| Journal of Coastal Research | 14 | 2 | 620–631 | Royal Palm Beach, Florida | Spring 1998 |
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# The Impact of the Grain-size Distribution of Nourishment Sand on Aeolian Sand Transport

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**ABSTRACT**

VAN DER WAL, D., 1998. The impact of the grain-size distribution of nourishment sand on aeolian sand transport. *Journal of Coastal Research,* 14(2), 620–631. Royal Palm Beach (Florida), ISSN 0749-0208.

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.

**ADDITIONAL INDEX WORDS:** *Beach nourishment, dune nourishment, fill material, ambient sand, grain-size distribution, aeolian sand transport, wind tunnel experiments, The Netherlands.*

## 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 (DAVIDSON *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. 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 borrow material compared to the ambient beach sand (Figure 1).

In The Netherlands, sediment in the borrow 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 borrow 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 and DAMOISEAUX, 1989). The nourishment sand represents a mixture of this borrow sand. 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 threshold wind velocity and eventually this may lead to a change in the rate of wind-borne sand transport.

*95159 received 23 October 1995; Accepted revision 20 March 1997.*

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). On the other hand, 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. 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 aspects that had been studied was the impact of the fill material on aeolian sand transport. The objectives of this study were (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 textual 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

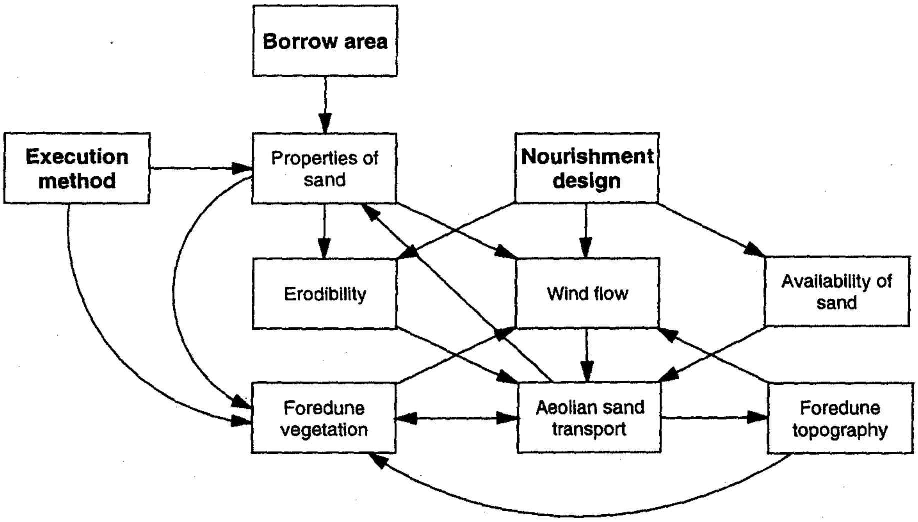


Figure 1. Main impacts of artificial beach nourishment on aeolian sand transport to the foredunes.

the 'susceptibility' of the sediments to mobilize, are compared and discussed. The results of the study will be discussed with reference to actual aeolian sand transport on nourished beaches. First, the use of nourishment along the Dutch coast is considered.

## NOURISHMENTS CARRIED OUT IN THE NETHERLANDS

In The Netherlands, nourishment projects have been executed since the early fifties. The method has been increasingly used as costs decreased, mainly due to technical innovation. The coast has been nourished for various reasons, but the most important was to safeguard the lowlying hinterland against flooding from the sea (HILLEN and ROELSE, 1995). Weak dune areas were strengthened by artificial nourishment of type a, b and c in Figure 2, to bring the dunes in line with the safety standard, as laid down under the Delta Act of 1953. Since 1992, dunes along the Dutch coast all fulfil the safety requirements (*i.e.* minimum dimensions or volumes (TECHNICAL ADVISORY COMMITTEE ON WATER DEFENCES, 1984; 1995)).

After careful consideration of a number of alternatives, the Dutch government decided that coastal regression should be halted by means of the dynamic preservation of the coastline at its position in 1990, with nourishment being a recommended measure to counteract erosion (RIJKSWATERSTAAT, 1990). Since 1991, some five to seven million $m^3$ of sand have been deposited along the Dutch coast every year (HILLEN and ROELSE, 1995). Fill is placed on the upper part of the beach (type d in Figure 2). In some cases this type of nourishment is complemented by a high buffer against the sea side front of the dunes (type e in Figure 2), a so-called 'banquet' (HIL-

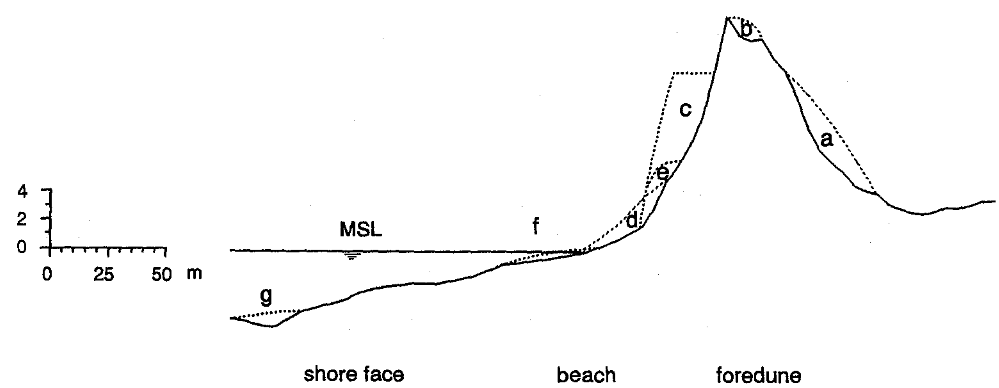


Figure 2. Cross section with fill placing a. at the leeward side of the foredune, b. on top of the foredune, c. against the sea side front of the dunes, d. on (the upper part of) the beach, often combined with e. a high buffer (a so-called 'banquet'), f. on the foreshore, and g. on the shore face.

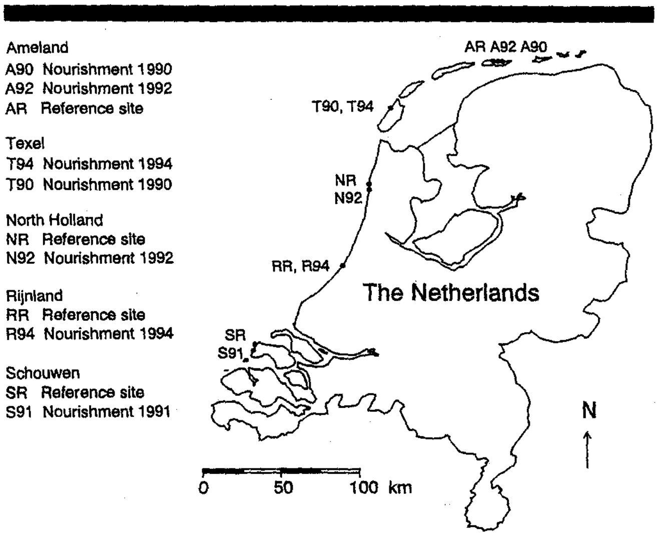


Figure 3. Location of sites.

Table 1. *Some characteristics of the nourishments on the investigated sites (data from Roelse and Hillen, 1993 and De Ruig, 1994).*

| Site | Year | Fill Volume ($10^6m^3$) | Length (km) | Placing |
|---|---|---|---|---|
| Ameland (Central part) | 1980 | 2.2 | 5.6 | dune face |
| | 1990 | 0.97 | 4.6 | dune and dune face |
| | 1992 | 1.7 | 8.1 | dune and beach |
| Texel (Eierland) | 1979 | 3.05 | 5.8 | beach (with 'banquet') |
| | 1985 | 2.85 | 6.0 | beach (with 'banquet') |
| | 1990 | 2.54 | 5.4 | beach (with 'banquet') |
| | 1994 | 1.33 | 3.0 | beach (with 'banquet') |
| North Holland (Bergen) | 1990 | 0.45 | 1.5 | beach (with 'banquet') |
| | 1992 | 1.47 | 12.3 | beach (with 'banquet') |
| Rijnland (Meyendel) | 1994 | 0.70 | 3.0 | beach |
| Schouwen (Kop) | 1987 | 1.83 | 2.4 | beach and foreshore |
| | 1991 | 2.5 | 5.7 | dune face, beach and foreshore |

LEN and ROELSE, 1995), especially when the beach to be supplied is narrow. In other cases the fill material is spread over the foreshore (type f in Figure 2), since this is often the place where the losses occur. However, from an executional point of view, nourishing the surf zone might be difficult (VAN DE GRAAFF *et al.*, 1991). In 1993, an experiment was carried out with a nourishment in the nearshore zone, with fill placing in the trough between the middle and outer breaker bar (type g in Figure 2) (HOEKSTRA *et al.*, 1996).

The planned lifespan of beach nourishments and dune nourishment vary 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 lifespan (HILLEN and ROELSE, 1995).

In general, nourishment sand is borrowed in the nearshore zone of the North Sea, as near as possible to the location to be nourished, but with the proviso that the borrow area is located seawards of the contour line of 20 m of depth or more than 20 km offshore (DELFT HYDRAULICS, 1987). To avoid negative impacts, sand with a minimum of clay and organic matter is opted for (DELFT HYDRAULICS, 1987). Various methods are used to borrow, transport and emplace the fill material. Usually, the sand is borrowed by a dredge and transported to a discharge location in the vicinity of the beach to be nourished and by the same or by another dredge the material is brought ashore and spread out over the beach (VAN OORSCHOT and VAN RAALTE, 1991). Bulldozers and cranes are used to remodel the fill.

More information on artificial nourishments carried out in The Netherlands can be found in DELFT HYDRAULICS (1987).

## METHODS

### Field Sites

From the locations nourished after 1990, five sites were chosen, with different corresponding borrow areas and various frequencies and ages of nourishments and fill placing (Figure 3). Besides, adjacent reference sites at unnourished beaches were selected.

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 Dutch 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 Figure 2 is given below (see also Table 1).

(1) Ameland. In the central part of the Wadden island of Ameland a first nourishment (type c) was carried out in 1980 to counter-act 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. Figure 4 shows the 1992 nourishment. Sand fences were erected at the dune foot, both parallel and perpendicular to the coast. At the west side of the area, a reference site was investigated.

(2) Texel. On Eierland on the Wadden island of Texel, structural erosion continues for many decades (ROELSE and HILLEN, 1993). After a first nourishment in 1979, the beach was repeatedly replenished in 1985, 1990 and in 1994 (all type d and e). Figure 5 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'.

(3) 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

Figure 4. The dune nourishment of 1992 on Ameland (photograph taken in August of 1994).

Figure 5. The beach nourishment of 1994 on Texel (photograph taken in July of 1994).

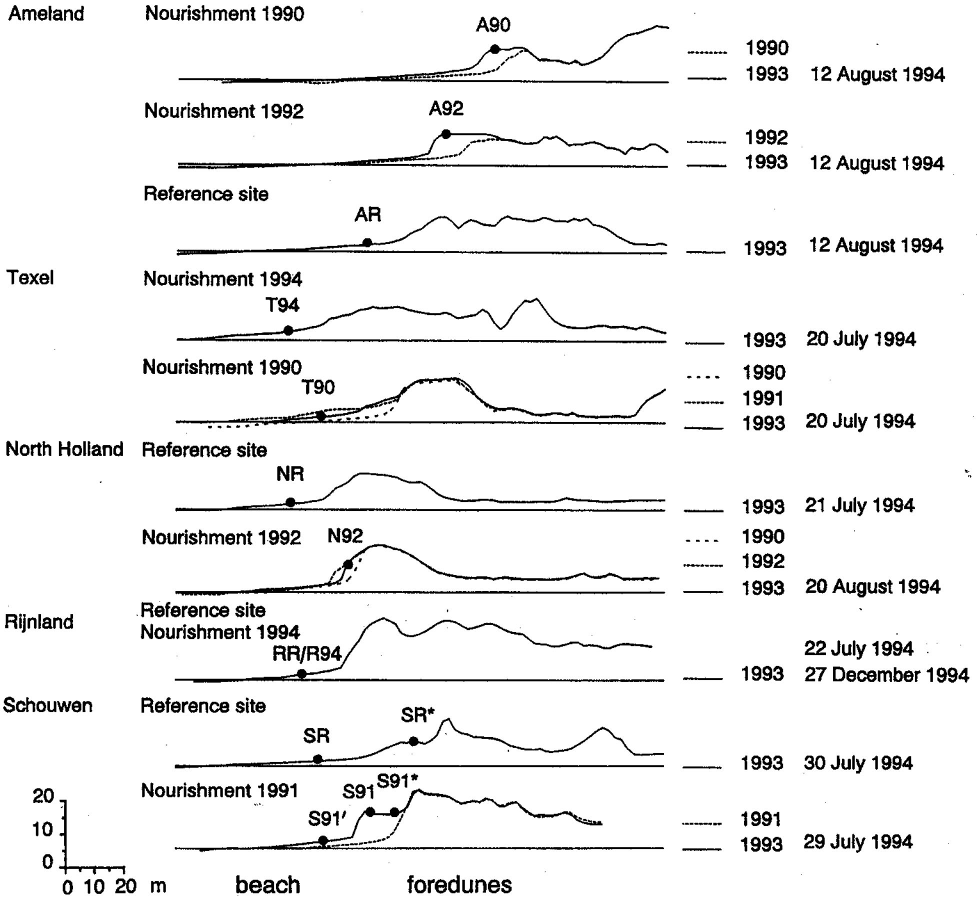


Figure 6. Transects of each site with sampling location and date.

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.

(4) 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.

(5) 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 and 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 borrowing 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 gram were collected. For wind tunnel experiments, one to three 11 kg samples were collected at each site. For each sample, a layer of 5 centimetres in depth was scraped from the surface.

In Figure 6, 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 and LOUISSE, 1991). 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, as is indicated in Figure 6. 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.

At a number of sites, additional samples were taken alongshore (about 200 metres 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 (Figure 5). For the other sites, aeolian selection acted on a time scale of over several 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 $\varphi$, starting with a mesh of 3.75 $\varphi$, 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 $\varphi$ 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, two samples of 11 kg were available, so that 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 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, 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 and VAN DER LEE, 1995). Average wind speed converted to a standard height of 10 m by applying the logarithmic wind law (BAGNOLD, 1960) would be about 20 m/s, 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. 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 shell fragments 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 2). This variable was plotted against a number of grain-size parameters derived from the analysis of the samples (Figures 8 to 12).

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 Figure 13). In case of nourishment sand containing a considerable amount of shell fragments, there was a larger variability in grain-size distribution between the samples (*cf.* samples in Figure 7). As a result, the variation in the amount of sand blown off during the wind tunnel experiments was larger for these nourished sites (Table 2).

Table 2. *Weight percentages of sand blown off during wind tunnel experiments with mean percentages (see text for explanation).*

| Site | | Sample | Experiment a | b | c | μ |
|---|---|---|---|---|---|---|
| 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 |

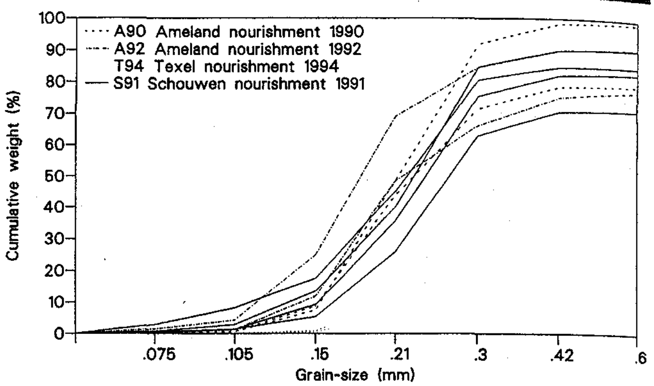


Figure 7. Cumulative curves of grain-sizes, showing variation in grain-size distribution within some nourished sites.

(1) Median grain-size. Table 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 was only slightly coarser than the corresponding native sand. Median grain-size of all samples ranged from 0.211 to 0.346 mm (Figure 8). 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.

(2) 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). 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) (Figure 9). 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.

(3) 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). 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 (Figure 10). A value of $U > 1.7$ was associated with low rates (*i.e.* <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.

(4) Fraction < 0.075 mm. The fraction < 0.075 mm 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% (Figure 11). The corresponding amount of sand transported during the wind tunnel experiments did not exceed 45% (Table 2). Both on Ameland and Schouwen, clayey sediment lay-

Table 3. *Median grain-size, uniformity index and sorting for nourished sites and nearby control sites. Percentiles are expressed in mm. Standard deviation is expressed in phi units.*

| Site | Sample | Nourished Site $d_{50}$ | $d_{60}/d_{10}$ | $d_{90}/d_{10}$ | σ | Reference Site $d_{50}$ | $d_{60}/d_{10}$ | $d_{90}/d_{10}$ | σ |
|---|---|---|---|---|---|---|---|---|---|
| Ameland | A90/AR | 0.227 | 1.70 | — | 1.00 | 0.211 | 1.44 | 1.77 | 0.29 |
| | A92/AR | 0.217 | 1.88 | — | 1.05 | 0.211 | 1.44 | 1.77 | 0.29 |
| Texel | T94 | 0.276 | 1.40 | 1.91 | 0.40 | — | — | — | — |
| | T90 | 0.346 | 1.93 | — | 0.93 | — | — | — | — |
| North Holland | N92/NR | 0.242 | 1.40 | 1.59 | 0.23 | 0.256 | 1.31 | 1.73 | 0.29 |
| Rijnland | R94/RR | 0.232 | 1.58 | 2.25 | 0.52 | 0.338 | 1.63 | 2.26 | 0.45 |
| Schouwen | S91/SR | 0.227 | 1.85 | 3.15 | 0.68 | 0.242 | 1.51 | 1.88 | 0.32 |

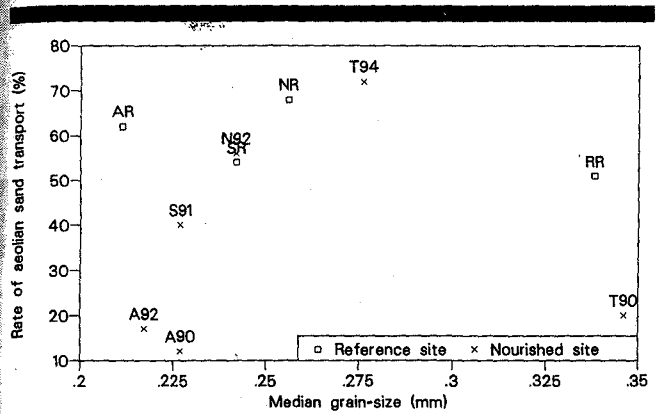


Figure 8. Median grain-size of the sand versus the rate of aeolian sand transport.

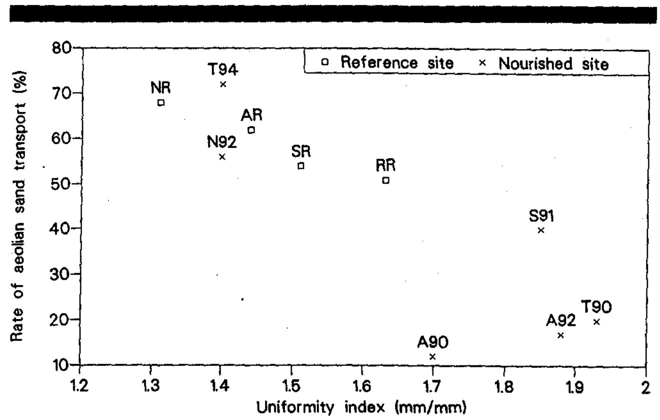


Figure 10. Uniformity index versus the rate of aeolian sand transport.

ers 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.

(5) 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, hindering wind-borne transport of sand (Table 2). Sand from Texel contained very coarse sand, gravel and stones, which also proved to be effective in reducing deflation (T90 in Figure 12). 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 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 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 > 0.6 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 sand from a nearby unnourished beach (Figure 13). 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

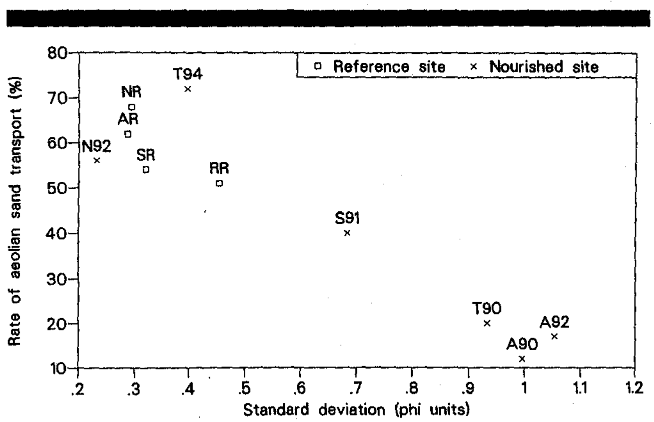


Figure 9. Standard deviation of the sand versus the rate of aeolian sand transport.

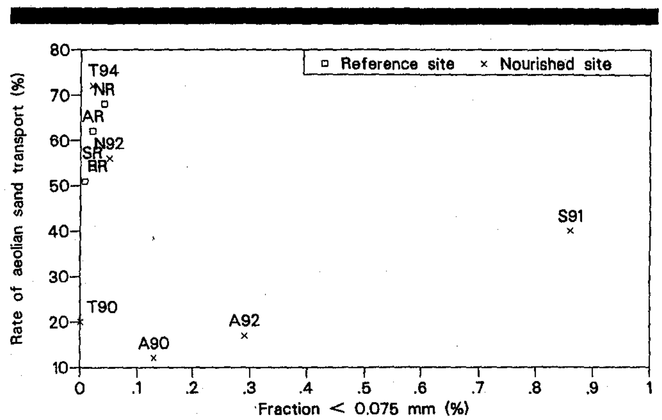


Figure 11. Fraction <0.075 mm versus the rate of aeolian sand transport.

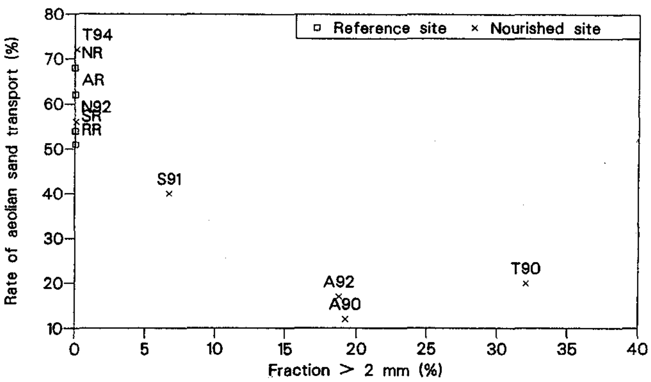


Figure 12. Fraction > 2 mm versus the rate of aeolian sand transport.

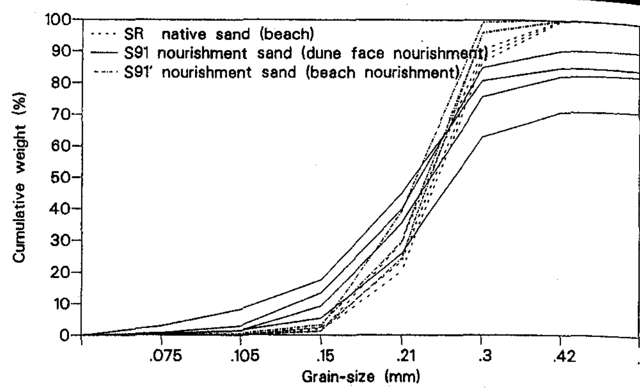


Figure 13. Cumulative curves of grain-sizes of three samples of sand from a natural beach, collected at the backshore (SR), four samples from the dune face nourishment on Schouwen (S91), and three samples from the beach nourishment on Schouwen, collected at the backshore (S91').

(Figure 14). 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.

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 above 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 susceptibility was in these cases the result of poor sorting of the quartz sand fraction (material < 2 mm).

## 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.

(1) Median grain-size. In aeolian sand transport studies, grain-size is recognized as an important parameter. Bagnold (1960) found that quartz sand grains of size 0.08 mm are most readily transported by the wind, because the threshold shear 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 was largely affected by sorting of sand.

(2) Sorting. Bagnold (1960) found 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 shear velocity, which was confirmed by studies conducted by *e.g.* Horikawa *et al.* (1983). Nickling (1988) found that critical wind velocities were smaller for more widely distributed sands. The smaller or more exposed surface grains were entrained at low shear velocities and set in motion a rapidly increasing number of grains by imparting

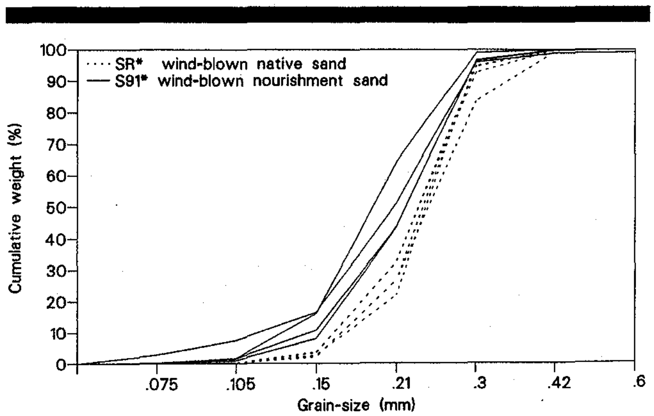


Figure 14. Cumulative curves of grain-sizes of five samples of wind-blown native sand and four samples of wind-blown nourishment sand from Schouwen.

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 shear 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 and (*i.e.*, sand with a standard deviation larger than 0.5 φ units).

(3) 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.

(4) 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, retarding aeolian sand transport. At two investigated sites, clays and silts could have hindered wind-borne transport, but the possible effect was overshadowed by the influence of shell fragments.

(5) 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 nonerodible particles however raises the threshold (NICKLING and MCKENNA NEUMAN, 1995). Semi-permanent 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 Figure 2), *e.g.* on Schouwen. They may also form on top of the 'banquets' (type e in Figure 2) and on the upper part of the beach (type d in Figure 2). On natural beaches, these extensive shell pavements were not encountered during the field work.

(6) 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 rate of sediment movement after nourishment in The Netherlands. In further studies, other factors than textural parameters, such as the influence of bonding agents (NICKLING and ECCLESTONE, 1981) on the sediment threshold and rate 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 decreases 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 in Figure 1, many other factors may be involved in altering aeolian sand transport rate 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). Assessing the impact of artificial nourishment on foredune development necessitates an exact method to determine the causes of short time and small scale variation in aeolian sand transport from nourished beaches. Furthermore, the 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.

## 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) grain-size distribution of sand and on (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 median grain-size, but also the whole grain-size distribution and the spatial variability of sand properties, since even well sorted sand in the borrow 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 borrow 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.

## ACKNOWLEDGEMENTS

The research was financially supported by the Road and Hydraulic Engineering Division of Rijkswaterstaat, on behalf of the Technical Advisory Committee on Water defences and by the National Institute for Coastal and Marine Management (RIKZ) The Netherlands. JARKUS data were kindly made available by the latter institute. For the experiment, the wind tunnel of the Institute for Soil Fertility (Haren, The Netherlands) was used. I am grateful to Prof. Dr. P.D. Jungerius for his contribution during this research. Finally, I thank Prof. Dr. K.F. Nordstrom and Dr. S.M. Arens for their valuable comments on the manuscript.

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