Arnott & Law, 1990; Kroon & Hoekstra, 1990; Arens, 1997). The overestimation can be explained by the fact that a number of factors that reduce aeolian sand transport are not well accounted for.

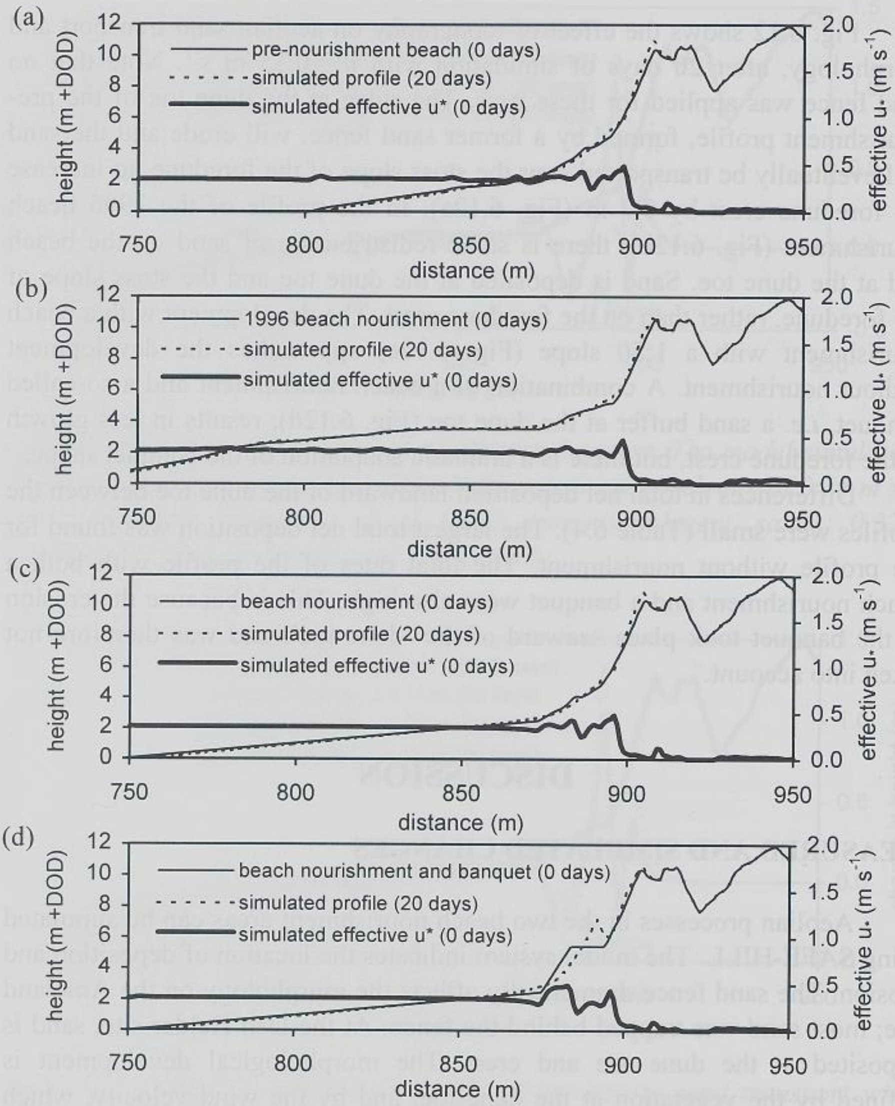

Figure 6.12. Effect of topography on aeolian sand transport and foredune morphodynamics. Four profiles were subject to 20 days of simulation with a reference friction velocity of 0.35 m s^{-1}: (a) the topography of spring 1996 ('pre-nourishment beach'), (b) the topography of autumn 1996 ('1996 beach nourishment'), (c) a template geometry, with beach fill under 2.5 m +DOD, sloping 1:50 ('beach nourishment'), and (d) a template geometry, with a so-called banquet of 5.45 m +DOD, 10 m in width and sloping 1:3, superimposed on the previous template ('beach nourishment and banquet'). Simulated values for the initial effective friction velocities are also displayed.

For these sites, soil moisture is probably the most important factor. Empirically and theoretically derived equations to predict the effect of moisture content on aeolian sand transport give a wide range of outcomes (Namikas & Sherman, 1995). In SAFE, moisture is empirically related to threshold friction velocity by relative humidity and by rain. Wetting of the beach by sea water is incorporated in SAFE by setting a deflation limit to mean sea level. The model instantaneously reacts to changes in conditions. The field situation is more complex. Moisture content is highly variable in both time and space. There is no instantaneous reaction to changes in conditions; the effect of rain on threshold friction velocity, for instance, does not cease directly after the rain has stopped. In addition, a wet surface can both restrict the supply of sand to the air stream and form a good surface for transport of sand. Furthermore, high wind speeds are relatively unimportant, because of their occurrence in combination with rainfall and flooding of the beach by sea water. Further research should focus on the effects of moisture on aeolian sand transport under field conditions.

Part of the overestimation of sand transport will be due to the uni-directionally modelled wind. Days with shore-parallel and offshore winds were discarded. This is justified, since velocities of offshore winds are lower, and the beach and dune toe are in the lee of the dunes during offshore winds. Sand transport during onshore winds leads to changes in the topography in particular, since the transported sand can be stabilized either behind a sand fence or within the vegetation. Discarding the parallel winds with an onshore component reduced the aeolian sand transport. The model system does not differentiate between days with oblique onshore winds and days with perpendicular onshore winds. In the field, oblique winds encounter slopes that are less steep. This results in less acceleration and deceleration of the air flow, and therefore in smoother transport gradients. The effect of a reduction of threshold friction velocity due to the decrease in slope angle is less pronounced. Deflection of the wind due to the presence of the foredune has to be taken into account when the wind direction strongly deviates from perpendicular onshore. In addition, sediment input per unit distance alongshore decreases as the wind angle departs from shore perpendicular (Nickling & Davidson-Arnott, 1990). Additional simulations with the current model system, in which a module is implemented that accounts for these effects of wind direction, results in a more accurate prediction of morphological changes in the foredunes, but also intensifies 'dune-building' on the beach, as the fetch of wind over sand is enlarged during oblique winds.

The model system has been designed to simulate aeolian sand transport on a time scale of several wind erosion events. The model performance on a time scale of months depends on the variability of factors that are not dynamically modelled, especially seasonal variation in vegetation and marine sediment transport. At the Ameland site, differences in vegetation height and cover were insignificant (*cf.* Figs 6.4a and b). In addition, the bulk of the sediment is deposited in the bare zone behind the sand fence. At the Den Helder site, vegetation growth at the dune toe controls dune development. Since the model system lacks any vegetation growth function, deposition zones change to transport zones once the vegetation is buried, thus moderating the morphological development. Especially at the dune toe on the Den Helder site, simulation therefore fails. For the situation in which vegetation is crucial for the morphological development, seasonal variation in vegetation characteristics has to be included in the model system. In addition, the geometry and distribution of plants have to be taken into account in more detail in this situation.

The model system generates micro-dunes on the beach. This occurs especially where the concave slope of the beach face, that is mainly under influence of marine processes, changes to a more convex slope, that is under influence of aeolian processes only. The dunes did not form on (sloping) flat beaches, such as in Figs 6.12a, c and d. The migration and growth of the micro-dunes is comparable to the development of the non-vegetated sine shaped dunes simulated by Van Dijk et al (1999). In reality, these dunes did not form on the beach. This discrepancy can be attributed to processes acting on the beach that are not included in the model system, or not modelled correctly, but are also likely to result from model artefacts. Wave and tidal processes control beach development (see for example the marine erosion in Fig. 6.3a and the swashbar formed in the spring-profiles in Fig. 6.3b), but are not included in the model system. In addition, values for, for example, threshold friction velocity and adaptation length may not be chosen properly. Finally, the individual factors that determine aeolian sand transport may not be well balanced in the model system. There is, for instance, a distinct response of friction velocity to small irregularities in the topography in the model system.

SIMULATED CHANGES FOR SEVERAL CASES

The model system is able to identify the impact of artificial beach nourishment, since the models incorporate variables that are changed by nourishment. The effects of grain-size, adaptation length for increasing sand transport, and topography were evaluated. Grain diameter acts in SAFE to change the threshold friction velocity. SAFE assumes well sorted, cohesionless sand. It does not include a (gradual) transition of the sand characteristics due to selection processes. Nourishment sand, however, is often only moderately sorted, and may contain silt, shell fragments and gravel (Van der Wal, 1998b; Chapter 3). The model system can be refined by adding procedures that consider the effect of such factors.

The model system is sensitive to the value of adaptation length. Larger values for the adaptation length cause smoother transport gradients and therefore a smoother topography, which corresponds more closely to the actual topography. SAFE uses an adaptation length of 20 m for increasing sand transport by default. Most wind tunnel studies (Kawamura, 1951; Butterfield, 1998) and model studies (McEwan & Willetts, 1993) give smaller values, whereas most field studies (Stout, 1990; Fryrear *et al.*, 1991) report larger values. Field observations indicate that surface conditions strongly affect the adaptation length, as far as they determine sediment supply (Davidson-Arnott & Law, 1990; Arens, 1996b; Van der Wal, 1998a; Chapter 5). Moisture content and lag deposits (of shells or gravel, for instance) can increase the adaptation length. It is important to quantify the value of adaptation length for different surfaces and conditions. The fetch of onshore winds over beach sand, depending on tide and beach topography, may be critical. The sine shaped tidal curve now used in SAFE could be replaced by tidal observations. The decrease in beach width after beach nourishment has to be simulated by coupling the model system to a model that simulates beach profile response to storm waves and water level, such as SBEACH (Hansen & Byrnes, 1991) or DUROSTA (Steetzel, 1993).

When dealing with the impact of topography on aeolian sand transport and morphology, SAFE-HILL simulates the effects of topography on the wind flow pattern (including the turbulent characteristics of the air flow), and also on the threshold friction velocity through slope angle. The coupling of an air flow model and a sediment transport model therefore demonstrates the mere impact of nourishment design on aeolian sand transport. Other potential effects of topography, such as effects of moisture conditions due to a raised beach level, are not taken into account in the model system.

CONCLUSIONS

The aeolian sand transport model SAFE and the air flow model HILL were applied to simulate aeolian sand transport and morphological development in beach nourishment environments on a time scale of months.

The model system qualitatively explained cross-shore profile development due to aeolian processes. It gave a good indication of erosion and deposition. The simulated morphological development corresponded with the measurements at the study sites. On a time scale of months, quantification of the volume changes remains to be improved. In general, the rates of transport were overestimated, since a number of factors that reduce aeolian sand transport are not well accounted for.

With these benefits and limitations of the model system in mind, the impact of beach nourishment parameters on profile development can be evaluated. The grain-size of the nourishment affected the rate of aeolian sand transport and therefore the morphology of the dune area. The adaptation length for increasing sand transport especially affected the beach topography. Pronounced differences in the erosivity of the wind over unnourished and nourished beaches were not found. In contrast, the erosivity of the wind over a so-called banquet resulted in a different morphological development.

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CHAPTER 7

SYNTHESIS AND RECOMMENDATIONS

DISCUSSION AND CONCLUSIONS

The present study aims to assess the impact of beach nourishment on aeolian sand transport and morphological development of the beach and adjacent foredunes. A number of methods have been used in this study, resulting in a contribution to the knowledge of aeolian transport of nourishment sand. In this section, the obtained results are discussed in relation to the general aim of the study.

In Chapter 2, aeolian transport of nourishment sand is studied on a time scale of years. Although a number of sediment budget studies have been made for the Dutch coast, these studies did not primarily focus on the aeolian component (*e.g.* Wijnberg & Terwindt, 1995), did not explicitly distinguish between aeolian and marine sediment transport (*e.g.* Van Vessem & Stolk, 1990; De Ruig & Louisse, 1991; Roelse, 1996), or did not quantify aeolian transport rates (*e.g.* Arens & Wiersma, 1994). In Chapter 2, aeolian input into the foredunes is quantified and compared to the magnitude of overall changes of the beach-dune environment. The study also provides insight into the impact of beach nourishment on aeolian sand transport. A significant increase in the rate of aeolian sand transport was found one year after beach nourishment. In addition, the buffer function of the nourishment against wave-energy and its role in foredune development is illustrated. However, the key parameter of the increase in aeolian sand transport after nourishment is not addressed in Chapter 2. This parameter may relate to, for instance, a change in the erodibility, availability of sand or beach topography, as has been studied in Chapters 3, 4, 5 and 6.

In Chapter 3, the impact of the characteristics of the fill material on the rate of aeolian sand transport has been studied. The properties of sand collected from nourishment sites and adjacent unnourished (control) sites are assessed. They are related to the susceptibility of sand to aeolian sand transport, as determined in a wind tunnel. In all cases, the nourishment sand corresponds to lower transport rates than the sand from nearby natural beaches, because of large amounts of shell fragments, poor sorting and suitability for compaction of the nourishment sand. These results confirm observations of Draga (1983), who attributed poor aeolian activity of nourishment sand to compaction and poor sorting. They also correspond with aeolian studies on sand containing non-erodible elements (Logie, 1982; McKenna Neuman, 1998; Davidson-Arnott *et al.*, 1997). However, the latter studies found an increase in aeolian sand transport at low densities of non-erodible particles, as these particles enhance turbulence. The present method does not allow for an assessment of such effects. The results of the wind tunnel study can also not directly be translated to the field situation, because conditions are confined to a dry and uniform surface and a uniform wind, whereas the field situation is more complex.

In Chapter 4, the behaviour of nourishment sand has been studied under field conditions, on a beach on Ameland. The study provides insight into the selective processes of the sea and the wind. Marine reworking results in a decrease of shell fragments and fines on the foreshore, providing a source for aeolian sand transport. Aeolian decoupling results in a backshore with surface lag deposits and superimposed wind-blown sand, and, on a time scale of years, foredunes with wind-blown nourishment sand that is more susceptible to wind erosion than the nourishment beach sand, but less than the native foredune sand. The study illustrates that selection processes can be more important on a nourished beach than on a native beach, as the latter often consists of well-sorted sand (*cf.* Pye, 1991), although sorting processes on native beaches can be significant (*e.g.* Shephard & Young, 1961; Bauer, 1991; Arens, 1994).

In Chapter 5, field measurements of aeolian sand transport are related to factors changed by beach nourishment, such as beach width and surface conditions. The rate of aeolian sand transport increases with increasing fetch of onshore winds over beach sand, as a saltation layer has to develop with distance downwind. Especially when there is no abundant sediment supply, fetch effects appear to be important (*cf.* Jackson & Cooper, 1999). The surface characteristics and conditions may control the availability of sediment sources for transport. However, the variability in surface characteristics and conditions inhibits a constant sediment flux. On a time scale of years, the wider beach is expected to result in larger transport rates (*cf.* Hesp, 1988; Davidson-Arnott & Law, 1990). The combined result of a wider beach and changed surface conditions on this time scale is unknown.

In Chapter 6, field measurements of the two sites are used to adapt, validate and apply the air flow (including its turbulent characteristics) model HILL (Van Boxel *et al.*, 1999) and the aeolian sand transport model SAFE (Van Dijk *et al.*, 1999). The model system explains cross-shore profile development due to aeolian processes on a time scale of months. The impact of several beach nourishment parameters is evaluated. Mean grain-size affects the aeolian sand transport rate to the foredunes and therefore the morphology, by determining the threshold friction velocity. Adaptation length, which is a measure for the distance (fetch) over which sediment transport adapts to a new equilibrium condition, affects the topography of the beach in particular; the larger the adaptation length, the more the morphological development is suppressed. The topography of a beach nourishment has a limited impact on both aeolian sand transport and morphology. A number of factors that relate to beach nourishment are not yet well accounted for in the model system. Sorting and amount of shell fragments appear to be important in aeolian transport of nourishment sand (Chapters 3 and 4), but the model system assumes well sorted sand. In addition, adaptation length appears to relate to surface conditions, and, therefore, varies both in time and space (Chapter 5), but is incorporated as a constant in the model system. Marine processes, affecting beach width and topography, have to be incorporated in order to evaluate beach nourishment on a larger time scale (Chapter 2).

IMPLICATIONS FOR COASTAL MANAGEMENT

From a geomorphological and ecological point of view, beach nourishment is a sound method to counteract marine erosion, especially when compared to static protective measures, such as groynes (*e.g.*, Nordstrom & Allen, 1980). Beach nourishment implies a direct supply of sediment to a beach. However, it also changes the sediment transfer rate in the beach-dune environment. Changes in the rate of aeolian sand transport have consequences for geomorphology, ecology, recreation, construction and coastal defence, and are therefore of significance to coastal management. In this section, considerations emerging from the present study are offered to optimize nourishment projects.

Performance of beach nourishment can benefit from environmental monitoring projects (Rijkswaterstaat, 1988; Roelse *et al.*, 1991; National Research Council, 1995). Many projects, however, do not consider aeolian sand transport. The present study shows that aeolian sand transport can make a substantial contribution to the sediment budget of a coast, and it can be increased by nourishment. Therefore, it is recommended to include aeolian sand transport in sustained and accurate beach nourishment monitoring, where appropriate. The duration of a monitoring project with respect to aeolian sand transport will relate to the scale of nourishment. For nourishments with a planned lifetime of approximately five years, monitoring should start before nourishment and should continue preferably until the fourth year after nourishment (Chapter 2). Annual height measurements in a fixed framework of cross-shore sections extending as far as the landward profile close-out, such as established for the DONAR (JARKUS) data base (De Ruig & Louisse, 1991), are sufficient for such a project. In addition to these yearly measurements, similar measurements of all sections within a nourishment area have to be performed directly after the fill has been placed.

When choosing compatible fill material, it is recommended not only to take into account the mean or median grain-size of the fill, but also the whole grain-size distribution and the spatial variability of sand properties in the source area (both horizontally and vertically), since different sources of well sorted sand may result in poor sorting of fill due to mixture (Chapter 3). For the Dutch situation, compatible fill consists of well sorted sand with a minimum amount of shell fragments, clay and silt.

The carbonate content of the sand largely determines the vegetation composition of the (fore)dunes (Rozema *et al.*, 1985; Van der Wal *et al.*, 1995). The present research shows that the carbonate content of the foredune sand is altered by nourishment, when using fill containing shell fragments. This suggests that vegetation effects can be expected. In some cases, such effects may be positive, for instance where carbonate influx can counteract soil acidification (Ketner-Oostra, 1998). Effects of carbonates and other constituents of nourishment sand on vegetation have to be anticipated when designing a beach nourishment (Chapter 4).

If the formation of shell pavements has to be avoided, nourishment sand containing large amounts of shells should be deposited mainly on the foreshore, rather than on the backshore. The shells are reworked by marine processes (Depuydt, 1972; Psuty & Namikas, 1991; Chapter 4), although armouring effects can also occur on the subaqueous beach (Swart, 1991; Tánczos, 1996). From a viewpoint of coastal protection, the shells in the nourishment sand offer a greater buffer against marine erosion than well sorted sand, since a part of the wave energy is used for the reworking of the shells. The reworked nourishment sand provides a source of well-sorted sediment for aeolian transport to the beach and dunes (Chapter 5).

The shape of a beach nourishment profile does not seem to have a pronounced effect on the erosivity of the wind and, therefore, on the pattern of erosion and deposition. However, the present study suggests that a banquet made out of well-sorted sand is reshaped due to wind speed-up at its stoss slope. The sand eroded at the slope is mainly deposited directly on top of the banquet (Chapter 6).

OUTLOOK

The understanding of aeolian transport of nourishment sand in beach-dune environments benefits from fundamental and applied studies of aeolian sand transport and coastal dunes. Although progress in understanding aeolian dynamics has been made in recent years, many opportunities and challenges for research still remain.

As suggested by Nickling and Davidson-Arnott (1990), aeolian research could consider more seriously the surficial and textural parameters that directly control the supply of sediment to the air stream and, ultimately, the sediment transport rate, rather than focus on loose, cohesionless sediments. The dynamic nature of surface conditions (coupled with the interaction between the wind, the surface and the developing saltation cloud) can also give rise to a fetch effect, i.e., the change in sediment flux with distance downwind (Gillette *et al.*, 1996; McKenna Neuman & Maljaars, 1997; Chapter 5). In the present study, the role of sorting and shell lag development in aeolian sand transport is evaluated. Future research should aim to find a quantitative formulation of the complex (feedback) mechanisms of factors such as shells, silt, sorting, packing of the sand, and moisture and their impact on thresholds for wind velocity, sediment supply and the rate of aeolian sand transport. Ignoring the effects of these controlling factors on aeolian sand transport, and applying equations developed for an infinite, dry sand surface would, generally, result in an overestimation of the rate of aeolian sand transport. Efforts have to be made to incorporate these controlling factors, including their complex (feedback) mechanisms and their inherent spatial and temporal variability, in physical deterministic models such as the SAFE-HILL model system.

The present study suggests that the rate of aeolian sand transport is altered by nourishment on a time scale of years (Chapter 2). Aeolian dynamics on this time scale are not fully understood. There is a need for research that links the driving forces (meteorological and hydrodynamic conditions) and controlling factors (such as surface conditions and beach width) of aeolian sand transport to the sediment budget on a time scale of years. Process-response models of aeolian dynamics developed for this meso-scale could aid in evaluating the effects of beach nourishment on aeolian sand transport and foredune development.

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SUMMARY

Beach nourishment is used worldwide as a method for restoring and maintaining coastal areas threatened by (structural) marine erosion. Nourishment implies a direct supply of sand to a beach, so that the sand acts as a buffer against wave energy during extreme events. However, nourishment may also affect the sediment exchange rate between the beach and the dune. The aim of this thesis is to assess the impact of beach nourishment on aeolian sand transport and morphodynamics (Chapter 1).

The study is conducted on several nourishment sites along the Dutch North Sea coast (Chapters 2 and 3). On two beaches, referred to as the Ameland and the Den Helder site, field measurements of aeolian sand transport and related factors were carried out, both prior to beach nourishment and after beach nourishment (Chapters 4 and 5). The topography and foredune vegetation has been monitored for several years. Data from these two sites have also been used to apply the aeolian sand transport model SAFE and the air flow model HILL, in order to identify the response of aeolian sand transport and morphology to several fill characteristics and nourishment design parameters (Chapter 6).

The overall effects of nourishment on the development of the beach-dune system are studied on a group of twelve beach nourishments sites (Chapter 2). Nourishment is found to promote dune building. The foredune is barely eroded in the first four years following nourishment. A negative sand budget is found for the entire supratidal beach, which does not change after nourishment. One year after nourishment, erosion of the beach increased. In the same year, the rate of aeolian sand transport to the foredunes significantly increased: net aeolian deposition in the foredunes was about 14 $m^3\ m^{-1}\ y^{-1}$ on average (versus about 9 $m^3\ m^{-1}\ y^{-1}$ on average in a control situation). There was, however, a large spatial and temporal variation in deposition. The method does not allow for an assessment of the effects in the year of nourishment.

The increase in sand transport may be due to many factors. Several factors, relating to characteristics of the fill material (such as the grain-size distribution of the sand) and nourishment design (such as beach width and beach topography) determine the erodibility of the surface, the availability of

sand, and the erosivity of the wind and may, therefore, restrict or amplify the rate of aeolian sand transport on a nourished beach, as compared to an unnourished beach. A number of these factors and their role in aeolian sand transport has been studied in detail.

Erodibility of the surface

The offshore source area is often characterized by a variety in material properties in both vertical (temporal) and horizontal (spatial) direction. The sand from this source area is mixed when brought ashore. The sand frequently contains admixtures of gravel, silt, shells or organic matter, which are insubstantial in the ambient beach sand. In addition, the fill material has not been subject to marine and aeolian sorting to the same extent as the sand that normally reaches the beach. Samples from several nourishment beaches and adjacent control sites along the Dutch coast show that nourishment sand is poorer sorted, has a platykurtic and negatively skewed grain-size distribution (*i.e.*, a coarse tail) and contains both more silt and more coarse grains or shell fragments (Chapter 3).

The grain-size distributions of the samples from nourished beaches and dunes and nearby unnourished beaches are related to the 'susceptibility' of the sediments to mobilize under controlled wind tunnel conditions (Chapter 3). The rates of aeolian sand transport depend on sorting of the sand and the amounts of shell fragments in the sand, and do not relate to mean grain-size of the sand. Shells eventually prevented further transport by forming a lag. The fill material, which is moderately sorted to moderately well sorted and contains shell fragments, is associated with low rates of sand transport during wind tunnel experiments, as compared to rates of sand from nearby unnourished beaches. At two nourished sites, however, sand is well to very well sorted, and samples from these nourishments exhibited high transport rates. For non-uniform sand, such as nourishment sand, sorting and amounts of shell fragments may therefore be more important than mean grain-size. Assuming very well sorted sand in process-response models, such as the SAFE-HILL model system, may therefore not be valid (Chapter 6).

As soon as the beach is nourished, marine and aeolian sorting processes alter the surface texture of the beach (Chapter 4). The grain-size-selective aeolian processes that take place after a beach nourishment with moderately sorted fill containing shell fragments were studied on the Ameland site. Marine reworking of the fill results in a decrease of shell fragments and a decrease in fines on the foreshore surface, with the exception of the swash mark. During aeolian sand transport, aeolian decoupling of the nourishment sand results in a backshore with surface lag deposits with moderately sorted sand containing a substantial amount of shell fragments, silt and coarse quartz grains, alternated with superimposed patches of wind-blown sand with less shell fragments. Silt and shells were underrepresented in sand transported under moderate and strong winds, indicating high threshold friction velocities for these components. Wind-laid nourishment sand, *i.e.*, the nourishment sand that is blown to the dunes, contains only small amounts of these shell fragments and the sand is finer and better sorted than the nourishment beach sand. Grain-size-selective processes lead to an assimilation of the grain-size distribution of the nourishment sand to the native sand, but the nourishment sand that is blown to the foredunes still deviates from the wind-laid native sand, in that it is more poorly sorted and more negatively skewed. Although the coarse material selectively lags behind, wind-laid nourishment contains more coarse material than the native beach sand and the wind-laid native sand found in the foredunes. Since a good correlation is found between the amount of this coarse material and carbonate content, this suggests that vegetation effects can be expected (Chapter 3).

Shell pavements develop especially on the backshore (Chapters 4 and 5) and on top of banquets, dune front nourishments and dune nourishments (Chapter 3). The shell pavement formed at the backshore of the Ameland beach results in a reduction of aeolian sand transport, but the sand transport does not cease (Chapter 5). During different conditions either the input of sand from the intertidal area, where the sand has been reworked by the sea, the sand supply from the shell pavement or superimposed patches of dry well sorted blown sand provide a source for aeolian sand transport. The large variability in surface characteristics probably enhances variation in aeolian sand transport over the beach.

Availability of sand

In order to develop a fully developed saltation layer, a critical fetch has to be exceeded. On a beach, the minimum available fetch for onshore sand transport is delimited by the beach width from the limit of run-up to the edge of the dunes. Wind direction determines the actual fetch length. Measured rates of aeolian sand transport relate to fetch of wind over beach sand (Chapter 5). Especially at the Den Helder site, measured transport rates increased with fetch. Since beach width (and fetch) is enlarged by nourishment, this suggests that larger sediment fluxes (and more erosion on the beach) can be expected as compared to before nourishment. The effect will be largest just after nourishment and will gradually decrease as the size and width of the nourishment diminish as a result of marine and aeolian processes. Sediment supply, which is influenced by surface characteristics and conditions, is recognized as an important parameter for the effect. However, the relation between aeolian sand transport and fetch is seriously affected by, *e.g.*, the variability in surface characteristics.

The impact of the adaptation length, relating to the distance over which sand transport adapts to a new equilibrium, and thus relating to the critical fetch, is evaluated by applying the SAFE-HILL model system: with increasing adaptation length, the development of the beach and foredune is suppressed (Chapter 6).

Erosivity of the wind

The SAFE-HILL model system is used to evaluate the impact of several nourishment designs on the erosivity of the wind (which is expressed in terms of friction velocity), and therefore on the pattern of erosion and deposition of the beach and foredune. The design of a beach nourishment had a limited impact on the erosivity of the wind. In addition, there are no pronounced differences in erosivity of the wind over the unnourished and nourished Ameland beach, respectively. However, the erosivity of the wind over a banquet (*i.e.*, a dune toe nourishment) made out of well sorted, loose sand results in a dramatic adaptation of the fill. The steep, bare windward side of the banquet erodes due to wind speed-up. Most sand is deposited directly on top of the banquet (Chapter 6).

The study shows that nourishment mainly promotes dune growth by forming a buffer against wave energy (preventing dune toe erosion), and by temporally enlarging the aeolian sediment transport rate to the dunes. Nevertheless, nourishment may reduce aeolian sand transport in individual cases. The factors studied often have complex feedback mechanisms that have to be taken into account when optimizing nourishment projects from a geomorphological and ecological point of view (Chapter 7).

SAMENVATTING

Zandsuppletie wordt wereldwijd toegepast om (structureel) eroderende kusten te herstellen of in stand te houden. Zandsuppletie betekent een directe toevoer van zand naar het strand, waar het zand zorgt voor een buffer tegen de golfenergie tijdens stormen. Suppletie kan echter ook de uitwisseling van zand tussen het strand en de duinen veranderen. In dit proefschrift is de invloed van zandsuppletie op verstuiving en zeereepontwikkeling bestudeerd (Hoofdstuk 1).

Het onderzoek is verricht op een aantal plaatsen langs de Nederlandse kust (Hoofdstukken 2 en 3). In twee gebieden, op Ameland en bij Den Helder, zijn veldmetingen gedaan naar verstuiving en hieraan gerelateerde factoren (Hoofdstukken 4 en 5). Er is zowel voorafgaand aan het opbrengen van het suppletiezand als na het opbrengen van het suppletiezand gemeten. Bovendien is de ontwikkeling van de topografie en de zeereepvegetatie gedurende enkele jaren gevolgd. De gegevens van de twee gebieden zijn ook gebruikt in het eolisch zandtransportmodel SAFE en het luchtstromingsmodel HILL. Met behulp van de beide modellen is de invloed geëvalueerd van verschillende materiaaleigenschappen en ontwerpen van zandsuppleties op de verstuiving en morfologische ontwikkeling van het strand-duin systeem (Hoofdstuk 6).

De effecten van zandsuppletie op de ontwikkeling van het strand en de zeereep zijn bestudeerd in twaalf suppletiegebieden (Hoofdstuk 2). Zandsuppletie op het strand bevorderde de ontwikkeling van de zeereep. De zeereep werd nauwelijks aangetast gedurende de eerste vier jaren na zandsuppletie. Er is een negatieve zandbalans gevonden voor de gehele zone boven de hoogwaterlijn. Deze negatieve zandbalans verandert niet na suppletie. Een jaar na het opbrengen van de zandsuppletie nam de erosie van het strand toe. In hetzelfde jaar nam ook de verstuiving naar de zeereep significant toe: er is een aanstuiving van gemiddeld 14 m^3 m^{-1} j^{-1} gemeten, tegenover gemiddeld 9 m^3 m^{-1} j^{-1} in jaren zonder invloed van zandsuppletie. De ruimtelijke en temporele variatie in aanstuiving was echter groot. De gehanteerde methode is niet geschikt om de verstuiving in het jaar van suppletie te bepalen.

De toename van de aanstuiving na zandsuppletie kan verschillende oorzaken hebben. Veel factoren die samenhangen met de eigenschappen van het suppletiezand (zoals de korrelgrootte-verdeling van het zand), en het ontwerp van een zandsuppletie (die bijvoorbeeld de breedte en de topografie van het strand bepaalt), beïnvloeden de stuifgevoeligheid van het zand (erodibiliteit), de beschikbaarheid van zand en de erosiviteit van de wind, en kunnen de verstuiving van suppletiezand daardoor verminderen of juist versterken. Een aantal van deze factoren en hun invloed op het verstuivingsproces is in detail bestudeerd.

Stuifgevoeligheid van zand

Het wingebied wordt over het algemeen gekenschetst door een grote verscheidenheid aan materiaaleigenschappen in zowel de verticale (temporele) als de horizontale (ruimtelijke) richting. Het materiaal in het wingebied wordt gemengd bij het vervoer naar het suppletiegebied. Het zand bevat vaak ook bijmengingen van grind, silt, schelpen en organische stof, die nauwelijks voorkomen in het oorspronkelijke strandzand. Bovendien is het suppletiezand niet gesorteerd door de zee en de wind zoals het zand dat onder natuurlijke omstandigheden het strand bereikt. Zandmonsters van een aantal gesuppleerde stranden en aangrenzende niet-gesuppleerde stranden langs de Nederlandse kust verschillen daarom (Hoofdstuk 3). Het suppletiezand is slechter gesorteerd, heeft een platte korrelgrootte-verdeling, die bovendien negatief scheef is (grove staart), en bevat meer siltdeeltjes, meer grove kwartskorrels en meer schelpen en schelpfragmenten.

De stuifgevoeligheid van het zand is in een windtunnel bepaald, en vervolgens gerelateerd aan de korrelgrootte-verdeling van het zand (Hoofdstuk 3). De stuifgevoeligheid van het zand hangt af van de sorteringsgraad van het zand en van de hoeveelheid schelpfragmenten in het materiaal, maar niet van de gemiddelde korrelgrootte van het zand. Aan het oppervlak werd vaak een schelpenvloertje gevormd, waardoor in een aantal gevallen het zandtransport uiteindelijk stopte. Het suppletiezand, dat slechts redelijk tot redelijk goed gesorteerd was, en veel schelpfragmenten bevatte, verstoof tijdens de proeven slechter dan het oorspronkelijke strandzand. Zand van twee suppleties die wel redelijk tot goed stoven, was goed tot zeer goed gesorteerd. Voor zand met een polymodale korrelgrootte-verdeling zoals suppletiezand geldt dat sortering en de aanwezigheid van schelpfragmenten daarom belangrijker kunnen zijn dan de gemiddelde korrelgrootte. Het is daarom niet gerechtvaardigd uit te gaan van goed gesorteerd zand in proces-respons modellen zoals SAFE-HILL.

Zodra het suppletiezand op het strand is opgebracht, wordt het oppervlak selectief bewerkt door mariene en eolische processen (Hoofdstuk 4). De sorterende werking van met name de wind is bestudeerd op Ameland, waar het strand met redelijk gesorteerd, schelphoudend zand was gesuppleerd. Omwerking van het zand door de zee zorgt voor een afname van schelpfragmenten en een afname van zeer fijne zand- en siltdeeltjes op het natte strand, met uitzondering van het vloedmerk. Tijdens verstuiving vindt ontmenging van het suppletiezand plaats: op het droge strand wordt een vloertje gevormd, met redelijk gesorteerd zand en een aanzienlijke hoeveelheid schelpfragmenten, silt en grove kwartskorrels, afgewisseld met hierop gesuperponeerde plekken met verstoven zand met minder schelpfragmenten. Silt en schelpfragmenten zijn ondervertegenwoordigd in het zand dat tijdens matige en sterke wind in verstuiving gaat, wat duidt op hoge drempelwaarden van deze componenten voor verstuiving. Naar de zeereep verstoven suppletiezand bevat slechts kleine hoeveelheden schelpfragmenten en is fijner en beter gesorteerd dan het suppletiezand op het strand. De sorterende werking leidt weliswaar tot een sterkere gelijkenis van de materiaaleigenschappen van het suppletiezand met die van het oorspronkelijke zand, maar er blijven verschillen. Het suppletiezand blijft slechter gesorteerd en heeft nog steeds een negatievere scheefheid. Bovendien bevat het naar de zeereep verstoven suppletiezand nog steeds meer grof materiaal dan zowel het oorspronkelijke strandzand als het naar de zeereep verstoven oorspronkelijke zand. Omdat een goed verband is gevonden tussen dit grove materiaal en het carbonaatgehalte, zijn effecten op de vegetatie te verwachten (Hoofdstuk 3).

Schelpenvloertjes ontwikkelen zich met name op het droge strand (Hoofdstukken 4 en 5), en op banketten (suppleties langs de duinvoet), duinfront- en duinsuppleties (Hoofdstuk 3). Het schelpenvloertje dat op het strand op Ameland was gevormd, leek weliswaar te leiden tot een afname in het zandtransport, maar het zandtransport stopte niet, zoals in de windtunnel is gevonden (Hoofdstuk 5). Tijdens verschillende omstandigheden wordt een bron voor verstuiving gevonden op het natte strand, waar het zand is omgewerkt door de zee, op het schelpenvloertje zelf of op de hierop gesuperponeerde plekken met goed gesorteerd droog zand. De ruimtelijke variabiliteit van het oppervlak droeg waarschijnlijk bij aan de variatie in verstuiving op het strand.

Beschikbaarheid van zand

Er is een bepaalde afstand nodig om verstuiving volledig op gang te doen komen, de zogenaamde kritische strijklengte. Op een strand wordt de minimale strijklengte voor aanlandig zandtransport bepaald door de breedte van het strand tussen de waterlijn en de duinvoet. De windrichting kan de strijklengte van de wind over het strand sterk vergroten. De gemeten verstuiving op het strand van Ameland en Den Helder blijkt verband te houden met de strijklengte (Hoofdstuk 5). Vooral op het Helderse strand nam het zandtransport toe met toenemende strijklengte. Omdat de breedte van het strand (en dus de strijklengte) positief gecorreleerd is met zandsuppletie, geeft dit aan dat een grotere zandflux (en meer erosie op het strand) verwacht kan worden na zandsuppletie. Dit effect zal direct na zandsuppletie het grootst zijn, en zal afnemen naarmate de zandsuppletie door de werking van water en wind wordt geërodeerd. De beschikbaarheid van zand voor verstuiving, die mede wordt bepaald door de aard en gesteldheid van het oppervlak, lijkt van belang voor dit effect. Het verband tussen verstuiving en de strijklengte van de wind over het strand werd echter in belangrijke mate verstoord door met name de variabiliteit in oppervlakte-eigenschappen.

De invloed van de aanpassingslengte, die verband houdt met de afstand waarop het zandtransport zich aanpast aan een nieuw evenwicht, en die dus gerelateerd is aan de kritische strijklengte, is geëvalueerd met behulp van het SAFE-HILL model: een toename van de aanpassingslengte beperkte de ontwikkeling van het strand en de zeereep (Hoofdstuk 6).

Erosiviteit van de wind

Het SAFE-HILL model is gebruikt voor het evalueren van de invloed van suppletieontwerp op de erosiviteit van de wind (die is uitgedrukt in wrijvingssnelheid), en daarmee op het patroon van erosie en depositie op het strand en in de zeereep (Hoofdstuk 6). Het ontwerp van een strandsuppletie had weinig effect op de erosiviteit van de wind. Bovendien was er nauwelijks verschil in de erosiviteit van de wind over het ongesuppleerde strand en het gesuppleerde strand op Ameland. De erosiviteit van de wind over een banket van goed gesorteerd los zand resulteerde echter wel in een sterke aanpassing van de suppletie. De steile, onbegroeide loefzijde erodeerde door versnelling van de wind. Depositie van dit zand vond vooral direct op de top van het banket plaats.

Dit onderzoek laat zien dat zandsuppletie vooral een positief effect heeft op de duinvorming doordat het zand op het strand een buffer vormt tegen golfenergie waardoor duinvoeterosie wordt voorkomen, en doordat de verstuiving van zand naar de duinen tijdelijk kan toenemen. Dit sluit niet uit dat zandsuppletie in individuele gevallen een afname in verstuiving tot gevolg kan hebben. De factoren die samenhangen met verstuiving hebben dikwijls complexe terugkoppelingen, die in beschouwing moeten worden genomen bij het optimaliseren van zandsuppleties vanuit het oogpunt van kustverdediging, maar ook van geomorfologie en ecologie (Hoofdstuk 7).

REFERENCES

Anderson, R.S. (1987). Eolian sediment transport as a stochastic process: the effect of a fluctuating wind on particle trajectories. Journal of Geology, 95, pp. 497-512.

Anderson, R.S. (1988). The pattern of grainfall deposition in the lee of aeolian dunes. Sedimentology, 35, pp. 175-188.

Anderson, R.S. & P.K. Haff (1991). Wind modification and bed response during saltation of sand in air. Acta Mechanica, Supplement 1, pp. 21-51.

Arens, S.M. (1994). Aeolian processes in the Dutch foredunes. Ph.D. thesis. University of Amsterdam, Amsterdam, 150 pp.

Arens, S.M. (1996a). Patterns of sand transport on vegetated foredunes. Geomorphology, 17, pp. 339-350.

Arens, S.M. (1996b). Rates of aeolian sand transport on a beach in a temperate humid climate. Geomorphology, 17, pp. 3-18.

Arens, S.M. (1997). Transport rates and volume changes in a coastal foredune on a Dutch Wadden island. Journal of Coastal Conservation, 3, pp. 49-56.

Arens, S.M. & G.E.M. van der Lee (1995). Saltation sand traps for the measurement of aeolian transport into the foredunes. Soil Technology, 8, pp. 61-74.

Arens, S.M. & D. van der Wal (1998). Zeereep open voor invloed natuur. Geografie, 7, pp. 18-21. (In Dutch.)

Arens, S.M., H.M.E. van Kaam-Peters & J.H. van Boxel (1995). Air flow over foredunes and implications for sand transport. Earth Surface Processes and Landforms, 20, pp. 315-332.

Arens, S.M. & J. Wiersma (1994). The Dutch foredunes: inventory and classification. Journal of Coastal Research, 10, pp. 189-202.

Bagnold, R.A. (1941). The physics of blown sand and desert dunes. Methuen, London, 1964 reprint, 266 pp.

Bauer, B.O. (1991). Aeolian decoupling of beach sediments. Annals of the Association of American Geographers, 8, pp. 290-303.

Bauer, B.O., D.J. Sherman & J.F. Wolcott (1992). Sources of uncertainty in shear stress and roughness length estimates derived from velocity profiles. Professional Geographer, 44, pp. 453-464.

Beaufort, G.A., G. Baarse, M. Pluym, P. Roelse & E.B. Peerbolte (1989). Strand- en duinsuppleties; effectiviteit en kosten. Kustverdediging na 1990. Technisch rapport 11. Rijkswaterstaat, The Hague, 60 pp. (In Dutch.)

Bird, E.C.F. (1996). Beach management. Wiley, Chichester, 282 pp.

Blumberg, D.G. & R. Greeley (1993). Field studies of aerodynamic roughness length. Journal of Arid Environments, 25, pp. 39-48.

Bowen, A.J., D.L. Inman & V.P. Simmons (1968). Wave 'set-down' and set-up. Journal of Geophysical Research, 73, pp. 2569-2577.

Burt, J.E. & G.M. Barber (1996). Elementary statistics for geographers. Guilford, New York, 2nd ed., 640 pp.

Butterfield, G.R. (1991). Grain transport rates in steady and unsteady turbulent flows. Acta Mechanica, Supplement 1, pp. 97-122.

Butterfield, G.R. (1998). Transitional behaviour of saltation: wind tunnel observations of unsteady winds. Journal of Arid Environments, 39, pp. 377-394.

Carter, R.W.G. (1976). Formation, maintenance and geomorphological significance of an aeolian shell pavement. Journal of Sedimentary Petrology, 46, pp. 418-429.

Carter, R.W.G. (1982). Some problems associated with the analysis and interpretation of mixed carbonate and quartz beach sands, illustrated by examples from North-West Ireland. Sedimentary Geology, 33, pp. 35-56.

Carter, R.W.G. & P. Wilson (1990). The geomorphological, ecological and pedological development of coastal foredunes at Magilligan Point, Northern Ireland. In: K.F. Nordstrom, N.P. Psuty & R.W.G. Carter (eds), Coastal dunes; form and process. Wiley, Chichester, pp. 129-157.

Chapman, D.M. (1990). Aeolian sand transport - an optimized model. Earth Surface Processes and Landforms, 15, pp. 751-760.

Clayton, K.M. (1980). Beach sediment budgets and coastal modification. Progress in Physical Geography, 4, pp. 471-486.

Cooke, R.U., A. Warren & A.S. Goudie (1993). Desert geomorphology. UCL Press, London, 1996 reprint, 514 pp.

Davidson-Arnott, R.G.D. & M.N. Law (1990). Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. In: K.F. Nordstrom, N.P. Psuty & R.W.G. Carter (eds), Coastal dunes; form and process. Wiley, Chichester, pp. 177-200.

Davidson-Arnott, R.G.D., D.C. White & J. Ollerhead (1997). The effects of artificial pebble concentrations on eolian sand transport on a beach. Canadian Journal of Earth Sciences, 34, pp. 1499-1508.

Davison, A.T., R.J. Nicholls & S.P. Leatherman (1992). Beach nourishment as a coastal management tool: an annotated bibliography on developments associated with the artificial nourishment of beaches. Technical communication. Journal of Coastal Research, 8, pp. 984-1022.

De Ploey, J. (1978). Some field measurements and experimental data on wind-blown sands. In: M. de Boodt & D. Gabriels (eds). Assessment of erosion. Wiley, Chichester, pp. 541-552.

De Rooij-Van der Goes, P.C.E.M., W.H. van der Putten & B.A.M. Peters (1995). Effects of sand deposition on the interaction between *Ammophila arenaria*, plant-parasitic nematodes, and pathogenic fungi. Canadian Journal of Botany, 73, pp. 1141-1150.

De Ruig, J.H.M. (1995). De kust in breder perspectief. Basisrapport kustnota 1995. Rijkswaterstaat, The Hague, 183 pp. (In Dutch.)

De Ruig, J.H.M. & R. Hillen (1997). Developments in Dutch coastline management: conclusions from the second governmental coastal report. Journal of Coastal Conservation, 3, pp. 203-210.

De Ruig, J.H.M. & C.J. Louisse (1991). Sand budget trends and changes along the Holland coast. Journal of Coastal Research, 7, pp. 1013-1026.

Dean, R.G. (1983). Principles of beach nourishment. In: P.D. Komar (ed.). CRC Handbook of coastal processes and erosion. CRC Press, Boca Raton, pp. 217-232.

Delft Hydraulics (1987). Manual on artificial beach nourishment. Delft Hydraulics, Delft, 195 pp.

Deltacommissie (1961). Rapport Deltacommissie. Deel 1. Eindverslag en interimadviezen. Staatsuitgeverij, The Hague, 173 pp. (In Dutch.)

Depuydt, F. (1972). De Belgische strand- en duinformaties in het kader van de geomorfologie der zuidoostelijke Noordzeekust. Verhandelingen van de Koninklijke Academie voor Wetenschappen, Letteren en Schone kunsten van België, 34 (122), 228 pp. (In Dutch.)

Draga, M. (1983). Eolian activity as a consequence of beach nourishment - observations at Westerland (Sylt), German North Sea coast. Zeitschrift für Geomorphologie, Supplement 45, pp. 303-319.

Eisma, D. (1968). Composition, origin and distribution of Dutch coastal sands between Hoek van Holland and the island of Vlieland. Ph.D. thesis. University of Groningen, Groningen, 267 pp.

Eitner, V. (1996). The effect of sedimentary texture on beach fill longevity. Journal of Coastal Research, 12, pp. 447-461.

Eitner, V. & G. Ragutski (1994). Effects of artificial beach nourishment on nearshore sediment distribution (Island of Norderney, Southern North Sea). Journal of Coastal Research, 10, pp. 637-650.

Eleveld, M.A. (1999). Exploring coastal morphodynamics of Ameland (the Netherlands) with remote sensing monitoring techniques and dynamic modelling in GIS. ITC publ. 70. Ph.D. thesis. University of Amsterdam, Amsterdam, 225 pp.

Erchinger, H.F. & H. Knaack (1995). Die Versuchstrandaufspülung 1992 auf Norderney und Messungen zum äolischen Sandtransport. Die Küste, 57, pp. 1-23. (In German.)

Fay, M.B. (1989). Grain size Analysis Program Package (GAPP). University of Dar es Salaam, Dar es Salaam, Tanzania.

Folk, R.L. (1966). A review of grain-size parameters. Sedimentology, 6, pp. 73-93.

Folk, R.L. (1971). Longitudinal dunes of the northwestern edge of the Simpson Desert, Northern Territory, Australia, 1. Geomorphology and grain size relationships. Sedimentology, 16, pp. 5-54.

Folk, R.L. & W.C. Ward (1957). Brazos River bar: a study on the significance of grain size parameters. Journal of Sedimentary Petrology, 27, pp. 3-26.

Fryrear, D.W., J.E. Stout, L.J. Hagen & E.D. Vories (1991). Wind erosion: field measurement and analysis. Transactions of the American Society of Agricultural Engineers, 34, pp. 155-160.

Gares, P.A., R.G.D. Davidson-Arnott, B.O. Bauer, D.J. Sherman, R.W.G. Carter, D.W.T. Jackson & K.F. Nordstrom (1996). Alongshore variations in aeolian sediment transport: Carrick Finn Strand, Ireland. Journal of Coastal Research, 12, pp. 673-682.

Geological Survey of the Netherlands (1996). Description cores 96DW2, 96DW6, 96DW9, 96DW12, 96DW15, 96DW16. Unpublished. (In Dutch.)

Gerety, K.M. & R. Slingerland (1983). Nature of the saltating population in wind tunnel experiments with heterogeneous size-density sands. In: M.E. Brookfield & R.S. Ahlbrandt (eds). Eolian sediments and processes. Developments in Sedimentology 38. Elsevier, Amsterdam, pp. 115-131.

Gillette, D.A., G. Herbert, P.H. Stockton & P.R. Owen (1996). Causes of the fetch effect in wind erosion. Earth Surface Processes and Landforms, 21, pp. 641-659.

Hagen, L.J. & D.V. Armbrust (1994). Plant canopy effects on wind erosion saltation. Transactions of the American Society of Agricultural Engineers, 37, pp. 461-465.

Hansen, M. & M.R. Byrnes (1991). Development of optimum beach fill design cross-section. Coastal sediments '91. American Society of Civil Engineers, New York, pp. 2067-2080.

Hesp, P.A. (1988). Surfzone, beach, and foredune interactions on the Australian South East coast. Journal of Coastal Research, Special Issue 3 (Dune/beach interaction), pp. 15-25.

Hesp, P.A. (1989). A review of biological and geomorphological processes involved in the initiation and development of incipient foredunes. Proceedings of the Royal Society of Edinburgh, 96B, pp. 181-201.

Hillen, R. & P. Roelse (1995). Dynamic preservation of the coastline in the Netherlands. Journal of Coastal Conservation, 1, pp. 17-28.

Hoekstra, P., K.T. Houwman, A. Kroon & B.G. Ruessink (1996). Morphodynamic behaviour of the Terschelling shoreface nourishment; morphological changes in response to hydrodynamical and sediment transport processes and sediment characterics. Report NOURTEC. Institute for Marine and Atmospheric Research, Utrecht, 64 pp.

Hoekstra, P., K.T. Houwman, A. Kroon, P. van Vessem & B.G. Ruessink (1994). The NOURTEC experiment of Terschelling: process-oriented monitoring of a shoreface nourishment (1993-1996). Coastal dynamics '94, American Society of Civil Engineers, New York, pp. 402-416.

Horikawa, K., S. Hotta, S. Kubota & S. Katori (1983). On the sand transport rate by wind on a beach. Coastal Engineering in Japan, 26, pp. 101-120.

Hotta, S., S. Kubota, S. Katori & K. Horikawa (1984). Sand transport by wind on a wet sand beach. Proceedings of the 19th Coastal Engineering Conference. American Society of Civil Engineers, New York, pp. 1265-1281.

Iversen, J.D. & K.R. Rasmussen (1994). Effect of slope on saltation threshold. Sedimentology, 41, pp. 721-728.

Jackson, D.W.T. & J.A.G. Cooper (1999). Beach fetch distance and aeolian sediment transport. Sedimentology, 46, pp. 517-522.

Kawamura, R. (1951). Study of sand movement by wind. Translated as Technical report Hydraulic Engineering Laboratory. University of California, Berkeley, 57 pp.

Ketner-Oostra, R. (1998). Effects of shoreface nourishment on the vegetation of Terschelling (NL). Coastline, 4, p. 28.

Knottnerus, D.J.C. (1976). Wind erosion research by means of a wind tunnel. Measures to control wind erosion of soil and other materials for reasons of economy and health. Institute for Soil Fertility, Haren, 14 pp.

Komar, P.D. (1998). Beach processes and sedimentation. Prentice Hall, Upper Saddle River (New Jersey), 2nd ed., 544 pp.

Kroon, A. & P. Hoekstra (1990). Eolian sediment transport on a natural beach. Journal of Coastal Research, 6, pp. 367-379.

Lancaster, N. (1996). Field studies of sand patch initiation processes on the northern margin of the Namib Sand Sea. Earth Surface Processes and Landforms, 21, pp. 947-954.

Larson, R., A. Morang & L. Gorman (1997). Monitoring the coastal environment; part II: sediment sampling and geotechnical methods. Journal of Coastal Research, 13, pp. 308-330.

Lee, C.T. (1997). Textural variations over a foreshore-backshore environment, Hawaii. Physical Geography, 18, pp. 263-290.

Leonard, L., T. Clayton & O. Pilkey (1990). An analysis of replenished beach design parameters on U.S. Coast barrier islands. Journal of Coastal Research, 6, pp. 15-36.

Logie, M. (1982). Influence of roughness elements and soil moisture on the resistance of sand to wind erosion. Catena, Supplement 1, pp. 161-173.

Mason, C.M. & R.L. Folk (1958). Differentiation of beach, dune and aeolian flat environments by size analysis, Mustang Island, Texas. Journal of Sedimentary Petrology, 28, pp. 211-226.

McEwan, I.K. & B.B. Willetts (1993). Adaptation of the near-surface wind to the development of sand transport. Journal of Fluid Mechanics, 242, pp. 99-115.

McKenna Neuman, C. (1998). Particle transport and adjustments of the boundary layer over rough surfaces with an unrestricted, upwind supply of sediment. Geomorphology, 25, pp. 1-17.

McKenna Neuman, C. & M. Maljaars (1997). Wind tunnel measurement of boundary layer response to sediment transport. Boundary Layer Meteorology, 84, pp. 67-83.

McLaren, P. & D. Bowles (1985). The effects of sediment transport on grain-size distributions. Journal of Sedimentary Petrology, 55, pp. 457-470.

Morton, R.A., J.G. Paine & J.C. Gibeaut (1994). Stages and durations of post-storm beach recovery, Southeastern Texas Coast, U.S.A. Journal of Coastal Research, 10, pp. 884-908.

Namikas, S.L. & D.J. Sherman (1995). A review of the effects of surface moisture content on aeolian sand transport. In: Tchakerian, V.P. (ed.). Desert aeolian processes. Chapman & Hall, London, pp. 269-293.

Namikas, S.L. D.J. Sherman (1998). AEOLUS II: an interactive program for the simulation of aeolian sedimentation. Geomorphology, 22, pp. 135-149.

National Research Council (1995). Beach nourishment and protection. National Academy Press, Washington, 334 pp.

Nickling, W.G. (1988). The initiation of particle movement by wind. Sedimentology, 35, pp. 499-511.

Nickling, W.G. & R.G.D. Davidson-Arnott (1990). Aeolian sediment transport on beaches and coastal sand dunes. In: Davidson-Arnott, R.G.D. (ed.). Proceedings of the symposium on coastal sand dunes. National Research Council, Ottowa, pp. 1-35.

Nickling, W.G. & M. Ecclestone (1981). The effects of soluble salts on the threshold shear velocity of fine sand. Sedimentology, 28, pp. 505-510.

Nickling, W.G. & C. McKenna Neuman (1995). Development of deflation lag surfaces. Sedimentology, 42, pp. 403-414.

Nordstrom, K.F. & J.R. Allen (1980). Geomorphologically compatible solutions to beach erosion. Zeitschrift für Geomorphologie, Supplement 34, pp. 142-154.

Nordstrom, K.F. & N.L. Jackson (1992). Effect of source width and tidal elevation changes on eolian sand transport on an estuarine beach. Sedimentology, 39, pp. 769-778.

Nordstrom, K.F. & N.L. Jackson (1993). The role of wind direction in eolian sand transport on a narrow sandy beach. Earth Surface Processes and Landforms, 18, pp. 675-685.

Nordstrom, K.F. & J.M. McCluskey (1985). The effects of houses and sand fences on the eolian sediment budget at Fire Island, New York. Journal of Coastal Research, 1, pp. 39-46.

Nordstrom, K.F., J.M. McCluskey & P. S. Rosen (1986). Aeolian processes and dune characteristics of a developed shoreline: Westhampton Beach, New York. In: W.G. Nickling (ed.). Aeolian geomorphology. Proceedings of the 17th annual Binghamton Geomorphology Symposium. Allen & Unwin, London, pp. 131-147.

Oke, T.R. (1987). Boundary layer climates. Methuen, London, 2nd ed., 436 pp.

Olij, E. (1993). Zandsuppleties, karakterisering en stuifgevoeligheid van suppletiezand van een aantal suppleties langs de Nederlandse kust. M.Sc. thesis. University of Amsterdam, Amsterdam, 61 pp. (In Dutch.)

Philips, C.J. & B.B. Willetts (1978). A review of selected literature on sand stabilisation. Coastal Engineering, 2, pp. 133-147.

Plant, N.G. & R.A. Holman (1997). Intertidal beach profile estimation using video images. Marine Geology, 140, pp. 1-24.

Psuty, N.P. (1993). Foredune morphology and sediment budget, Perdido Key, Florida, USA. In: K. Pye (ed.). The dynamics and environmental context of aeolian sedimentary systems. Geological Society Special Publication 72, pp. 145-157.

Psuty, N.P. & M.E.S.A. Moreira (1992). Characteristics and longevity of beach nourishment at Praia da Rocha, Portugal. Journal of Coastal Research, 8, pp. 660-676.

Psuty, N.P. & S.L. Namikas (1991). Beach nourishment episodes at the Sandy Hook unit, Gateway national recreation area, New Jersey, USA: a preliminary comparison. Coastal Sediments '91, American Society of Civil Engineers, New York, pp. 2116-2129.

Pye, K. (1991). Beach deflation and backshore dune formation following erosion under storm conditions: an example from Northwest England. Acta Mechanica, Supplement 2, pp. 171-181.

Raudkivi, A.J. (1967). Loose boundary hydraulics. Pargamon, Oxford, 331 pp.

Raupach, M.R. (1992). Drag and drag partition on rough surfaces. Boundary Layer Meteorology, 60, pp. 375-395.

Raupach, M.R., D.A. Gillette & J.F. Leys (1993). The effect of roughness elements on wind erosion threshold. Journal of Geophysical Research, 98 (D2), pp. 3023-3029.

Rijkswaterstaat (1988). Handboek zandsuppleties. Waltman, The Hague, 310 pp. (In Dutch.)

Rijkswaterstaat (1990). A new coastal defence policy for The Netherlands. Rijkswaterstaat, The Hague, 103 pp.

Rijkswaterstaat (1995). Kustlijnkaarten. Rijkswaterstaat, The Hague, 274 pp. (In Dutch.)

Rijkswaterstaat (1996). Jaarboek monitoring Rijkswateren; presentatie van fysische, chemische en biologische kenmerken; 1994. Rijkswaterstaat, The Hague, 163 pp. (In Dutch.)

Roelse, P. (1996). Evaluatie van zandsuppleties aan de Nederlandse kust 1975-1994. Report. Rijkswaterstaat, The Hague, 72 pp. (In Dutch.)

Roelse, P., J. Coosen. & F.A.J. Minneboo (1991). Beach nourishment and monitoring programme. Coastal Engineering, 16, pp. 43-59.

Roelse, P. & R. Hillen (1993). Evaluatie van zandsuppleties; een morfologische beschouwing. Report. Rijkswaterstaat, The Hague, 86 pp.

Royal Netherlands Meteorological Institute (1996). Dagoverzicht van het weer. DOW Bulletin, 8. Koninklijk Nederlands Meteorologisch Instituut, De Bilt. (In Dutch.)

Royal Netherlands Meteorological Institute (1997). Dagoverzicht van het weer. DOW Bulletin, 9. Koninklijk Nederlands Meteorologisch Instituut, De Bilt. (In Dutch.)

Rozema, J., P. Laan & R. Broekman (1985). On the lime content in the Dutch coastal sand dunes in the province of North-Holland. In: W.G. Beeftink, J. Rozema & A.H.L. Huiskes (eds). Ecology of coastal vegetation. Proceedings of a symposium. Junk, Dordrecht, pp. 559-560.

Sarre, R.D. (1988). Evaluation of aeolian sand transport equations using intertidal zone measurements, Saunton Sands, England. Sedimentology,

35, pp. 671-679.
Sarre, R.D. (1989a). Aeolian sand drift from the intertidal zone on a temperate beach: potential and actual rates. Earth Surface Processes and Landforms, 14, pp. 247-258.
Sarre, R.D. (1989b). The morphological significance of vegetation and relief on coastal foredune processes. Zeitschrift für Geomorphologie, Supplement, 73, pp. 17-31.
Schuiling, R.D., R.J. de Meijer, H.J. Riezebos & M.J. Scholten (1985). Grain size distribution of different minerals in a sediment as a function of their specific density. Geologie en Mijnbouw, 64, pp. 199-203.
Shao, Y. & M.R. Raupach (1992). The overshoot and equilibration of saltation. Journal of Geophysical Research, 97 (D7), pp. 20559-20564.
Sharp, R.P. (1964). Wind-driven sand in Coachella Valley, California. Geological Society of American Bulletin, 75, pp. 785-804.
Shephard, F.P. & R. Young (1961). Distinguishing between beach and dune sands. Journal of Sedimentary Petrology, 31, pp. 196-214.
Sherman, D.J. & W. Lyons (1994). Beach-state controls on aeolian sand delivery to coastal dunes. Physical Geography, 15, pp. 381-395.
Sherman, D.J. & K.F. Nordstrom (1994). Hazards of wind-blown sand and coastal sand drifts: a review. Journal of Coastal research, Special Issue 12 (Coastal hazards), pp. 263-275.
Short, A.D. (1991). Beach morphodynamic systems of the central Netherlands coast, Den Helder to Hoek van Holland. Utrecht University, Utrecht, 106 pp.
Socci, A. & W.F. Tanner (1980). Little known but important papers on grain-size analysis. Short communication. Sedimentology, 27, pp. 231-232.
Spaan, W.P. & G.D. van den Abeele (1991). Wind borne particle measurements with acoustic sensors. Soil Technology, 4, pp. 51-63.
Stam, J.M.T. (1997). On the modelling of two-dimensional aeolian dunes. Sedimentology, 44, pp. 127-141.
Steetzel, H.J. (1993). Cross-shore transport during storm surges. Ph.D. thesis. Technical University Delft, Delft, 276 pp.
Stive, M.J.F., R.J. Nicholls & H.J. de Vriend (1991). Sea-level rise and shore nourishment: a discussion. Coastal Engineering, 16, pp. 147-163.
Stout, J.E. (1990). Wind erosion within a simple field. Transactions of the American Society of Agricultural Engineers, 33, pp. 1597-1600.
Stull, R.B. (1988). An introduction to boundary layer meteorology. Kluwer, Dordrecht, 666 pp.
Svasek, J.N. & J.H.J. Terwindt (1974). Measurements of sand transport by wind on a natural beach. Sedimentology, 21, pp. 311-322.

Swart, D.H. (1991). Beach nourishment and particle size effects. Coastal Engineering, 16, pp. 61-81.
Sykes, M.T. & J.B. Wilson (1990). An experimental investigation into the response of New Zealand sand dune species to different depths of burial by sand. Acta Botanica Neerlandica, 39, pp. 171-181.
Tánczos, I.C. (1996). Selective transport phenomena in coastal sands. Ph.D. thesis. Groningen University, Groningen, 184 pp.
Technical Advisory Committee on Water Defences (1984). Leidraad voor de beoordeling van de veiligheid van duinen als waterkering. Staatsuitgeverij, The Hague, 38 pp. (In Dutch.)
Technical Advisory Committee on Water Defences (1995). Leidraad zandige kust. Staatsuitgeverij, The Hague, 76 pp. (In Dutch.)
Thom, B.G. & W. Hall (1991). Behaviour of beach profiles during accretion and erosion dominated periods. Earth Surface Processes and Landforms, 16, pp. 113-127.
Tsoar, H. & D. Blumberg (1991). The effect of sea cliffs on inland encroachment of aeolian sand. Acta Mechanica, Supplement 2, pp. 131-146.
Ungar, J.E. & P.K. Haff (1987). Steady state saltation in air. Sedimentology, 34, pp. 289-300.
Van Alphen, J.S.L.J. & M.A. Damoiseaux (1989). A geomorphological map of the Dutch shoreface and adjacent part of the continental shelf. Geologie en Mijnbouw, 68, pp. 433-443.
Van Boxel, J.H., S.M. Arens & P.M. van Dijk (1999). Aeolian processes across transverse dunes. I: Modelling the air flow. Earth Surface Processes and Landforms, 24, pp. 255-270.
Van de Graaff, J. (1977). Dune erosion during a storm surge. Coastal Engineering, 1, pp. 99-134.
Van de Graaff, J., H.D. Niemeyer & J. van Overeem (1991). Beach nourishment, philosophy and coastal protection policy. Coastal Engineering, 16, pp. 3-22.
Van der Putten, W.H. (1989). Establishment, growth and degeneration of *Ammophila arenaria* in coastal sand dunes. Ph.D. thesis. Agricultural University Wageningen, Wageningen, 152 pp.
Van der Putten, W.H., J.T. van der Werf-Klein Breteler & C. van Dijk (1989). Colonization of the root zone of *Ammophila arenaria* by harmful soil organisms. Plant and Soil, 120, pp. 213-223.
Van der Wal, D. (1998a). Effects of fetch and surface texture on aeolian sand transport on two nourished beaches. Journal of Arid Environments, 39, pp. 533-547.

Van der Wal, D. (1998b). The impact of the grain-size distribution of nourishment sand on aeolian sand transport. Journal of Coastal Research, 14, pp. 620-631.

Van der Wal, D. (1999a). Beach-dune interactions in nourishment areas along the Dutch coast. Submitted to Journal of Coastal Research.

Van der Wal, D. (1999b). Grain-size-selective aeolian sand transport on a nourished beach. Journal of Coastal Research, 15, in press.

Van der Wal, D. (1999c). Modelling aeolian sand transport and morphological development in two beach nourishment areas. Earth Surface Processes and Landforms, 24, in press.

Van der Wal, D., B.A.M. Peters, W.H. van der Putten & O.F.R. van Tongeren (1995). Inventariserend onderzoek naar de ecologische effecten van zandsuppletie. University of Amsterdam and Netherlands Institute of Ecology, for Rijkswaterstaat, Heteren, 115 pp. (In Dutch.)

Van Dijk, P.M. (1990). Wind erosion measurements on Schiermonnikoog. A study with acoustic sensors and sediment catchers. Report. Wageningen Agricultural University, Wageningen, 86 pp.

Van Dijk, P.M., S.M. Arens & J.H. van Boxel (1999). Aeolian processes across transverse dunes. II: Modelling the sediment transport and profile development. Earth Surface Processes and Landforms, 24, pp. 319-333.

Van Oorschot, J.H. & G.H. van Raalte (1991). Beach nourishment; execution methods and developments in technology. Coastal Engineering, 16, pp. 23-42.

Van Rijn, L.C. (1997). Sediment transport and budget of the central coastal zone of Holland. Coastal Engineering, 32, pp. 61-90.

Van Vessem, P. & A. Stolk (1990). Sand budget of the Dutch coast. Proceedings of the 22nd Conference on Coastal Engineering, American Society of Civil Engineers, New York, pp. 1895-1908.

Veenstra, H.J. & A.M. Winkelmolen (1976). Size, shape and density sorting around two barrier islands along the north coast of Holland. Geologie and Mijnbouw, 55, pp. 87-104.

Verhagen, H.J. (1996). Analysis of beach nourishment schemes. Journal of Coastal Research, 12, pp. 179-185.

Veugen, L.M.N. (1984). De nauwkeurigheid van strandprofielen, fotogrammetrische data-acquisitie. Report. Rijkswaterstaat, Delft, 20 pp. (In Dutch.)

Von Kármán, T. (1934). Turbulence and skin friction. Journal of Aeronautical Sciences, 1, pp. 1-20.

Watson, R.L. (1971). Origin of shell beaches, Padre Island, Texas. Journal of Sedimentary Petrology, 41, pp. 1105-1111.

Weihan, C., Y. Zuotao & D. Zhibao (1995). Vertical distribution of grain-size parameters of drifting particles during sand storms in the Taklamakan Desert, Central Asia. Physical Geography, 16, pp. 503-523.

Wesemael, J.C. (1955). De bepaling van het calciumcarbonaatgehalte van gronden. Chemisch Weekblad, 51, pp. 35-36. (In Dutch.)

Westhoff, V. & M.F. van Oosten (1991). De plantengroei van de Waddeneilanden. KNNV, Utrecht, 420 pp. (In Dutch.)

White, B.R. (1979). Soil transport by winds on Mars. Journal of Geophysical Research, 84 (B8), pp. 4643-4651.

Wieringa, J. & P.J. Rijkoort (1983). Windklimaat van Nederland. Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute). Staatsuitgeverij, The Hague, 264 pp. (In Dutch.)

Wiggs, G.F.S. (1993). Desert dune dynamics and the evaluation of shear velocity: an integrated approach. In: K. Pye (ed.). The dynamics and environmental context of aeolian sedimentary systems. Geological Society Special Publication 72, pp. 37-46.

Wijnberg, K.M. & J.H.J. Terwindt (1995). Extracting decadal morphological behaviour from high-resolution long-term bathymetric surveys along the Holland coast using eigen function analysis. Marine Geology, 126, pp. 301-329.

Willetts, B.B., M.A. Rice & S.E. Swaine (1982). Shape effects in aeolian grain transport. Sedimentology, 29, pp. 409-417.

Williams, G. (1964). Some aspects of the eolian saltation load. Sedimentology, 3, pp. 257-287.

Wilson, N.R. & R.H. Shaw (1977). A higher order closure model for canopy flow. Journal of Applied Meteorology, 16, pp. 1197-1205.

Zeman, O. & N.O. Jensen (1987). Modifications of turbulence characteristics in flow over hills. Quarterly Journal of the Royal Meteorological Society, 113, pp. 55-80.

APPENDIX

-Overview of the nourishments carried out in the Netherlands between 1950 and 1998 (arranged from north to south). The main fill placing is indicated, with s is shoreface, f is foreshore, b is beach, bq is banquet and d is dune nourishment (see Fig. 1.1). Values between brackets have not been verified. Sources are Rijkswaterstaat (1988), Beaufort et al. (1989), Roelse & Hillen (1993), De Ruig (1995), Rijkswaterstaat (1995), Roelse (1996) and unpublished data of Rijkswaterstaat.

Site		Km-poles		Year	Volume ($\times 10^6$ m^3)	Type
Ameland	Midden	10.20	15.00	1980	2.20	d
Ameland	Midden	12.40	17.00	1990	0.97	d
Ameland	Midden	11.50	19.00	1992	1.62	b,d
Ameland	Midden	7.20	11.20	1996	1.36	b
Ameland	Midden	11.00	18.00	1998	2.30	s,f
Ameland	West	1.80	2.30	1979	0.21	b
Ameland	West	48.60	49.60	1994	0.19	b
Ameland	West	1.20	3.00	1997	0.52	b
Terschelling	Midden	13.80	17.80	1993	2.00	s
Vlieland	Oost	53.50	54.50	1995	0.19	b
Vlieland	Oost	46.70	48.20	1997	0.28	b
Texel	Eierland	26.20	31.00	1979	3.05	b,bq
Texel	Eierland	26.00	31.00	1985	2.85	b,bq
Texel	Eierland	25.00	30.80	1990	2.54	b,bq
Texel	Eierland	25.30	28.80	1994	1.33	b,bq
Texel	Eierland	28.20	29.60	1995	1.08	b
Texel	De Koog	18.00	24.00	1984	3.02	b,bq
Texel	De Koog	18.30	23.40	1991	2.00	b,bq
Texel	De Koog	15.30	23.40	1996	1.98	b
Texel	Zuidwest	12.50	18.10	1993	1.30	b
Texel	Zuidwest	9.30	12.30	1994	0.76	b
Texel	Zuidwest	10.00	21.00	1997	1.00	b
Noord-Holland	Kop	1.00	7.50	1992	0.61	b
Noord-Holland	Kop	3.50	5.70	1993	0.26	b
Noord-Holland	Kop	2.50	8.00	1996	0.85	b

[illegible] (1998). Vertical distribution of grain-size parameters of drifting particles during sand storms in the Taklamakan Desert, Central Asia. Physical Geography, 19, pp. 503-523.

[illegible] (19[illegible]). De bepaling van het calciumcarbonaatgehalte van gronden. Chemisch Weekblad, 31, pp. 35-36. (In Dutch.)

Westhoff, V. & M.A. van Oosten (1991). De plantengroei van de Waddeneilanden. KNNV, Utrecht. 420 pp. (In Dutch.)

White, B.R. (1979). Soil transport by winds on Mars. Journal of Geophysical Research, 84 (B9), pp. [illegible].

Wieringa, J. & P.J. Rijkoort (1983). Windklimaat van Nederland. Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute). Staatsuitgeverij, The Hague. 264 pp. (In Dutch.)

Wiggs, G.F.S. (1993). Desert dune dynamics and the evaluation of shear velocity: an integrated approach. In: K. Pye (ed.), The dynamics and environmental context of aeolian sedimentary systems. Geological Society Special Publication 72, pp. 37-46.

Wijnberg, K.M. & J.H.J. Terwindt (1995). Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. Marine Geology, 126, pp. [illegible].

Willetts, B.B., M.A. Rice & S.E. Swaine (1982). Shape effects in aeolian grain transport. Sedimentology, 29, pp. 409-417.

Williams, G. (1964). Some aspects of the eolian saltation load. Sedimentology, 3, pp. [illegible].

Wilson, N.R. & R.H. Shaw (1977). A higher order closure model for canopy flow. Journal of Applied Meteorology, 16, pp. 1197-1205.

[illegible] (1987). Modifications of turbulence characteristics [illegible]. Quarterly Journal of the Royal Meteorological Society, [illegible], pp. [illegible].

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Overview of the nourishments carried out in the Netherlands between 1950 and 1998 (arranged from north to south). The main fill placing is indicated, with s is shoreface, f is foreshore, b is beach, bq is banquet and d is dune nourishment (see Fig. 1.1). Values between brackets have not been verified. Sources are Rijkswaterstaat (1988), Beaufort et al. (1989), Roelse & Hillen (1993), De Ruig (1995), Rijkswaterstaat (1995), Roelse (1996) and unpublished data of Rijkswaterstaat.

Site		Km poles		Year	Volume ($\times 10^6$ m^3)	Type
Ameland	Midden	10.20	15.80	1980	2.20	d
Ameland	Midden	12.40	17.00	1990	0.97	d
Ameland	Midden	11.50	19.60	1992	1.67	b, d
Ameland	Midden	7.20	11.20	1996	1.56	b
Ameland	Midden	11.00	18.00	1998	2.50	s, f
Ameland	West	1.60	2.30	1979	0.31	b
Ameland	West	48.60	49.60	1994	0.19	b
Ameland	West	1.20	3.00	1997	0.52	b
Terschelling	Midden	13.80	17.80	1993	2.00	s
Vlieland	Oost	53.50	54.40	1995	0.19	b
Vlieland	Oost	46.70	48.50	1997	0.28	b
Texel	Eierland	26.20	31.00	1979	3.05	b, bq
Texel	Eierland	26.00	31.00	1985	2.85	b, bq
Texel	Eierland	25.60	30.80	1990	2.54	b, bq
Texel	Eierland	25.50	28.80	1994	1.33	b, bq
Texel	Eierland	28.20	29.60	1995	1.08	b
Texel	De Koog	18.00	24.00	1984	3.02	b, bq
Texel	De Koog	18.30	23.40	1991	2.00	b, bq
Texel	De Koog	15.30	23.40	1996	1.98	b
Texel	Zuidwest	12.50	18.10	1993	1.50	b
Texel	Zuidwest	9.30	12.30	1994	0.76	b
Texel	Zuidwest	10.00	21.00	1997	1.00	b
Noord-Holland	Kop	1.00	7.50	1992	0.63	b
Noord-Holland	Kop	3.30	5.70	1993	0.26	b
Noord-Holland	Kop	2.50	8.00	1996	0.85	b

Site		Km poles		Year	Volume ($\times 10^6$ m^3)	Type
Noord-Holland	Kop	4.70	5.90	1998	(0.25)	b
Noord-Holland	Callantsoog	13.00	13.80	1976-1977	0.34	d
Noord-Holland	Callantsoog	11.50	12.80	1979-1980	0.47	d
Noord-Holland	Callantsoog	10.80	13.70	1986	1.32	b, d
Noord-Holland	Callantsoog	10.80	13.80	1991	0.54	b, bq
Noord-Holland	Callantsoog	12.20	14.10	1996	0.45	b
Noord-Holland	Zwanenwater	13.80	18.10	1987	1.92	b, d
Noord-Holland	Petten	18.00	20.20	1991	0.37	b
Noord-Holland	Petten	16.20	17.60	1995	0.31	b
Noord-Holland	Petten	18.80	20.40	1995	0.36	b
Noord-Holland	Petten	17.20	20.20	1998	0.23	b
Noord-Holland	Camperduin - Egmond	26.20	38.50	1992	1.47	b
Noord-Holland	Camperduin - Egmond	26.00	38.00	1997	1.50	b
Noord-Holland	Bergen	32.30	33.80	1990	0.45	b, bq
Noord-Holland	Bergen	33.00	33.50	1994	0.10	b
Noord-Holland	Bergen	32.70	33.60	1995	0.31	b
Noord-Holland	Egmond	37.00	38.50	1990	0.32	b
Noord-Holland	Egmond	37.70	38.60	1992	0.07	b
Noord-Holland	Egmond	37.80	38.20	1994	0.11	b, bq
Noord-Holland	Egmond	37.30	38.30	1995	0.31	b
Noord-Holland	Wijk aan Zee	50.00	51.00	1996	0.48	b
Noord-Holland	Wijk aan Zee	50.00	51.00	1997	0.25	b
Noord-Holland	IJmuiden	57.00	57.00	1962	1.50	b
Rijnland	Bloemendaal	62.00	63.30	1990	0.26	b
Rijnland	Bloemendaal	60.50	63.00	1994	0.26	b
Rijnland	Bloemendaal	61.50	63.50	1998	0.19	b
Rijnland	Zandvoort	65.00	67.20	1994	0.35	b
Rijnland	Zandvoort	66.00	67.30	1998	0.31	b
Rijnland	Noordwijk	80.50	83.50	1998	(1.25)	f
Rijnland	Katwijk	87.50	89.50	1998	(0.75)	f
Rijnland	Wassenaar	92.00	94.00	1996	0.50	b
Rijnland	Meijendel	94.30	96.30	1994	0.70	b
Delfland	Scheveningen	100.50	101.50	1953	0.07	b
Delfland	Scheveningen	100.00	101.50	1969	0.05	b
Delfland	Scheveningen	99.70	101.50	1975	0.70	b, bq
Delfland	Scheveningen	99.00	101.00	1981	0.01	b
Delfland	Scheveningen	99.00	101.00	1982	0.02	b
Delfland	Scheveningen	99.00	101.00	1985	0.33	b, bq

Site		Km poles		Year	Volume (×10^6 m^3)	Type
Delfland	Scheveningen	99.00	101.00	1987	0.01	b
Delfland	Scheveningen	97.80	101.40	1991	1.01	b, bq
Delfland	Scheveningen	97.00	101.00	1996	0.80	b
Delfland	Ter Heijde	107.90	115.60	1986	3.23	b, d
Delfland	Ter Heijde	106.20	112.20	1993	1.15	b
Delfland	Ter Heijde	114.00	118.80	1993	0.70	b
Delfland	Ter Heijde	112.20	114.20	1995	0.30	b
Delfland	Ter Heijde	107.70	114.00	1997	1.00	f, b
Delfland	Hoek van Holland	115.70	119.00	1971-1972	18.94	b
Delfland	Hoek van Holland	115.70	119.00	1976-1977	1.50	b
Delfland	Hoek van Holland	115.70	119.00	1977-1978	0.87	b
Delfland	Hoek van Holland	117.70	118.80	1988	0.20	b
Delfland	Hoek van Holland	118.00	118.50	1989	0.10	b
Delfland	Hoek van Holland	117.80	118.80	1990	0.18	b
Delfland	Hoek van Holland	117.80	118.80	1991	0.22	b
Delfland	Hoek van Holland	117.80	118.80	1992	0.56	b
Delfland	Hoek van Holland	117.50	118.50	1993	0.20	b
Delfland	Hoek van Holland	117.50	118.50	1994	0.20	b
Delfland	Hoek van Holland	117.70	118.80	1995	0.20	b
Delfland	Hoek van Holland	117.70	118.80	1996	0.20	b
Delfland	Hoek van Holland	117.70	118.80	1997	0.20	b
Delfland	Hoek van Holland	117.70	118.80	1998	0.20	b
Maasvlakte	Slufterdam	11.50	13.40	1979	0.15	b
Maasvlakte	Slufterdam	9.00	10.40	1991	0.10	b
Maasvlakte	Slufterdam	9.00	10.40	1992	0.96	b
Maasvlakte	Slufterdam	7.00	10.20	1996	0.90	b
Maasvlakte	Slufterdam	6.50	10.00	1997	2.72	b
Voorne	De Punt - Rockanje	10.50	12.50	1973	0.25	b
Voorne	De Punt - Rockanje	8.80	12.50	1977	1.10	b
Voorne	De Punt - Rockanje	8.00	14.00	1984	3.40	d
Voorne	De Punt - Rockanje	9.40	13.40	1987	3.00	d
Voorne	Rockanje	12.60	15.20	1974	0.26	b, d
Voorne	Rockanje	11.60	14.40	1983	0.44	b
Voorne	Rockanje	14.40	15.40	1986	1.00	d
Goeree	Kwade Hoek	4.00	6.00	1970	0.20	d
Goeree	Noord	5.70	9.80	1977	1.60	d
Goeree	Noord	9.70	11.30	1978	2.00	d
Goeree	Noord	10.20	12.00	1994	0.56	b

Site		Km poles		Year	Volume ($\times 10^6$ m^3)	Type
Goeree	Noord	9.20	10.80	1998	0.70	b
Goeree	Kop	15.00	17.00	1966	0.15	d
Goeree	Kop	13.00	15.00	1968	0.80	d
Goeree	Kop	14.50	18.50	1969-1970	0.40	b, d
Goeree	Kop	14.70	16.80	1971	0.61	b, d
Goeree	Kop	17.00	19.00	1972	0.20	d
Goeree	Kop	14.50	17.50	1973-1974	3.65	b, d
Goeree	Kop	18.50	19.00	1976	0.05	d
Goeree	Kop	14.50	17.30	1977	1.27	b, d
Goeree	Kop	14.50	17.50	1984	0.33	b
Goeree	Kop	14.50	17.50	1985	0.53	b
Goeree	Kop	15.00	19.00	1997	0.50	b
Schouwen	Noorderstrand	0.80	3.20	1989	0.43	b, d
Schouwen	Noorderstrand	1.70	2.90	1994	0.10	b
Schouwen	Noorderstrand	0.60	3.00	1995	0.08	b
Schouwen	Renesse	3.00	6.00	1995	0.82	b
Schouwen	Kop	17.00	17.40	1975	0.11	b
Schouwen	Kop	13.20	14.90	1987	1.83	f, b
Schouwen	Kop	11.80	17.30	1991	2.67	f, b, d
Schouwen	Kop	11.60	17.30	1996	0.73	b
Noord-Beveland	Onrustpolder	1.80	2.20	1973	0.21	b
Noord-Beveland	Onrustpolder	2.20	3.70	1993	0.41	b
Noord-Beveland	Onrustpolder	2.10	3.80	1996	0.44	b
Walcheren	Veerse Dam	4.80	5.50	1993	0.23	b
Walcheren	Oranjezon	9.50	10.50	1984	0.15	d
Walcheren	Oranjezon	10.00	10.30	1990	0.02	b
Walcheren	Oranjezon	9.00	10.30	1993	0.29	b
Walcheren	Oranjezon	9.00	10.50	1996	0.46	b
Walcheren	Domburg	16.50	17.30	1986	0.23	b, d
Walcheren	Domburg	14.80	15.90	1989	0.21	b, d
Walcheren	Domburg	14.70	17.40	1990	0.41	b, d
Walcheren	Domburg	12.80	17.50	1992	0.64	b, d
Walcheren	Domburg	14.30	15.90	1993	0.32	b
Walcheren	Domburg	14.40	15.90	1994	0.45	b
Walcheren	Domburg	16.90	18.90	1995	0.55	b
Walcheren	Westkapelle	22.90	23.60	1984	0.10	b, d
Walcheren	Westkapelle	21.80	22.10	1988	0.03	b
Walcheren	Westkapelle	22.50	23.60	1988	0.41	b, d

Site		Km poles		Year	Volume ($\times 10^6$ m^3)	Type
Walcheren	Westkapelle - Zoutelande	24.80	25.80	1988	0.15	b, d
Walcheren	Westkapelle - Zoutelande	23.70	24.90	1990	0.11	b
Walcheren	Westkapelle - Zoutelande	21.90	25.90	1991	0.83	b, d
Walcheren	Westkapelle - Zoutelande	21.80	27.10	1997	0.70	b
Walcheren	Zoutelande	25.50	26.00	1995	0.05	b
Walcheren	Zoutelande - Vlissingen	29.50	29.70	1987	0.03	d
Walcheren	Zoutelande - Vlissingen	25.90	31.70	1992-1993	0.87	b
Walcheren	Zoutelande - Vlissingen	27.00	33.00	1998	(0.50)	b
Walcheren	Vlissingen	34.00	34.40	1952	0.05	f
Walcheren	Vlissingen	32.60	33.40	1952-1959	0.78	b
Walcheren	Vlissingen	34.00	34.40	1966	0.03	f
Walcheren	Vlissingen	34.00	34.40	1975	0.05	b
Walcheren	Vlissingen	31.70	34.60	1992	0.17	b
Walcheren	Vlissingen	29.90	33.00	1995	0.46	b
Walcheren	Vlissingen	33.90	34.70	1997	0.13	b
Zeeuws-Vlaanderen	Breskens	0.40	0.90	1971	0.21	b
Zeeuws-Vlaanderen	Schoneveld	1.90	3.10	1989	0.23	b
Zeeuws-Vlaanderen	Schoneveld	2.40	3.10	1993	0.09	b
Zeeuws-Vlaanderen	Schoneveld	2.90	3.50	1996	0.13	b
Zeeuws-Vlaanderen	Schoneveld	2.90	3.50	1997	0.19	b
Zeeuws-Vlaanderen	Groede	5.30	6.00	1989	0.44	b
Zeeuws-Vlaanderen	Adornispolder	8.10	9.20	1994	0.90	b
Zeeuws-Vlaanderen	Tienhonderdpolder	10.40	11.10	1990	0.64	f, b, d
Zeeuws-Vlaanderen	Tienhonderdpolder	10.00	11.50	1998	(0.30)	b
Zeeuws-Vlaanderen	Cadzand	11.60	13.50	1988	1.03	f, b
Zeeuws-Vlaanderen	Cadzand	13.30	14.30	1990	0.37	f, b, d
Zeeuws-Vlaanderen	Cadzand	13.50	14.90	1992	0.07	b
Zeeuws-Vlaanderen	Cadzand	10.60	13.50	1994	0.56	b
Zeeuws-Vlaanderen	Cadzand	13.60	14.20	1994	0.09	b
Zeeuws-Vlaanderen	Cadzand	13.50	14.60	1997	(0.10)	b

CURRICULUM VITAE

I was born on 2 November 1969 in Alkmaar, the Netherlands. I have spent my youth in the coastal village of Bergen, where I also followed primary education. After completing pre-university education (VWO) at the former Rijksscholengemeenschap Noord-Kennemerland in Alkmaar, I started studying Physical Geography at the University of Amsterdam in 1988.

During my studies, I specialized in geomorphological processes in coastal dunes, and in Geographical Information Systems (GIS). The M.Sc. thesis dealt with the development of models for foredune morphology. As a research assistant of prof. dr. P.D. Jungerius, I worked for two years on behalf of Rijkswaterstaat (in collaboration with the Netherlands Institute of Ecology) on a project on the effects of sand movement by wind on the vigour of marram grass, and on several other projects concerning the management of the Dutch coast.

I went to Strasbourg as a trainee at the Louis Pasteur University within the framework of the European Union exchange programme Erasmus. I did a second traineeship at the Staring Centre in Wageningen, where I studied morphodynamics of river systems. In 1994, I completed my M.Sc. in Physical Geography.

Subsequently, I held a position at the University of Amsterdam, and conducted a study on the ecological effects of beach nourishment for the 'Kustnota 1995' (second governmental coastal report) of Rijkswaterstaat, together with the Netherlands Institute of Ecology. In 1996, I continued the research on aeolian transport of nourishment sand as a Ph.D. student, which resulted in this thesis.

Currently, I am working as a post-doc in the Geology Department of Royal Holloway, University of London, on the effects of changes in wave climate and sea level on estuarine shores.