Aeolian transport of nourishment sand in beach-dune environments
van der Wal, D.

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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):

\[ q = C \left( \frac{d}{D} \right) \frac{\rho_s}{\rho_a} u_*^2 \]  

(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 (\( \mu \)m), \( D \) is the grain diameter of a standard sand (250 \( \mu \)m), \( \rho_a \) 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:

\[ q = K \frac{\rho_s}{g} (u_* + u_t)^2 (u_* - u_t) \]  

(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:

\[ u_t = A \sqrt{\frac{(\rho_s - \rho_a)}{\rho_a}} gd \]  

(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)), \( \rho_s \) 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 (Nickle & 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).
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).

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 $1.56 \times 10^6$ 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 unworked 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
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 $0.85 \times 10^6$ 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.

<table>
<thead>
<tr>
<th></th>
<th>Mean grain-size (mm)</th>
<th>Sorting (ϕ)</th>
<th>No. of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before nourishment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface sample</td>
<td>0.332</td>
<td>1.59 (1.41-1.83)</td>
<td>5</td>
</tr>
<tr>
<td><strong>After nourishment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface samples</td>
<td>0.272</td>
<td>1.88 (1.54-2.13)</td>
<td>6</td>
</tr>
<tr>
<td>Depth samples</td>
<td>0.354</td>
<td>1.50 (1.24-1.73)</td>
<td>6</td>
</tr>
</tbody>
</table>
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 \( \phi \) (272 \( \mu \text{m} \)), with a sorting of 0.42 \( \phi \). 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.

![Diagram](image-url)

**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:

\[ u_z = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \]  
(Equation 5.4)

where \( u_z \) is the wind velocity (m s\(^{-1}\)) at height \( z \) (m), \( u_* \) is the friction velocity (m s\(^{-1}\)), \( \kappa \) is the Von Karman constant (taken as 0.4) and \( z_0 \) is the aerodynamic roughness length (m) (Von Karman, 1934). Eq. 5.4 applies to neutral atmospheric conditions and uniform flow (Stull, 1988; Bauer et al., 1992). For large friction velocities \( (u_*>0.4 \text{ m s}^{-1}) \) these conditions were satisfied. The aerodynamic roughness length appeared to be fairly constant during periods with sand transport \( (z_0=0.001 \text{ m}) \). For lower friction velocities, either non-uniform wind flow during offshore winds or instability 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 \( (0.5 \text{ to } 4 \text{ m}) \), 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.

![Map of study sites](image)

**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 $\eta$ is the total set-up (m) at the still water level, $\gamma$ 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 $\alpha$ 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 \(w_j\) 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 ($u_*$) and total rain fall for selected wind erosion events at the Ameland site.

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

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 ($u_* > 0.7 \text{ m s}^{-1}$). 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 21 m 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 $u_r=0.21 \text{ m s}^{-1}$). On 21 October 1996, the threshold friction velocity was found to be $u_* = 0.4 \text{ m s}^{-1}$. Using this value in Eq. 5.2 instead of $u_* = 0.21 \text{ m s}^{-1}$ 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>
<thead>
<tr>
<th>Date</th>
<th>Period (h:min)</th>
<th>Wind direction</th>
<th>Wind velocity (m s$^{-1}$)</th>
<th>Rain (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 Nov 1996</td>
<td>11:00-12:00</td>
<td>283 (260-305)</td>
<td>onshore</td>
<td>9.83 (9.36-10.29)</td>
</tr>
<tr>
<td>1 Dec 1996</td>
<td>12:00-16:00</td>
<td>221 (216-225)</td>
<td>onshore</td>
<td>11.90 (10.68-13.53)</td>
</tr>
<tr>
<td>3 Dec 1996</td>
<td>12:30-16:00</td>
<td>180 (174-190)</td>
<td>parallel</td>
<td>10.10 (9.24-11.00)</td>
</tr>
<tr>
<td>4 Dec 1996</td>
<td>12:00-16:30</td>
<td>230 (220-241)</td>
<td>onshore</td>
<td>10.91 (10.63-11.55)</td>
</tr>
<tr>
<td>14 Dec 1996</td>
<td>13:30-16:00</td>
<td>272 (269-275)</td>
<td>onshore</td>
<td>9.17 (8.92-9.34)</td>
</tr>
</tbody>
</table>

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 $0.25 < u_* < 0.50 \text{ m s}^{-1}$). 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
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 \( \mu \text{m} \) (impact threshold \( u^* = 0.19 \text{ m s}^{-1} \)).

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.](image-url)
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 5.12.** 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.

**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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