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Application of mathematical modelling of sand transport to Kuwait environment

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ABSTRACT

The sand transport rate in Kuwait was estimated by a sand movement mathematical model. The model calculates the potential sand drifts in each direction sector and presents the net sand transport for a certain time period. The model shows that Kuwait is subjected to intense sand encroachment problems. The net annual rate of sand movement in Kuwait is estimated to be more than 62,000 kg/(m.yr) toward the southeast.

1. INTRODUCTION

In most engineering applications related to sand transport by wind, the fundamental quality that has to be estimated is the amount of sand flux that crosses a certain reach during a given time period. This quantity plays an important role in assessing the magnitude of the problem and the means to control it.

The occurrence of aeolian sand deposits in most parts of Kuwait can cause severe engineering problems, especially in the areas where there is insufficient vegetative protection. The problem of sand movement in Kuwait is compounded by the extensive deterioration of the natural vegetative cover from over-grazing, sand and gravel quarrying and off-road traffic. Therefore, the Kuwaiti Government should take sand transport into consideration in planning such activities as highways, airports, farms and army camps, which necessitate the establishment of developments in the desert.

Realizing the importance of sand movement problems, this paper predicts the rate of sand flux in the Kuwaiti desert. A mathematical model is developed to predict sand flux for particular wind conditions.

2. TYPES OF SAND MOVEMENT BY WIND

Most sand movement by wind is found in desert regions and coastal areas. When the shear velocity of the wind U_* at the surface reaches a value above the threshold value

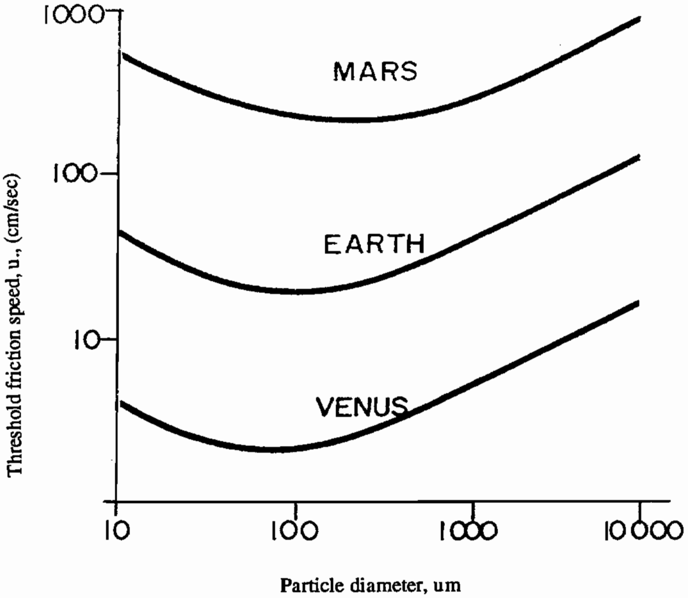

Fig. 1. Comparison of the threshold friction speed versus particle diameter for Mars, Earth, Venus (Source: Iversen *et al.*, 1976, p. 4).

U_{*t}, some particles from a loose sand surface are put into motion. The greater the value of U_*, the more particles will be put into motion. Iversen *et al.* (1976) presents a threshold curve for earth that relates the minimum wind speeds required to set particles of different sizes into motion (Fig. 1). This threshold curve has been first derived by Bagnold (1941).

According to Bagnold (1941, 1954), particles are commonly transported by wind in one or more modes: suspension, saltation, surface creep, gravitational sliding or reptation.

2.1. Suspension

Most sand grains are too large to be carried in true suspension because the settling velocity of sand grains in air is high due to the large difference in the density of sand grains and that of air.

2.2. Saltation

Once a sand grain rises from the surface, three forces act on the grain: gravity, drag, and lift due to the wind. Since the lift force decreases as the particle rises, the gravitational force results in a large settling velocity of the sand grains. Accordingly, the grain rises and travels in a low and smooth trajectory and falls to the surface with large downward momentum. In this case, the falling grain may either rebound into the air or cause another sand grain to become airborne and then come to rest (Horikawa 1987). This type of grain movement is referred to as the saltation mode. According to Bagnold (1954), the upper limit for height of particle travel by saltation transport lies between 1.5 and 2.0 m.

2.3. Surface Creep

Bagnold described the mode of motion by surface creep as follows: a portion of the energy which a falling sand grain has gained from the wind is dissipated in disturbing a large number of surface grains and the greater part of energy is passed on to the grain that is ejected upward to continue the saltation. The net result of continued disturbance of the surface grains moves the grains slowly forward by creeping or rolling. This mean that the sand grains moving by surface creep gain energy through impact from other saltating grains.

According to Greeley & Iversen (1985), the sand grain smaller than 60 μm in diameter (silt and clay particles) is carried by wind in the suspension mode, whereas most sand-size grains, 60–2000 μm in diameter, are carried by wind in the saltation mode. Figure 1 shows that saltation is probably the critical mode of transport, and the grain size most easily moved by the wind is about 100 μm in diameter. Saltation usually accounts for 75% of sand transport and may increase up to 95% depending on the grain size (Bagnold, 1941).

3. WIND SHEAR VELOCITY—U_*

The gradient of the wind velocity profile is related to the shear stress acting on the surface through the following relationship

$$U_* = (\tau/\rho)^{1/2} \tag{1}$$

where

τ: surface shear stress (N/m^2)
ρ: density of the air (Kg/m^3)

Horikawa (1987) gives the following equations to calculate the shear velocity (cm/s) from the wind speed

$$U_* = (U_{10} - U_1)/5.75 \tag{2}$$

$$U_* = 0.0690U_{100} - 18.4 \tag{3}$$

$$U_* = 0.0548U_{446.5} - 14.7 \tag{4}$$

In these equations, U_1, U_{10}, U_{100} and $u_{446.5}$ are the wind speeds at elevations of 1 cm, 10 cm, 100 cm, and 446.5 cm above the sand surface.

3.1 Threshold shear velocity of sand grains—U_{*t}

The threshold value of the wind shear velocity that causes the initiation of aeolian motion of the sediment has been studied both theoretically and experimentally by Bagnold (1941), Zingg (1953), and Greeley & Iversen (1985). The most commonly adopted formula is the one proposed by Bagnold (1941)

$$U_{*t} = A\left[\frac{(\sigma - \rho)}{\rho} \cdot g \cdot d\right]^{1/2} \text{(m/s)} \tag{5}$$

where

σ: grain density (Kg/m^3)
g: acceleration due to gravity (m/s^2)

d: grain diameter (mm)
A: an empirical non-dimensional constant with a value of about 0.1.

3.2. *Velocity profiles under the threshold:* $U_* < U_{*t}$

The sand transport rate is zero under these conditions, all particles being at rest (Janin & Cermak 1988). Therefore, the vertical distribution of wind velocity can be expressed either by

$$U_z = \frac{U_*}{k} \ln \frac{Z}{Z_0} \tag{6}$$

or by

$$U_z = 5.75 U_* \log \frac{Z}{Z_0} \tag{7}$$

where

U_z: wind speed at a height Z (m/s)
Z: height above the ground (m)
k: von Kármán constant, usually 0.4 for all surfaces
Z_0: surface roughness height, $1/30 < Z_0 < 1/8$ of the particle diameter (Greeley & Iversen, 1985).

3.3. *Effect of mobile particles on wind profile:* $U_* > U_{*t}$

When the wind velocity increases beyond the threshold velocity U_{*t}, the drag and lift forces generated exceed the force of gravity and thus sand particles begin to move from the surface. Due to this movement, the blowing surface is modified. Bagnold (1941) shows that the modified surface wind profile is shifted up (for same sized sand) from the normal logarithmic profile, given by Eqns. 6 or 7, by $(Z' - Z_0)$, where Z' is a focal point (modified roughness height). Furthermore, Janin & Cermak (1988) show that the velocity profiles over the threshold are characterized by a velocity varying logarithmically with height below the lower 10% of the boundary-layer depth. Also, they state that at higher elevations, the velocity is higher than a value predicted by using Eqns. 6 or 7.

Bagnold (1941) suggests the following basic modified wind velocity profile, due to the interaction of transported particles with the blowing wind, to replace Eqns. 6 or 7

$$U_z = \frac{U_*}{k} \ln \frac{Z}{Z'} + U' \tag{8}$$

which can be rewritten as follows

$$U_z = 5.74 U_* \log \frac{Z}{Z'} + U' \tag{9}$$

where Z' and U' are called the "focal point" values and U' is the approximate threshold velocity for sand movement at height Z'. Zingg (1953) proposes a value of 0.375 for k in Eqn. 8, which is modified now to

$$U_z = 6.13 U_* \log \frac{Z}{Z'} + U'. \tag{10}$$

Considerable scatter appears in the data of focal point values measured by various experts in the sand field. For example, Zingg's (1953) experiment with five different sands obtained the following expressions for the focal point

$$Z' = 0.01\,\mathrm{d}\,(\mathrm{m}) \tag{11}$$

$$U' = 8.94\,\mathrm{d}\,(\mathrm{m/s}) \tag{12}$$

where d is the sand grain size (in mm).

Also, Kadib (1965) suggests values for Z' and U' as follows

$$Z' = 0.010668\,\mathrm{d}\,(\mathrm{m}), \qquad \text{if } d < 0.44\,\mathrm{mm} \tag{13}$$

$$Z' = 0.04572\,\mathrm{d}^3\,(\mathrm{m}), \qquad \text{if } d \geqslant 0.44\,\mathrm{mm} \tag{14}$$

$$U' = 9.144\,\mathrm{d}\,(\mathrm{m/s}) \tag{15}$$

A summary of some available measurements on the coordinates of the focal points is presented in Table 1. According to comprehensive field observational results, Horikawa (1987) argues that Zingg's (1953) empirical formula for the focal point value gives an approximate representative value in the scattered data and it is acceptable for engineering use.

Table 1. Summary of the available experimental data on the coordinates of the focal point U' and Z'.

Tested by	d (mm)	U' (m/s)	Z' 10^{-3} (m)
Zingg	0.200	1.798	2.28
Zingg	0.275	2.240	3.04
Zingg	0.360	3.352	3.65
Zingg	0.505	4.450	6.09
Zingg	0.715	7.924	21.33
Belly	0.440	3.962	4.39
Belly	0.300	2.743	3.04
Kadib	0.145	1.950	3.81

Source: Kadib 1965.

4. SAND TRANSPORT RATES

Wind tunnel experiments on sand movement have been reported by several investigators. Conclusive results were published by Belly (1962) when he compared his findings with previous measurements and with the semi-empirical theories developed, among others, by Bagnold (1941), Kawamura (1951) Zingg (1953), Kadib (1965) and Lettau & Lettau (1978). A brief account of the most commonly used formulae is given below.

On the basis of laboratory and field observations, Bagnold (1936) derived the following transport rate formula from a model of saltation motion, modified with a correction for surface creep

$$q = B\frac{\rho}{g}\left[\frac{d}{D}\right]^{1/2} U_*^3 \tag{16}$$

where non-dimensional B is a coefficient of order unity to be determined empirically, and D is the standard sand grain diameter (0.25 mm).

The coefficient B depends on the sorting of the sand and has the following values: $B = 1.5$ for nearly uniform sand, 1.8 for naturally graded sand such as dune sand, and 2.8 for sand with a broad grain size distribution.

Bagnold also reexpressed this formula assuming $d/D = 1$, $B = 1.8$ and $\rho/g = 1.25 \times 10^{-6}$ (g.s^2/cm^4) and introduced the concept of a threshold when $U_{100} > U_{100t}$ as

$$q = 1.5 \times 10^{-9}(U_{100} - U_{100t})^3 \text{ (g/(cm.s))} \tag{17}$$

where U_{100} is the wind velocity in cm/s at height 100 cm, and $U_{100t}$is the threshold wind speed in cm/s at height 100 cm.

Chepil (1945) indicates that the Bagnold formula without the factor (d/D) could be used to describe the transport rate of soils that have a broad grain size range

$$q = C\frac{\rho}{g}U_*^3 \tag{18}$$

The empirical coefficient C varies between 1.0 and 3.1 depending on soil texture.

Kawamura (1951) made theoretical and experimental investigations of sand transport rates by wind and proposed the formula

$$q = K_a\frac{\rho}{g}(U_* + U_{*t})^2(U_* - U_{*t}) \tag{19}$$

where K_a is a non-dimensional empirical coefficient. Kawamura conducted extensive experiments with sand of a mean diameter of 0.25 mm and estimated that $K_a = 2.78$.

Zingg (1953) measured transport rates for different grain sizes in a wind tunnel and obtained the following empirical formula

$$q = Z_g\frac{\rho}{g}\left[\frac{d}{D}\right]^{3/4}U_*^3 \tag{20}$$

where Z_g is a non-dimensional empirical coefficient equal to 0.83.

Kadib (1965) developed a theory for calculating the rate of bed-load transport under wind action, but since the general solution with this method is not closed, it is difficult to use for practical engineering purposes.

Hsu (1974) found that the sand transport rate by wind could be expressed as a function of sand particle Froude number

$$F = U_*/\sqrt{gd} \tag{21a}$$

$$q = HF^3 \tag{21b}$$

in which H is a dimensional empirical coefficient related to the mean grain size

$$H = [\exp(-0.47 + 97.7d)]10^{-5} \text{ (kg/(m.s))} \tag{22}$$

where d is sand particle size in mm.

Lettau & Lettau (1978) developed yet another model for the transport rate of sand by wind. The starting point of their model is a rigorous consideration of wind power, i.e., force (ground drag), multiplied by displacement per time unit. The force is given by the surface stress $\tau = \rho U_*^2$ (N/m^2), and the displacement per unit time is assumed to be proportional to the excess of the shear velocity above a local threshold value U_{*t}. Thus, the basic relationships between wind power and sand discharge are combined to give the following formulations

$$q = L\frac{\rho}{g}(U_*)^2(U_* - U_{*t}), \qquad \text{if } U_* > U_{*t} \tag{23a}$$

$$q = 0, \qquad \text{if } U_* \leqslant U_{*t} \tag{23b}$$

where L is a non-dimensional empirical constant that depends on the nature of the mobile surface and the availability of loose sand, which is to be determined from a field investigation. For example, Wippermann & Gross (1986) considered $L = 5.5$ for their experiments in Pampa de-La Joya (Peru). This model has been successfully used in several studies related to mobile sand phenomena (Wippermann & Gross, 1986).

Horikawa *et al.* (1983) have verified that most of the basic formulae are valid for well sorted sand. For sand widely distributed in grain size, however, the measured transport rate was found to be larger than that predicted. To account for the effect of the grain size distribution, Horikawa *et al.* (1983) introduced the expression

$$q = H_k\frac{\rho}{g}U_c^n\left[\frac{d_{50}}{D_{50}}\right]^{1/2}(U_* + U_{*t})^2(U_* - U_{*t}) \tag{24}$$

where H_k and n are empirical parameters, D_{50} is the median grain diameter of the underlying sand bed, and d_{50} is the median diameter of the blown sand. The uniformity coefficient U_c is defined as

$$U_c = \frac{d_{60}}{d_{10}} \tag{25}$$

where d_p is the grain diameter for which p percent of the sand weight is finer. Based on results of a field study using a trap in the form of a large trench, Horikawa *et al.* (1984) found it is necessary to allow the empirical coefficients in Eqn. 25 to vary to describe transport rates occurring over different time intervals of the observation period. It was found that the value of H_k has to be reduced when wind is strong and increased when it is weak.

As can be seen, many alternative sand transport formulae are found in the literature. Unfortunately, all the formulae show considerable differences in their results, illustrating the difficulty in obtaining accurate transport measurements either in the field or a wind tunnel. Most aeolian sand investigators related this difficulty to the trap efficiency (comparing various traps they found that overall efficiency of some was less than 60%) and the formation of ripples which have feedback into the transport process (McEwan, 1991).

5. FACTORS AFFECTING SAND MOVEMENT

Wind is the main factor responsible for sand movement which does not depend only upon the horizontal wind velocity but, to a large extent, is controlled by the strength of upward rising currents of air. Besides wind, there are other factors, the geomorphology and topography of the area for example, that influence sand drift. Particle size is also important since the wind can carry only a certain size of sand. Moisture content also affects sand movement. An increase in the moisture content reduces sand movement. Another important factor affecting sand movement is the extent of vegetative cover (Al-Sari & Uddin 1981).

Under actual field conditions, the sand transport rate cannot be predicted solely from the above equations. This is because of the extremely complex interactions and interdependence of the various factors involved in the phenomenon.

In the following sections, the effects of some natural factors on sand movement are given.

5.1. Effect of Surface Roughness

The effect of surface roughness on sand transport is important. This is mainly due to local modifications of U_* near roughness elements and the ability of a given wind to move sand grains from the surface. The most important natural control on the surface roughness is the vegetation. The main impact of vegetation on the sand movement rate is closely related to the modification of the wind flow and its aerodynamic characteristics. This modification, however, is difficult to assess by theoretical approaches, and it is not easy to generate a realistic model of vegetation for wind tunnel investigations (Omar *et al.* 1989).

Several studies undertaken under controlled field conditions have been reported in the literature (Deacon 1949; Tanner & Pelton 1960; Hesp 1981). It was found that the roughness height, Z_0, changes with vegetation height and wind speed. Over tall grass (60 to 70 cm), the Z_0 value changed from 9.0 cm at a wind speed of 1.5 m/s to 3.7 cm at a wind speed of 6.2 m/s. These wind speeds are recorded at 2 m height. Over short grass, the reduction in resistance is less pronounced. It is believed that the change in resistance over tall grass is the result of the blades of grass bending over with the force of wind. To consider the effect of vegetation on a wind profile, the following formula has been suggested

$$U(Z) = \frac{U_*}{k} \ln \frac{(Z - d')}{Z_0} \tag{26}$$

where d' is the displacement height, an empirically derived variable accounting for the effective height of the canopy.

Equation 6 has been substantiated by a series of field trials, and it was found by Kotoda (1979) that

	U_* (m/s)	Z_0 (m)	d' (m)
For short grass (1–5 cm)	0.33	5×10^{-3}	0
For tall grass (60–70 cm)	0.5×10^{-2}	0.3×10^{-2}	0.3

5.2. Effect of Surface Topography

According to Omar *et al.* (1989), there have been few studies estimating the transport rate of sand along non-horizontal or sloping surfaces. The formula that relates the sediment transport rate on a sloping surface to that of an equivalent rate on a flat surface was proposed by Howard *et al.* (1978)

$$q' = \frac{q}{\cos\theta(\tan\alpha + \tan\theta)} \tag{27}$$

where

q' = sediment transport rate on the sloping surface
q = equivalent rate on a flat surface obtained by conventional formula

θ = slope of the surface in the direction of transport
α = angle of repose of sand (about 30°–35°)

6. SAND TRANSPORT MODEL

A mathematical model in the form of a FORTRAN computer program has been developed, based on equations of Bagnold (1954), Kawamura (1951), and Lettau & Lettau (1978). The model predicts the amount of sand flux in each direction (8 or 16 sectors) per one meter length for a specific period. The following steps should be taken to run the model:

Step 1.
Collect wind-speed data over the past years (usually at standard 10 m height) and analyze data for 8 or 16 sectors.

Step 2.
Determine the mean grain diameter of the sand particle by sieve analysis.

Step 3.
Estimate the focal point values Z' and U' either by using the expressions of Zingg (1953) or Kadib (1965).

Step 4.
Find the threshold shear velocity of the sand grain, U_{*t}, from the curve of Iversen *et al.* (1976), shown in Fig. 1. For an alternative value, use Eqn. 5.

Step 5.
Select a transport formula and determine its empirical coefficient by field investigation.

Step 6.
To account for the effects of surface topography and surface roughness on the sand transport rate, obtain the following parameters from the field: Θ (slope of the surface in the direction of sand transport) and d' (effective height of the canopy).

7. APPLICATION OF SAND TRANSPORT MODEL

The sand transport model is used to estimate the amount of sand drift potential in Kuwait. Estimates of sand drift were predicted using the average of 27 years of wind data collected at Kuwait International Airport at a height of 10 m (Fig. 2). Khalaf *et al.* (1990) obtained the average mean grain diameter, Md_{50}, of Kuwait aeolian sand from Table 2. Its value is 0.27 mm. This value was used in the model as input.

Horikawa (1987) argued that the formulae of Zingg (1953) for the focal point value, U' and Z', give an approximate representative value in the scattered data and concluded that his formulae are acceptable for engineering use. Thus, Eqns. 11 & 12 were used to obtain the focal point values. Based on the focal point values and the mean sand diameter determination, the shear velocity U_* was calculated using Eqn. 8 or 9. The threshold shear velocity of sand grain U_{*t} was calculated using Eqn. 5.

To predict the sand transport rate in Kuwait, three sand transport formulae were

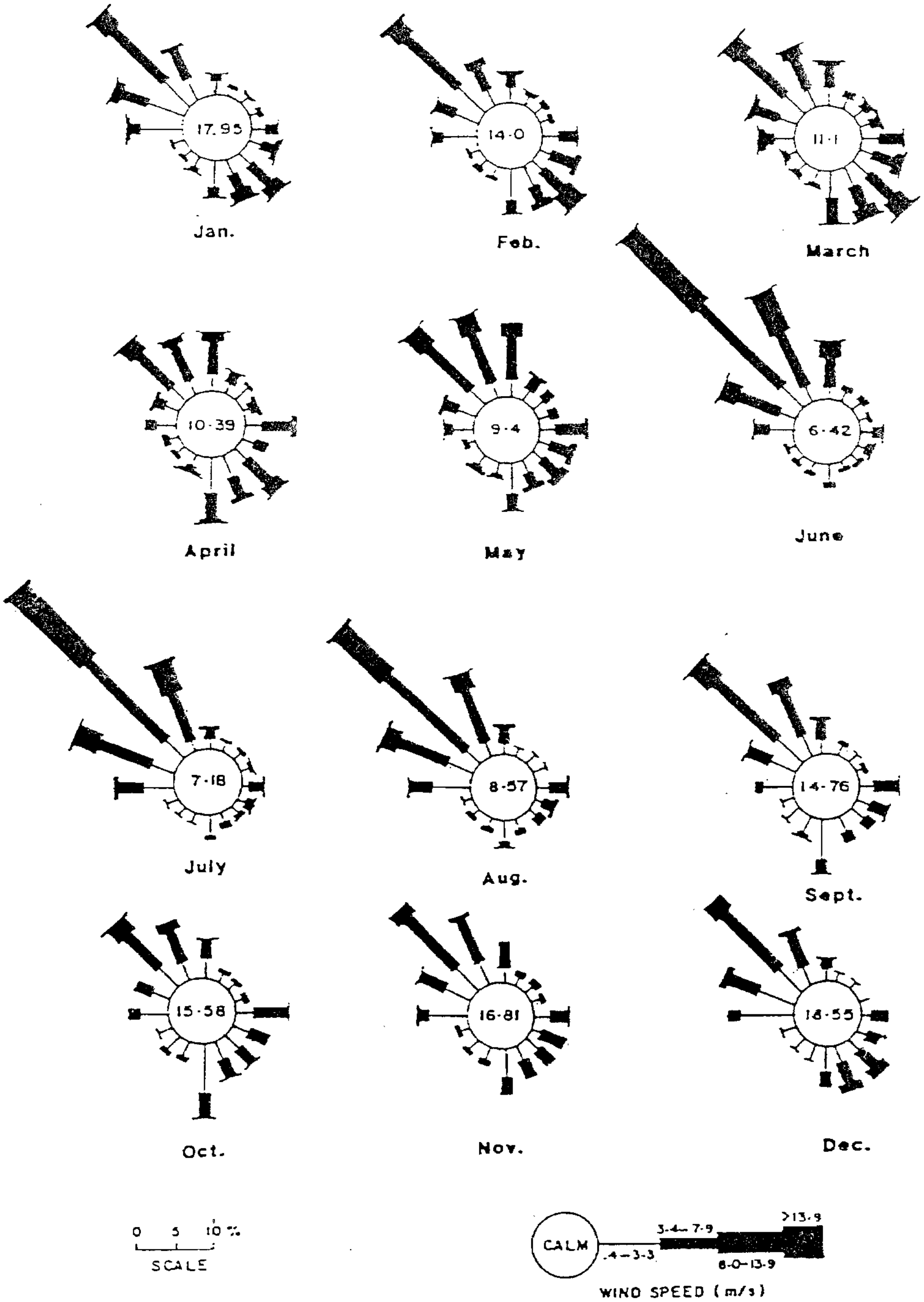

Fig. 2. Monthly wind rose for 1962–1989 at Kuwait Airport.

Table 2. Average statistical size parameters of the various types of aeolian sediments in Kuwait.

Types of aeolian sediment	Number of samples	Size fractions % (mm)							Size parameters		
		G	VCS	CS	MS	FS	VFS	ST	Mz mm	SK	K
Active sand sheet	101	0.4	3.0	16.0	39.6	25	12	4.0	0.26	SFS	L
Smooth sand sheet	48	8.2	13.8	18.0	22.0	20	15	3.0	0.45	FS	P
Rugged vegetated sand sheet	15	0.8	7.0	24.2	31.0	24	10	3.0	0.39	SFS	M
Wadi fill	34	0.1	2.0	14.0	27.6	31.3	22	3.0	0.23	SY	P
Sand dune	81	0.0	0.0	6.8	52.8	30	9	1.4	0.25	SFS	L
Desert sand drift	8	0.0	2.0	10.7	50.5	24	10	2.8	0.28	SFS	M
Coastal sand drift	47	0.0	0.0	7.1	39.7	33	18	2.2	0.25	SFS	P

G = >2.0 mm, VCS = 2.0–1.0 mm, CS = 1.0–0.5 mm, MS = 0.5–0.25 mm, VFS = 0.25–0.125 mm, ST = <63 μm, SFS = strongly fine skewed, FS = fine skewed, SY = symmetrical, LS = leptokurtic, P = platykurtic, mesokurtic.
Source: Khalaf *et al.* 1990.

applied. These were the formulae of Bagnold (1954), Kawamura (1951), and Lettau & Lettau (1978), with empirical coefficients of 1.8, 2.78 and 5.5, respectively. Then, the mean outputs of the three equations were taken to be the predicted value. The sand transport rate in Kuwait was calculated assuming a flat ground surface, barren of vegetation. This assumption is in close agreement with the general features of the surface topography and roughness of Kuwait. To account for the variability of wind speed with time and direction, the model is applied to estimate the sand transport rate based on data available for each month of the year. Furthermore, since wind blows from different directions, data available for wind speed and frequency in the 16 different directions of the wind rose are used according to the following equation

$$q_\alpha = \Sigma_u q_{u,\alpha} \tau_{u,\alpha} \tag{28}$$

where the summation is taken over the different wind speeds in a particular direction α, and $\tau_{u,\alpha}$ is the estimated time period during which the wind velocity u is blowing in direction α. $q_{u,\alpha}$ is calculated using one of the sand transport formulae. This process is repeated for all 16 wind rose directions. Thus, the corresponding potential sand drifts in these directions are estimated.

Once all necessary input into the model was calculated, the calculations for the potential sand drifts were made. These calculations present the amount of sand transported from each direction sector on a one meter length per one month period in the Kuwaiti desert.

The results of the model indicate that the net transport of the sand was generally from the western sectors to the eastern sectors, and that the amount of sand transport is much higher during summer than winter months (the difference is up to a factor of 12). The highest average net flux amount of sand transport is 18,620 kg/(m.mo) in June and lowest average amount of sand transport is 592 kg/(m.mo) in December

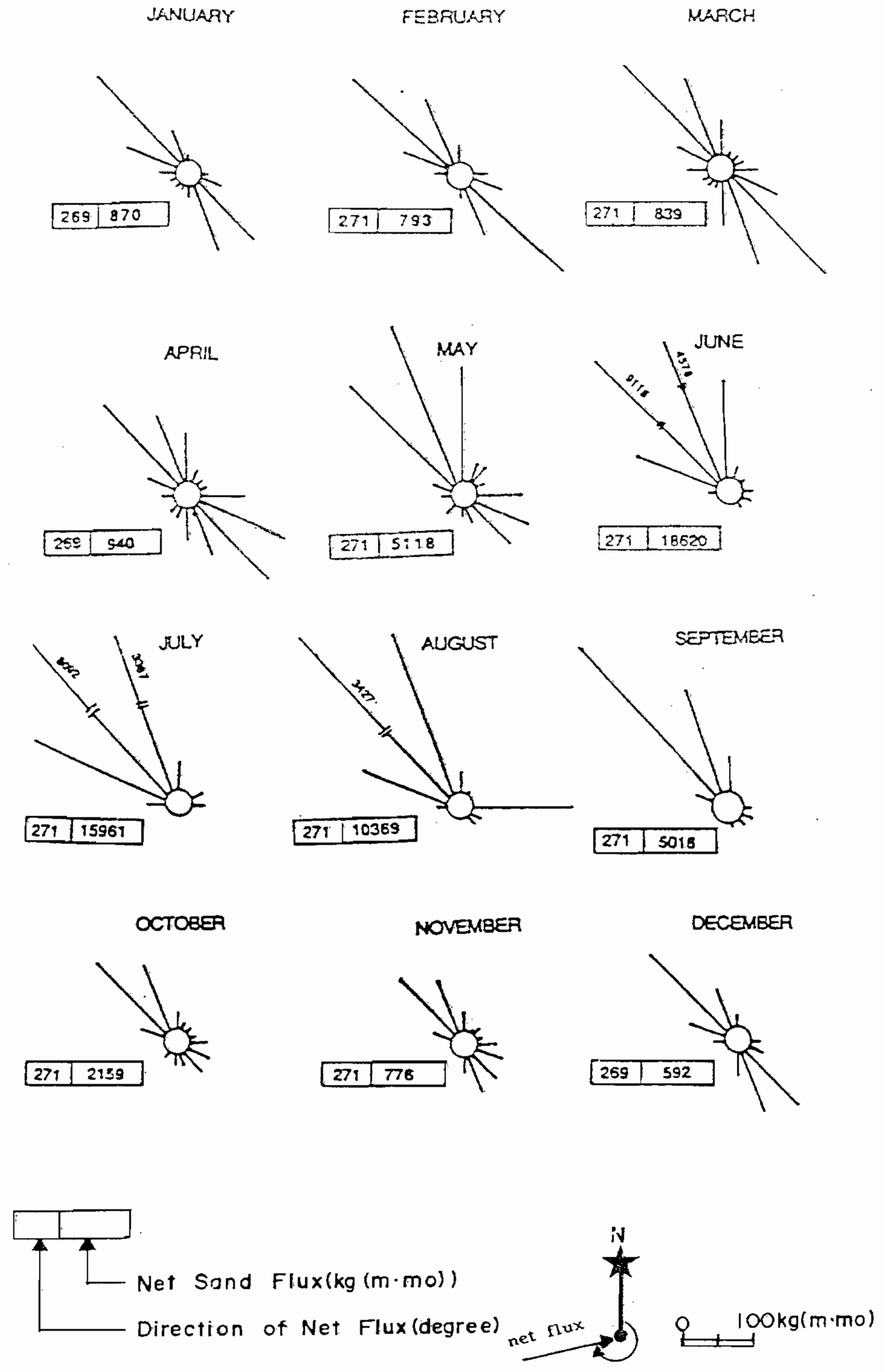

Fig. 3. Monthly sand flux potentials and their net values in Kuwait.

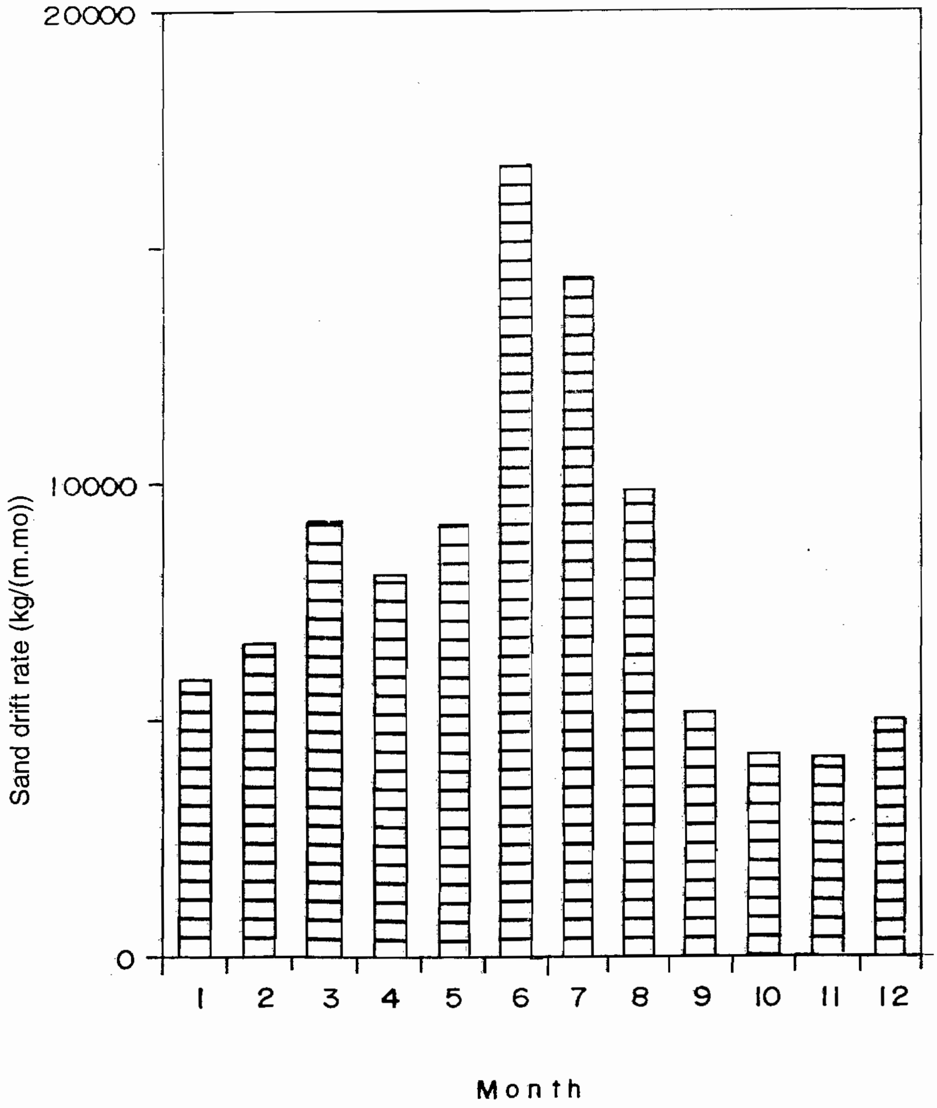

Fig. 4. Monthly sand drift in Kuwait.

(Fig. 3). The average annual amount of sand drift in Kuwait is calculated from Fig. 4 and is found to be 99,596 kg/(m.yr). This information indicates that Kuwait faces severe sand-encroachment problems.

8. CONCLUSIONS

The model results indicate that the major encroachment of sand in Kuwait takes place during the summer months (May, June, July & August) mainly from a northwesterly direction. This trend is in general agreement with the known wind characteristics in Kuwait, which are high in NW, W and SE sectors than in the others and more active during the summer months. The average total drift that occurs in Kuwait during this period is estimated by the model at about 51% of the annual total drift.

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تطبيق النموذج الحسابي لانتقال الرمال على بيئة الكويت

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خلاصة

تم تقدير معدل انتقال الرمال في الكويت بوساطة نموذج حسابي لتحرك الرمال يحسب النموذج امكانية اندفاع الرمال في كل اتجاه ويبين المعدل الكلي لحركة الرمال خلال فترة زمنية محددة.

يبين النموذج ان الكويت معرضة لمشاكل جسيمة لزحف الرمال حيث يقدر المعدل السنوي الاجمالي لزحف الرمال بأكثر من ٦٢,٠٠٠ (م. سنة)/كلغ باتجاه الجنوب الشرقي.