

# Grain-Size-Selective Aeolian Sand Transport on a Nourished Beach

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## ABSTRACT

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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 unworked 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.

**ADDITIONAL INDEX WORDS:** *Beach nourishment, grain-size distribution, aeolian decoupling, marine reworking, shell pavement, carbonate, foredunes, the Netherlands.*

## 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.

World-wide, 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, 1998a). 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.

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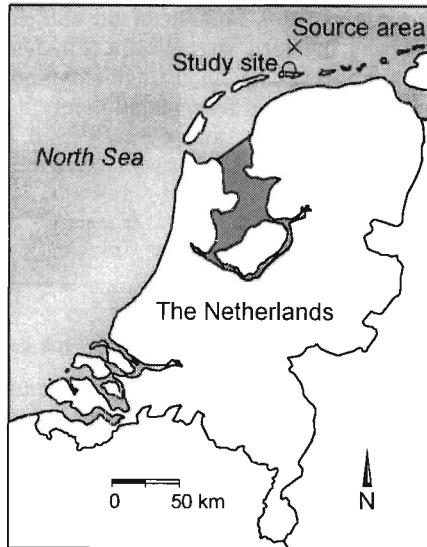


Figure 1. Location of the study site on the Wadden island of Ameland and the source area that provided the nourishment sand.

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 in the dunes is an important factor for dune vegetation and largely explains the differences in plant species between the dunes north and south of Bergen (ROZEMA *et al.*, 1985).

Offshore, the geographical distribution of sands is more complex (EISMA, 1968). Therefore, offshore dredged nourishment sand may differ in mineral content from native beach sand. Consequently, aeolian transport of this nourishment sand to the dunes may alter the characteristics and 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 focuses on:

- (1) the differences in grain-size between native and nourishment sand,
- (2) the aeolian selection of grain-size,

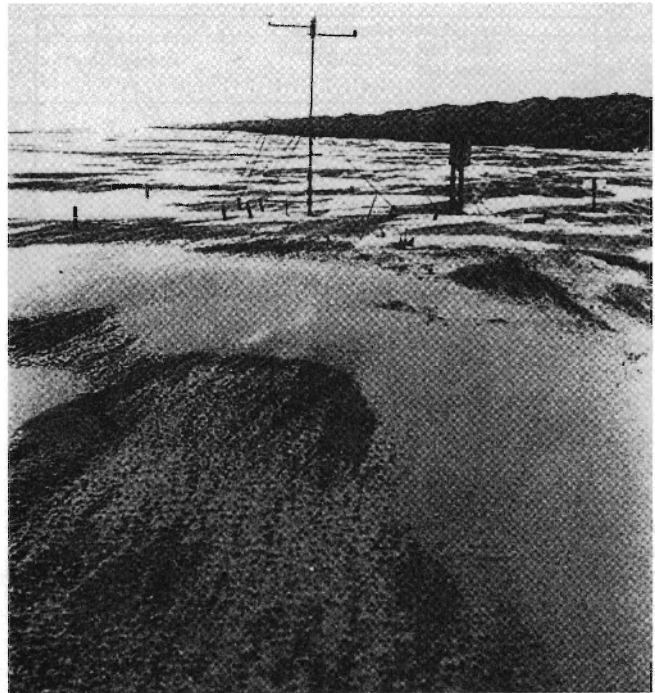


Figure 2. View of the nourished beach towards the foredunes (photograph taken on 30 October 1996 after a period with strong winds).

- (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 (Figures 1 and 2). 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 million m<sup>3</sup> of sand were deposited on the beach along 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 (Figure 1), transported by ship to a location about 5 km offshore, from which the sand was pumped to the beach. Here, it was remodelled using cranes and bulldozers. Cross-shore profiles were measured both before and after beach nourishment with EDM (laser Electronic Distance Measurement) equipment (Figure 3). There is a foredune ridge of about 10 m above the Dutch Ordnance Datum adjacent to the beach. A sand fence was erected at the dune foot 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 (*Ammo-*

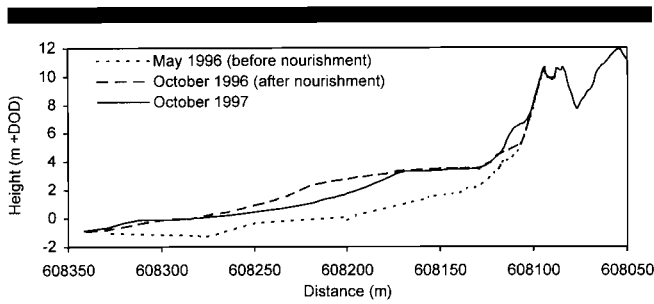


Figure 3. Cross-shore profiles of the site before and after nourishment. The profile of October 1997 shows erosion on the beach and deposition landward of the sand fence at the dune foot and in the foredunes. Height (m) is relative to DOD (Dutch Ordnance Datum), which is about mean sea level. Distances (m) refer to the Dutch rectangular co-ordinate system.

*phila arenaria*) and baltic marram grass (*Calammophila baltica*) and the inner dunes are covered by mosses and sea buckthorn (*Hippophæ 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 and VAN OOSTEN, 1991). VEENSTRA and WINKELMOLEN (1976) found CaCO<sub>3</sub> 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; TANCZOS, 1996). In their study on Ameland sand, VEENSTRA and WINKELMOLEN (1976) locally found garnet percentages of over 30% in the fraction 3.00 to 3.25 φ (0.105 to 0.125 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.

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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 *Spisula sp.*, *Donax vittatus*, and *Cerastoderma edule*. The (quartz) grains in the nourishment sand have ferric hydroxide coatings.

**METHODS**

**Sediment Sampling**

**Sediment and Subsurface Sand**

The surface was sampled along 1 m spaced transects from the low water line to the dune foot, both before (11 May 1996) and after (17 October 1996) nourishment (Figure 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 weighted 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 (Figure 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-or-

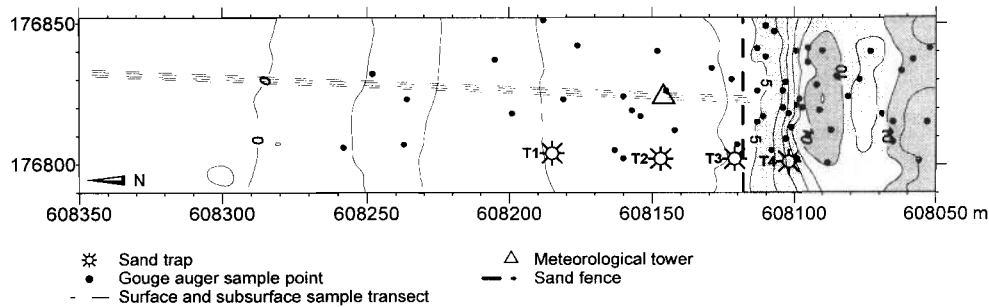


Figure 4. Sampling scheme. The contours display the situation of October 1996, after nourishment. A sand fence was present before nourishment (*i.e.*, there was a sand fence during sampling of the native beach), buried by nourishment (*i.e.*, there was no sand fence during sampling of the nourished beach) 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.

Table 1. Specifications of selected onshore wind erosion events, with average, minimum and maximum 30-min averages of wind direction and wind velocity and total rain fall during the measuring periods.

Date	Period (hr:min)	Trap Exposure	Wind Direction (°)	Wind Velocity (m/s)	Rain (mm)
Before nourishment					
7 May 1996	02:30–23:00	total period	69 (50–82)	8.34 (6.37–10.00)	0
14 May 1996	13:00–23:00	total period	2 (358–9)	7.14 (6.16–8.23)	0
After nourishment					
21 October 1996	09:30–18:00	30-min intervals	296 (290–300)	10.08 (8.63–10.96)	0
29 October 1996	10:00–17:30	30-min intervals	297 (285–311)	15.08 (13.89–15.90)	2.2

ganic 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).

### 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 and VAN DER LEE (1995), were installed on the beach (trap T1, T2 and T3 in Figure 4) and at the seaside of the foredune (trap T4 in Figure 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 registering saltiphone, described by SPAAN and 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 and 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 1.

### 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 sam-

ples 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 and 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  $0.50 \phi$ , starting with a mesh of  $3.75 \phi$  (0.075 mm). A sieve with mesh  $-1.00 \phi$  (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  $<-1.00 \phi$  ( $>2$  mm) is considered to be centred around  $-2.25 \phi$ , and the fraction  $>3.75 \phi$  ( $<0.075$  mm) is considered to be centred around  $4.00 \phi$ .

The amount of fines ( $>3.75 \phi$ ) and the amount of coarse material ( $<0.75 \phi$  and  $<-1.00 \phi$ , 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  $>0.75 \phi$  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:  $>3.25 \phi$  ( $<0.106$  mm),  $1.25-3.25 \phi$  ( $0.106-0.425$  mm) and  $<1.25 \phi$  ( $>0.425$  mm). From each fraction of a sample, 2 to 5 g of homogenised 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  $\text{CO}_2$ . 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  $\text{CaCO}_3$  were calculated assuming that all carbonates were present in  $\text{CaCO}_3$  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

#### Differences in Grain-Size Between Native 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 of the grain-size distribution),
- (3) contains more material  $<0.75 \phi$  and  $<-1.00 \phi$ , and
- (4) contains more material  $>3.75 \phi$ .

#### 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  $<0.75 \phi$  and  $<-1.00 \phi$ , and
- (4) contains more material  $>3.75 \phi$ .

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  $-0.10\text{m}$  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  $<0.75 \phi$ , and
- (3) contains less material  $>3.75 \phi$ .

#### Differences in Carbonate Content Between Native and Nourishment Sand

The  $\text{CaCO}_3$  content of the native and nourishment surface sand is determined along a cross-shore transect (Figure 5). On the native beach  $\text{CaCO}_3$  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  $\text{CaCO}_3$  and patches of wind-blown sand deposited on top

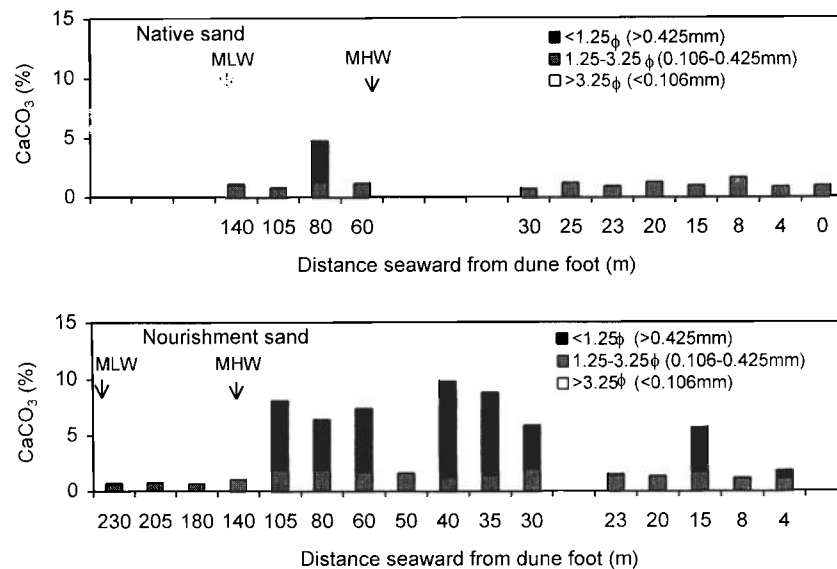


Figure 5.  $\text{CaCO}_3$  content (%) of native and nourishment surface sand along a cross-shore transect on the beach. The distance from the dune foot is not to scale.

of the lag with lower  $\text{CaCO}_3$  contents.  $\text{CaCO}_3$  contents of nourishment sand are significantly higher than  $\text{CaCO}_3$  contents of native sand, both in the fraction 1.25–3.25  $\phi$  (0.106–0.425mm) and in the fraction  $<1.25\phi$  ( $>0.425\text{mm}$ ).

The coarse material ( $<1.25\phi$ ) determines the  $\text{CaCO}_3$  of the total sample. The finer fractions ( $>1.25\phi$ ) also contain carbonate, but they do not contribute much to the total amount of  $\text{CaCO}_3$ . The  $\text{CaCO}_3$  content of both the total sample and the coarse material ( $<1.25\phi$ ) are proportional to the amount of material  $<0.75\phi$ , but the  $\text{CaCO}_3$  content of medium grained material (1.25–3.25  $\phi$ ) is not (Figure 6). A plot of the  $\text{CaCO}_3$  content of native sand would show the same trends.

### Wind-laid sand

#### Differences in Grain-Size Between Native and Nourishment Sand

The wind-laid nourishment foredune sand differs from the native foredune sand (Figure 7). The nourishment foredune sand contains more sand in the fraction 1.75–2.25  $\phi$  and, especially, in the fraction 1.25–1.75  $\phi$ .

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  $<0.75\phi$  but not more material  $<-1.00\phi$ .

The differences are illustrated by bivariate scatter plots (Figure 8). In addition, moment measures have been calcu-

lated for sand  $>0.75\phi$  ( $<0.600\text{mm}$ ), comprising the entire quartz component of the sand. The grain-size distribution of the fractions  $>0.75\phi$  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 Figure 3. The amount of nourishment sand that was deposited during two years gradually decreased with distance inland (Figure 9). Behind the sand fence, more than 0.25 m sand was deposited. At the seaside 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 (Figure 7) show that the nourishment beach sand contains coarse material, but mainly material sized 1.25 to 2.75  $\phi$ . The sand fence deposits of nourishment sand have a distinct peak at the fraction 2.25–2.75  $\phi$  and contain less coarse material. The nourishment foredune sand resembles the sand fence deposit, apart from the absence of the coarse fraction.

A Mann Whitney test was performed to compare nourishment beach sand and fence deposits, and fence deposits and sand deposited in the foredunes, respectively. 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  $<0.75\phi$  and  $<-1.00\phi$ , and
- (5) contains more material  $>3.75\phi$ .

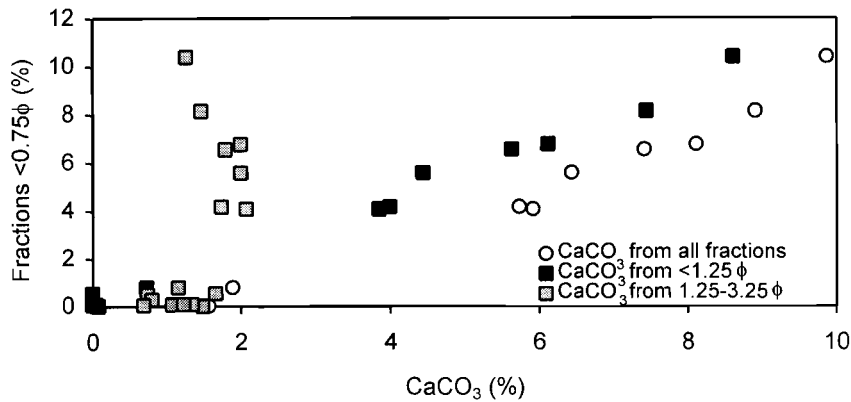


Figure 6.  $\text{CaCO}_3$  content versus fractions  $<0.75 \phi$  ( $>0.600 \text{ mm}$ ) for the nourishment sand samples displayed in Fig. 5.

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

- (1) have larger values for the kurtosis of the grain-size distribution, and
- (2) contain more material  $<-1.00 \phi$ .

The bivariate scatter plots (Figure 8) illustrate these differences.

**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 1). Grain-size distributions of sand in transport (Figure 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  $\phi$  (0.150 to 0.425 mm). At the seaside of the foredunes, nourishment sand in the fraction 2.25–2.75  $\phi$  is abundant, with admixtures of sand in the fractions 1.75–2.25  $\phi$  and 2.75–3.25  $\phi$  and only small amounts of fraction 1.25–1.75  $\phi$ . The native sand transported on the beach shows a distinct peak at fraction 2.25–2.75  $\phi$ . Native sand transported at the seaside of

the foredunes is similar, but contains less sand in the fraction 1.75–2.25  $\phi$ .

The bivariate scatter plots (Figure 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  $>0.75 \phi$  is platykurtic or mesokurtic for nourishment sand in transport on the beach and leptokurtic for all other trapped sand. The material  $<0.75 \phi$  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 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 (Figure 12). Groups of sand transported during moderate ( $u_2 = 8\text{--}12 \text{ m/s}$ ) and strong ( $u_2 = 12\text{--}16 \text{ m/s}$ ) 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,

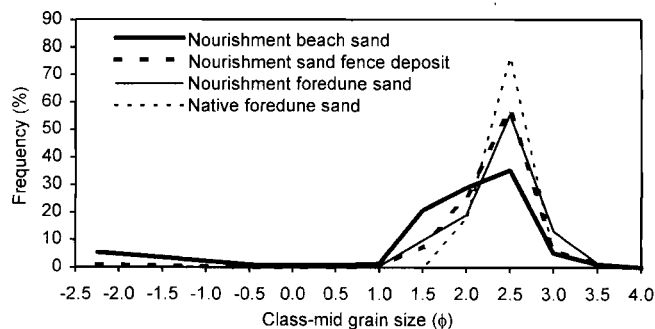


Figure 7. Examples of grain size distributions of nourishment sand and native and nourishment wind-laid sand.

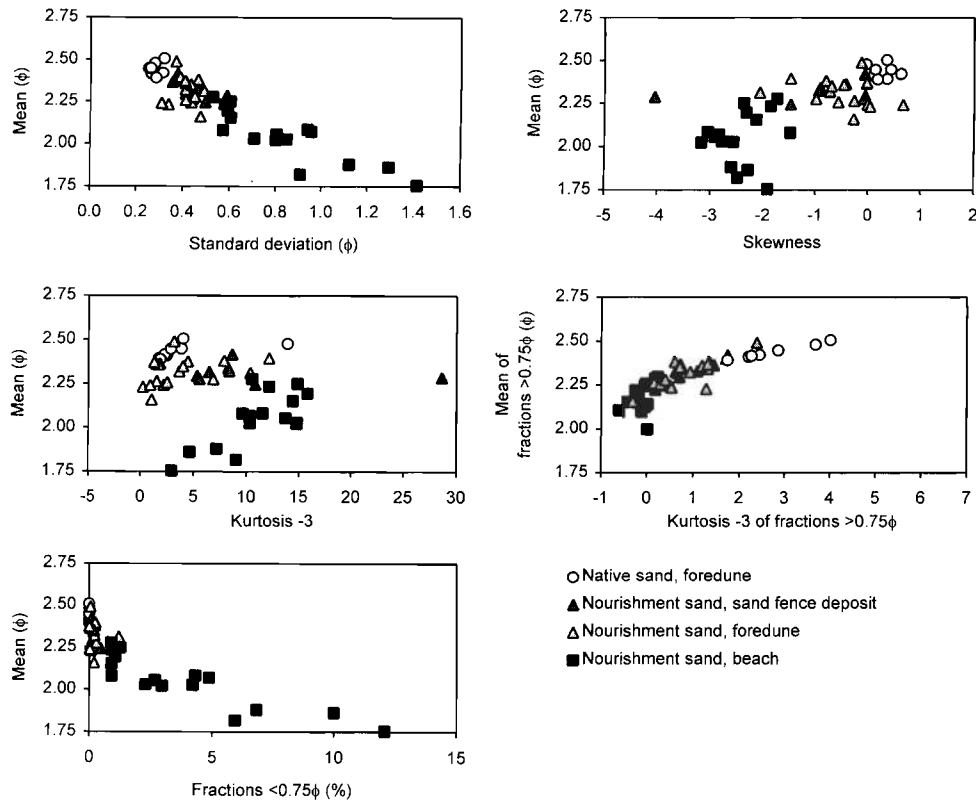


Figure 8. Bivariate scatter plots of nourishment sand and native and nourishment wind-laid sand.

- (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  $< 0.75 \phi$  and  $< -1.00 \phi$ , and
- (6) contains more sand sized  $> 3.75 \phi$ .

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

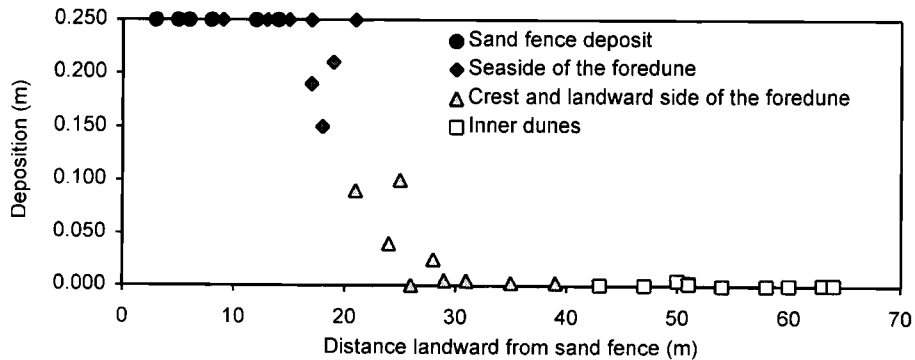


Figure 9. Cross-shore transect from the sand fence inland showing the depth of wind-laid nourishment sand (measured up to 0.250 m).



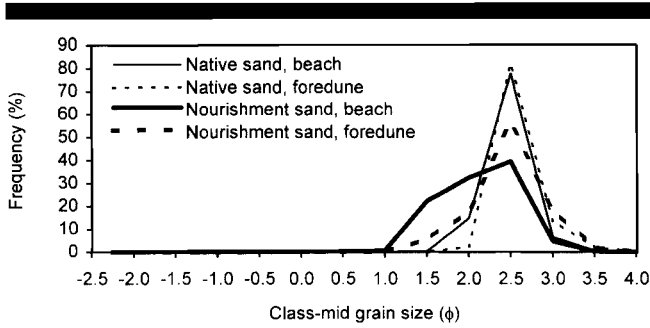


Figure 10. Examples of grain size distributions of sand in transport, integrated by height.

grains ( $<0.75 \phi$  and  $<-1.00 \phi$ , respectively) with height. There is a tendency of an increase in sand in the fractions 0.25 to 2.25  $\phi$  (0.212 to 0.850 mm) with height and a decrease in sand in the fractions  $>2.25 \phi$  ( $<0.212$  mm) with height. This tendency applies both to percentages of these fractions for the entire sample and for the sand  $>0.75 \phi$  ( $<0.600$  mm), and both for moderate ( $u_2 = 8-12$  m/s) and strong ( $u_2 = 12-16$  m/s) 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  $\phi$  with height was only significant for sand trap T3

and for the grouped data, the decrease in fraction  $>3.75 \phi$  ( $<0.075$  mm) was only significant for the grouped data. An example in which the fraction 1.25–1.75  $\phi$  increases with height relative to the fraction 2.25–2.75  $\phi$  indicates the importance of the 0.00 to 0.05 m layer, in which the bulk of the sand is transported (Figure 13).

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, 1996). 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.

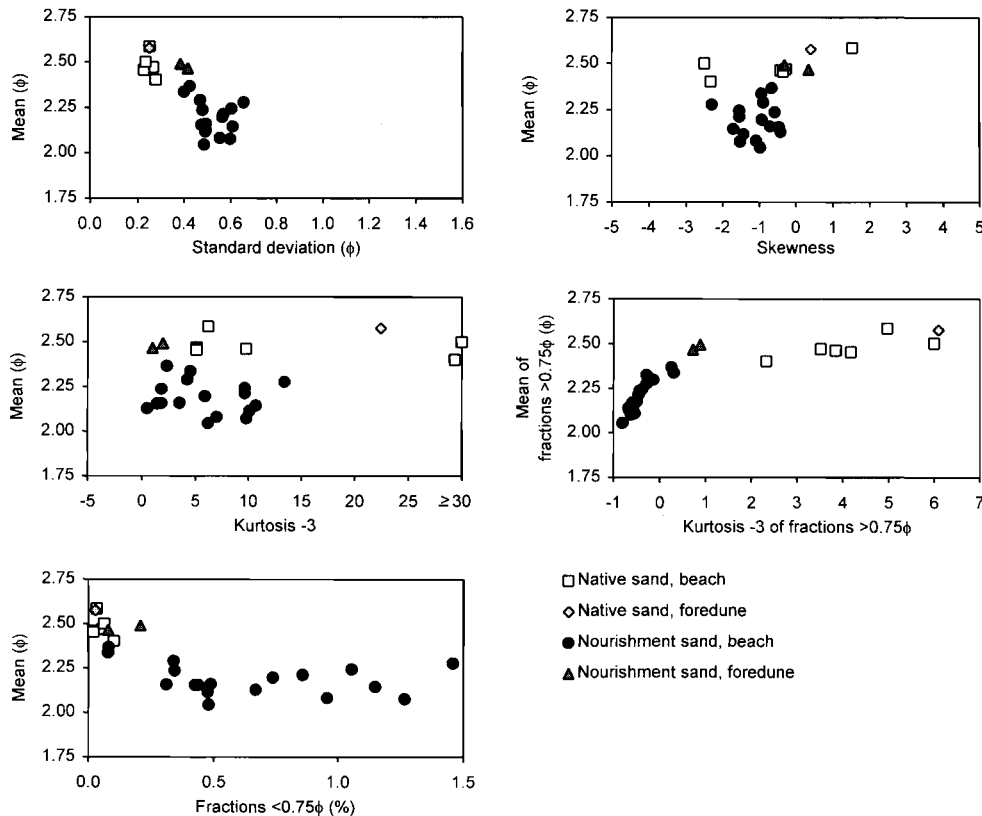


Figure 11. Bivariate scatter plots of sand in transport (using grain size distributions integrated by height).

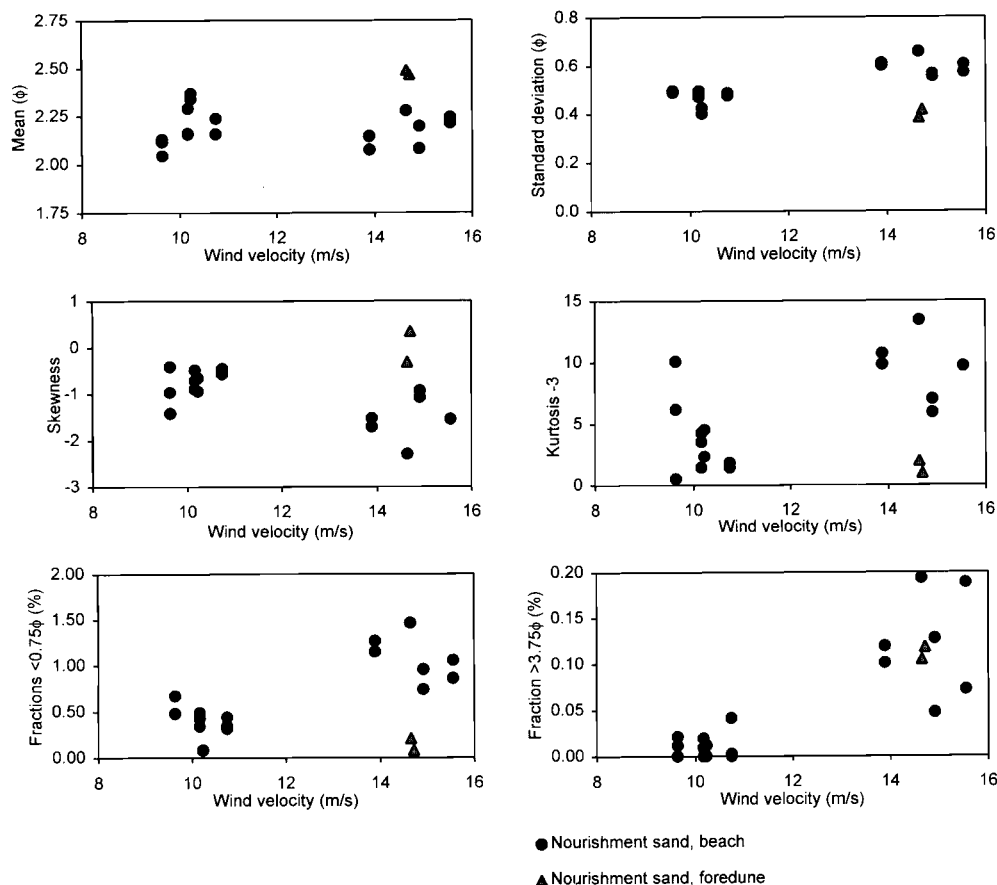


Figure 12. Some textural parameters of sand in transport versus wind velocity (using grain size distributions integrated by height).

On the beach a wide range of sand is in transport. The shells, and to a lesser extent the material  $>3.75 \phi$  ( $<0.075$  mm) and  $1.25-1.75 \phi$  ( $0.300-0.425$  mm) fraction, selectively lag behind. Even during strong winds ( $u_2 = 14-16$  m/s), 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 and 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, 1998b) probably enhanced the variation in shell concentrates found at the surface.

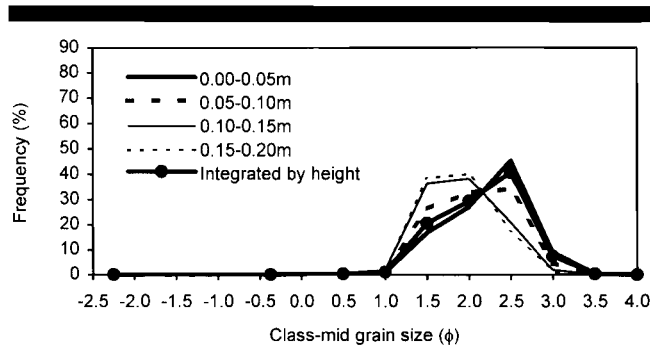


Figure 13. Example of the distribution of grain size with height (trap T3, 21 October 1996, 10:30-11:00).

The lags can initially enhance aeolian sand transport but eventually lead to a decrease in transport rates (LOGIE, 1982; NICKLING and 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 (1998b). 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 ( $>3.75 \phi$ ) 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 and WARD (1957), SHEPHARD and YOUNG (1961) and McLAREN and BOWLES (1985) in natural beach, desert, and river environments. The wind-laid nourishment sand in the foredunes contains 4.9% of the material  $<0.75 \phi$  ( $>0.600$  mm) and only 0.6% of the material  $<-1.00 \phi$  ( $>2$  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 decrease in deposition (Figure 9) confirmed findings of ARENS (1996), who attributed a rapid decrease in deposition between the dune foot 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 and 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  $<3.00 \phi$  ( $>0.125$  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 and 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 and 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  $\phi$  with height and the absence of such a trend for the fractions  $<0.75 \phi$  (*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  $\phi$  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.

### Differences in Carbonate Content Between Native and Nourishment Sand

CaCO<sub>3</sub> 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 ( $>3.25 \phi$ ) contain up to 0.7% CaCO<sub>3</sub> (which is 0.0% of the total sample), and the sand sized 1.25 to 3.25  $\phi$  contains 1.2% CaCO<sub>3</sub> at most (which is 1.2% of the total sample). The CaCO<sub>3</sub> content of beach sand was significantly higher after nourishment. The CaCO<sub>3</sub> contents of the separate fractions in the wind-blown nourishment sand were not studied. However, the coarse fraction of the sand ( $<0.75 \phi$ ) (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 dis-

tricts 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  $\phi$  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  $<0.75 \phi$  ( $>0.600$  mm) selectively lags 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.

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