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# Rates of aeolian transport on a beach in a temperate humid climate

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## Abstract

Short term field measurements of aeolian transport, using a saltiphone, indicate that actual rates of transport deviate considerably from the potential rates predicted by transport equations. When examined in detail, however, potential rates are approached during special conditions: mostly when the wind blows offshore, parallel or slightly oblique to the beach and relative humidity is below 85%. Also, the potential rates of transport may be approached when wind speeds considerably exceed threshold speed, even during showers. The main cause of the large deviation of actual from potential rates is in the absence of transport during very wet conditions (prolonged rainfall) regardless of wind speed, and the variation of threshold velocity with time. The threshold velocity increases during wet conditions, with onshore winds or because of the presence of algae. Therefore, potential transport is defined as the transport optimum. To predict the actual rates of transport accurately, insight into the variation of the threshold velocity is essential. Aeolian transport of sand seems to be related to moderate events and not to extreme events, conforming to the principle of magnitude and frequency.

## 1. Introduction

A thorough understanding of aeolian processes in the coastal environment is necessary for several reasons. In many parts of the world coastal dunes are of vital importance with respect to coastal defence. The ecological significance of coastal dunes is considerable (e.g. Van der Meulen and Van der Maarel, 1993). In The Netherlands, dunes serve as a storage and filtering medium for drinking water. Optimum fulfilment of these functions is not possible with a dune management that lacks a scientific base. Knowledge of the processes of dune development is essential for the prediction and evaluation of management activities. An increased knowledge of the aeolian processes acting on a short time scale will

improve our understanding of the sediment budget of foredunes.

With an accelerated sea level rise the rates of sediment supply are expected to change and an increase in coastal erosion will lead to reactivation of sand in stabilized dune areas (Nordstrom et al., 1990). Prediction of the effects of these changes on dune development is only possible when the mechanics of aeolian processes are known.

The first equations for prediction of aeolian transport were developed in 'simple' environments: desert dunes and wind tunnels (Kawamura, 1951; Bagnold, 1954; Horikawa and Shen, 1960; Kadib, 1965; Hsu, 1971; Lettau and Lettau, 1977; White, 1979). The potential transport calculated by these equations was confirmed by measurements. Since then, several

studies have been conducted in which field measurements in coastal areas were compared to potential transport (e.g. Svasek and Terwindt, 1974; Berg, 1983; Rutin, 1983; Sarre, 1988). Often these studies aimed to find the transport equation with the most predictive power. Comparisons between the different transport equations suggest that none is of general reliability but each is related to the particular circumstances of the calibration experiment (Willetts et al., 1982). In general the actual rates of transport measured in the field are much lower than the potential rates predicted by the transport equations.

In the coastal dune environment, aeolian transport is much more complicated than in the desert environment (e.g. Psuty, 1990). Most natural eroding surfaces tend to have higher threshold velocities and lower rates of sediment supply because of textural and surficial factors (Nickling and Davidson-Arnott, 1990). These last authors refer to a 'supply limited system', where the total sediment flux is controlled by the ability of the surface to supply grains to the air stream. Among the factors influencing transport (for an overview see Nickling and Davidson-Arnott, 1990; Sherman and Hotta, 1990) are beach width (Nordstrom and Jackson, 1992), rainfall (Rutin, 1983; De Lima et al., 1992), surface moisture (Belly, 1964; Svasek and Terwindt, 1974; Hotta et al., 1984; Sarre, 1988), sediment characteristics such as density (Willetts, 1983; Iversen, 1985, Iversen, 1986) and shape (Willetts et al., 1982; Willetts, 1983; Rice, 1991), crust formation (Nickling and Ecclestone, 1981; Nickling, 1984) and vegetation (Bressolier and Thomas, 1977; Hesp, 1983; Wasson and Nanninga, 1986; Buckley, 1987). Transport equations thus far give a good (theoretical) prediction for the aeolian transport process in its most simple form, where the sand is dry, and source and fetch are infinite. In this most simple case, the influence of the complicating factors mentioned above can be neglected. Efforts (mostly empirical) have been made to take account of the influence of moisture (Belly, 1964; Hotta et al., 1984; Sarre, 1988), vegetation (Wasson and Nanninga, 1986; Buckley, 1987) and slope (Howard et al., 1978; Hardisty and Whitehouse, 1988). Accurate prediction of aeolian transport in humid and coastal environments is not possible until the influence of all relevant factors can be quantified.

In this paper results are presented from several

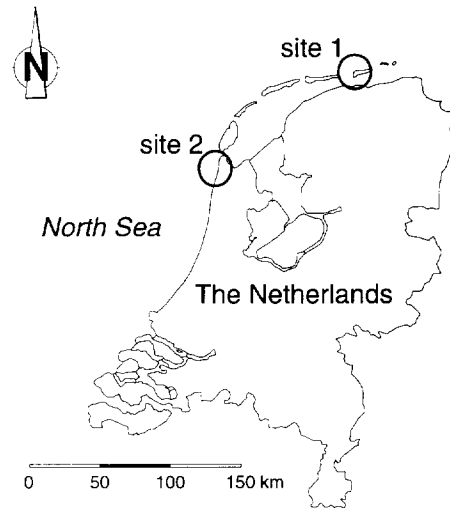


Fig. 1. Location of study areas.

months of process measurements on the beaches of two sites in The Netherlands. The aim of the measurements was to gain insight into relationships between aeolian sand transport, meteorological conditions, and environmental factors. This paper discusses the relationship between transport and meteorological conditions, with special attention to the deviation between actual and potential rates of transport.

### 1.1. Field sites

The study sites are situated in The Netherlands. Climate in The Netherlands is temperate humid, with strong seasonal contrasts. The stormy season, with strong winds from the southwest, west, or northwest, usually extends from October to February, mostly alternated by cold periods often with moderate winds from easterly directions.

Detailed measurements were performed on two sites described by Arens (1994) and Arens et al. (1995). Location of the sites is shown in Fig. 1. Site 1, on the Wadden island of Schiermonnikoog, is characterized by a very wide beach and low, vegetated foredunes with an orientation parallel to the frequently blowing southwesterly winds. Tidal difference is about 2 m. The beach is only flooded during very high tides (accompanied by winds from the west or northwest). Because of stagnation of rain

water on the beach, a narrow zone, close to the foredunes, remains wet during winter. In this zone algae crusts develop in spring. Isolated embryonic dunes are scattered over the beach. The sand is characterized by a mean grain size of  $2.55 \phi$  ( $190 \mu\text{m}$ ) and a sorting of  $0.30 \phi$ .

Site 2 is situated on the mainland coast, approximately 10 km to the south of Den Helder. The beach is narrow and tidal range is 1.5 m. On the beach groins are present, with a spacing of about 200 m. These are flooded during high tide. The foredunes are steeper, higher and less vegetated than those of Site 1. Locally small blowouts are present. The sediment is slightly coarser with a mean of  $1.94 \phi$  ( $259 \mu\text{m}$ ) and a sorting of  $0.45 \phi$ .

## 2. Methods

An extensive overview of instrumentation and measurements of meteorological variables is given by Arens (1994). For the present study measurements of wind speed and direction (at 5 m above the surface), air temperature and radiation were performed at 5-s intervals. Measurements were averaged over 10 min. Averages, standard deviation, minimum and maximum of each 10-min period were stored. Air humidity was calculated from dry and wet bulb temperatures recorded at 5 m above the surface. Total amount of rainfall was measured every 10 min.

Transport of sand was determined at several time scales. Short term process measurements were performed with the saltiphone (Spaan and Van den Abeele, 1991; Van Dijk and Hollemans, 1991), which counts the number of impacts of sand grains on a microphone, installed at a height of 10 cm above the surface. Every 5 s the total number of impacts was recorded, and averaged over 10-min periods. Fig. 2 presents the relationship between grain impacts and wind speed, determined in the wind tunnel (Van Dijk and Hollemans, 1991). This indicates that the saltiphone can record very high rates of transport. Because the saltiphone is a grain counting device, mass fluxes are not recorded directly. With different grain size of the sediment different results are obtained. Also the measurement height is important, because the concentration of the transported sand decreases exponentially with height. In case of large rates of

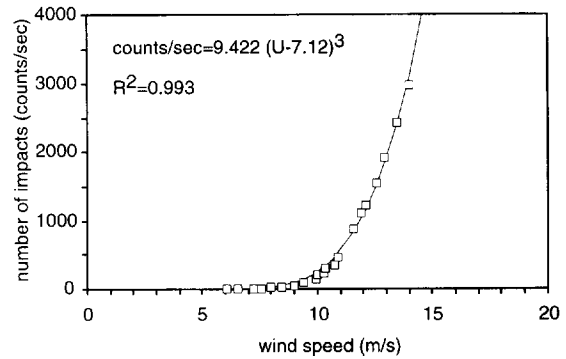


Fig. 2. Relationship between saltiphone counts and wind speed (after Van Dijk and Hollemans, 1991). Wind speed is measured at 0.35 m (centre of wind tunnel); impacts with the saltiphone were recorded at 0.03 m height.

transport during rainfall the saltiphone gets choked, and reliable registration is not possible.

Mass fluxes were measured using sand traps over a period of some minutes to more than a day, depending on conditions. The traps used consist of stacks of funnel-shaped trays, with a total height of 0.50 m. Detailed specifications of the traps are presented by Arens and Van der Lee (1995). The relationship between mass flux and saltiphone counts is illustrated by Fig. 3. The total number of saltiphone counts measured over several periods are plotted against the amounts of sand trapped in the same periods. The amount of sand trapped apparently is proportional to the number of grain counts, but some scatter occurs, probably related to spatial variability,

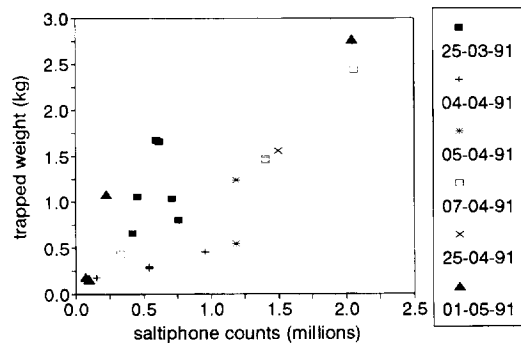


Fig. 3. Relationship between trapped weights (not corrected for trap-efficiency) and saltiphone counts over several periods. Amounts of sand trapped in period =  $0.961 \times$  total number of Mcounts in period + 0.197;  $R^2 = 0.589$ .

creep (not measured with the saltiphone), synchronisation and measurement errors because of variation in the sand traps.

Measurements on the beach of Schiermonnikoog (Site 1) took place from 3 March to 27 May 1991, at a distance of 70 to 100 m in front of the dunebase. At Site 2 (Groote Keeten) field measurements lasted from 5 to 24 February 1992. Here, the saltiphone was placed near the dunefoot, because the beach is very narrow. Occasionally a second saltiphone was used for comparison. Sand traps were placed on the beach during transport events, at several distances from the dunefoot.

### 3. Results

The relationship between saltiphone counts and wind speed for the two sites (Fig. 4) apparently is

not constant. A transport optimum could be defined as the potential transport. The optimum can be described by a power law. In many cases the observed transport is either zero or below the optimum. Days with rainfall are separated from days without rainfall. The relationship differs for the two cases. For Groote Keeten, the data indicate that transport during wet days is always larger than during dry days, but a lot of scatter occurs (an explanation is given below). For the data of Schiermonnikoog, transport during dry days is often close to the (dry) transport optimum. On days with rainfall, the threshold velocity is higher, but during strong winds the transport optimum exceeds the dry optimum. Apparently during strong winds with rainfall, high rates of transport may occur (see also De Lima et al., 1992).

The scatter in Fig. 4 is the result of changes in conditions during the measuring period. When examined at a shorter time scale, it appears that, for some

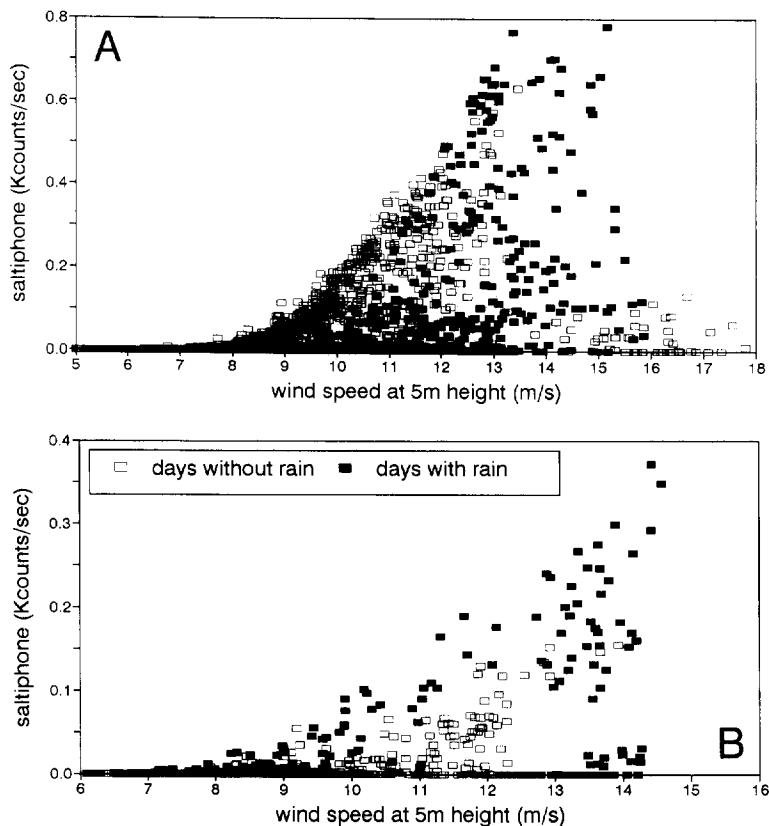


Fig. 4. Saltiphone counts (at 0.10 m height) versus wind speed (at 5 m height), for days with and without rainfall. (A) Schiermonnikoog (measuring period 3 March–27 May 1991); (B) Groote Keeten (measuring period 5–24 February 1992).

days, the relationship between saltiphone counts and wind speed is rather constant, which probably reflects steady conditions. Some examples for Schiermonnikoog are presented in Fig. 5.

The relationship between grain counts and wind speed can be described by:

$$\text{saltiphone counts} = a(U - U_t)^b \quad (1)$$

with  $a$  and  $b$  as constants,  $U$  = wind speed at height  $z$  (5 m) (m/s),  $U_t$  = critical threshold velocity at height  $z$  (m/s).

When  $b = 3$  and:

$$a = C_{\text{saltiphone}} \alpha C_B \sqrt{\frac{d}{D}} \frac{\rho}{g} \quad (2)$$

with  $C_{\text{saltiphone}}$  = constant which relates the number of counts to the mass flux,

$$\alpha = \left( \frac{0.174}{\log \frac{z}{k'}} \right)^3,$$

Table 1  
Meteorological parameters and results of curve fitting

Day Number	Period (h)	Wind direction	Rainfall (mm)	%Rel. humid.	$U_{\text{max}}$ (m/s)	$a$ in curve	$U_t$ (m/s)	Scatter?
Site 1 (Schiermonnikoog); period 3 March–27 May 1991								
78	1	188–197	0.2	79–85	10.4	0.033	8.1	y
78	19	197–270	9.6	88–100	15.2	0.067	11.3	y
80	1	234–245	0	87–89	15.4	0.181	14.4	y
83	6	40–60	0	85–90	10.0	0.036	7.8	n
* 84	39	50–90	0	50–85	12.1	0.0097	5.9	n
89	4	270–280	0	55–90	9.0	0.014	7.4	±
91	2 +	225–238	0?	88–94	14.9	0.026	7.8	y
* 94	42	180–220	0	40–90	12.8	0.010	5.9	n
97	19	190–250	0.6	69–98	13.4	0.026	8.0	n
98	5	239–254	0.4	77–93	12.6	0.096	10.0	y
101	5	155–180	0	36–46	7.2	0.0067	5.9	±
103	9	7–32	0	84–99	13.1	0.024	8.8	y
105	24	320–360	0.8	59–83	17.8	0.039	9.4	y
114	2	56–68	0	75–80	7.6	0.149	7.0	±
115	10	50–61	0	65–90	9.8	0.016	6.7	n
116	12	51–59	0	84–68	10.0	0.019	6.7	n
117	3	49–65	0	67–79	8.6	0.020	6.7	n
* 120	15	20–78	0	70–93	12.2	0.0094	6.4	n
121	14	50–19	0.2	72–93	13.5	0.013	7.2	n
121	5	350–25	0.2	80–91	13.5	0.040	9.5	y
122	5	336–357	0.4	68–82	13.6	0.013	9.6	y
124	8	29–40	0	78–91	11.5	0.161	9.4	y ±
134	25	294–356	≥ 1.4	68–100	13.3	0.042	9.3	y
Site 2 (Groote Keeten); period 5–24 February 1992								
41	1	226–229	0	93–95	9.0	0.0013	7.0	
* 43	4	190–206	0	88–99	9.3	0.0007	5.1	
* 43	7	194–243	0.4	85–97	13.1	0.0018	4.5	n
* 44	5	215–229	0	87–96	9.0	0.0007	5.8	
45	3	258–264	0	86–88	9.5	0.0091	8.0	y
45	10	204–248	0.4	82–96	13.0	0.0070	6.8	
* 46	11	253–280	0.2	71–91	15.7	0.0037	7.6	±
53	12	212–234	0.4	80–99	14.6	0.0048	7.8	± n

Saltiphone counts =  $a(U - U_t)^b$ . Parameters fitted are  $a$  and  $U_t$ ;  $b$  is set at 3.

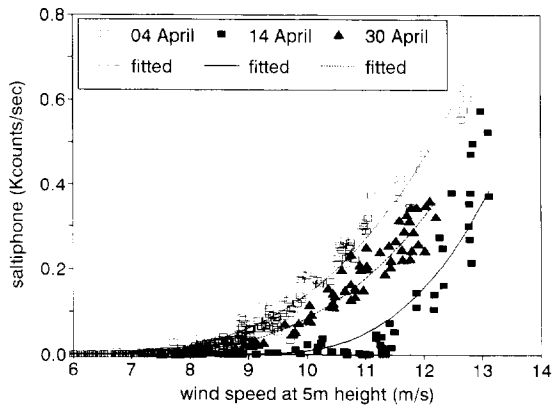


Fig. 5. Actual transport and fitted curves for potential transport (Eq. 1) for three days in April 1991, Schiermonnikoog. Predictions are based on curve-fitting procedure described below.

with  $k'$  = the focal length (approximately 1 cm),  $C_B$  = Bagnold's constant (1.8 for naturally graded dune sands),  $d/D$  = ratio between grain size and standard grain size (0.25 mm),  $\rho$  = density of air,  $g$  = gravitational constant, Eq. 1 is equal to Bagnold's (1954) equation.

For most days good curve fits are obtained when, according to the transport equation of Bagnold (and most others), the value of  $b$  is set at 3. Results of the curve fitting procedure are presented in Table 1, together with some meteorological data. The last column of Table 1 indicates if scatter occurs (variation in conditions) or if the curve obtained fits the data well. Only on some days better fits are obtained with a lower value of  $b$ . Also for the transport optima the curves obtained deviate from the third power law. For dry days the equation  $\text{Saltiphone counts} = 0.067 \times (U - 6.8)^{2.2}$  describes the optimum. Approximately 30% of the data are within the range of  $\pm 0.5$  times the prediction. For wet days the best fit is obtained with  $\text{Saltiphone counts} = 0.17 \times (U - 8.6)^{2.1}$ . In this case only 10% of the data deviate less than 50% from the predicted value.

The actual values of the threshold velocity deviate a little from the results discussed in this study. The actual value of the threshold velocity should be determined at a time scale of seconds. Especially at wind speeds just above threshold, most of the transport takes place during gusts. The use of 10-min averages will, therefore, cause an underestimation of the threshold velocity. Because the saltiphone records

at a certain height above the surface, the value of the threshold velocity is overestimated. At lower wind speeds, sand transport might occur, but the height of the saltation cloud will be below the measuring height of 10 cm.

### 3.1. Relationship between transport rates and rainfall

The largest deviation from the potential transport curve is observed during days with strong winds and without sand movement, because of prolonged rainfall and high relative humidity, and often high water levels. Gales from the west, northwest and north are usually accompanied by high water levels, causing most of the beach to be flooded by sea water. Between November 1990 and February 1991, hardly any sand movement was observed during gales (wind speed 15 to 25 m/s) on Schiermonnikoog. The absence of transport under these conditions is one important cause of the deviation between potential and actual transport.

The strongest sand movement is observed during days with short but sometimes heavy showers and strong winds (10–14 m/s at 5 m), when raindrop impact triggers the entrainment of grains. This confirms observations by Rosen (1979), De Ploey (1980), Draga (1983), Sarre (1989) and De Lima et al. (1992). In Fig. 4, it seems that for Schiermonnikoog, during strong winds, the wet transport optimum exceeds the dry optimum. During rain, the energy available for the ejection of grains is possibly enlarged because of the extra input of impulse by the rain drops. The impact of rain drops could be compared to the impact of saltating grains, which causes the dynamic (impact) threshold to be lower than the static (fluid) threshold (Bagnold, 1954). Only a small percentage of the data points in Fig. 4, however, approach the transport optimum. Apparently the increase in transport capacity because of rainfall is limited to short periods. With on-going rain the surface becomes too wet, and cohesive forces between the sand grains cannot be overcome any more. From the measurements it is concluded that transport decreased or stopped when rainfall exceeded 0.20 mm in 10 min, or continued for more than 10 min. Strong winds are often accompanied by rain.

To give an indication of the extent of sand trans-

port during wet conditions, Table 2 presents a frequency distribution of sand transport events, based on periods of 6 h. For every period, the mean wind speed is recorded together with the occurrence of either rain or sand transport or both (regardless of magnitude). The number of periods with transport and rain is 7% (11 of 163) for Schiermonnikoog and 30% (9 of 31) for Groote Keeten. Regarding wind speeds above 9 m/s, percentages are 16% for Schiermonnikoog and 41% for Groote Keeten.

### 3.2. Relationship between rates of transport and wind direction

The wind direction is of importance for sand transport on the beach (Svasek and Terwindt, 1974; Nickling and Davidson-Arnott, 1990; Nordstrom and Jackson, 1993). When the wind blows parallel to the beach, the fetch and sand source are practically infinite, which results in a wind that is saturated with sand. Because of the impact of the saltating grains, the threshold velocity will reach its minimum (dynamic threshold). The source is infinite, and the amount of imported sand is comparable to the amount exported. No net transport of sand occurs out of the system, which means that no change actually occurs in surface height.

With onshore winds, the fetch is often limited, especially on narrow beaches. In The Netherlands strong onshore winds are almost always accompanied by high water levels, which even further reduces the fetch. The incoming amount of sand is

limited or zero and, therefore, the threshold velocity approaches the static threshold. After some hours of transport, the driest grains will be removed from the system, resulting in an increasing influence of surface moisture. Especially when evaporation is insignificant, this will result in a decrease in transport.

According to Nordstrom and Jackson (1992) an arithmetic reduction in beach width results in an exponential reduction in transport. Nordstrom and Jackson (1993) observed that during oblique winds rates of transport were more than 20 times larger than during perpendicular winds.

To gain more insight in the influence of wind direction, the data of Fig. 4 are sorted on wind direction and plotted in Fig. 6. The ranges of wind direction are defined as follows: parallel  $\pm 15^\circ$ , perpendicular onshore/offshore  $\pm 30^\circ$  and the rest is oblique. The closest approach to the maximum potential transport is when the wind blows offshore, parallel or slightly oblique to the foredunes. The strongest deviation occurs during onshore winds. The largest rates of transport are observed during oblique onshore winds.

During offshore winds, the distance between dunefoot and saltiphone is limited, but apparently the wind is saturated with sand. In this case, the wind moves down slope (slope ca.  $1^\circ$ ) over a dry surface with a lot of loose sand. Besides, offshore winds at this site blow from easterly directions and are accompanied by relative humidities of less than 60%.

The differences between parallel and oblique winds disappear under strong wind speeds ( $> 12$

Table 2

Frequency of sand transport events in relation to wind speed and rainfall (number of periods of 6 h during which sand transport and/or rain occurred)

Speed (m/s)	Dry		Wet		Very wet	
	$q > 0$	$q = 0$	$q > 0$	$q = 0$	$q > 0$	$q = 0$
Site 1 (Schiermonnikoog); period 3 March–27 May 1991						
6–9	21	53	1	9	0	5
9–12	18	18	5	5	1	2
12–15	4	2	2	2	1	2
> 15	1	0	1	0	0	0
Site 2 (Groote Keeten); period 5–24 February 1992						
6–9	5	4	2	3	0	0
9–12	3	0	5	1	0	2
12–15	3	0	1	0	1	1
> 15	0	0	0	0	0	0

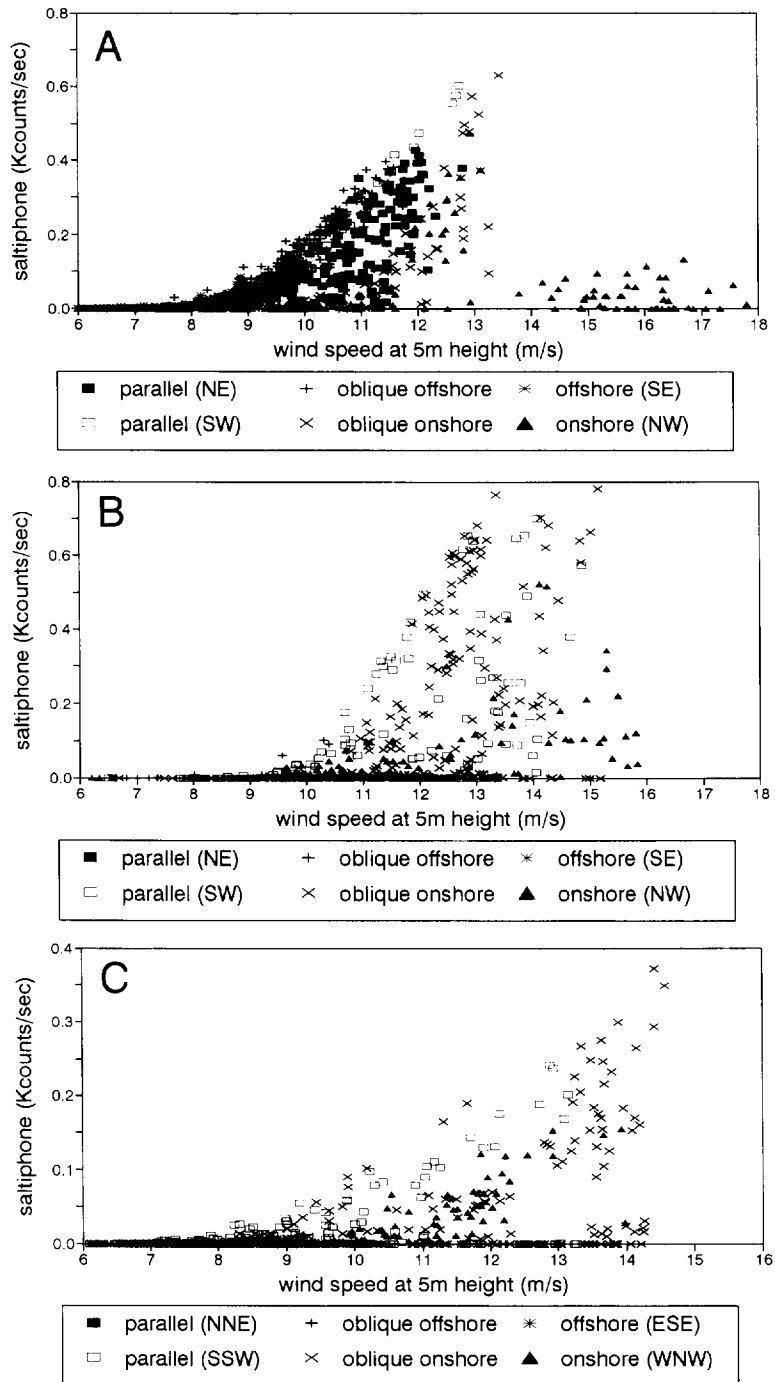


Fig. 6. Saltiphone counts versus wind speed, for several ranges of wind direction. (A) Schiermonnikoog, dry days; (B) Schiermonnikoog, wet days; (C) Grootte Keeten.



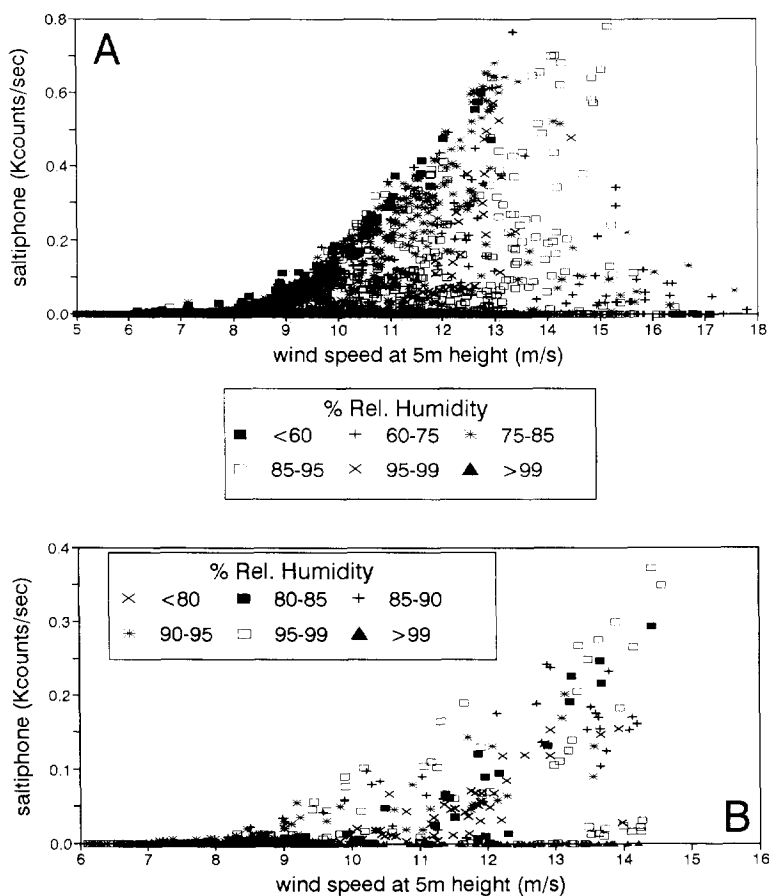


Fig. 7. Saltiphone counts versus wind speed, for several ranges of relative humidity. (A) Schiermonnikoog; (B) Groote Keeten.

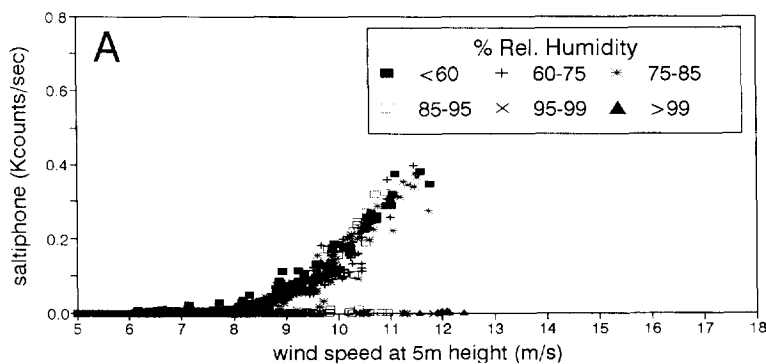


Fig. 8. Saltiphone counts versus wind speed, for several ranges of relative humidity: (A) offshore winds (60–210°); (B) parallel winds (210–240° and 30–60°), dry days; (C) id., wet days; (D) oblique onshore winds (240–285° and 345–30°), dry days; (E) id., wet days; (F) onshore winds (285–345°), dry days; (G) id., wet days.

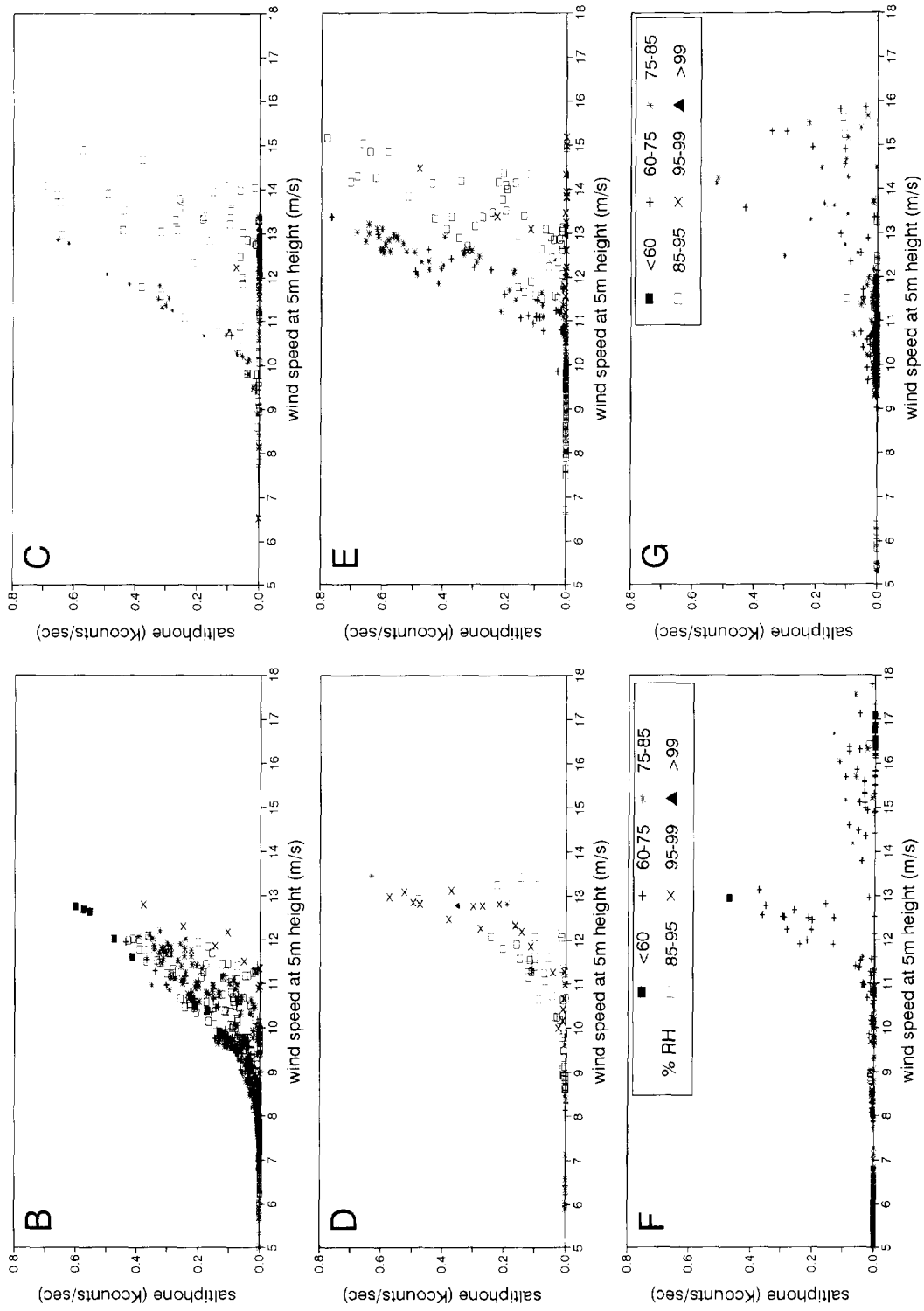


Fig. 8 (continued).

m/s). When examined in total, the threshold velocity increases from parallel to perpendicular onshore winds (see also Fig. 8). These patterns are observed for both Sites 1 and 2. The limited transport during strong onshore winds is related to the occurrence of high water levels, implying that during strong onshore winds the width of the (dry) beach is not relevant. With respect to dune development we can state that under these conditions the transport of sand from the beach to the foredunes is always much lower than the potential transport.

When comparing Figs. 4 and 6, clearly the rates of transport for Groote Keeten are lower during dry days than during wet days: during dry days the wind was perpendicular onshore, whereas during wet days it was mostly parallel or oblique onshore.

### 3.3. Relationship between rates of transport and relative humidity

Evidence from several studies (e.g. Belly, 1964; Knottnerus, 1980; Sarre, 1988; Hotta et al., 1984) indicate a relationship between aeolian transport and humidity (either surface or air). The humidity of the surface is related to the relative humidity of the air (Belly, 1964). The relationship between relative humidity and transport is presented in Fig. 7. When relative humidity exceeds 99%, both for Sites 1 and 2 no transport occurs. The relationship is not com-

pletely clear, unless the influence of wind direction is taken into account. For Schiermonnikoog, the data, sorted by wind direction and relative humidity, are plotted in Fig. 8: Fig. 8A for (oblique) offshore winds, Fig. 8B for parallel (NE and SW), Fig. 8D for oblique onshore winds and Fig. 8F for onshore winds. For Groote Keeten, too little data are available. Within the same range of wind directions the relationship between relative humidity and transport becomes clear.

For parallel winds, a general increase of the threshold velocity with increasing humidity is observed. Little difference exists between parallel winds from the northeast and from the southwest. For wet days the transport curve shifts to the right with increasing humidity, which means that it is mainly the threshold velocity that changes. For dry days, the shape of the curve also changes: at low wind speeds the rate of transport diminishes because of a higher threshold, but at higher wind speeds the differences in transport under low and high relative humidity tend to decrease. The same pattern is visible in Figs. 8D and 8E for oblique onshore winds. The larger rates of transport during oblique winds on wet days when compared to dry days are possibly caused by a lower relative humidity. For perpendicular onshore winds the relationship with humidity is masked by other factors, of which water level (effective beach width) is probably the most important.

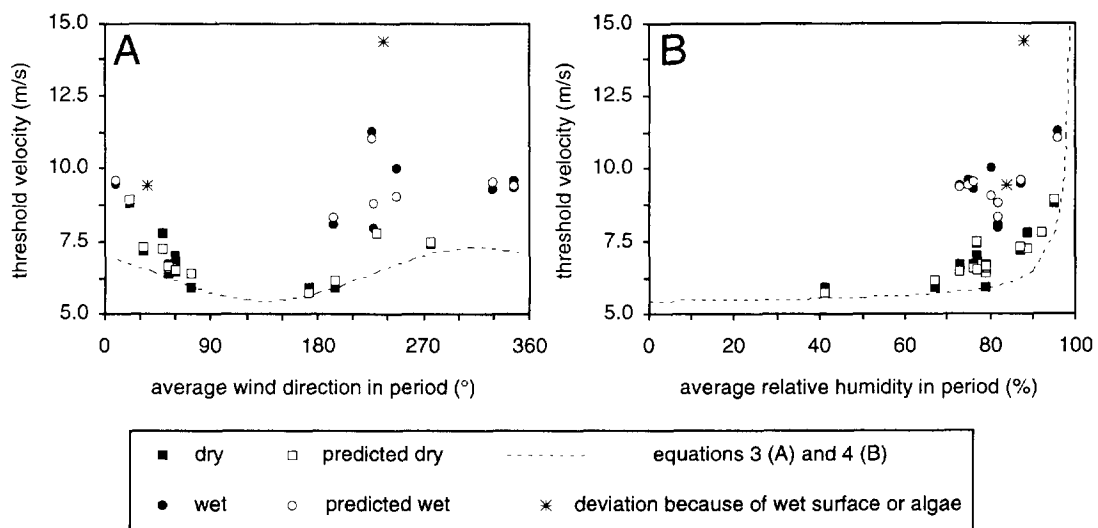


Fig. 9. Observed and predicted threshold velocities versus (A) wind direction and (B) relative humidity.

In conclusion, the rates of transport on both wet and dry days are strongly influenced by the amount of rainfall, wind direction, and relative humidity. Taking these factors into account, rates of transport on wet days are lower than on dry days when wind speeds are below 12 m/s. For higher wind speeds the differences are small. Larger rates of transport during wet days as observed in Fig. 4, can be explained in terms of wind direction and relative humidity. The frequency of sand transport, however, decreases during wet days, as is reflected in Table 2. This is in agreement with observations of Kuhlman (1958). He concluded that the magnitude of rates of transport measured during a wet year was comparable to the magnitude during a dry year, but the frequency of occurrence was much less.

### 3.4. Biological factors

Some evidence is found for the increase in threshold velocity because of the presence of algae. Recent studies have reported on the stabilising action of algae in dunes (Van den Ancker et al., 1985; Pluis, 1990) and on tidal flats (De Boer, 1981; Vos et al., 1988). But little is known of sand-binding by algae on beaches. At the end of the measuring period, after a period of higher temperatures (15–25°C), a crust of algae developed on the beach surface, resulting in higher threshold velocities (see Table 1, values of  $U_t$  for days 121 to 134). Despite high wind velocities, transport of sand on the beach was negligible. Also at other locations algae crusts were observed on the beach surface in late spring or summer.

### 3.5. Estimation of the threshold velocity

The relationship between wind direction, relative humidity and threshold velocity is summarized in Fig. 9. For several days the estimated threshold velocities (data of Table 1) are plotted versus wind direction and relative humidity. Because of the influence of both variables, the relationships between threshold and wind direction (Fig. 9A) and relative humidity (Fig. 9B) are not completely clear. In general the threshold increases when the direction of the wind changes from parallel (45° or 225°) to onshore (315°). For this relationship a cosine function is

proposed, also drawn in Fig. 9A. The shape of the function is:

$$U_t = U_{\min} \times \{1 + \text{amplitude}(1 + \cos[dd])\} \quad (3)$$

with  $dd$  = effective wind direction, relative to coastal orientation. Fig. 9B shows the increase of threshold velocity with increasing humidity, but only for dry days. At low humidity the threshold seems to reach a minimum. When relative humidity exceeds 99%, the threshold velocity approaches a very high value, because no transport was observed under these conditions. For days with showers the threshold velocity is higher, but the relationship with humidity seems to be absent. A function is proposed that yields a minimum value of the threshold velocity at low humidity and a maximum (infinite) when relative humidity approaches 100%. The function is given by:

$$U_t = U_{\min} \times \left\{ 1 - \frac{A}{100} + \frac{A}{100 - \%RH} \right\} \quad (4)$$

Estimation of the parameters in Eqs. 3 and 4 was executed by using an optimising procedure to minimize the value  $\sum_{i=1}^n (U_{tiOBS} - U_{tiPRED})^2$ , where  $n$  is the number of observations. The obtained values are:

$$U_{\min} = 5.45 \text{ (m/s)}$$

$$\text{Amplitude} = 0.17 \text{ (-)}$$

$$A = 2.11 \text{ (-)}$$

For wet days an additional parameter  $C_{RAIN}$  is needed:

$$U_t = U_{\min} \times \{1 + C_{RAIN}\} \quad (5)$$

Using the same procedure, the best value for  $C_{RAIN}$  appeared to be:

$$C_{RAIN} = 0.35 \text{ (-)}$$

and

$$C_{RAIN} = 0 \text{ (-) for dry days}$$

Combination of Eqs. 3, 4 and 5 yields:

$$U_t = 5.45 \times \left\{ 1 + 0.17(1 + \cos[dd]) - \frac{2.11}{100} + \frac{2.11}{100 - \%RH} \right\} \quad (6)$$

for dry days and

$$U_t = 5.45 \times \left\{ 1 + 0.17(1 + \cos[dd]) - \frac{2.11}{100} + \frac{2.11}{100 - \%RH} + 0.35 \right\} \quad (7)$$

for wet days. In Fig. 9, predicted values of  $U_t$  using Eqs. 6 and 7 are compared to the observed values. The calculated values of the threshold velocity correspond very well to the observed values.

#### 4. Discussion and conclusions

Only under special conditions can aeolian transport of sand on a beach in a temperate humid climate be predicted using current transport equations. On a time scale of hours to days, potential rates of transport may be approached, but actual rates deviate from the potential rates on a longer time scale.

The main reason for the deviation of actual from potential rates is in the variation of threshold velocity with time. Within a time period of days the critical threshold velocity may vary substantially. An accurate prediction of transport of sand by wind on beaches in a humid climate is, therefore, only possible if the variation of the threshold velocity is taken into account.

In this study the transport of sand by wind is shown to depend on rainfall, wind direction (fetch and extent of the source area), and relative humidity. During very wet conditions (prolonged rainfall), transport declines to zero, regardless of wind speed. High rates of transport are, however, observed during showers. The influence of rainfall results in an increase in threshold velocity, causing a reduction of transport at wind speeds just above threshold. At higher wind speeds ( $> 12$  m/s) rates of transport may approach the transport optimum, probably because of the extra energy transfer because of the impact of rain drops. When wind speeds exceed 15 m/s (at 5 m height) the observed rates of transport deviate extensively from the potential rates. Sarre (1988) expressed his doubt about the validity of the cubic relationship between transport and wind speed at such high speeds. According to Sørensen (1991) the high concentration of grains close to the surface

at higher shear velocities results in a decreased efficiency of the collision, which explains the deviation from the cubic relationship.

Because of the finite width of the beach, wind direction is an important factor. With parallel winds fetch and source are virtually infinite, whereas with perpendicular onshore winds fetch and source are at its minimum. Even on very wide beaches this causes a deviation from the potential transport. The deviation increases during strong winds, when sea water level rises and most of the beach is flooded. Because of the limited extent of the beach during onshore winds, the wind is not saturated with sand. Therefore, the value of the threshold velocity will range between the static and the dynamic threshold velocity, closer to the static threshold when beach width diminishes.

The value of the threshold velocity also depends on surface conditions. Probably the most important factor during the year is the moisture content of the surface. In the present study no data on surface humidity are available, but it is assumed that a relationship exists between surface humidity and relative air humidity. The best correlation between relative air humidity and rates of transport is obtained, when the data are arranged on the basis of wind direction. For parallel and slightly oblique winds, the threshold velocity increases significantly with rising humidity. Up to about 80% the influence of humidity is limited; above 99% transport seems to decline to zero. Besides a general increase in threshold velocity, the relationship between transport and wind speed changes a little: at higher wind speeds, the differences because of humidity decrease, especially during dry days.

Based on these observations simple relationships are proposed in which the critical threshold velocity is related to rainfall, wind direction and relative humidity. The calculated values are in good agreement with the observed critical velocities.

Transport of sand by wind is a short term process. According to Butterfield (1991) rates of transport respond almost instantaneously (1–2 s) to velocity accelerations. Butterfield states that the grain flux under steady wind speeds are more variable than might have been expected from time-average values. Our measurements indicate that for almost all periods of 10 min the minimum transport rate (measured

at intervals of 5 s) equals zero, even at very high wind speeds. This implies that even within such a short period, transport is not continuous. Therefore, the use of long term averages (hourly or even daily wind speeds) will lead to inaccuracies, because of unsteady conditions, and the predictive power for transport will be reduced.

Because of the sensitivity of the transport process to many meteorological conditions, it is not justified to evaluate transport equations on basis of field measurements on a beach in a temperate climate. Too many variables are involved of which the influence is not completely quantified yet. The differences in transported quantities predicted by the different transport formulae might be in the range of measurement errors and noise created by variability of meteorological conditions. To be able to evaluate transport equations, and to make accurate estimations of the parameters used in these equations, many data on rates of transport are needed, together with measurements of air flow, rainfall, humidity, evaporation and water level (fetch).

Potential transport predicted by the conventional transport equations should be considered as the optimum transport of sand under certain (optimal) conditions. For yearly rates of transport it is far from indicative. To predict yearly rates of transport the reduction caused by rainfall, diminished beach width and surface conditions should be taken into account. The use of only a frequency distribution of wind data for the estimation of yearly fluxes of sand transport by wind is, therefore, not sufficient.

With respect to aeolian transport on a beach, extreme conditions (associated with rainfall) are less important than moderate conditions. Especially during gales often no transport of sand occurs at all. On average most of the sand is transported during strong winds (approximately 10 to 13 m/s, 5 m, 10-min averages), often during short but sometimes heavy showers. This is in accordance with the principle of magnitude and frequency (Wolman and Miller, 1960).

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