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The effect of rainfall intensity on surface runoff and sediment yield in the grey dunes along the Dutch coast under conditions of limited rainfall acceptance

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Abstract

Surface runoff and sediment yield in the grey dunes along the Dutch coast are rare events restricted to conditions of water repellency in summer. The sediment moves in mudflow-like tongues. From March 1989 to December 1990, weekly surface runoff and sediment yield have been measured on an experimental plot, along with a number of meteorological parameters. Rainfall intensity is more important than total amount of precipitation for the production of runoff and sediment. Rainfall intensity affects the erosion process in two ways: by supplying the large amount of water needed for the high water: sand ratio in the sand flow, and by providing the high frequency drop impact needed to maintain a high hydraulic pressure in the sand flow.

1. Introduction

Coastal dune landscapes are not commonly associated with erosion by surface wash, presumably because it is believed that dune sand will absorb any amount of rain that can be expected under normal conditions. It is little known that erosion by water can be a major geomorphological process in areas of socalled "grey" dunes. Bridge and Ross (1983) described the effects of water erosion in vegetated sand dunes in Australia. Erosion by surface runoff was measured in Dutch coastal dunes (Rutin, 1983; Jungerius and De Jong, 1989). Shallow rills incised in the dune slope between shrubs, with fan-shaped deposits at their base testify to the water erosion process, but are poorly visible after a few days of drought. Unconcentrated slope wash is even more difficult to detect soon after its occurrence. Nevertheless it is much more effective than rill wash as an erosion process. South-exposed slopes with an incomplete cover of moss and algae are most affected. On slopes with an angle of more than 6 degrees, the surface runoff entrains sand grains in mudflow-like tongues

(Fig. 1) to the foot of the slope (Bridge and Ross, 1983; Thompson, 1983). If uninterrupted, this erosion process leads eventually to the subdued topography which is characteristic for landscapes subject to the downhill displacement of superficial slope materials by moving water. Paradoxically, unconcentrated slope wash is also one of the main causes of aeolian activity: removal of the grey surface sand on upper slopes exposes the original, yellow sand which is susceptible to wind erosion and the formation of blowouts (Jungerius and Dekker, 1990). The formation of blowouts and the associated Ammophila dunes counteracts the downwearing of the dunes by slope wash and results in increased relief.

Modeling hillslope hydrology of the Dutch coastal dunes, Witter et al. (1991) found statistically significant (5%) values for the Pearson correlation coefficient between rainfall, surface runoff and sediment yield. However, they used log-transposed scales which hide the fact that the relationship between rainfall and its effects is far from linear (Fig. 2). This is due to water repellency: surface runoff and erosion in the grey dunes are restricted to the summer months when the surface has the opportunity to dry out prior to a rain shower (Debano, 1981). In this condition even slightly humic sand repels water very strongly (Dekker and Jungerius, 1990). Witter et al. (1991) believed that rainfall intensity is an additional factor of runoff and sediment yield when the sand is water-repellent.

Rainfall intensity is commonly associated with splash erosion. Although splash is certainly part of the erosion process in the dunes, its efficiency falls far short of that of
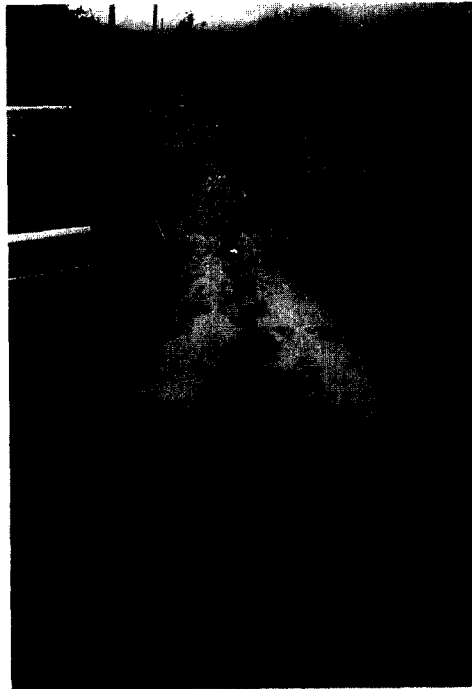

Fig. 1. The characteristically open landscape of the grey dunes around the measuring station, after the event of week 26 (Table 3a).
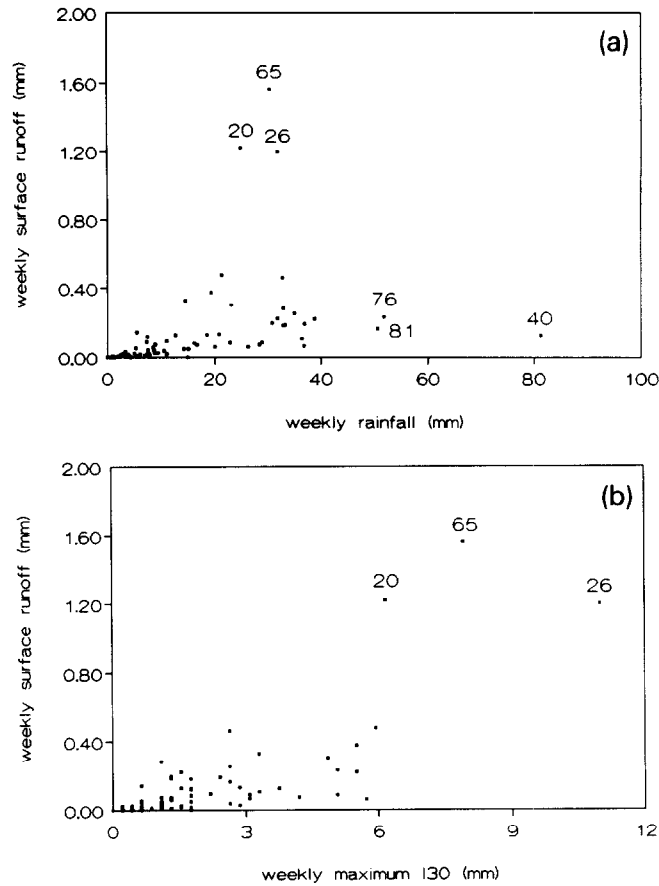
Fig. 2. Surface runoff and rainfall relationships: (a) weekly surface runoff and weekly rainfall, (b) weekly surface runoff and weekly maximum 30-minute rainfall. The numbers refer to the weeks of measurement in Table 3a.

runoff on grey sandy slopes with an incomplete vegetation cover. On a 20 degree, south exposed slope in the grey dunes in a nearby dune terrain, splash produced less than 2% of the yearly sediment yield by runoff (Jungerius and Van der Meulen, 1988).

However, rainfall intensity contributes to erosion of the dunes in much more effective ways, by its influence on runoff and sediment yield. Sealing by splash impact of a soil surface which is already impervious because of water repellency is one of the ways to increase runoff (Slattery and Bryan, 1994), but the main effect of rainfall intensity is specific for the grey dues and is due to the temporary increase in the rate of water supply. Much water is needed:

— during the erosion phase when many water drops rolling downslope over the water-repellent sand must coalesce to form the sand flows, and
— during the transport phase when the ratio of water to sand must be high in order to keep the sand tongues flowing downslope.

During both phases, rainfall intensity should also be important for the production of sediment. The impact of the water drops breaks up any protective crust which may have formed at the surface prior to the storm and, more importantly, creates a high positive hydraulic pressure between the sand grains which facilitates flow.

It is the aim of this paper to study the response of the soil to high rainfall intensity at times of water repellency. The maximum half-hourly rainfall is used as a measure of rainfall intensity. It was introduced as an estimator of soil loss by Wischmeier (1955).

2. Methods

Since 1987, the University of Amsterdam and the Dune Water Company of South Holland jointly operate a measuring station for geo-ecological and slope-hydrological research in the Meijendel dunes near The Hague. The station comprises a number of experimental plots. These plots are representative for landscape types which are widespread in the coastal dunes of The Netherlands (Ten Harkel et al., 1991). The plot which is characteristic for the landscape of the grey dunes with an incomplete vegetation cover on south-oriented slopes was chosen for the present study (Table 1).

For logistical reasons, the monitoring programme of the station is run on a weekly basis. This setup excludes event-based observations for parameters which are not electronically registered such as runoff and sediment yield. The following variables are relevant for this study:

– precipitation in mm (P),
– maximum 30-minute rainfall in mm (I_{30}),
– air temperature at 150 cm height in °C (AT)
– surface runoff in mm (Q),
– sediment yield in grammes per m^2 (S),

Table 1
Site and average soil characteristics of the plot analysed in this paper

aspect (degrees NE)	110
slope angle (degrees)	7
height (m)	10
position on slope	upper
vegetation cover (%)	30
A11 horizon (cm)	6
A12 horizon (cm)	33
depth C hor (cm)	39
mean grain size (μ)	210
humus content A11 (%)	1.7
CaCO$_3$ content A11 (%)	0
pH (CaCl$_2$, 1 : 2.5) A11	5.9
pH (H$_2$O, 1 : 2.5) A11	6.5
EC 25, (μs/cm, 1 : 2.5)	115

 – soil temperature at 1 cm depth in °C (ST),
 – soil moisture at 5 and 20 cm depth in % (SM_1 and SM_2).

Precipitation was collected in a tipping bucket rainfall gauge (Casella). Surface runoff and sediment were collected in a trough at the lower boundary of the plot. Soil temperature was measured with thermistors (Grant). Soil moisture was recorded with a capacitive soil moisture measuring device.

The plot was not enclosed to avoid boundary effects which can be severe on the poorly coherent dune soils when runoff flow is allowed to concentrate along solid partitions (Rutin, 1983). The contributing area amounted to 8.4 m^2 as determined from the microtopography of the slope and from visual effects of surface runoff. The experimental plots were kept small to avoid redeposition effects. Also, it was found for this area that surfaces between 0.5 and 10 m^2 are homogeneous with respect to infiltration conditions (Van Gelder, 1988).

For this study the data collected from March 1989, when the equipment for measuring soil temperature and soil moisture was installed, to and including December 1990 have been analysed. The SYSTAT system was used for statistical analysis (Wilkinson, 1990).

3. Results

3.1. Surface runoff

Table 2 confirms that the linear relationship between surface runoff (Q) and rainfall (P) is not strong. Fig. 2a visualizes this relationship. The data points fall apart into two populations. One group of runoff values hardly reacts to rainfall. In fact, the three weeks with the highest amount of rainfall produced very little surface runoff, clearly because the soil was at that time highly permeable and absorbed all precipitation. The other group shows the high response to rainfall which is characteristic for water-repellent dune soils in summer.

To study the response of surface runoff to precipitation in more detail, the variables of the six extreme cases of Fig. 2a which are numbered according to the weeks of measurement, are set apart in Tables 3a and 3b.

The values for temperature and soil moisture reflect the water-repellent conditions in the high-response weeks of Table 3a which all occur in summer. Mean air and soil

Table 2
The values of the Pearson correlation coefficient between weekly runoff (Q), weekly sediment yield (S), weekly rainfall (P) and weekly maximum 30-minute rainfall (I_{30}) ($n = 87$, $r(99\%) = 0.25$)

	Q	S	P
Q			
S	0.78		
P	0.43	0.20	
I_{30}	0.77	0.64	0.62

Table 3
Variables of the six extreme cases of Fig. 1a. Q = surface runoff, S = sediment yield, P = rainfall, AC = runoff coefficient, I_{30} = maximum 30-minute rainfall, AT and ST are mean air and soil temperature, respectively, SM_1 and SM_2 refer to soil moisture. For dimensions see Methods

week	ending	Q	S	P	AC	I_{30}	AT	ST	SM_1	SM_2
(a) Weeks with high Q and S production										
20	03-08-89	1.2	111	25	4.9	6.2	16	nd	3.0	8.8
26	14-09-89	1.2	1399	32	3.8	11.0	16	20	3.0	9.5
65	05-07-90	1.6	1029	31	5.1	7.9	14	20	4.5	12.2
(b) Weeks with low Q and S production										
40	21-12-89	0.1	10	81	0.2	3.7	8	8	12.9	9.5
76	27-09-90	0.2	15	52	0.5	1.8	11	16	6.1	12.9
81	01-11-90	0.2	4	51	0.3	2.6	9	12	9.3	13.4

temperature (AT and ST) were high and mean soil moisture was low especially in the surface soil (SM_1). In contrast, the soil accepted the high precipitation of the three low-response weeks of Table 3b apparently without any problem. Low temperatures and high soil moisture are indicative of the absence of water-repellent properties in these cool and moist autumn weeks.

The relationship between surface runoff (Q) and rainfall intensity (the maximum weekly 30-minute rainfall, I_{30}) is unambiguous. It is clear from the high value of the correlation coefficient in Table 2 and from the data in Table 3a that weeks with much surface runoff are also characterized by a high rainfall intensity. This is also expressed in Fig. 2b. It confirms the assumption that high rainfall intensity in combination with conditions of impeded water acceptance leads to a high rate of surface runoff, even if the total amount of precipitation is relatively low.

Runoff and sediment were collected no more than once every week, but the other data listed under Methods were recorded electronically and can be integrated over any chosen time period. This makes it possible to study the relationship between these variables in much more detail. The rainfall distribution in the 6 weeks of the two tables is shown in Figs. 3 and 4. The concentration of rainfall in short time periods in the high-response weeks is expressed by the height of the rainfall peaks. Rainfall peaks in the low-response weeks are lower and more evenly spread over the period of measurement.

3.2. Sediment yield

The relationship between sediment yield (S) and runoff (Q) is expected to be strong. The linear correlation coefficient is 0.78 (Table 2) whereas Fig. 5c shows that the three weeks with much runoff also produced most of the sediment. In fact, sediment yield is an even more extreme process than runoff: the three high-response weeks of Table 3a account for 89% of the sediment produced in the period of measurement, as against only 38% of the runoff.

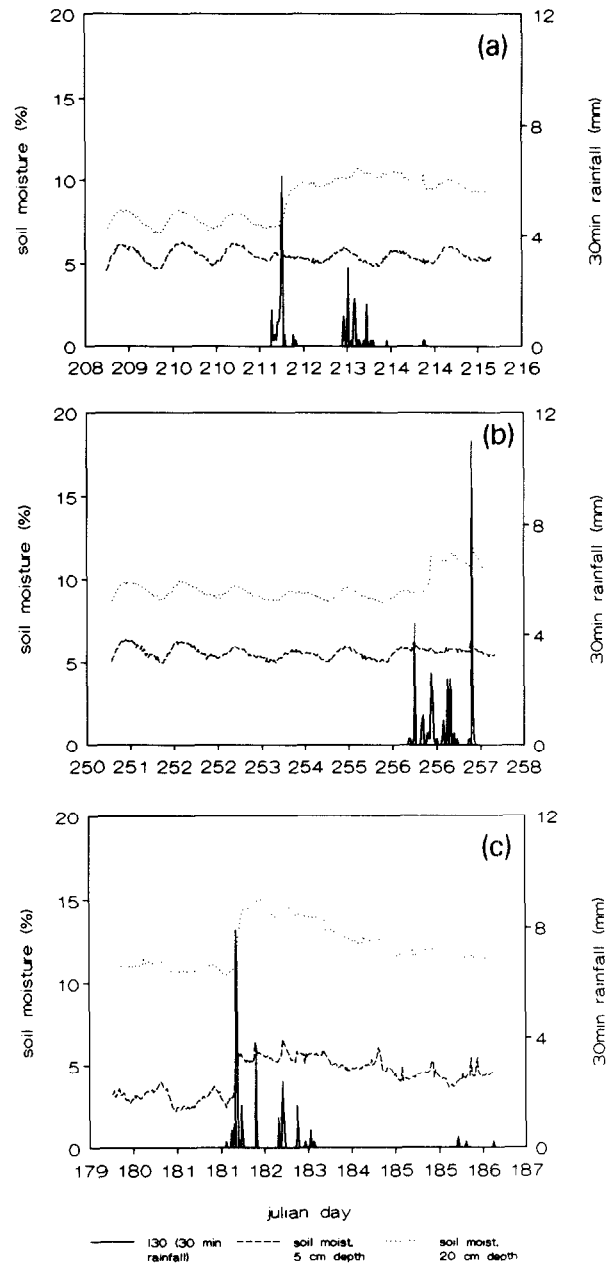The relationship between sediment yield (S) and precipitation (P) is weak. The low

Fig. 3. Rainfall intensity and soil moisture in the weeks with high production of surface runoff and sedimen of Table 3a: (a) week 20, (b) week 26, (c) week 65.
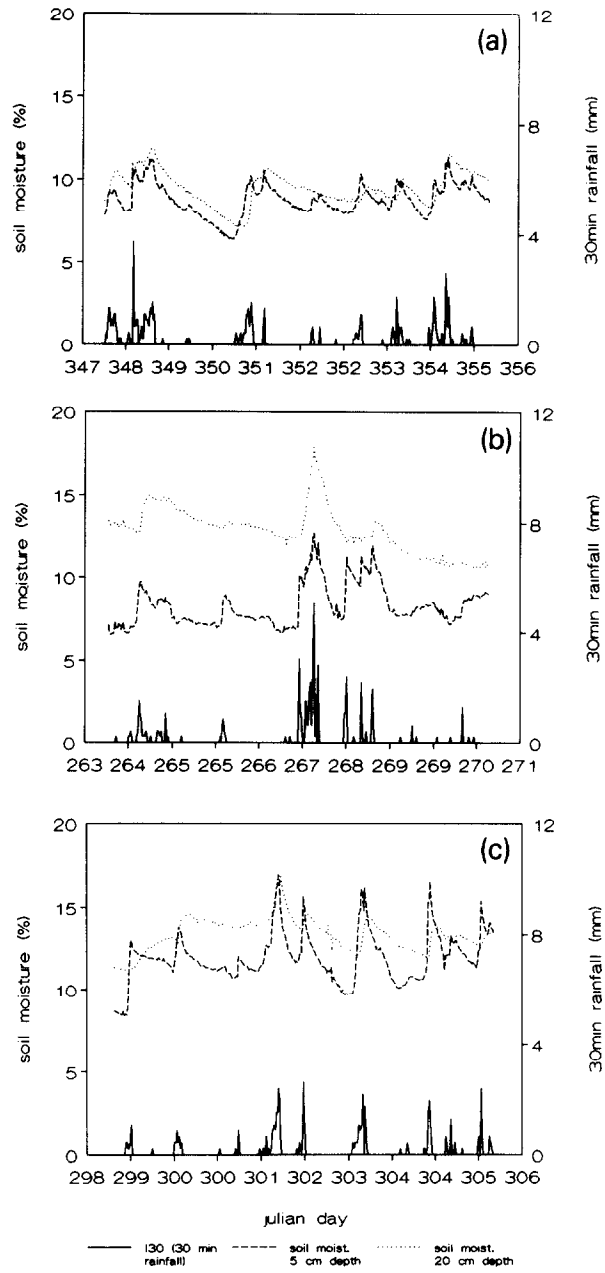
Fig. 4. Rainfall intensity and soil moisture in the weeks with low production of surface runoff and sediment of Table 3b: (a) week 40, (b) week 76, (c) week 81.
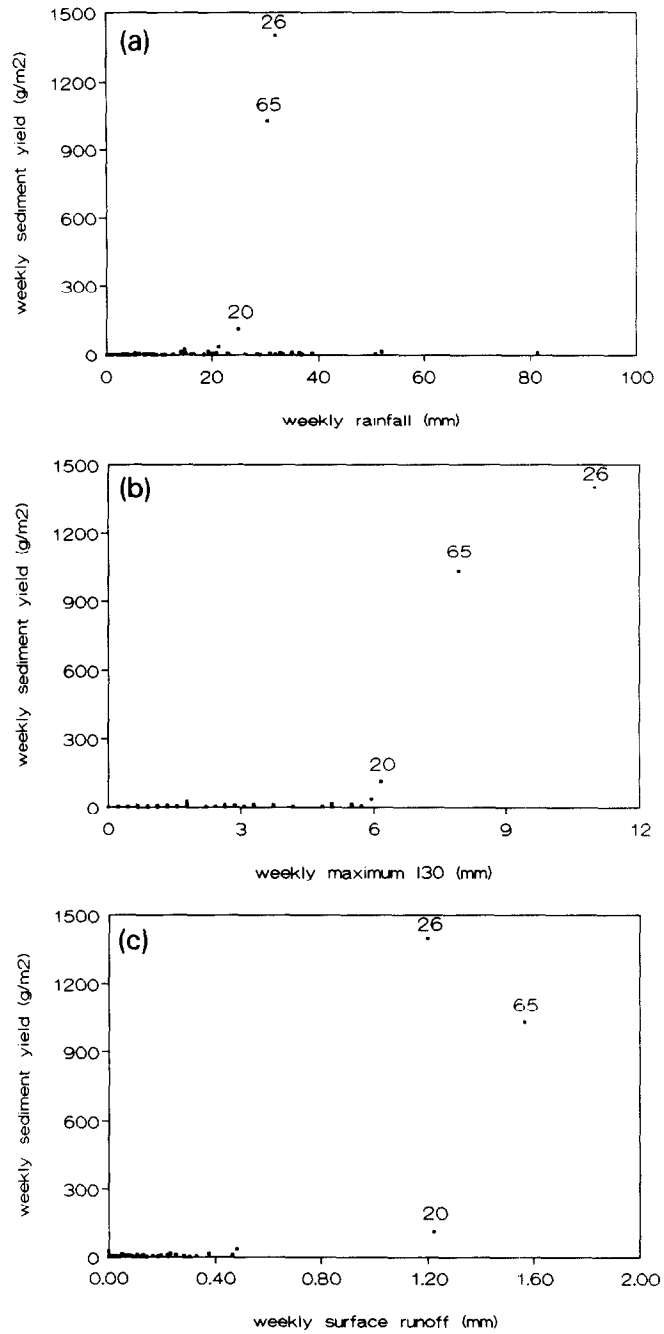
Fig. 5. Sediment yield, surface runoff and rainfall relationships: (a) weekly sediment yield and weekly rainfall, (b) weekly sediment yield and weekly maximum 30-minute rainfall, (c) weekly sediment yield and weekly surface runoff. The numbers refer to weeks of measurement.

value of the correlation coefficient between these two variables ($r = 0.2$) is explained by Fig. 5a: storms with much higher amounts of precipitation than the weeks of Table 3a but occurring at a time of unrestricted water acceptance are ineffective.

By comparison, rainfall intensity (I_{30}) exhibits a much stronger relationship with sediment yield (Table 2 and Fig. 5b). Fig. 5c reveals that sediment production occurs only when the weekly maximum 30-minute rainfall is more than about 6 mm.

4. Discussion

As was argued in the Introduction, rainfall intensity is assumed to affect the erosion process essentially in two ways: by supplying the large amount of water needed for the high water:sand ratio in the sand flow, and by providing the high frequency drop impact needed to maintain a high hydraulic pressure in the sand flow. The first process presupposes a strong relationship of rainfall intensity with surface runoff, the second process a strong relationship of rainfall intensity with sediment yield. The strength of both relationships is demonstrated in the previous paragraphs.

The effect of high rainfall intensity during times of unlimited water acceptance could not be studied, because storms with high rainfall intensities always coincided with conditions of water repellency. Both phenomena are largely restricted to the summer months. In this period, water repellency is a persistent property of the dune sand. Figs. 3a and 3b show that the surface soil is not wetted by the rain. Sand wetted at the surface is apparently entrained by runoff exposing the underlying dry sand. This means that the surface remains water-repellent not only during the rain, but also afterwards, keeping the soil sensitive to erosion by subsequent high-intensity storms. On the other hand, the runoff coefficient is low, even at times of water repellence, and most of the precipitation disappears into the soil. At first sight this appears to be incompatible with the notion of water repellency. What happens is that water infiltrates along preferential flow paths leaving the bulk of the soil dry (Dekker and Jungerius, 1990). These flow paths are often formed by roots channels and have a semi-permanent character. The sensor of SM_2 reacts immediately to rainfall because it is situated in one of these flow paths or below the zone with flow paths.

Of course, water repellency is the prime condition for soil erosion in the dunes. Water repellency has also important ecological consequences which are important for the erosion process: seeds of higher plants will not easily germinate in the dry surface soil. In this way the normal sequence of colonization found in other parts of the dunes is interrupted and no protective vegetation cover will be formed. Indeed, sequential air photo analysis of these dune terrains reveals that the incomplete cover of mosses and algae is a persistent feature of south-exposed slopes.

References

Bridge, B.J. and Ross, P.J., 1983. Water erosion in vegetated sand dunes at Cooloola, Southeast Queensland. Z. Geomorph. N.F. Suppl., 45: 227–244.

Debano, L.F., 1981. Water repellent soils: a state-of-the-art. Pacific Southwest Forest and Range Exp. Station Gen. Tech. Report PSW 46, 21 pp.

Dekker, L.W. and Jungerius, P.D., 1990. Water repellency in the dunes with special reference to The Netherlands. In: Th.W.M. Bakker, P.D. Jungerius and J.A. Klijn (Editors), Dunes of the European Coast, Geomorphology, Hydrology, Soils. Catena Suppl., 18: 173–183.

Van Gelder, G., 1988. Water repellency of dune sands. M.Sc.thesis, Laboratory of Physical Geography and Soil Science, University of Amsterdam.

Ten Harkel, M.J., Heil, G.W., Van der Hagen, H.G.J.M. and Witter, J.V., 1991. Abiotic–biotic interactions in dry dune ecosystems. Mitteilungsbl. Hydrogr. Dienstes Oesterr., 65/66: 58–62.

Jungerius, P.D. and De Jong, J.H., 1989. Variability of water repellence in the dunes along the Dutch coast. Catena, 16(4/5): 491–497.

Jungerius, P.D. and Dekker, L., 1990. Water erosion in the dunes. In: Th.W.M. Bakker, P.D. Jungerius and J.A. Klijn (Editors), Dunes of the European Coast, Geomorphology, Hydrology, Soils. Catena Suppl., 18: 185–193.

Jungerius, P.D. and Van der Meulen, F., 1988. Erosion processes in a dune landscape along the Dutch coast. Catena, 15(3/4): 217–228.

Rutin, J., 1983. Erosional processes on a coastal sand dune, De Blink, Noordwijkerhout. Publications of the Laboratory of Physical Geography and Soil Science, University of Amsterdam, 35 pp.

Slattery, M.C. and Bryan, R.B., 1994. Surface seal development under simulated rainfall on an actively eroding surface. Catena, 22(1): 17–34.

Thompson, C.H., 1983. Development and weathering of large parabolic dune systems along the subtropical coast of Eastern Australia. Z. Geomorph. N.F. Suppl., 45: 205–225.

Wilkinson, L., 1990. SYSTAT: the system for statistics. SYSTAT, Inc., Evanston, IL.

Witter, J.V, Jungerius, P.D. and Ten Harkel, M.J., 1991. Modelling water erosion and the impact of water repellency. Catena, 18(2): 115–124.

Wischmeier, W.H., 1955. Punch card record runoff and soil loss data. Agric. Eng., 36: 664–666.