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Mobility of a remobilised parabolic dune in Kennemerland, The Netherlands

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Abstract

A parabolic dune in the Netherlands was remobilised in December 1998 by removing vegetation and soil. The main aim of the experiment was ecological: to investigate whether permanent rejuvenation at the landscape scale is possible by restoration of natural processes. If processes can be reactivated at coarse scale, periodic rejuvenation of the landscape over the long term is possible, without the need for managers to interfere further. The experiment provides the opportunity to address another important question: can large parabolic dunes in the Netherlands be mobile in the present climate? Mobility of the dune is investigated by means of erosion pins, aerial photography and measurement of cross sections. Activity indices are derived from erosion pin recordings and correlated to weather conditions. From 1999 to 2001, displacement of the dune ranged from 0 to 12 m in east–northeasterly direction. Activity of the dune is related to wind conditions, but the relationship is strongly influenced by precipitation and therefore differs for wet and dry periods. Periods with extreme wind speeds resulted in much less geomorphic change than expected.

Keywords: Parabolic dunes; Sand transport; Erosion pins; Dune mobility; Activity index; Dune management

1. Introduction

A large proportion of the Dutch coastal dunes are parabolic (Fig. 1). They developed between 800 and 1850 AD (Jelgersma et al., 1970; Klijn, 1990) but it is not clear what conditions were responsible for the sudden development of these dunes. Jelgersma et al. (1970) state that steepening of the sea floor resulted in a massive input of sand into the shoreface and beach, resulting in the formation of the Younger Dunes. Deforestation of the former beach barrier landscape in the late Middle Ages enabled the development of extensive dune fields of several kilometres wide. Klijn (1990) argued that coastal erosion of the barrier landscape, induced by sea level rise and increased storminess, must be the main cause of the massive input of sand and subsequent transgressive dune formation. Due to stabilising activities, but possibly also to climate change, all these dunes have been stabilised in the past 150 years. At present, aeolian activity in the coastal dunes is restricted to small features like blowouts.

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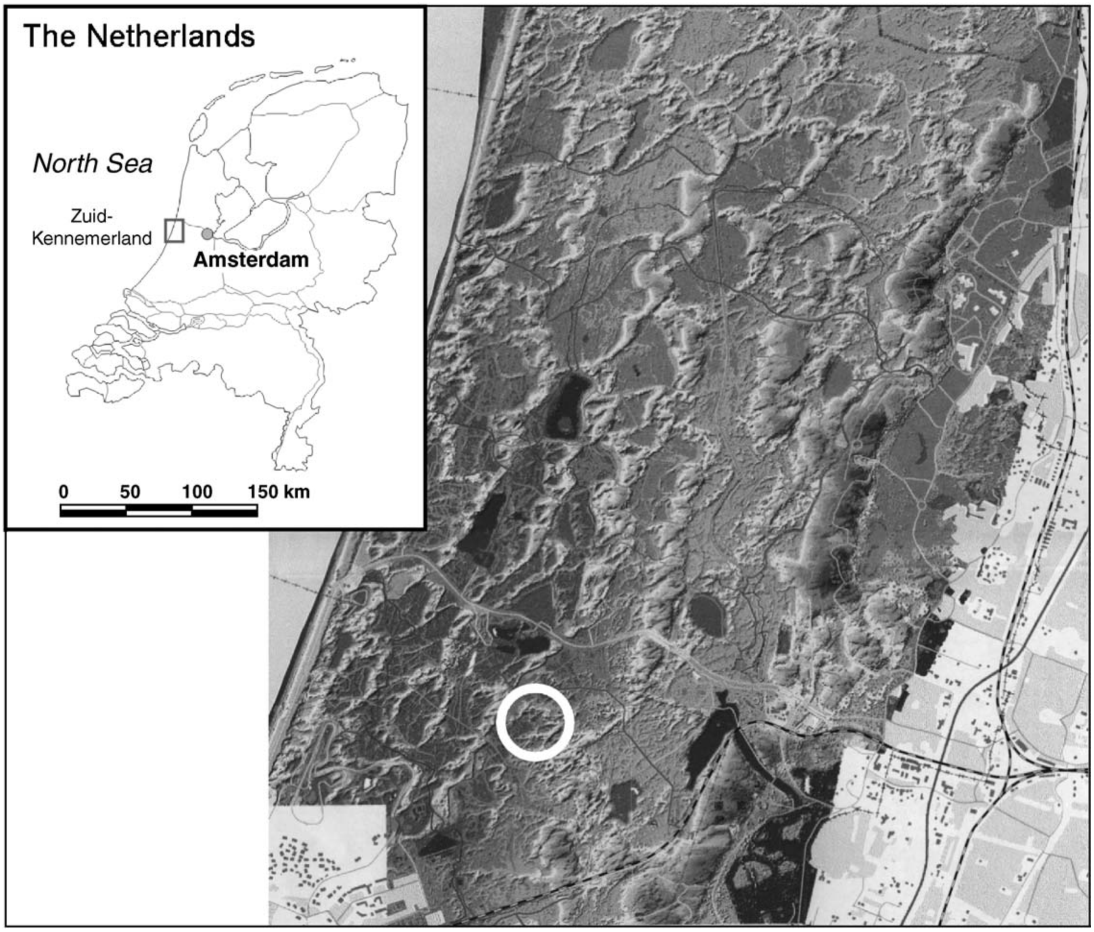

Fig. 1. Location of Zuid-Kennemerland. The studied dune is located in the white circle.

Parabolic dunes are believed to be features of a transitional landscape between complete mobility (transgressive dunes) and complete stability (vegetated dunes). Several authors ascribe transitions from stability to mobility to human influence (grazing, sod and wood cutting; planting; war) and/or to climate change (decreased/increased precipitation, increased/decreased windiness) (e.g. Heidinga, 1984; Lancaster, 1997; Hesp, 2001; McLachlan et al., 1994; Tsoar and Blumberg, 2002). Hesp (2001) describes transitions from parabolic dunes to transgressive dunes and vice versa in New Zealand due to human activity. Tsoar and Blumberg (2002) show that decrease of human pressure resulted in a transition from barchanoid to parabolic dunes in Israel.

The key question addressed in this paper is whether parabolic dunes in the Netherlands can be mobile under present conditions. The best way to answer this question is by experimental approach. In 1998, a complex parabolic dune in Zuid-Kennemerland (Kennemerduinen), North-Holland, The Netherlands, a dune area managed by nv PWN North-Holland Water Supply, was remobilised by removing vegetation (pine trees, *Pinus nigra*) and soil. The main aim of the experiment was ecological: due to stabilisation and eutrophication by nitrogen input by acid rain, biodiversity of the coastal system tends to decrease (e.g. Kooijman and van der Meulen, 1996). Managers are searching for methods to restore ecological value (van Bohemen, 1996). Most methods aim at rejuvenation of the system by creating opportunities for pioneer vegetation, either by removal of vegetation (mowing) or soil. Recently, studies were performed to investigate whether rejuvenation at the landscape scale is possible through reactivation of natural processes. In a dynamic dune system, pioneer stages are continuously developing as a result of deflation and sand burial. If processes can be reactivated at a coarse scale, periodic rejuvenation of the landscape over the long term is possible, without need for managers to interfere further. Other experiments with coarse-scale remobilisation are in preparation. This paper discusses the mobility and geomorphic activity of a reactivated parabolic dune in relation to wind and rainfall conditions after 4 years of development and monitoring.

2. Study area

The study site contains a complex parabolic dune (combe dune, Klijn, 1981) with several lobes, located between Bloemendaal and Zandvoort at a distance of 2 km from the sea (Fig. 1). The northern part consists of a 150-m-wide parabolic shape with west–south-

a

b

Fig. 2. Upwind side of the parabolic dune (above, February 2002) and downwind side of the northern lobe (below, April 2002).

westerly exposure, which was completely devegetated, including crest and slip face. Before devegetation, the dune was completely immobile and stabilised. The stoss slope is steep and the crest is rounded. Fig. 2 shows the front and the lee of the dune. The southern part consists of a narrower, 50-m-wide parabolic shape, more westerly exposed, of which only the stoss slope was devegetated. The stoss slope is steep, the lee slope is a true slip face and the crest is sharp. An extensive deflation plane, 500 m wide, is situated west of the parabolic heads. Locally, deflation has reached a base level that is related to the groundwater table. However, in the deflation plane, many hummocky dunes are present as well as low ridges, partly anthropogenic in origin, created during small-scale agricultural activity. The vegetation and topsoil, including all present dunes, were removed from this plane.

3. Methods

The geomorphologic development of the area will be monitored for at least 5 years. Coarse-scale development of geomorphology, sand drift and vegetation establishment is monitored using aerial photographs, at a scale of 1:2500 (dated 28-04-1999 and 04-07-2001). Every 4–6 weeks, erosion and deposition are measured using erosion pins. Five transects on several significant places over the area (total about 100 pins, Fig. 3) were established. Absolute heights of the erosion pins and transects are measured yearly with a laser theodolite. Coordinates of fixed points were recorded with GPS equipment. Results give insight into slope development, rates of processes, and a general indication of geomorphic activity in the area.

Erosion pins are representative of only some small area surrounding the pin, and therefore total volume change for the entire dune is only an estimate. However, pins give very good indications of change during specific periods and of variation within the system. They also give information on profile change, and when profiles are measured in detail every year, the pin results give excellent information on seasonal trends. For this paper, all pins were treated as equal. Of course, some pins are representative of smaller areas than others. For example, the erosive surface in the deflation area is much larger than the total surface of the parabolic dune. Despite this, more pins were placed over the dune than over the deflation area because important changes occur over a much smaller area.

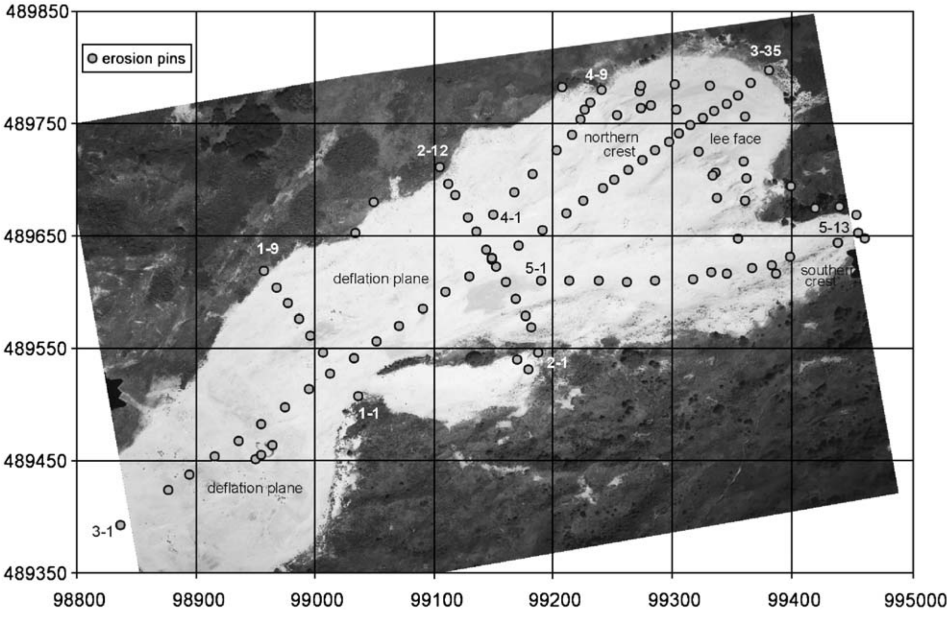

Fig. 3. Location of erosion pins and transects.

For every period, an activity index for the whole area was constructed as:

$$A_i = \frac{\sum \text{deposition} + |\sum \text{erosion}|}{\text{number\_of\_pins}} \tag{1}$$

which gives a measure of the geomorphic activity for periods with different lengths. To standardize for period length, an averaged daily activity was calculated as:

$$A_{i\_\mathrm{d}} = A_i/\text{number\_of\_days\_in\_period} \tag{2}$$

Due to summation of the absolute values of observed changes in height, measurement errors may contribute to average daily activity. For example, if all pins on a stable surface showed a change of + 0.5 cm in one period, which is then cancelled by a change of − 0.5 cm in the next period, this still results in a positive activity index. This error only occurs if a positive change in one period alternates with a negative change in the previous or following period. From calculations, it appears that such error contributes a maximum of about 3–14% of the calculated activity index. The index gives a relative measure of activity that is very useful to compare trends between periods and to relate them to weather conditions.

Meteorological data from several stations were used. Hourly wind data of the Royal Meteorological Office were used to get insight into wind energy and to compare this to ‘average’ wind conditions. Data are gathered at a large breakwater near IJmuiden (shoreface conditions), 7.8 km to the north, and at the airfield of Valkenburg (inner dune conditions), which is located 27.4 km to the southwest. For long-term studies (yearly storm frequencies), these stations are representative of wind conditions near the study site. Yearly frequency tables were established with wind directions divided into 12 classes. From these frequency tables, potential transport in all directions was calculated applying the Law of the Wall

$$U_z = \frac{U_*}{\kappa}\ln\left(\frac{z}{z_0}\right) \tag{3}$$

and the Kawamura (1951) equation

$$q = C_\mathrm{K}\frac{\rho}{g}(U_* - U_{*_\mathrm{t}})(U_* + U_{*_\mathrm{t}})^2 \text{ in kg m}^{-1}\text{ s}^{-1} \tag{4}$$

assuming a roughness length z_0 of 0.0002 m (0.0005 m for Valkenburg), a measuring height z of 18.5 m (10.0 m for Valkenburg) and a threshold friction velocity $U_{*\mathrm{t}}$ of 0.22 m/s. κ is the von Karman constant (0.41), C_K an empirical constant introduced by Kawamura (2.78), ρ the air density (1.22 kg/m^3) and g the gravitational constant (9.81 m/s^2). The calculated yearly transport values for 1999–2001 are compared to the average potential transport over the period 1987–1998 (the largest complete data range). For these calculations, no correction for decreased transport due to rainfall is applied. Previous studies in the Netherlands indicate that actual transport over periods of months ranged between 5% and 20% of the total potential transport (e.g. Arens, 1997).

Some remarks must be made on the calculations of potential transport. The results are extremely sensitive to the value of the roughness length. This is always an uncertain variable when using remote data. Therefore, the results here are only regarded as relative, giving indications of the directions in which average transport is expected and the years or periods in which more or less transport than average are predicted.

The potential transport per hour is calculated with

$$q_i = 3600q \tag{5}$$

Application of a wind frequency distribution yields the total transport Q_j per windsector j in m^3 m^{-1} by summation of all calculated hourly transport rates q_i

$$Q_j = \frac{1}{1600}\sum_{i=1}^{n_j} q_i \tag{6}$$

with n_j the total number of hours i for windsector j and assuming a bulk density of sand of 1600 kg m^{-3}. Total transport potential then can be calculated by summation of the contribution of all sectors:

$$\text{TP\_Q} = \sum_{j=1}^{12} Q_j \tag{7}$$

assuming a wind frequency distribution based on 12 sectors of 30° each.

The resultant transport potential is calculated by computing the cardinal vectors per wind direction sector dd_j and summation of the vectors of all sectors:

$$\mathrm{RTP\_}Q_{jX} = Q_j \times \sin[dd_j] \tag{8}$$

$$\mathrm{RTP\_}Q_{jY} = Q_j \times \cos[dd_j] \tag{9}$$

$$\mathrm{RTP} = \sqrt{\left(\sum_{j=1}^{12} \mathrm{RTP\_}Q_{jX}\right)^2 \left(\sum_{j=1}^{12} \mathrm{RTP\_}Q_{jY}\right)^2} \tag{10}$$

The resultant angle of transport is given by

$$\alpha_{\mathrm{RTP}} = \arctan\left[\sum_{j=1}^{12} \mathrm{RTP\_}Q_{jX} \Big/ \sum_{j=1}^{12} \mathrm{RTP\_}Q_{jY}\right] \tag{11}$$

These calculations are similar to those of Fryberger (1979), with the difference that the Kawamura equation is used for the transport calculations instead of the formula for the drift potential as proposed by Fryberger.

Rainfall data (daily totals) are used from station Overveen, located 2 km to the east of the study area, and station Zandvoort, located 3 km to the west. Daily averages of wind speed, temperature and daily totals of rainfall and rainfall duration were used from station De Kooy, which is located at the airfield of Den Helder, 55 km to the north. Unfortunately, no hourly rainfall data are available.

Daily rainfall and daily wind speeds were combined to get insight in the correlation between rainfall and strong winds. Days with strong winds and heavy precipitation are less important for aeolian sand transport than dry days with strong winds. A rainfall index was constructed as:

$$P_i = \frac{\sum \mathrm{number\_of\_days\_with\_}U_{\mathrm{day}} > 4\ \mathrm{m/s\_AND\_}P > 5\ \mathrm{mm}}{\mathrm{number\_of\_days\_with\_}U_{\mathrm{day}} > 4\ \mathrm{m/s}} \times 100\% \tag{12}$$

based on the assumptions that a daily average wind speed of 4 m/s may exceed the threshold for sediment transport, a daily total precipitation of < 5 mm does not impede sediment transport, while during days with >5 mm rainfall, transport is likely to be hindered. This index will be used later for a distinction between ‘wet’ and ‘dry’ periods.

For a better evaluation of the effects of rainfall, hourly data should be taken into consideration. However, these data were not available. Furthermore, the effects of evaporation should be incorporated, but these data were also not available.

4. Results

4.1. Weather conditions

In 1999, wind conditions were average for IJmuiden, but slightly below average for Valkenburg. Both 2000 and 2001 experienced less wind energy than average. Table 1 shows the calculated transport potentials and resultant transport potentials for both IJmuiden and Valkenburg. Potentials are expressed as a percentage of the 1987–1998 average.

Table 1
Transport potential and resultant transport potential for Valkenburg and IJmuiden

Period	Transport potential, TP′ (% of average)		Resultant transport, RTP′ (% of average)		Direction of transport (deg)		RTP′/TP′ (−)	
	IJmuiden	Valkenburg	IJmuiden	Valkenburg	IJmuiden	Valkenburg	IJmuiden	Valkenburg
1987–1998	100	100	100	100	61	59	0.52	0.60
1999	101	88	120	98	60	72	0.62	0.67
2000	96	83	124	95	54	66	0.66	0.69
2001	82	69	86	69	79	90	0.55	0.60

Data for 1999–2001 are expressed as percentages of the average 1987–1998. RTP′/TP′ expresses the directionality of transport. If RTP′/TP′= 1, transport is unidirectional (Fryberger, 1979).

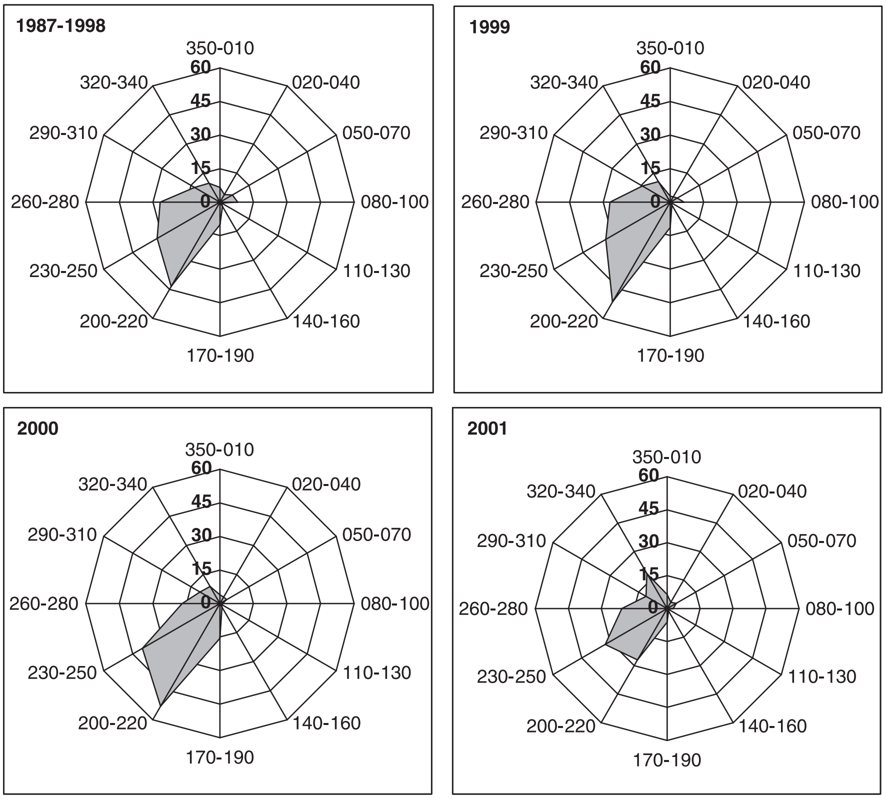

Fig. 4. Sand roses showing transport potential for all wind directions (roses show direction from where the wind blows).

Fig. 4 shows sand roses for 1999, 2000 and 2001, based on the IJmuiden data. Resultant transport direction for these years is to the ENE (1999, 2000) to E (2001). Resultant transport directions in 1999 and 2000 are a little more to NE than average and a little more unidirectional.

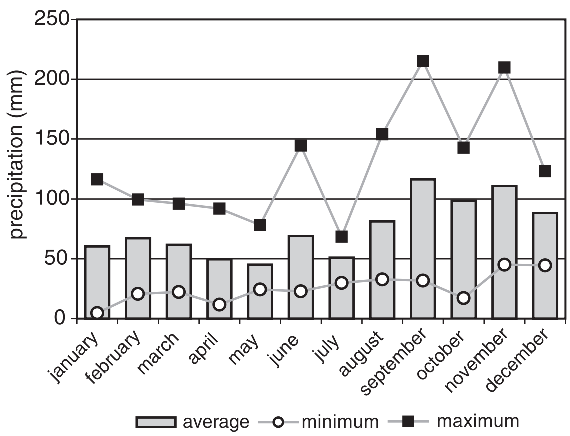

Fig. 5. Average monthly rainfall data for Overveen, 1995–2001 with minimum and maximum (source KNMI).

Rainfall in the Netherlands is spread fairly evenly over the seasons although dry months do occur. On average, highest rainfall amounts are experienced

Table 2
Annual precipitation data for Overveen, Zandvoort and De Kooy (precipitation in mm/year)

	Overveen	Zandvoort	De Kooy
1995	744	711	704
1996	716	622	614
1997	671	625	569
1998	1143	1056	985
1999	954	939	937
2000	1012	967	888
2001	1054	999	888
2002	900 + [a]	800 + [b]	882
Mean (1995–2001)	899	845	798

[a] Data of December are missing.
[b] Data of November and December are missing.

during late summer and autumn, lowest rainfall during spring (Fig. 5). Storms with very high wind speeds often coincide with lots of rainfall. Annual rainfall was more than average, with total amounts of around 954 mm in 1999, 1012 mm in 2000 and 1054 mm in 2001 for station Overveen (Table 2). Despite these 'unfavourable' conditions for sand transport, considerable changes occurred in the area and large volumes of sand were transported.

4.2. General development

The deflation plane is mostly erosive, although locally the surface has reached the water table and vegetation is beginning to establish (mainly *Ammophila arenaria* in clumps, *Carex arenaria* and mosses, *Bryum* sp., *Juncus articulatus*, *Juncus alpino-articulatus*, *Carex trinervis* and algae), especially at the western part of the area. In February 2001 the water

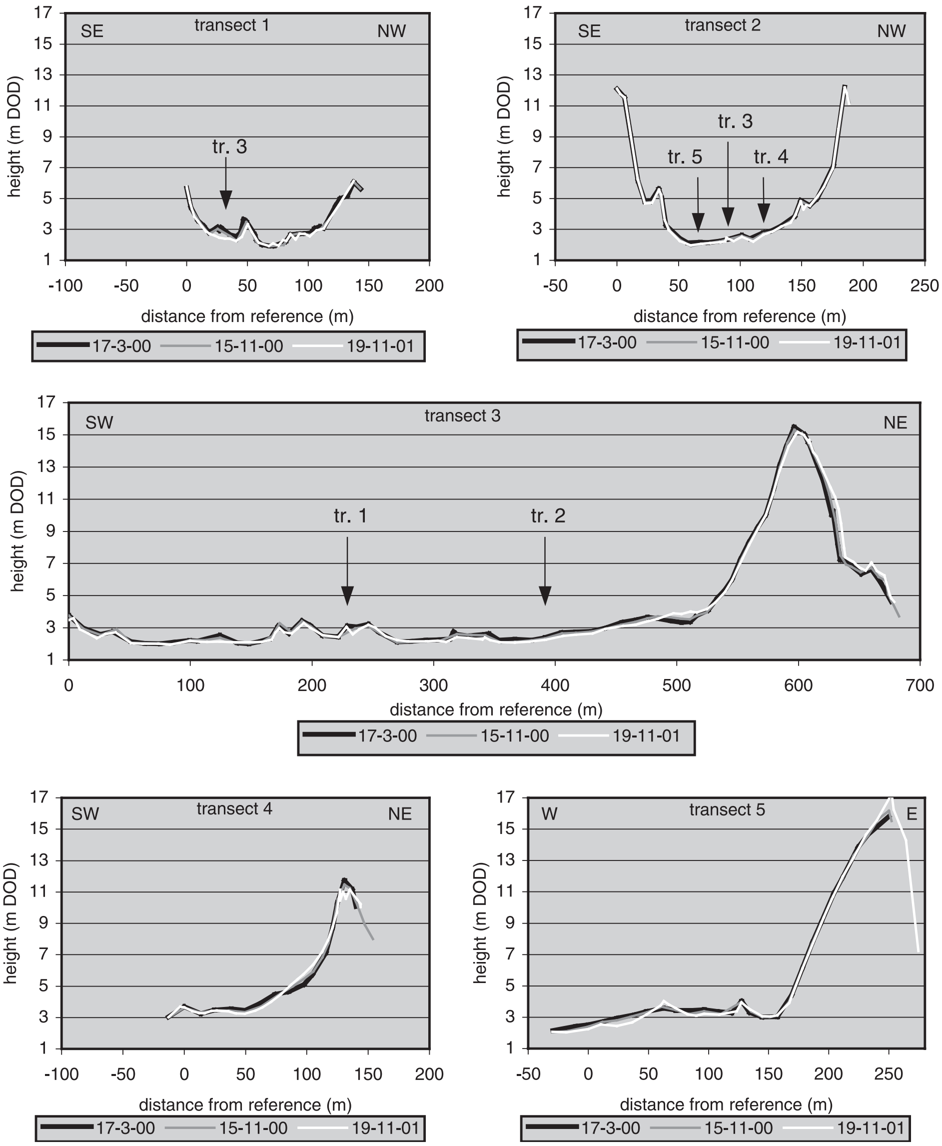

Fig. 6. Profile development of cross sections 1 to 5 between 17 March 2000 and 19 November 2001.

table rose above the surface for a couple of weeks. Locally, vegetation (mainly *C. arenaria*) traps some sand, resulting in a slight increase in height.

Strongest erosion occurs on the low, anthropogenic ridges in the deflation plane and on the crest. In several places clumps of marram grass (*A. arenaria*) pop up, but on average vegetation cover density is below 1%. On the trailing ridges of the parabolic dune vegetation cover increases, and erosion and deposition is limited. Deposition in front of the parabolic crests is high, locally up to 1.4 m (transect 4, Fig. 6). Since erosion on the crest is also severe (maximum erosion of more than 3 m since the start of the experiment, with an average of 1.27 m, measured over eight pins), it appears that the whole structure is flattening and adapting aerodynamically to the new situation of a bare dune. The characteristics of the dune have changed from parabolic into transgressive, dome-shaped. In the crest, several blowouts have been developing. Parts of the crest are still covered with old tree roots, which may reduce erosion. Only recently, some vegetation (*A. arenaria*) has been establishing on the northern crest, but until now (August 2002) vegetation cover is far less than 1%. Very strong deposition occurs on the leeward side. Also here, marram grass established from seed in the summer of 2002. Especially at the southern part of the parabolic crest (which is vegetated) this results in slip face formation. Most of the sand is usually trapped on the lee face, but during very strong winds, sand moves in suspension (jettation, see Arens et al., 2002) and is deposited in the vegetation farther downwind. After storms from the west, minor deposition was found at distance up to 200 m from the crest. At the northern part, the lee face is smoother and mostly influenced by three-dimensional flow around the crest and the lee face. Here some more sand (up to 0.5 m) is deposited eastward of the dune.

Fig. 7 shows the mobility of the crest line and the (toe of the) lee face. The lee face moved between 5–12 m (northern part) and 0–7 m (southern part) in the period April 1999 to July 2001. From transect 3 (Fig.

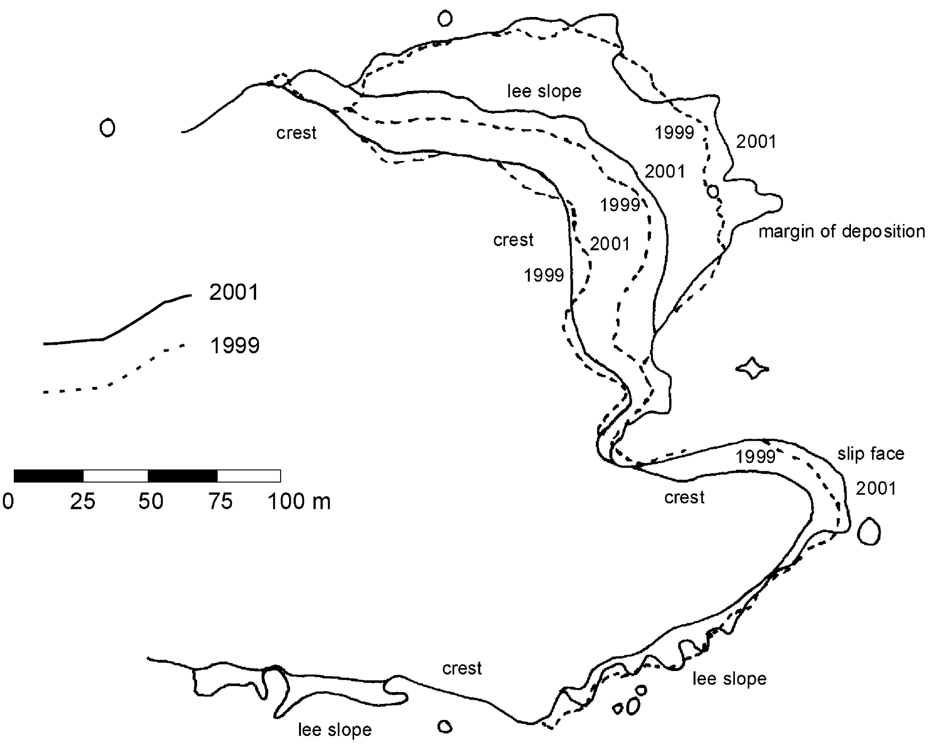

Fig. 7. Positions of crest and slip face in summer 1999 and summer 2001.

Table 3
Volume changes per section, calculated from profile measurements of transect 3

Section	Length of section (m)	Volume (m^3/m)	
		17/03/2000 to 15/11/2000	15/11/2000 to 19/11/2001
Deflation area	484	− 19.81	− 36.20
Toe stoss slope	61	3.59	9.75
Upper stoss slope and crest	63	− 3.60	− 2.51
Lee face	35	7.32	20.32
Leeward of dune	33	3.74	7.50
Net difference		− 8.76	− 1.14

6) it appears that the displacement of the crest and slip face are 2.5 and 4.3 m, respectively, between November 2000 and November 2001.

For transect 3, volume changes were calculated (Table 3) for the two periods over which heights were recorded with the theodolite. Ideally, the net difference for all sections would equal zero. Table 3 indicates that this is not the case, partly because of measurement errors, partly because of oblique transport through the cross sections and partly because not the whole leeward section was measured. The results for 15/11/2000 to 19/11/2001 indicate huge transport, which is larger than the amounts measured in foredune environments in the Netherlands (Arens and Wiersma, 1994; van der Wal, 1999). In accreting foredunes maximum changes of 25 m^3/m year are observed. The large amount of sand that is deposited in front of the dune is especially noticeable in transect 3.

4.3. Activity of processes

For each period over which erosion pins were monitored, the transport potential was calculated. Results are plotted in Fig. 8, together with the geomorphologic activity index (Eq. (1)). The relation between transport potential and geomorphologic activity is not perfect. Periods with the highest transport potential do not always correspond with peaks in the observed changes.

Most peaks in activity are observed in autumn and winter, but surprisingly some peaks occur in summer and spring. Seasonal variation is much more variable than expected. Stormy periods in the winter of 1999–2000 resulted in much less important changes than expected, whereas in summer 2001 large changes were observed. Geomorphic activity in the winter 2001–2002 was large and resulted in the most important changes since the start of the experiment.

Fig. 8 suggests that the correlation between ‘observed’ (activity index) and ‘expected’ (resultant

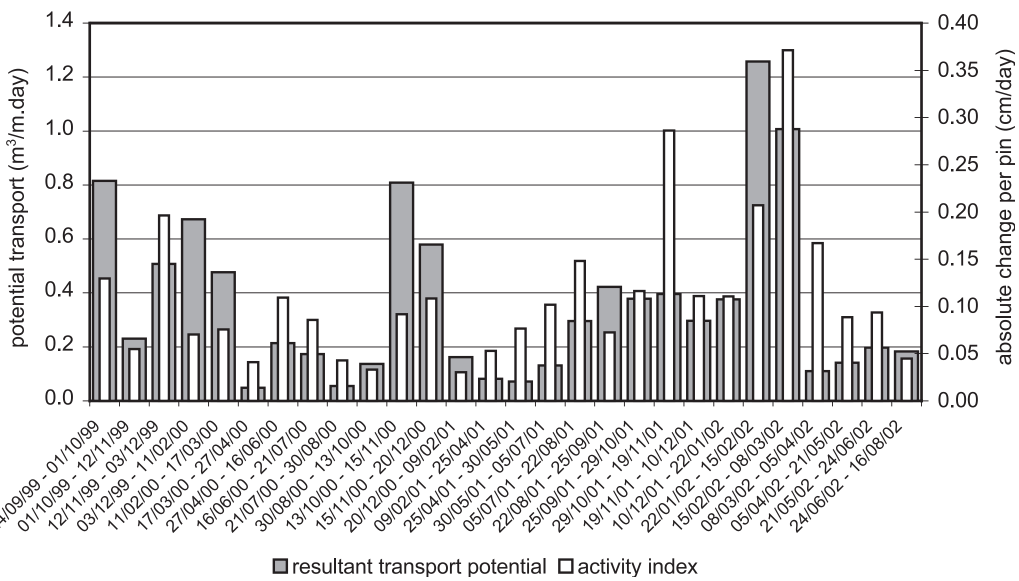

Fig. 8. Calculated resultant transport potential (left axis) and observed activity (right axis) for all periods: September 1999 to May 2002.

transport potential) transport is poor. Apparently, there are other factors that obscure the relationship. The most important of these is likely moisture. To gain some insight in the effects of rainfall, the rainfall indices for all periods were calculated (Eq. (12)). A somewhat arbitrary value of 20% (which means that in 20% of the days with strong winds rainfall exceeded 5 mm) was used to distinguish between dry and wet periods.

This rough division gives a fairly good distinction between wet periods and dry periods and gives better insight in the correlation between 'predicted' and 'observed' transport (Fig. 9). There appears to be some relationship that differs for wet and for dry periods: during dry periods, the observed transport follows the predictions much more closely than during wet periods. During wet periods with very large transport potentials (storm periods), the observed change is apparently much lower than expected. The period July–August 2001 makes a clear exception. The rainfall index for this period amounted to 24%. However, during this period, strong winds (up to 23 m/s) were accompanied by high temperatures (30 °C) and occasional thunderstorms with high rainfall intensities. It can be argued that due to high evaporation and rainfall clustered over some short intervals, this period could be marked as 'dry'. If this period is classified as 'dry', the correlation between 'observed' and 'expected' transport is reasonably good, with correlation coefficients R^2 of 0.66 for dry periods and 0.67 for wet periods. With detailed (hourly) data on these variables, better quantitative relationships could be established, but this is beyond the scope of the research.

5. Discussion

The parabolic dune seems to be adapting to the new circumstances imposed by devegetation and remobilisation. The dune probably developed in a situation with a vegetated deflation plane and a crest covered with marram (comparable to the present situation in Merlimont, France and Aberffraw, Wales). Most of the transport (erosion) would have occurred on the windward slope with sand deposition on the crest. Consequently, the stoss slope was steep and concave. In the new situation, with a large source of sand and limited vegetation growth, the dune transformed into a transgressive dune with a long and smooth stoss slope (comparable to the situation in Råbjerg Mile, Denmark). The crest will continue to erode until the ratio between stoss slope length and height is in equilibrium.

Based on the present observations, dune remobilisation seems to be possible in the present climate in the Netherlands, even though conditions over the past 4 years are less windy and much wetter than average. Either plants cannot establish on a surface that is high enough to be regularly eroded, or plants cannot

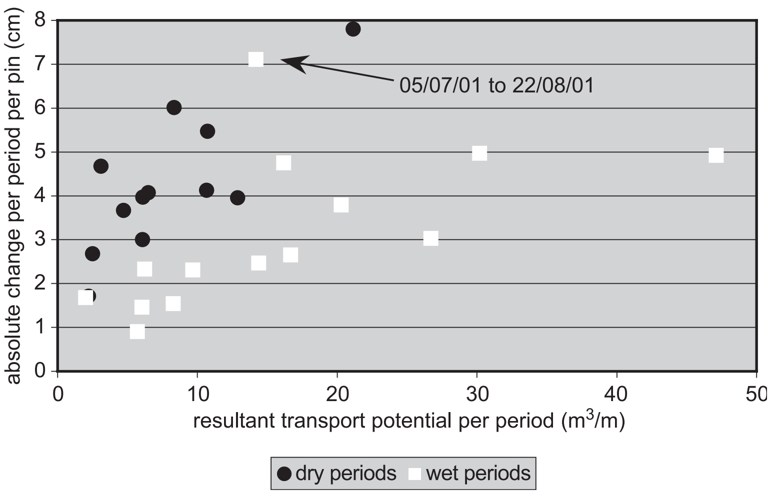

Fig. 9. Resultant transport potential versus geomorphic activity for dry and wet periods.

withstand the severe burial due to deposition. In the Dutch case, the differences between the seasons also contribute to dune dynamics. Several plants that cover the surface in summer, decay in winter and leave the surface more or less bare (see also Arens and Geelen, 2001). If no vegetation is present, summer mobility is also observed. This is in contrast to foredune environments where marram grass has its maximum cover in summer, and consequently transport of sand from the beach into the dunes is limited by the dense cover (Sarre, 1989; Arens, 1996b). The relatively limited extent of dynamic features in the Dutch coastal dunes is evidently related to the stabilising efforts of humans. However, it is likely that the large-scale dynamics in the past were also the result of human action (see Hesp, in press), even though Klijn (1990) argues that this cannot be the sole explanation for the large-scale mobility these dunes experienced in the past, especially the massive input of sand.

In Fig. 10, the ratio of transport potential to observed activity is plotted versus total rainfall per period. For the dry group the ratio fluctuates roughly between 1 and 3, and there is no clear relationship with total rainfall. For the wet group, the ratio increases with larger amounts of rainfall, meaning that the wetter the period the larger the deviation between prediction and observation becomes. The ratio is highest for periods with high wind energy but also large amounts of rainfall. Very strong winds are often accompanied by large quantities of rain (correlation coefficient $R^2=0.49$). Apparently, in the Dutch system ideal conditions for transport during very strong wind speeds are rarely if ever met. Similar conclusions, but based on short-term process measurements, were drawn by Sarre (1988) and Arens (1996a).

Mobility is governed by sand supply (availability), wind energy, and vegetation characteristics (e.g. Nishimori and Tanaka, 2001). There is some threshold for transition from mobile to stable dunes and reverse. Apparently, this threshold reflects a range of conditions in which parabolic dunes are the characteristic features. Depending on local variations, particular spots are mobile or stable. Thus, in one landscape, fine-scale transgressive dunes, parabolic dunes and stabilised dunes can coexist. If a dune landscape is completely stabilised, for whatever reason, a huge disturbance is required to remobilise the sand, even if enough wind energy is available. This disturbance can either be a further increase in wind energy, a decrease in rainfall resulting in changing vegetation types with different trapping capacities, overgrazing by herbivores (e.g. rabbits) or a change in land use. If a dune landscape is completely mobile, even though precipitation is enough to support vegetation growth, similar ‘disturbances’ are needed for stabilisation, such as: a number of years with excessive rainfall, which directly prevents transport; the introduction of

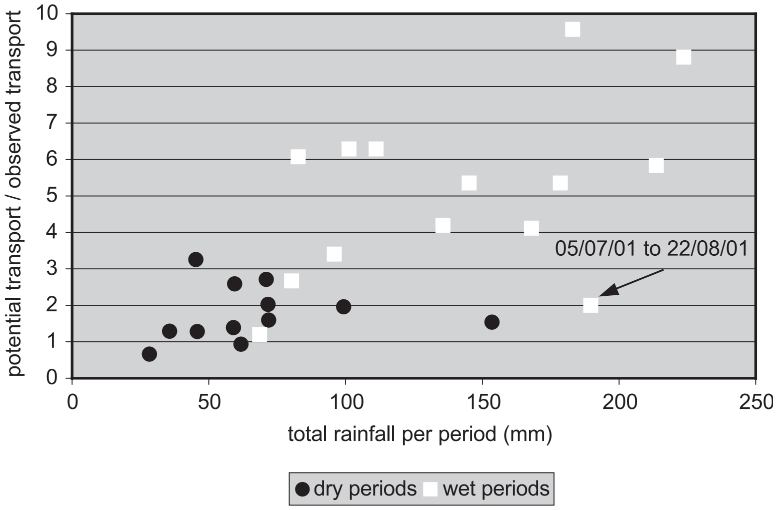

Fig. 10. Ratio of transport potential to observed activity versus rainfall per period for dry and wet periods.

new plant species with high trapping capacity; planting efforts by humans; or withdrawal of grazing animals from the landscape. This supports the idea of hysteresis (Tsoar, 2002): stable and vegetated dunes stay stable unless some kind of disturbance remobilises them; mobile and bare dunes stay mobile unless some changes stabilise them; there is a range of conditions in which dunes can be either mobile or stable, depending on the exact configuration. In the Dutch case, a huge disturbance of the system is required, but then it seems that the subsequent transport can be so high that stabilisation due to the establishment of vegetation is prevented, at least for a couple of years.

6. Conclusions

The results prove that a large-scale aeolian structure in the Netherlands can, at least for a period of 4 years, be remobilised by removal of vegetation and soil, even with the limited wind energy and the relative large amounts of rainfall that prevailed in the last 3 years. In the lowest parts of the deflation plane, which are close to the water table, and along the trailing ridges of the parabolic dune, the vegetation is recovering, but in the rest of the area vegetation cover remains very scarce (less than 1%) and of no influence on sediment transport.

Before the reactivation, mobility was zero. After reactivation, the lee face of the parabolic dune moved between 5–12 m (northern part) and 0–7 m (southern part) in the period April 1999 to July 2001. From volume changes measured in a cross section it appeared that in a year more than 30 m^3/m year was transported, which is in the order of maximum foredune accretion rates in the Netherlands. In this cross section, the displacement of the crest and slip face was 2.5 and 4.3 m, respectively, between November 2000 and November 2001.

The observed periods were divided into dry and wet, based on the correlation of daily rainfall and daily wind speed. For both wet and dry periods, activity was reasonably correlated to the transport potential as calculated with the Kawamura transport equation, but the relationships were quite different. Periods with the largest amount of wind experienced much less change than expected, probably because of excessive rainfall. With increasing wind energy, the deviation between measured change and transport potential becomes larger.

Seasonal variability of mobility is large. On average, most activity is observed in autumn and winter, but in summer large changes can also occur. Big storms do not necessarily result in geomorphic change because of the impeding influence of rainfall. Because of the strong seasonal variation in the Netherlands, it is useless to calculate mobility indices based on yearly meteorological data.

Finally, we wish to stress that our conclusions on dune mobility are based on a limited time period of only 3 years. The study area should be re-evaluated after 5–10 years.

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