Eolian Sediment Transport on a Natural Beach

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ABSTRACT ■

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An eolian sediment transport model has been used to estimate the average, annual sediment transport from the beach into the dunes and to compute the spatial variability of the transport rates in an alternating erosional and accretionary beach and dune area. The computed accumulation rates in the dune area have been compared with leveling surveys of the dune field, showing good agreement. Various field parameters as the roughness factor, the grainsize distribution, the width of the beach, the beachslope, the moisture content of the beach surface and the angles of the transect and mid-tide line as well as the wind velocity were measured on different morphological units of the beach. Model computations with respect to the sensitivity of the model indicate that the reliability mainly depends on the accuracy of both the roughness factor and the beach width.

ADDITIONAL INDEX WORDS: *Coastal management, dunes, sediment budget, wind-blown sand.*

INTRODUCTION

Coastal dunes and sandy beaches along the shorelines of the low-lying deltaic countries around the North Sea form an important natural defense against coastal erosion. The presence of coastal dunes not only effectively reduces the costs of coastal protection but they are also part of a natural coastal scenery and are highly preferable to the large infra-structural constructions such as seawalls and dykes. At several locations along the Dutch coast (VELLINGA, 1986), as anywhere else in the world, dunes suffer from erosion. Therefore, monitoring the height, condition and extent of coastal dunes is and has been an important aspect of Dutch coastal management. With the expected increase in sea-level rise (WIND, 1987), this aspect will even gain more attention. Knowledge of the eolian sediment transport process on natural beaches and the rate of accumulation of sand in dunes is an essential tool that assists understanding and prediction of dune growth and development.

Hydrodynamic and associated sediment transport models for the nearshore zone are

nowadays widely accepted methods for coastal research and the evaluation of beach protection measures in the framework of coastal management. Mathematical simulations of eolian sediment transport on natural beaches, coupled with a verification based on field data, are techniques which are certainly less widely applied. This paper presents an eolian sediment transport model, principally based on the elementary physics already described by BAGNOLD in 1941, and the empirical work of ADRIANI and TERWINDT (1974). Model calculations have been verified making use of sand budget calculations which are available through regular leveling. The model opens the opportunity to estimate the average annual sediment transport into the dunes.

STUDY AREA

The investigated beach and dune area is located in the southwestern part of The Netherlands near the connection of the former island of Goeree and the Brouwersdam, an artificial dam closing the former tidal inlet Grevelingen from the North Sea (Photograph 1, Figure 1).

Since 1972, the year when construction of the Brouwersdam was finished, a large primary dunefield (width: 100 m, height: 4 m) and a wide
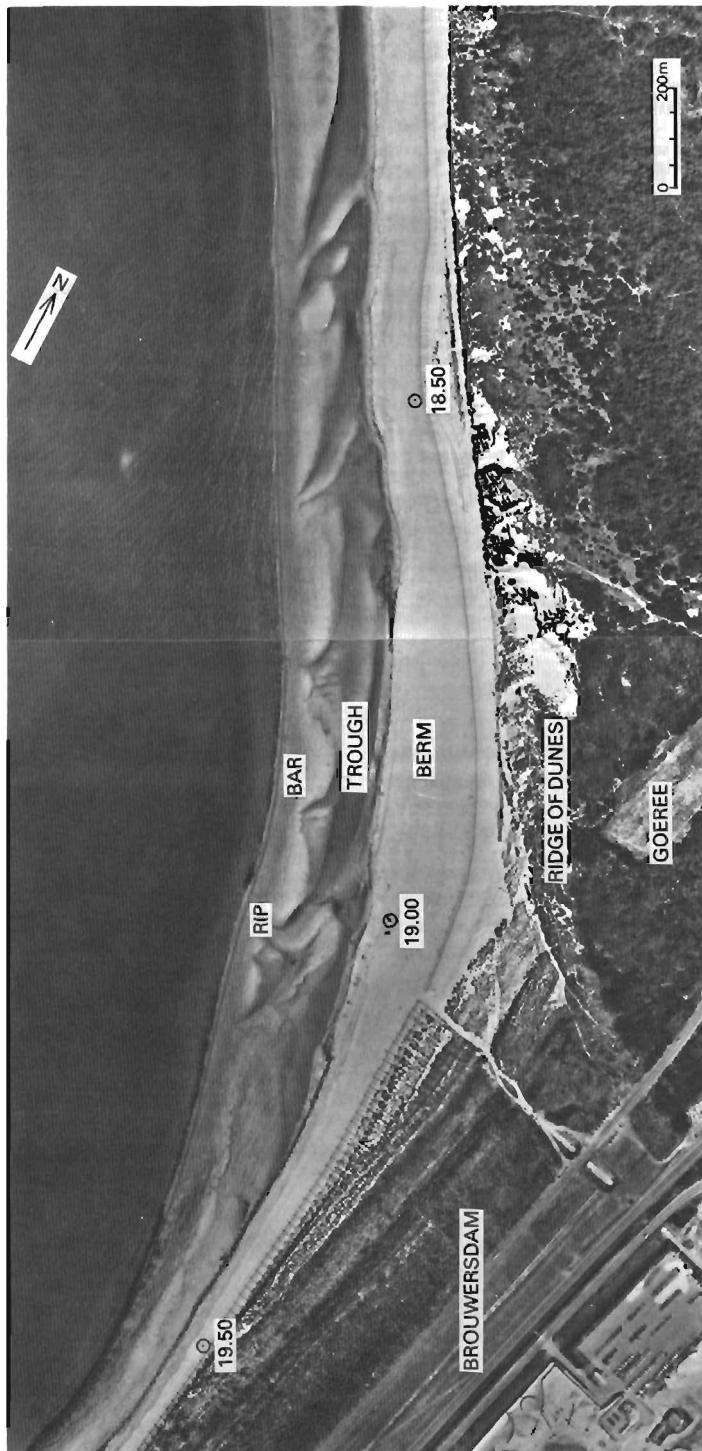
study area

Figure 1. Location of the study area.

beach (125–150 m) have developed in the central part of this area where the dunes of Goeree (height: 10–20 m) and the sand dam (height: 10–12 m) make an angle of 135°. The northern and particularly the southern part of the area do not show any primary dune development. In these parts the beach is much smaller (70–100 m) and *circa* one degree steeper. The southern part of the sand dam near beach pole 19.50 is subjected to erosion as a result of wave processes. The artificial dune face in this part is

being scarped, showing a sand cliff *ca.* 5 m in height.

The morphology of the beach and surfzone is characterized by the occurrence of a longshore bar-trough system, with a rip-current spacing of between 200 and 500 meters. The vegetation of the dune area can be classified in three different zones, whereas there is no vegetation on the beach. The seaward side of the foredunes and the sand dam is overgrown by lyme-grasses, which effectively cover the dune surface. Going from the landward side of the foredunes and the second ridge of dunes to the dune

Photograph 1 *(facing page)*. Study area (Photography: KLM-AERO-CARTO, The Hague).

swale, there is a succession from a mixed zone, containing lyme-grasses and low bushes (*e.g.* sea buckthorn) to a densely-vegetated zone, consisting of 1.5 to 2 meters high bushes.

The main reason to choose this beach and dune area is the alternation of an erosional and an accretionary section along the three–kilometers long coastline. This alternation results in a spatial variability of the eolian sediment transport rate caused by differences in the exposure of the beach and foredunes to the dominant wind direction. This spatial variability of the eolian sediment transport can be compared with the sediment accumulation rates, derived from successive leveling profiles of the dune area.

The human influences—after the phase of construction of the Brouwersdam—are relatively limited, certainly in comparison to other parts of the Dutch coast, where dune stabilization and beach nourishment are of frequent occurrence.

MEASUREMENTS

The field data for the input of the eolian sediment transport model and the sediment budget analysis have been collected during the spring and summer of 1984 and 1985 as well as in the autumn of 1985.

The wind velocity above the beach surface was measured on six different heights (1,2,8,20,40,100 cm) with the use of pitot tubes. With these wind data many vertical wind velocity profiles (Figure 2) were drawn to determine the threshold shear velocity of the wind and the roughness factor, related to the combined influence of saltating grains and bedforms. The wind velocity and wind direction on a height of 1.5 meter above the beach near beach pole 19.00 (Figure 1) were collected to estimate the local wind climate, necessary for the prediction of the total potential eolian sediment transport in one year. These wind data have also been performed with the use of a pitot tube during 10 minutes of every hour and have been correlated with the wind measurements of the KNMI-weather station Vlissingen. Using these correlations, made for different meteorological conditions, the wind climate of the weather station Vlissingen has been adjusted and extrapolated to create the local wind climate for the beach of Goeree.

The spatial variability of the wind velocity distribution at 1.5 meter above the surface of the beach and foredune area was measured by two cup-anemometers. The wind data from these anemometers were synchronously collected during 10 minute intervals on different locations in the study area.

The length of the line over which the sediment transport was calculated (workline) and the beach slope have been derived from the leveling profiles of the beach. The angles of the transect, the mid-tide line and the dunefoot in relation to the geographical north have been found by using existing maps of the study area and a compass. The location and height of the mid-tide mark were also based on existing maps and leveling surveys of the beach area. The difference in height of the waterline in relation to the absolute height of the mid-tide mark, as a function of the wind force and wind direction, has been derived from a reference table of Brouwershaven (TERWINDT, 1968).

Several sediment samples have been collected on different morphological units of the beach to determine the spatial variability of the grain-size distribution with the use of a sieving method (¼ φ sieves). Since the fraction smaller than 52 μm represents less than 2% of the total weight of the sample, no mud-analysis has been executed.

The sediment samples of the upper 1 to 5 mm of the beach surface have also been used to determine the moisture content of the beach. These data have been calculated by measuring the wet and dry weight of the sediment samples.

EOLIAN SEDIMENT TRANSPORT MODEL

According to HORIKAWA *et al.* (1986) and SARRE (1988) the most predictive expressions for the eolian sediment transport rate show a cubic dependence on the shear velocity. The present model starts from this dependence and is based on the concepts of BAGNOLD (1941). BAGNOLD describes that the amount of sediment transport is determined by the rate at which work is done by the wind in moving the sand particles, whether in saltation or as surface creep. The physical relationship between the shear velocity of the wind and the transport rate can be derived from the turbulent energy equation applicable in the atmospheric boundary layer (HSU, 1987).
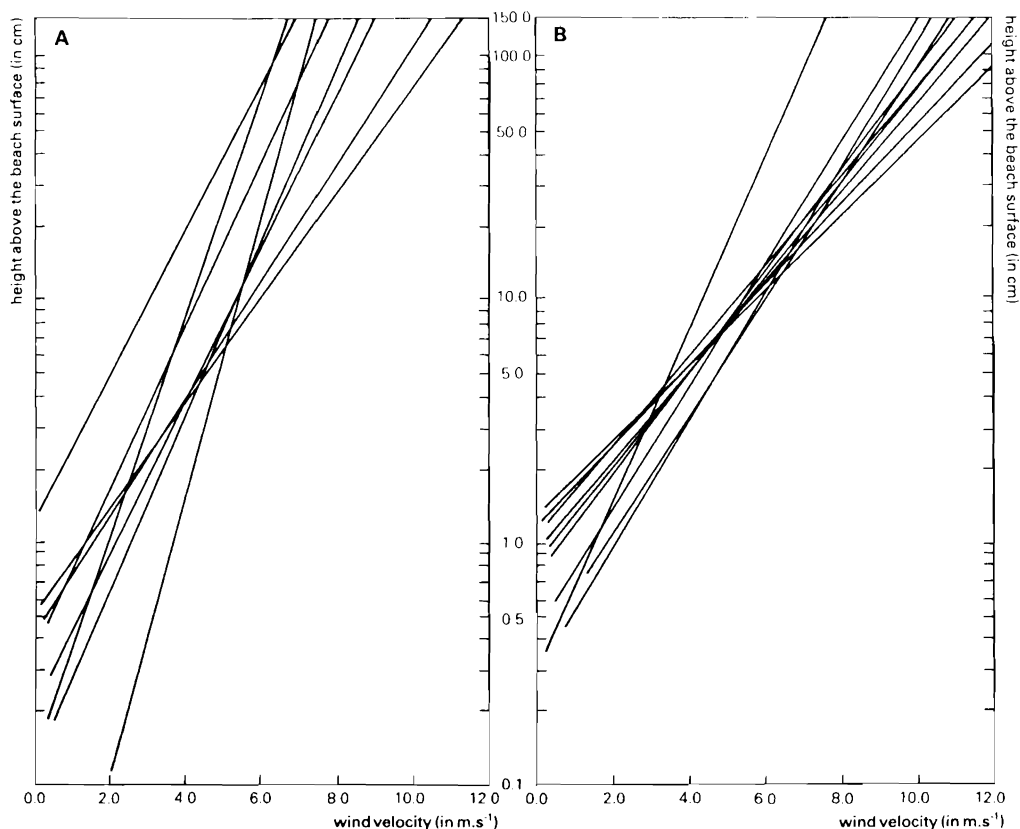
Figure 2. Vertical wind velocity profiles at the beach of Goeree. (a) summer conditions 1985; (b) autumn conditions 1985.

The potential eolian sediment transport is calculated by the equation:

$$q_j = C.(\frac{d}{D})^{1/2} \cdot (\frac{\rho_1}{g}). (v_*)^3$$

$$(\text{kg. period} - 1.m - 1) \quad (1)$$

where q_j is the sediment transport rate at windforce j (kg.s^{-1}.m^{-1}), C is an empirical coefficient, about 2.0 for well-sorted sands as found on Dutch beaches, d is the mean grainsize diameter of sand (m), D is the standard grainsize diameter of 250 μm, ρ_1 is the density of air (kg.m^{-3}), g is the gravitational acceleration (m.s^{-2}) and v_* is the shear velocity of the wind (m.s^{-1}). This shear velocity of the wind is calculated with the equation:

$$v_* = (v_z - v_t) / 5.75 \log(\frac{z}{k}) \quad (m.s^{-1}) \quad (2)$$

where v_z is the wind velocity (m.s.$^{-1}$) at mea-

surement height z (m), v_t is the threshold wind velocity at height k (m), presenting the entrainment level of the cohesionless beach surface sediments and having a value of circa 4.1 m.s^{-1} on Dutch beaches and k is the surface roughness factor, having a value of ($\frac{1}{30}$).d (m).

Equations 1 and 2 are used since the assumptions of a logarithmic distribution of the wind velocity in a vertical direction and the presence of a focuspoint where different velocity distributions intersect (Figure 2) are satisfied.

The total potential eolian sediment transport through a transect on the beach over which the sediment transport will be calculated (workline) is given by (ADRIANI and TERWINDT, 1974):

$$q_t = \sum_i \sum_j f_{ij} q_j a_{ij} \sin \alpha_i \quad (\text{kg.period}^{-1}) \quad (3)$$

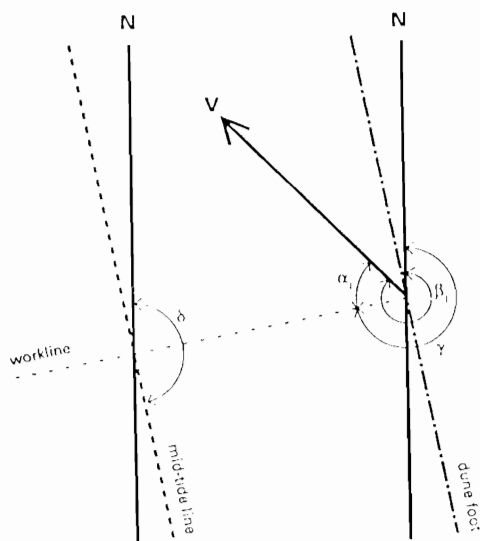where f_{ij} is the frequency of occurrence of wind-

Figure 3. Schematization of the beach near profile 19.00.
    α_i = angle between the direction in which the wind is
            blowing and the direction of the workline;
    β_i = angle between the geographical north and the
            direction in which the wind is blowing;
    γ =   angle between the geographical north and the
            direction of the workline;
    δ =   angle between the geographical north and the
            mid-tide line;
    v =   wind velocity vector.

force j at wind direction i (hours a year), a_{ij} is the effective length of the transect (m) and α_i is the angle between the direction in which the wind is blowing and the direction of the transect (Figure 3).

The effective length of the transect is a function of the water level variation around the mid-tide mark due to wind-induced set-up of seawater on the beach. This aspect is strongly related to the windforce j and direction i and is described by equation 4:

$$a_{ij}' = M_o - \frac{(hm + mv_{ij})}{\sin\beta} \quad (m) \quad (4)$$

where M_o is distance from the dunefoot to the mid-tide mark (m), hm is the absolute height of the mid-tide mark to a fixed reference level, *e.g.* the Dutch Ordnance Datum [N.A.P.] (m), mv_{ij} is the difference in height between the waterline and the level of hm (m) and β is the beach slope (°).

In case of onshore winds, there is a second

reduction in the effective length of the transect, because the fetch at the intertidal part of the beach near the low-tide line is too short to have the wind already saturated with sediments. For this reduction, ADRIANI and TERWINDT (1974) derived the next equation (5), partly based on field observations at Dutch beaches:

$$a_{ij} = a_{ij}' - [20.\sin(360 - \beta_i \quad (5)$$
$$+ \delta)]/\sin(\gamma - \delta) \ (m)$$

where a_{ij}' is the effective length of the transect as described in equation 4, β_i is the angle between the geographical north and the direction in which the wind is blowing, γ is the angle between the geographical north and the direction of the transect and δ is the angle between the geographical north and the mid-tide line.

The components of the resultant sediment transport vector parallel to, and perpendicular to the transect, are obtained by multiplying equation 3 with $\cos^2\alpha_i$ and $\sin^2\alpha_i$, respectively (ADRIANI and TERWINDT, 1974).

The influence of the moisture content of the beach surface is quantitatively described by BELLY (1964). In his approach the threshold wind velocity (see equation 2) is multiplied by a factor $(1.8 + 0.6 \log w)$, where w is the moisture content in percent dry weight.

Finally, the total potential sediment transport passing the dunefoot per unit width and unit time is calculated by the equation:

$$q_{rt} = \sum_i (-\sin\alpha_i \sum_j f_{ij} q_j)$$
$$(kg.period-1.m-1) \quad (6)$$

As can be seen in this equation the effective length of the transect is not included, assuming a situation where the beach width is unlimited without any fetch limitations.

SEDIMENT BUDGET ANALYSIS

The development of the dune area as a result of eolian processes and the related sediment budget have been studied both qualitatively and quantitatively with the use of aerial photographs and leveling profiles of the dunes. Comparing these profiles over successive years gives an indication of the accretion or erosion of the dunes for each period. Since the dune profiles have a spacing of about 500 m the calculated sediment budget for one profile is only based on the sediment transport between the
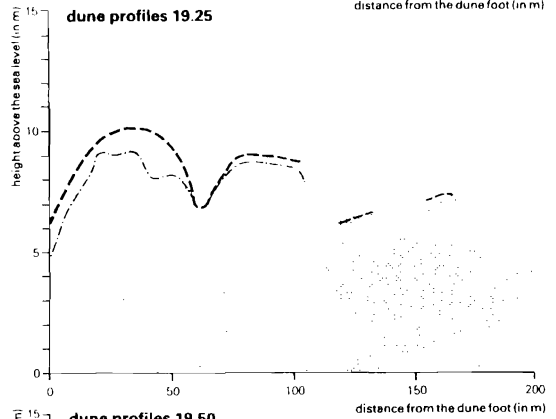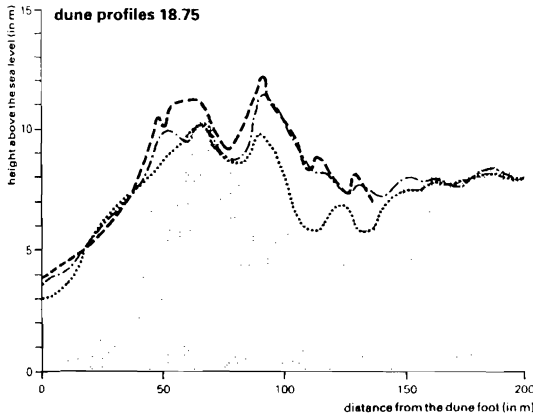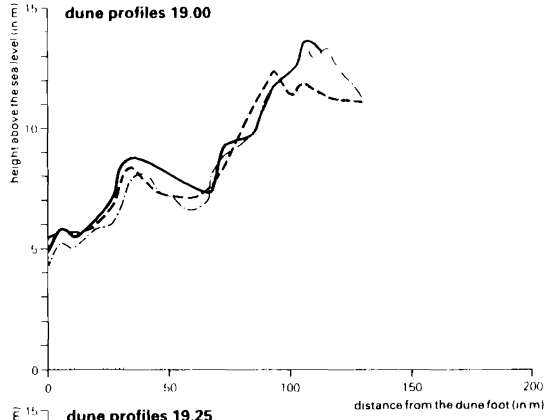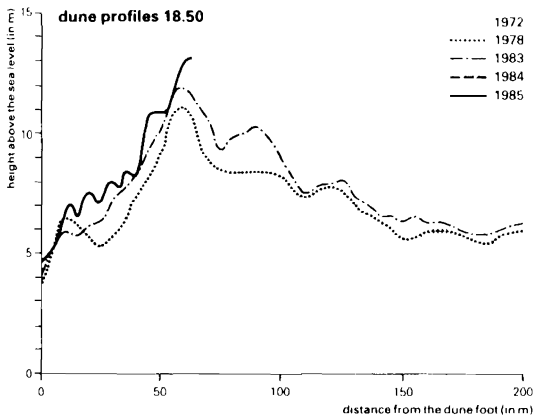
Figure 4.   Levelling profiles of the dune area.

Figure 4.   Continued.

beach and the dunes, neglecting the longshore transport of sediments in the dune area. According to the profiles in Figure 4 there is no net sediment transport between the foredunes and the dune swale.

RESULTS

The comparison of the wind measurements at the beach of Goeree and near the weather station at Vlissingen indicates a slight underestimation of the higher wind velocities (> 12 m.s^{-1}) at Vlissingen, for all wind directions. The frequency of occurrence of the higher wind velocities in the wind climate of Vlissingen has therefore been adjusted to create the local wind climate at the beach of Goeree. This wind climate, shown in Figure 5, is characterized by the dominance of southern, southwestern, and western winds, especially with respect
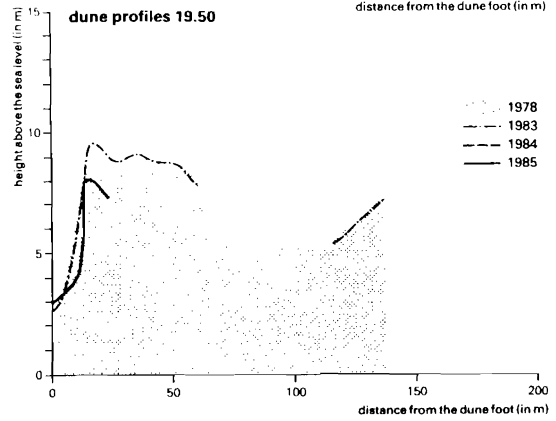
to the larger windforces. The spatial variability of the wind velocity over the beach and dune area is presented in Table 1. These data show two different tendencies. Firstly, wind velocities near the low-tide line and on the top of the foredunes are significantly higher than those on the beach near the dunefoot. This is probably a
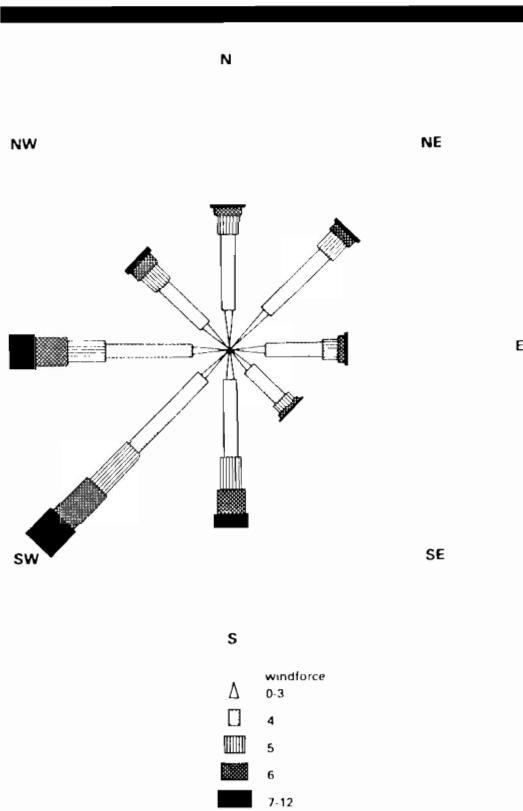
Figure 5.   Wind climate at the beach of Goeree.

ure 1) appeared to be higher than the wind velocities near the beach poles in northern (18.75) and southern (19.25, 19.50) direction. This is partly explained by the local morphology near the measurement sites, showing a smooth beach and dune profile near beach pole 19.00, but a sand cliff in the profile near beach pole 19.50 (Figure 4).

The combined roughness factor of the grains and bedforms, necessary to estimate the threshold wind velocity, is determined from vertical wind velocity profiles (Figure 2). Although these velocity profiles do not show an explicit focuspoint and display a certain scatter in k'-values, the k'-value above beach sand with 0.03 m high bedforms measured under summer conditions is approximately 0.04, whereas the k'-value determined above shell patches (in the autumn) is about 0.085.

The mean grainsize of 45 samples, taken from different morphological units of the beach, ranges from 226 μm (trough) to 263 μm (intertidal beach and dune foot). The mean grainsize of the longshore bar, the supratidal beach (berm) and the primary dunes is about 237 μm. The moisture content of the beach surface at Goeree is not very high, average values vary from 1 to 5%.

The total potential eolian sediment transport through the transect on the beach, perpendicular to the dunefoot near beach pole 18.50, 19.00 and 19.50, respectively, has been calculated for a combined roughness factor of the grains and bedforms of 0.01 and a mean grainsize diameter of 260 μm. The results are pre-

result of the sheltering effect of the foredunes, functioning as an up-stream limiting condition (SVASEK and TERWINDT, 1974). Secondly, the wind velocities near beach pole 19.00 (Fig-

Table 1.   *Spatial variability of wind velocity.*

| | | Wind Velocities | |
		Linear Correlation Coefficient	Location 2 (%) / Location 1
Location 1	Location 2		
beach pole 19.00	beach pole 18.75	0.98	97 ± 7
beach pole 19.00	beach pole 19.25	0.96	87 ± 7
beach pole 19.00	beach pole 19.50	0.92	74 ± 7
beach pole 18.75	low-tide line 18.75	0.95	105 ± 7
beach pole 19.00	low-tide line 19.00	0.97	101 ± 8
beach pole 19.25	low-tide line 19.25	0.97	112 ± 12
all beach poles	all low-tide lines	0.95	106 ± 10
beach pole 18.75	top foredune 18.75	0.96	119 ± 42
beach pole 19.00	top foredune 19.00	0.99	99 ± 16
beach pole 19.25	top foredune 19.25	0.68	138 ± 52
beach pole 19.50	top foredune 19.50	0.93	194 ± 79
all beach poles	all tops foredune	0.68	136 ± 57

study area
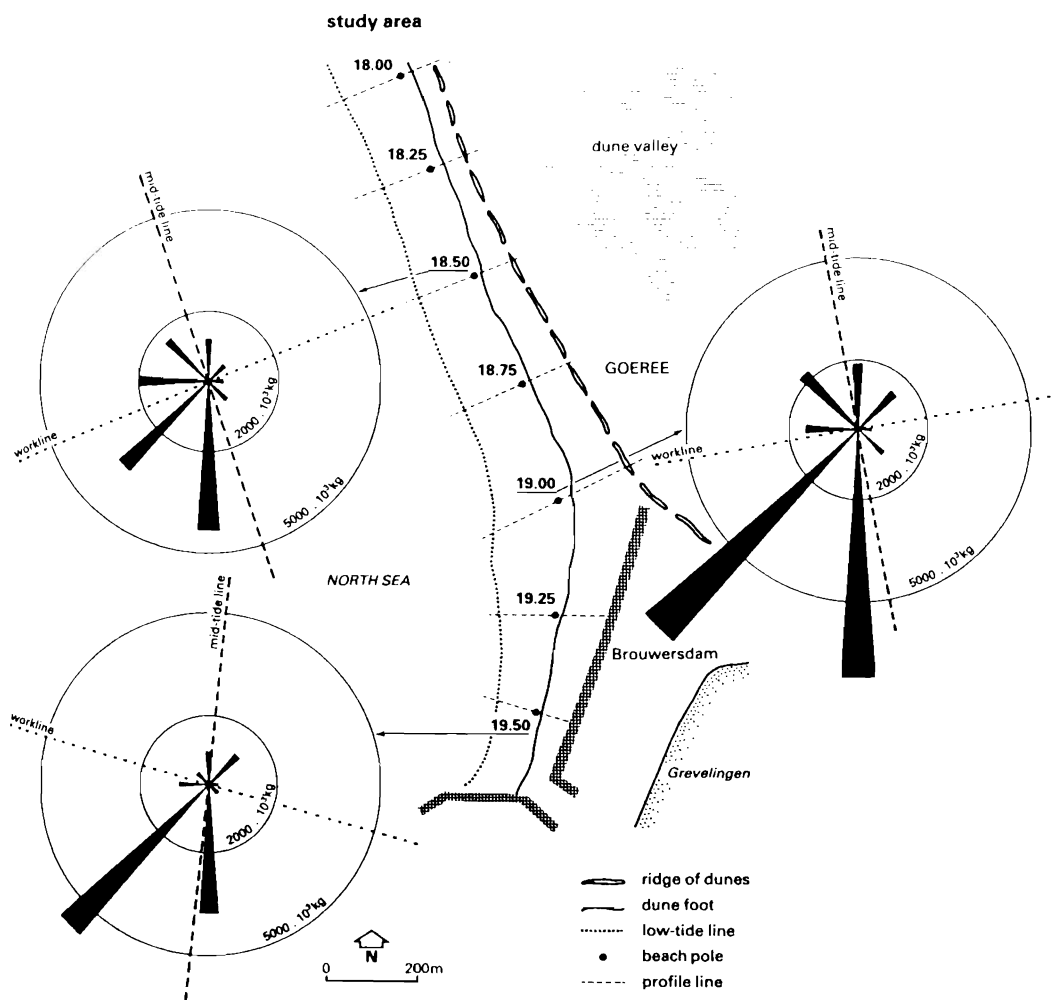
Figure 6. Spatial variability of the annual eolian sediment transport at the beach of Goeree.

Table 2. *Total potential eolian sediment transport rates (1000 kg. year $^{-1}$).*

Profile Number	Through the Workline	Perpendicular to the Workline	Parallel to the Workline
18.50	3370	2087	1282
19.00	9550	6442	3108
19.50	9689	7853	1836

sented in Figure 6 and Table 2. The largest eolian sediment transport rate from the beach to the dune area is observed near beach pole 19.00. This is in good agreement with the morphological development of the dune area (see Figures 1 and 2).

The quantity of sand crossing the dunefoot per unit width has only been calculated for the location near beach pole 19.00, because only at this point is the beach wide enough to assume a situation with an infinitely wide beach and a limited influence of the wind fetch reduction. The calculation results in an amount of 199 tons per year going from the beach into the dunes, giving an average annual accumulation rate of 47 cm in the 160 m wide dunefield.

The sediment budget analysis of the dune area, based on successive leveling, gives an average accumulation rate of 37 $cm.m^{-1}.year^{-1}$ near beach pole 19.00. However, there are con-

Table 3. *Mean annual accumulation rate of sediment in the dune area (in cm. m^{-1}. year^{-1}).*

Profile Number	Period			
	1972–1975	1975–1978	1978–1981	1981–1983
18. 50	32	19	8	21
18. 75	10	22	8	17
19. 00			36	37
19. 25		12	8	14
19. 50		2	0	

siderable differences between the successive years and at different locations along the beach and in the dune area (Table 3).

DISCUSSION

Sediment transport rates, based on model calculations, clearly show an overestimation of the actual, annual rates of deposition in the dune area, as deduced from regular leveling (47 versus 37 cm.m^{-1}.year^{-1}). This overestimation is expected since the transport rates should always be greater because sediments will be transported several times before they come to rest and accumulate. Assuming a total sediment trap, the difference can also be explained by different phenomena, which are partly related to the various parameters within the model.

The first aspect is the simplification of the beach morphology. The model deals with only one beach slope and one beach width, which is a very rough schematization of the natural and complicated bar-trough morphology. The sensitivity of these parameters with respect to the model output is shown in Figure 7a, giving a linear increase in sediment transport rates with an increase in beach width, and a small decrease of the sediment transport rate with increasing beach slope (β: 1.00 to 2.00°, ca. 1% decrease).

Another aspect affecting the model output is the spatial and temporal variability of the grainsize distribution and the roughness factor of the saltating grains and associated bedforms. The sensitivity of these parameters is presented in Figure 7b. An increase of the mean grainsize from 150 μm to 300 μm is accompanied by an increase in the sediment transport rate of about 10%. Meanwhile, the sediment transport rate increases circa 25% going from a k'-value of 0.05 to 0.1.

A third aspect is the assumption of a cohesionless beach. In natural field conditions the threshold shear velocity of the wind depends on cohesion factors such as the moisture content of the beach surface (BELLY, 1964; SARRE, 1988) and the amount of soluble salts in the beach sediments (NICKLING and ECCLESTONE, 1981; NICKLING, 1984). Consequently, model calculations will commonly overestimate the natural sediment transport rates.

Using the threshold wind velocity equation of BELLY (1964), an increase of the moisture content from 0.01 to 1.00% (Figure 7c) results in a logarithmic decrease in the sediment transport rate of 47%. This contradicts the results of SARRE (1988) where he demonstrates that a moisture content up to 14%, measured near the beach surface for a wide range of wind velocities, has no distinct influence on the sediment transport rates. However, the lowest moisture content of SARRE (1988) has been 7%, whereas Figure 7c shows the results in the range of 0.01 to 2.0%.

The effect of soluble salts in the beach sediments of Goeree is very small. A salt crust at the high-tide line (dimensions: height 1–3 mm, length few dm, width some cm) was only observed during three days in the summer of 1985, when the air temperatures were over 25°C and the windforce below 3 BF. Under these circumstances there was no eolian sediment transport.

The accuracy of the eolian sediment transport model, presented in this paper (equations 1–6), definitely depends on the measuring methods of the various parameters as well as a number of assumptions and schematizations. With the use of the lowest and highest measured values of various field parameters of Goeree (mean grainsize: 220–270 μm; roughness factor: 0.005–0.085 m; effective beach width: 70–150 m; beach slope: 0.5–5.0°), the computed eolian sediment transport ranges between a minimal rate of 4878.10^3 kg.year^{-1} and a maximal rate of 29432.10^3 kg.year^{-1}.

Finally, the computed accumulation rates for the dune area are only based on the sediment transport rates passing the dunefoot, assuming a closed sediment budget in a longshore direction as well as between the ridge of foredunes and the dune swale. However, according to the occurrence of blow-outs at the top of the foredunes with an unvegetated sediment tail in the
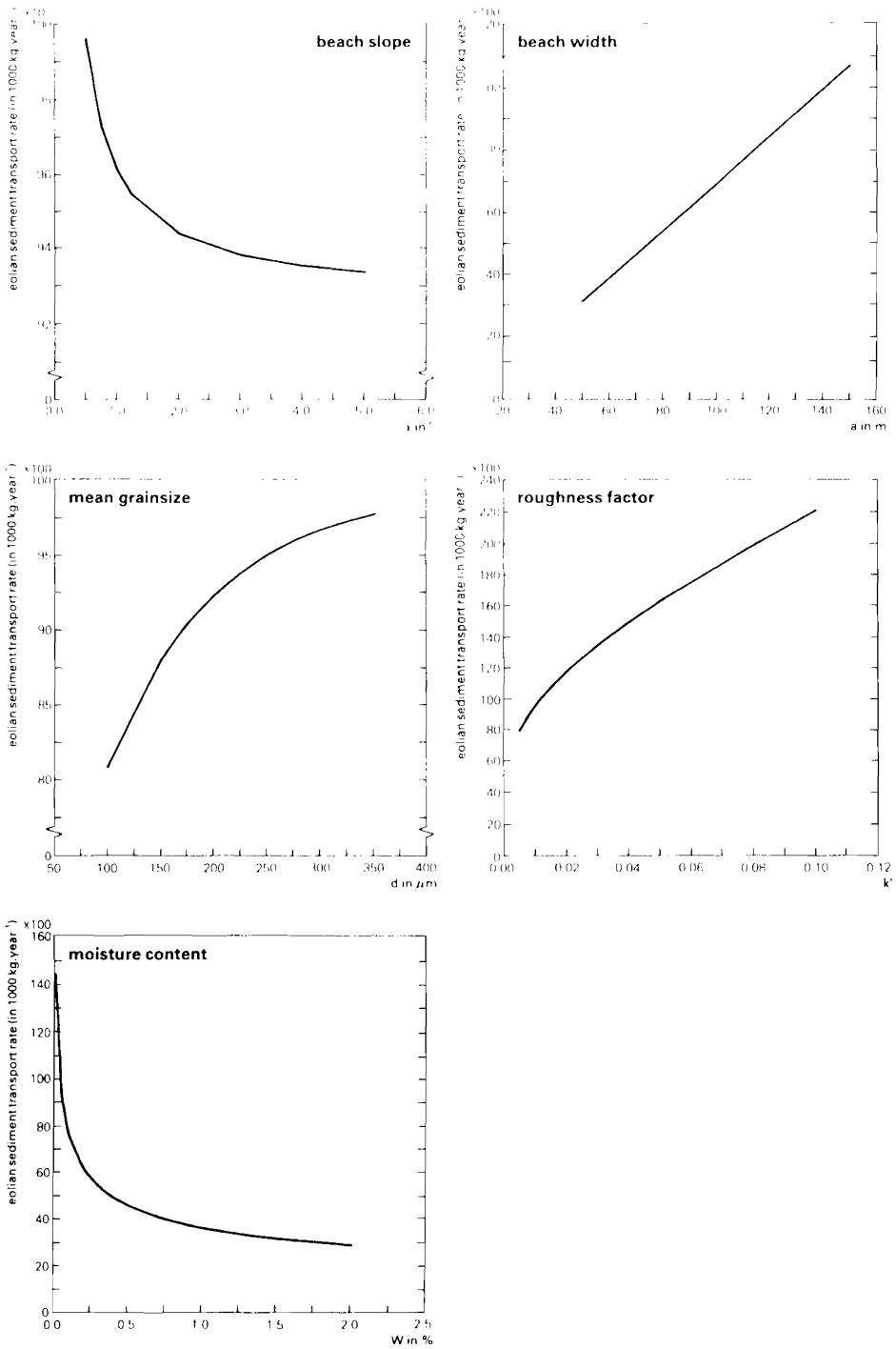
Figure 7. The sensitivity of the various parameters within the model to the rate of eolian sediment transport. (a) beach slope and beach width; (b) mean grainsize and roughness factor; and (c) moisture content.

direction of the dune swale, the accumulation rate of eolian sediment in the natural foredune area will be lower in comparison to the calculated model values.

CONCLUSIONS

The eolian sediment transport model is a valuable tool for the quantitative prediction of the sediment transport rates on a natural beach. The morphological development of the investigated beach and dune area is in good agreement with the spatial variability of the sediment transport rates, as computed by equation 3.

The sensitivity analysis of the various field parameters within the model demonstrates a dominance of the roughness factor of both saltating grains and bedforms and the length of the transect at the beach on the accuracy of the model computations. These parameters require a detailed survey in the field to enhance the reliability of the model. The determination of the local wind climate is strongly dependent on the position of the anemometer, due to the spatial variability of the wind velocity. For the prediction of sediment transport rates from the beach towards the dunes, it is recommended to execute the velocity measurements near the dunefoot.

The quantity of sediment crossing the dunefoot per unit width can only be calculated successfully if the beach has an imaginary and unlimited width and the windfetch reduction is only of minor importance. Therefore, model simulations have only been performed near beach pole 19.00. The overestimation of the computed accumulation rate in the dune area in comparison to the actual results of leveling, is basically the result of the above described assumptions, the difference between the transport process and the net accumulation rate, the accuracy of the various field parameters within the model and the 'one-boundary' approach in the eolian sediment budget of the dunes.

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⌐ RESUMEN ⌐

Se ha utilizado un modelo de transporte eólico de sedimento para estimar el transporte medio anual desde una playa hacia las dunas y para calcular la variabilidad espacial de las tasas de transporte en un área de duna y playa alternativamente en erosión y acreción. Las tasas de acumulación en el área de dunas se comparan con medidas topográficas del camp de dunas, encontrándose un buen ajuste. Se ha medido en diferentes unidades morfológicas varios parámetros de camp tales como: factor de rugosidad, distribución del tamaño de grano, anchura y pendiente de playa, contenido en humedad de la superficie de la playa, los ángulos de la curva de nivel a media marea con la dirección del viento y la velocidad del viento En cuanto a la sensibilidad del modelo, los cálculos indican que su fiabilidad depende principalmente de la aproximación con que se precisen el factor de rugosidad y la anchura de la playa.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ RÉSUMÉ □

Un modèle de transport éolien a servi à estimer le transport annuel depuis la plage vers la dune, et à calculer la variabilité spatiale des quantités transportées sur un couple plage-dune où alternent érosion et accumulation. Les taux d'accumulation calculés pour la dune ont été comparés aux données de nivellements et concordent bien avec celles-ci. Des paramètres de terrain comme le

paramètre de rugosité, la distribution des tailles de grains, la largeur de la plage, sa pente et sa teneur en eau, les angles du transect et la place du niveau de mi-marée ont été mesurés, ainsi que la vitesse du vent, sur différentes unités morphologiques de la plage. Des calculs tenant compte de la sensibilité du modèle, indiquent aue la fiabilité de celui-ci dépend surtout de la justesse du paramètre de rugosité et de la largeur de la plage.—*Catherine Bressolier, Géomorphologie E.P.H.E., Montrouge, France.*

□ ZUSAMENFASSUNG □

Ein Modell zum äolischen Sedimenttransport wurde benutzt, um den mittleren jährlichen Sedimenttransport vom Strand in ein Dünengelände abzuschätzen und die räumliche Variabilität der Transportrate bei alternierend erosiven und akkumulativen Strand- und Dünengebieten vorherzusagen. Die vorhergesagte Akkumulationsrate im Dünengelände wurde mit Vermessungen der Dünenfelder verglichen, wobei eine gute Übereinstimmung festgestellt wurde. Zahlreiche Feldparameter wie Reibungsfaktor, KorngröBenverteilung, Strandbreite, Strandböschung, Feuchte der Strandoberfläche und Winkel des Gesamtstrandes sowie Winkel an der Mittelwasserlinie ebenso wie Windgeschwindigkeit wurden auf verschiedenen morphologischen Einheiten der Strände gemessen. Berechnungen zur Sensitivität entsprechender Modelle weisen darauf hin, daB die verläBlichsten Kriterien jene des Reibungsfaktors und der Strandbreite sind.—*Dieter Kelletat, Essen/FRG.*