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Field assessment of aeolian sand processes and sand control measures in Kuwait

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Abstract

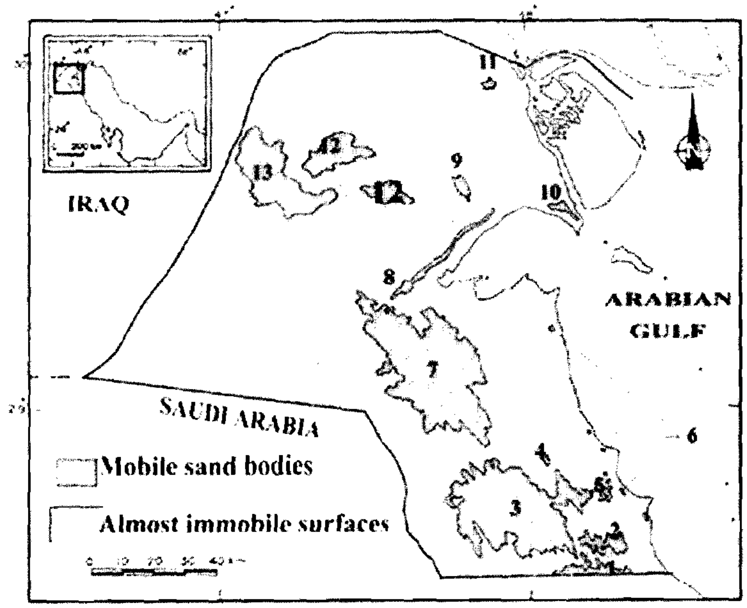
In Kuwait, the scarcity and irregularity of rainfall, the availability of sand supply areas and the prevalence of strong northwesterly winds significantly influence the stability of the fragile ecosystem. The misuse of land and irrational exploitation of natural vegetation and soils have accelerated wind erosion. Sand encroachment over development facilities is a serious environmental and socio-economic problem. To minimize sand encroachment problems, several measures are applied. These include physical, biological and chemical measures. In some cases, ecologically insignificant and economically unfeasible measures are adopted.

Keywords: Aeolian sand; Erosion; Problem; Control.

INTRODUCTION

Kuwait, which covers an area of 17,818 km^2, witnesses active aeolian processes that are attributable to numerous factors, the most significant of which are the scarcity and irregularity of rainfall (annual rainfall varies between 28.3 and 260.2 mm), the prevalence of strong northwesterly winds (sometimes reaching 30 m/s) during the dry season (i.e., May–September), the rarity of water supplies of suitable quality, the availability and variability of detrital materials (sources of drift sand), and the location upwind of the high deflational area of the Mesopotamian flood plain in southern Iraq. Since 1993, the natural pattern and rate of sand transport from the Mesopotamian flood plain has been highly disturbed. This is attributable to the construction of the security fence along the Iraq-Kuwait border. This fence consists of a trench, about 5 m in width and 3 to 5 m in depth, followed by a 2 to 3 m high sandy berm.

In Kuwait, some 13 mobile sandy bodies were recently mapped by the present authors (Fig. 1). The majority of these bodies encroach on desert facilities. As indicated from the recent field surveys and the analysis of Landsat TM (1989 and 1995), spot images (1991–1992) and aerial photographs (1992 and 1997), four zones of sand encroachment occur in Kuwait. Each zone has been classified according to the degree of sand encroachment depending on morphological features, nature of surface sediments, relief, and surface roughness. Figure 2 shows these zones, which are termed severe, moderate, slight and rare sand encroachment zones.



1 - Al-Nuwsib - Al-Wafra sand sheet
2 - West Al-Khiran sand sheet
3 - South Burgan sand sheet
4 - Al-Gurain sand sheet
5 - Stabilized sand ridges
6 - Coastal sand drifts & dunes
7 - Kabd sand sheet
8 - Jal Az-Zour falling dunes & olluvial fans
9 - Umm Al-Aish sand dunes & sheet
10 - Ras As-Subbiyah sand dune & sheet
11 - Umm Nega sand dunes & sheet
12 - Accumulated sand Associated with quarrying tailing
13 - Al-Huwamiliyah complex sand dune belts & sheet

Fig. 1. Identifying mobile sand bodies in Kuwait, using Landsat^{TM} and field observation.

The comparison of aerial photographs and Landsat images from different periods (1989–1995) indicated that mobile sands are progressively expanding. As a result of the Gulf War (1990–1991) and related activities, newborn sandy bodies are developing in several areas, e.g., Ras As Subiyah (Fig. 1) and the southwestern portion of Kuwait, indicating that the desert of Kuwait is progressing toward severe degradation.

Sand encroachment in Kuwait is a serious economic and social problem (Al-Awadhi 1988). Continuous sand drifts in Kuwait form large sand accumulations up to 2–4 m high in and around some man-made constructions. These sand accumulations sometimes block the entrances to desert installations. Other problems related to sand drifts in the Kuwaiti desert may also be noted. These include: (a) huge accumulations of sand around fences that subsequently collapse from the weight of the sand, constituting security risks for sensitive installations since unauthorized persons, camels or sheep can then easily enter the sites; (b) machinery and equipment

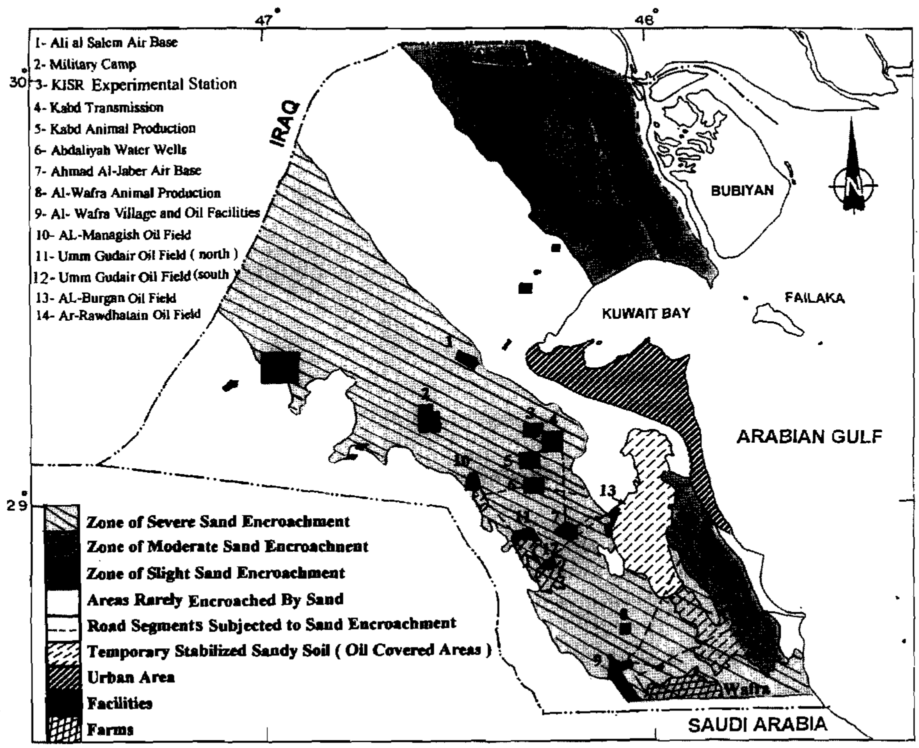


Fig. 2. Zones of sand encroachment in Kuwait.

suffer from corrosion and damaged parts due to drifting sand; and (c) loss of fertility and productivity of cultivated soil, as in the case of the Al-Wafra farms in southern Kuwait and the Al-Abdali farms in northern Kuwait.

Losses caused by sand encroachment have been evaluated by the authors, in terms of time and money, for most of the desert developments of Kuwait, especially for those installations located within the main passage of the wind corridor (i.e., the severe encroachment zone, Fig. 2). The Ministry of Public Works spends about a quarter million Kuwaiti dinars (KD 1 $\simeq$ US$3.3) yearly to clear sand accumulation from highways. Some 80% of the sand clearance is from the Sixth Ring Motorway which extends west of Kuwait City. Within the period from 18 April 1993 until 12 February 1995, the total amount of sand removed from the main highways was 1,559,710 m^3 at a total cost of KD 510,636.

According to Ahmed *et al.* (1996), the total sand removed from oil installations in the years 1989, 1993, 1994 and 1996 was 1,417,725 m^3 at a total cost of KD 1,003,369. Within the period from April 1993 until June 1995, the total amount of sand removed at the Ali Al-Salem air base was 1,301,400 m^3 at a total cost of KD 100,000. The electric power stations also suffer from about 85,000 m^3 of encroached sand every year. A large amount of sand was removed from such installations after Kuwait's liberation (26 February 1991) at a total cost of KD 68,000 for only two years.

The severity of the sand encroachment problem in Kuwait has prompted the adoption of different philosophies of sand control, which are not appreciated scientifically (Al-Awadhi 1989, Khalaf & Al-Ajmi 1993). The techniques used to control mobile sand in Kuwait consist of physical, chemical and biological measures.

Mathematically, sand will be deposited if $\partial q/\partial x$ is less than zero, where q is the rate of sand transport per unit time per unit width. The net rate at which sand is deposited in each unit area is $(q_s - q_o)$ where q_s is the rate at which sand is being supplied to the unit area, and q_o is the rate at which sand is leaving it. Thus over any period, Δt, the weight of net deposition is $(q_s - q_o)\Delta t$, and the volume change of sand present in the unit area is $(q_s - q_o)\Delta t/\gamma$, where γ is the bulk specific weight of the sediment.

Assuming that the sand is evenly distributed in a plane over the unit area (control volume), the local increase in the height of sand accumulation, z, can then be calculated based on the unsteady continuity equation given by:

$$y\ \partial z/\partial t + 1/\gamma(\partial q/\partial x) = 0 \tag{1}$$

where y is the width of unit area (Δy).

Equation 1 can be re-expressed using the finite difference method as:

$$\Delta z = (q_s - q_o)\Delta t/(\gamma\Delta y\Delta x) \tag{2}$$

where Δz is the rate of change of the sand accumulation profile.

Although considerable literature already exists concerning the deposition of sand around various types of fences in coastal areas (Savage & Woodhouse 1968, Manohar & Bruun 1970, Phillips & Willetts 1979, Knutson 1980), comparatively little work has been undertaken in open desert regions of the Middle East like those that exist in Kuwait (Kerr & Nigra 1952, Watson 1985). Thus this paper aims to consider the problems associated with blown sand and review various factors controlling aeolian processes in the State of Kuwait. In addition, the existing sand control measures in the country are reviewed and evaluated.

FACTORS CONTROLLING AEOLIAN PROCESSES

Natural Factors

The rate and pattern of sand movement are controlled by a wide variety of natural conditions.

Surface sediments. The desert ecosystem of Kuwait comprises about 80% of the state's total area. The majority of this ecosystem is vulnerable to wind erosion and sand encroachment. The desert of Kuwait is covered by several types of surface sediment (Khalaf *et al.* 1984), the most significant of which are (a) aeolian deposits; (b) residual gravel deposits; and (c) playa deposits. Aeolian sand deposits are the most frequent and cover more than 50% of the surface of Kuwait. The residual gravels and playa cover about 35%. The rest of the country is covered by coastal deposits, exposures of sandstone, clay and calcareous rocks.

In general, the surface sediments of Kuwait may be divided into two distinctive zones, namely, a northern zone characterized by the predominance of gravel lag cover (desert pavement) and a southern zone dominated by sand sheets. The northern zone extends about 53 km southwards from the Iraq-Kuwait border. From east to west, this zone stretches for about 95 km. It is interrupted by a series of ridges and depressions. The southern zone extends in a NW-SE direction for about 105 km. Its average width is about 25 km. This zone is interrupted by low hills and shallow depressions. The contribution of the northern zone to the aeolian sand budget is limited; however, the lag pavement acts as a hard crust that accelerates the movement of saltating sands which are driven from the southern desert of Iraq and act as transit sand. The near absence of perennial vegetation on the gravel lag allows the free movement of saltating sand on its surface. Saltating sand in this zone reaches more than 2 m in height. The southern zone with sand sheets acts as a local source for mobile sand which does not allow fast transport of aeolian sand (Khalaf & Al-Ajmi 1993).

Under the prevailing arid conditions, aeolian processes are extremely active, particularly in the summer season. Active aeolian processes are attributed to the combined influence of the following factors: (a) the scarcity and irregularity of rainfall; (b) the occasional occurrence of runoff with heavy loads of out-washed materials, i.e., a source of shifting sands after intensive rainfall (i.e., 30–40 mm in 2–3 hr); (c) the occurrence of an almost rainless, hot, dry season (i.e., May–September) during the period of prevailing northwesterly winds with maximum speeds (i.e., 30 m/s); (d) the high susceptibility of the majority of surface sediment types to wind and water erosion (i.e., the local sand supply); (e) the location of Kuwait downwind of the high deflational area of the Mesopotamian flood plain (i.e., a regional sand supply); and (f) the near absence of effective biological soil stabilizers (i.e., deep-rooted shrubs and trees) due to the unfavorable soil and water potentials.

Wind. Wind is the main factor responsible for sand movement, which largely depends upon the horizontal wind velocity. The deflated sand in Kuwait migrates downwind under two systems of seasonal winds, i.e., the prevailing northwesterly and, to a lesser extend, the southeasterly. The prevailing winds in Kuwait are from the northwesterly quadrant throughout the year, but are more frequent ($\approx 60\%$) in summer. Statistical analysis of wind data collected during 1957–1997 indicates the average wind speed in Kuwait is about 4.3 m/s, with 16% of the year having calm weather (Khalaf & Al-Ajmi 1993, Al-Awadhi & Cermak 1995, Misak *et al.* 1999). The average monthly wind speed reaches its highest in June (5.1 m/s), and its lowest in January (3.2 m/s).

Surface roughness. The most important natural control on the surface roughness in Kuwait is the micro-relief of the flat, residual gravel deposits in the northern zone. The main impact of such micro-relief on the sand movement rate is closely related to the modification of the wind flow and its aerodynamic characteristics. In this process, the finer particles are removed, except those hidden on the lee-side of gravel grains, leaving a concentration of residual gravel. If the shear stress exceeds the threshold (i.e., wind speed >5.5 m/s), silt and clay particles quickly blow away forming a dust storm hundreds of meters high. Vortices in the storm can be seen as dark columns advancing in front of the cloud, and blowing dust in an explosion-like pattern.

Rainfall. Field and experimental observations have shown that surface moisture content is an extremely important variable controlling aeolian sand transport in Kuwait (Al-Awadhi & Cermak 1995). The surface moisture content in Kuwait is very low because of the dry, hot summer and scant precipitation in the cool season.

During the period from 1957 to 1998, the total seasonal rainfall fluctuated between 28.3 and 260.2 mm with an average of 112 mm/yr. Irregularity of rainfall has a direct influence on sand transport rate. During wet periods, e.g., 1995–1996 when the average seasonal rainfall was around 251.5 mm, the soil moisture was higher than usual and supported the growth of dense annual grass. The roots of these grasses penetrated 10–15 cm into the soil. The vegetation stabilized the mobile sands and almost zero values were recorded for sand transport in the summer of 1996. On the other hand, during the dry periods, e.g., 1988–1989, when the average seasonal rainfall was around 31.6 mm, the annual vegetation was almost absent. Accordingly, large sand transport rates were recorded in the summer of 1989 (Table 1).

In a study by Al-Awadhi & Cermak (1998), the drift rate of sand in the Managuish oil field (severe encroachment sand zone) was measured in eight directions using a modified directional sand trap similar to that designed by Fryberger & Ahlbrandt (1980). The grain size analysis of nine deposits in the site reveals a large amount of fine sand, about 32.86%, and a smaller amount of very fine and medium sand, about 19.93% and 15.02%, respectively. Table 1 presents the results of sand that drifted from eight sectors into the trap orifice (0.05 x 1.2 m) during each sampling period over one year. The results showed that much more sand was collected in the NW, W and SE sectors with only traces of sand collected from the remaining directions. This trend is in general agreement with the known wind characteristics in Kuwait, the wind being the strongest in the NW, W and SE sectors. Significantly, large amounts of sand were collected during the summer period, May to August, when active winds are relatively more frequent. The average total drift occurring during this period was determined to be 66% of the annual total drift. The annual total sand drift measured by the directional sand trap in the study area was on the order of 7.8×10^4 kg/m width/yr.

Socio-Economic Aspect

In the 1940s, the oil boom in Kuwait brought about economic changes that not only altered the traditional way of life, but also brought on urban development. Suddenly, Kuwait was faced with an increasing population that necessitated urban expansion (Table 2). This rapid population growth has warranted urban expansion, and a need for increased productivity to support it. As a result of this growth and socio-economic transformation a significant increase in the rate and the extent of sand encroachment is observed.

The extensive urban development in Kuwait has created a great demand for gravel aggregates by the construction industry. This has led to extensive exploration and exploitation of the aggregate deposits, especially in the northern part of Kuwait. The expected demand for gravel for the next 10 years ranges between 2.7 and 3.8 million cubic meters annually (Redha 1996). The total area of the existing gravel quarries is measured to be 383 km^2, which is equivalent to about 2.14% of the total area of the country. However, since October 1997 gravel quarrying from the Kuwaiti desert has been prohibited.

All of the gravel deposits are presented in relatively thin layers; therefore, the required quantities were produced by almost horizontal quarrying (Al-Bakri *et al.* 1988). According to Khalaf (1989) and Khalaf & Al-Ajmi (1993), gravel exploration has led to the following effects: (a) elimination of the vegetative cover

Table 1. Sand collection data from a directional sand trap in the Al-Managuish area.

Period and Date	Sand collected from 8 wind directions in gms								Total
	N	NW	W	SW	S	SE	E	NE	
05-23/07/89	31860	27500	211	3620	-	-	-	617	63808
23/07-13/08/89	20250	36200	8600	1400	780	200	260	2150	69840
13-21/08/89	Maintenance stop								
21-27/08/89	849	1990	-	-	-	-	-	253	3092
27/08-18/09/89	15900	26750	7250	1080	-	-	163	2890	54033
18/09-02/10/89	2900	750	-	-	-	-	-	2850	6500
02-15/10/89	4300	27500	770	-	-	-	-	700	33270
15-30/10/89	180	2170	123	-	-	-	-	-	2473
30/10-18/11/89	-	-	529	-	-	1480	-	-	2009
18/11-03/12/89	-	456	-	656	-	208	-	-	1320
03-18/12/89	-	2260	-	-	980	375	-	-	3615
18-30/12/89	-	1800	167	-	-	-	-	-	1967
30/12/89-15/01/90	815	6480	1030	-	478	820	-	-	9623
15-28/01/90	-	-	200	-	-	-	-	-	200
28/01-10/03/90	Maintenance stop								
10-25/03/90	-	553	-	1900	-	-	800	-	3253
25/03-15/04/90	-	200	850	740	2160	5760	1374	-	11084
15/04-06/05/90	356	556	-	-	-	-	-	-	912
06-26/05/90	2160	1800	508	-	-	-	-	-	4468
26/05-10/06/90	14400	28080	2880	-	-	-	-	-	45360
10-24/06/90	12240	23040	1080	-	-	720	-	-	37080
24/06-15/07/90	5760	32400	1650	-	-	-	-	-	39810
Total	111970	220485	25848	9396	4398	9563	2597	9460	393717

Table 2. Population dynamics in Kuwait (source: Kuwait Central Statistics Office).

Year	Population	Population density (person/km^2)
1910	35000	1.9
1935	75000	4.2
1950	100000	5.6
1957	206000	11.5
1988	1712133	96
1990	2100000	118
1995	1500000	84

and the associated fauna community on production sites and in surrounding areas; (b) removal of the gravel lag that used to cover the northern area of Kuwait and protected the underlying finer materials from wind action; (c) formation of sandy and silty tailings that are associated with gravel deposits in and around the gravel quarries; and (d) release of a huge amount of fine particles that can be easily airborne. (For example, dust from the Jal Al-Liyah gravel quarry northwest of Kuwait city can be seen from several kilometers away.) In addition, quarrying causes severe hydrologic disruption, i.e., loss of rainwater in the quarries and development of new sets of micro-drainage basins.

The off-road traffic activity associated with heavy-duty machinery and lorries transporting gravel from various localities in the desert to urban areas can be seen as scars across the desert on satellite imagery as no particular access roads are used. All of these mechanisms of land degradation not only produce surface erosion, but also alter the micro-relief, disturb the surface and damage the vegetation cover and, consequently, disturb wild fauna as well as the soil cover.

Recent field observations conducted by the authors indicated adverse changes in the physical properties of compacting soil by off-road transport; e.g., high bulk density, low infiltration rate (Fig. 3) and high water loss. Experiments show that the average volume of infiltrated water is 40 cm^3/min for compacted soil and about 80 cm^3/min for uncompacted soil. Reducing the rate of infiltration by 50% causes difficulties for plant roots in penetrating the top soil and for runoff water in moving and circulating in the soil.

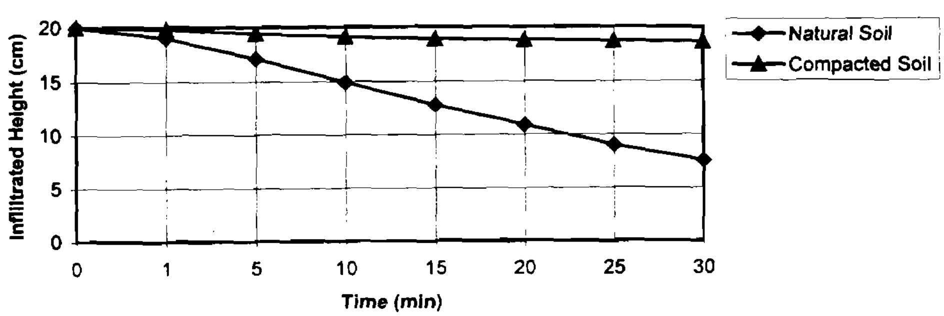


Fig. 3. Comparison between infiltration rates of compacted and uncompacted soil.

The sand encroachment problems are also augmented by uncontrolled over-grazing which increases dramatically every year. For example, the numbers of sheep in 1971–1972 and 1988–1989 were 89,758 and 230,812, respectively (Malik *et al.* 1994). The effect of over-grazing can be clearly seen in a protected area where the vegetation grows thick naturally (80–100% cover), whereas outside that area, the vegetation is almost extinct (0% cover in most cases). This obviously reduces the role of vegetation cover as an efficient barrier against mobile sand attack and enlarges the source area for sand drifting.

As stated by Misak *et al.* (1999), some 19 types of land use are identified in the highly fragile desert ecosystem of Kuwait. In this ecosystem, overgrazing is the primary cause of land degradation in general and soil erosion in particular. It affects about 60% of degraded lands. Spring camping in open desert areas follows overgrazing as the second most important mechanism of land degradation. It affects some 7–10% of degraded land. Gravel quarrying, off-road transport and military maneuvers affect the rest of degraded lands.

War Activities

In addition to traditional human activities, war machinery and ground fortifications used during the Gulf War (2 August 1990–26 February 1991), and its consequences (1990–1994), truncated and bisected the desert surface. Fine sediments were exposed to surface winds, and new sand dunes accumulated in areas like Al-Subiya. Moreover, huge amounts of soil were excavated to construct berm-trench defense systems and roads. The Iraqi troops constructed some 727,995 bunkers and trenches in different areas in Kuwait and the total length of these systems exceeded 300 km (Ministry of Defense of Kuwait 1999, personal communication). On the other hand, the amount of excavated sediments resulting from the formation of a road base reached 4000 m^3/km length (Al-Ajmi *et al.* 1994). The excavated sand is now free to be transported southward by the wind, and during the rainy season, water continuously erodes the loose sand, channeling it to lower lying areas. Evaporation rates are high, and the sand is once again susceptible to wind transport.

The oil lakes and tarmats which resulted from the destruction and igniting of 727 oil wells in Kuwait caused observable changes in soil cohesion that directly affected the rate of sand transport. The lakes and the tarmats, which cover an area of about 1000 km^2, act as temporary stabilizers for the underlying sand soils.

CONTROL OF SHIFTING SAND IN DIFFERENT SECTORS OF KUWAIT

Protection of Desert Settlements

In Kuwait, several desert settlements are subjected to sand encroachment. A combination of biological and mechanical methods are applied to control the sand drifts threatening settlements such as Umm Al-Hayman in the south and Jahra City in the north. Multiple rows of green belts of *Tamarix, Acacia, Ziziphus, Prospis, Pheonix dectylon, Albizzia* and *Eucalyptus* that are suitable for cultivation under Kuwait's climate have been established around such settlements. The plants are protected from moving sand by corrugated metal sheets or wire fences supporting a rubber mesh of 50–70% porosity. Sometimes longitudinal or transverse trenches 5 m wide

× 3 m deep are dug to trap the sand, or artificial sand ridges 2 m in height are built perpendicular to the prevailing wind direction. The space between these different methods ranges from 5 to 10 m.

Protection of Highways

In 1987, the Ministry of Public Works applied a multi-fence system along part of the Sixth Ring Motorway to the north of Jahra City, which is a region of strong winds. The protection was applied to a total length of 11 km on the northern side of the highway. Each of these fences was set up at a right angle to the prevailing NW winds. The fences were made of fabric with 50% porosity while their height was 2 m. Field investigations showed that the fences trapped sand efficiently on both sides up to their tops (Fig. 4).

Different methods are used to stabilize highway slopes against sand erosion by wind or water. In this case, the checkerboard system, rectangular (160 x 30 cm) micro-windbreaks made of 20 cm high precast concrete blocks, is widely used. However, covering highway slopes with plants is still considered the most effective method of sand control in Kuwait. Sometimes chemical stabilizers are added to protect the vegetation.

A popular method of protecting roads in open areas in the desert is by constructing sand ridges on one or both sides of the road. This method has been applied to a part of the Al-Wafra-Mina Abdullah road in the southern part of Kuwait. A sand ridge, if erected properly, can be a good sand trap, but some trapped sand may extend to the protected road downwind (Fig. 5).

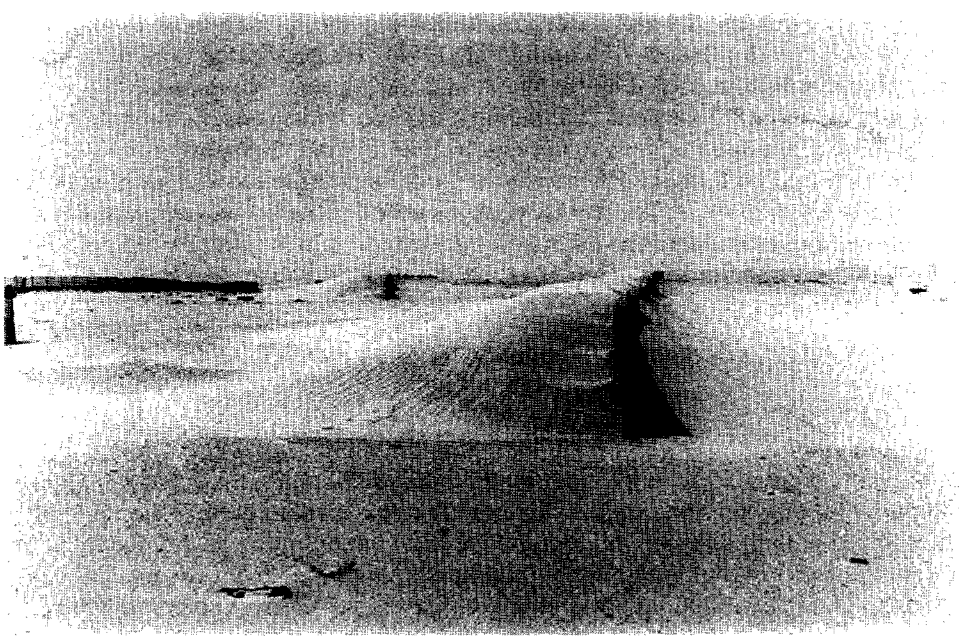


Fig. 4. Sand accumulation on a porous fence along the highways in the north part of the country

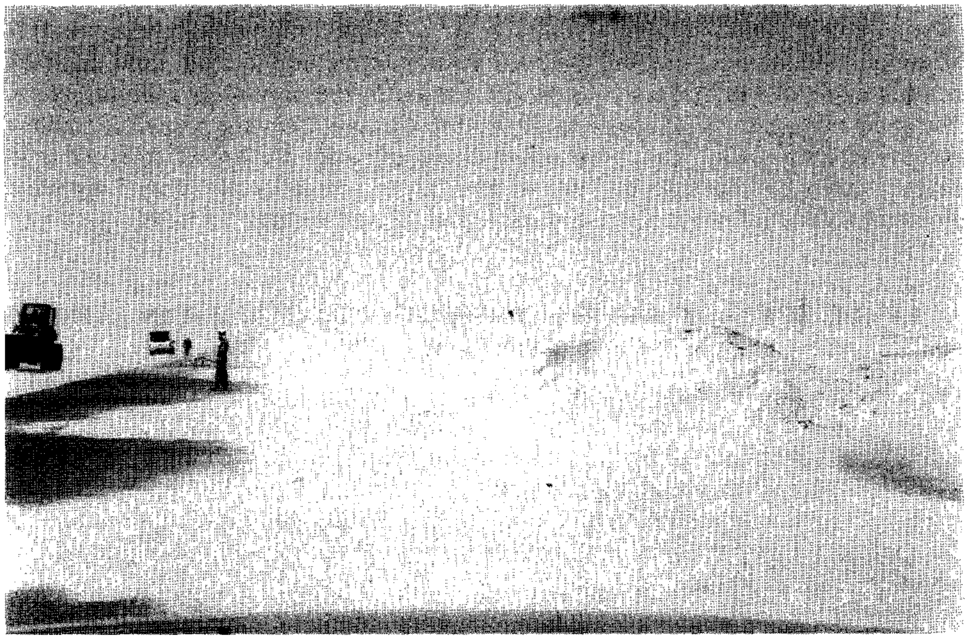


Fig. 5. Sand accumulation on a desert road due to improper erection of a sand ridge along the road.

Protection of Agricultural Areas

Agricultural areas are highly vulnerable to sand encroachment problems. Field investigations in these areas, namely at Al-Abdali in the north, Al-Wafra in the south, and Sulaibiyah in the center, showed similar sand control measures but different applications. However, artificial sand ridges 1–2 m in height and two-row green belts, besides other techniques discussed previously, are commonly applied.

Biological control measures adopted at different agricultural areas included belts consisting of one to two rows of *Tamarix aphllae, Eucalyptus* sp., and *Acacia* sp.. The height of the trees varies between 3 and 8 m and the porosity from 25 to 50% in most cases.

Protection of Isolated Installations

Construction of sand ridges perpendicular to the N and NW winds is a common mechanical protective measure against sand encroachment for most huts, police posts and fire stations in Kuwait's desert. At some of these sites, e.g., air-bases, the sand ridge technique and biological method are used with another mechanical method that consists of setting up used water tanks (125 × 125 × 125 cm) in a row perpendicular to the prevailing wind direction. The tanks act as an impounding fence and cause deposition of sand before it can reach the protected target.

Protection of Oil Gathering Centers and Wells

Many oil gathering centers and production sites are protected from sand drifts by multiple rows of sand ridges constructed normal to the prevailing wind direction. The sand ridges are 2–3 m high and 10–50 m upwind from the protected centers and about 50 m away from each other. Some oil wells are protected from sand encroachment by constructing curved sand ridges normal to the prevailing wind direction (NW); other wells are not protected by any means.

EVALUATION OF THE PRESENT TECHNIQUES USED IN SAND CONTROL

The accumulation of sand around an obstacle is impossible without sand transport. When an obstacle is presented to such an approach flow, the transport rate changes and creates a pattern of either erosion or deposition. This change may occur in time as well as space. Erosion occurs where the amount of sand transported by saltation increases with the downstream distance (i.e. $\partial q/\partial x > 0$), and deposition occurs where the opposite is true (i.e. $\partial q/\partial x < 0$). In stable conditions (i.e. $\partial q/\partial x = 0$) neither deposition or erosion occurs.

The efficiency of the present control measures adopted by several installations in Kuwait varies depending on their design, materials and location, as well as the local conditions. The current approach to controlling shifting sands is based on settling the sands (i.e. to achieve $\partial q/\partial x < 0$) against mechanical and/or biological barriers (such as artificial fences, sand ridges and tree belts) before the sands reach the point objects. Generally, these on-site measures are ineffective as they are restricted to settling areas. In some cases, for example, the oil or water wells which were protected are found to have accumulated sand, whereas the unprotected wells were almost free of sand; in the latter case sand drifts away freely.

Measures to reduce the sand supply at the transportation and source areas (i.e. to achieve $\partial q/\partial x > 0$), are almost never applied, except in the pilgrims' camp to the north of Jahra City. In this camp, the open area facing the prevailing wind direction is protected by scattering used asphaltic material (nonerodible elements) over the surface (Fig. 6). These materials reduce sand erosion by wind by absorbing some of the disturbing forces of the wind and incoming saltating sand that would otherwise move the erodible surface sediments. The main influence of nonerodible elements on erosion is sheltering. The extent of reduction in erosion, or the degree of sheltering, largely depends on the partition of the wind forces between the erodible and nonerodible elements (Gillette & Stockton 1989).

In a stable condition, i.e. $\partial q/\partial x = 0$, if sand drift offers no problem, no stationary solution should, therefore, exist. Most roads in the Kuwaiti desert, for example, are constructed in a stable erosion/deposition environment and sand settlement on the road is only seen when high surface roughness exists upwind of the road or the cross- sectional slope of the road faces down with respect to the blowing sand. Therefore, sand drifts and other adverse occurrences on Kuwait's roads can be minimized, first, by proper route selection. This is achieved by making the maximum possible use of experience in the design, construction and operation of roads in sandy deserts. Roads in the Kuwaiti desert have to be built taking into consideration the relief of the land because the type of relief may influence sand accumulation.

Fig. 6. Used asphalt scattered of over the sand surface to stabilize the local sand.

The creation of artificial sand ridges to protect sites from mobile sand encroachment is a common method of sand control in Kuwait. The sand ridges are also considered useful sand traps; however, accumulated sand should be cleared periodically because, when the area becomes full of sand, the sand ridge reaches a stable condition and no longer acts as a trap (Fig. 7). Most ridges are built of earthen materials. They are established in the transport zone at distances 10–100 m upwind of encroached facilities. The height of the ridges ranges between 1 and 3 m. Their efficiency is controlled by local conditions, such as the nature of the soil (e.g., the surface roughness) and by their distance from the protected objects. Occasionally, the soil ridges in open areas are deflated by severe winds, especially after an intensive rainy season.

Sand fences, if correctly erected, can effectively control aeolian sand problems (Kerr & Nigra 1952, Phillips & Willetts 1979). Most of the fences that have been erected for sand control are 2 m high and are made of corrugated metal plates (non-porous). However, owing to the high level of turbulence in the case of a solid fence, the deposition of sand does not extend far from such a solid fence (Plate 1971). As a result of their solid nature and improper placement, the sand fences have almost no effect and the encroaching sands invade the project sites. Moreover, the fences sometimes collapse. Implanting porous fences of about 50% porosity, however, can effectively stop sand movement (Fig. 8). The horizontal extent of the sand trapped by porous fences extends about 20 m on the downwind side and about 10 m on the upwind side of the fence. In some cases, the weak material components of fences are damaged by the wind and harsh environment causing loss of trapped sand.

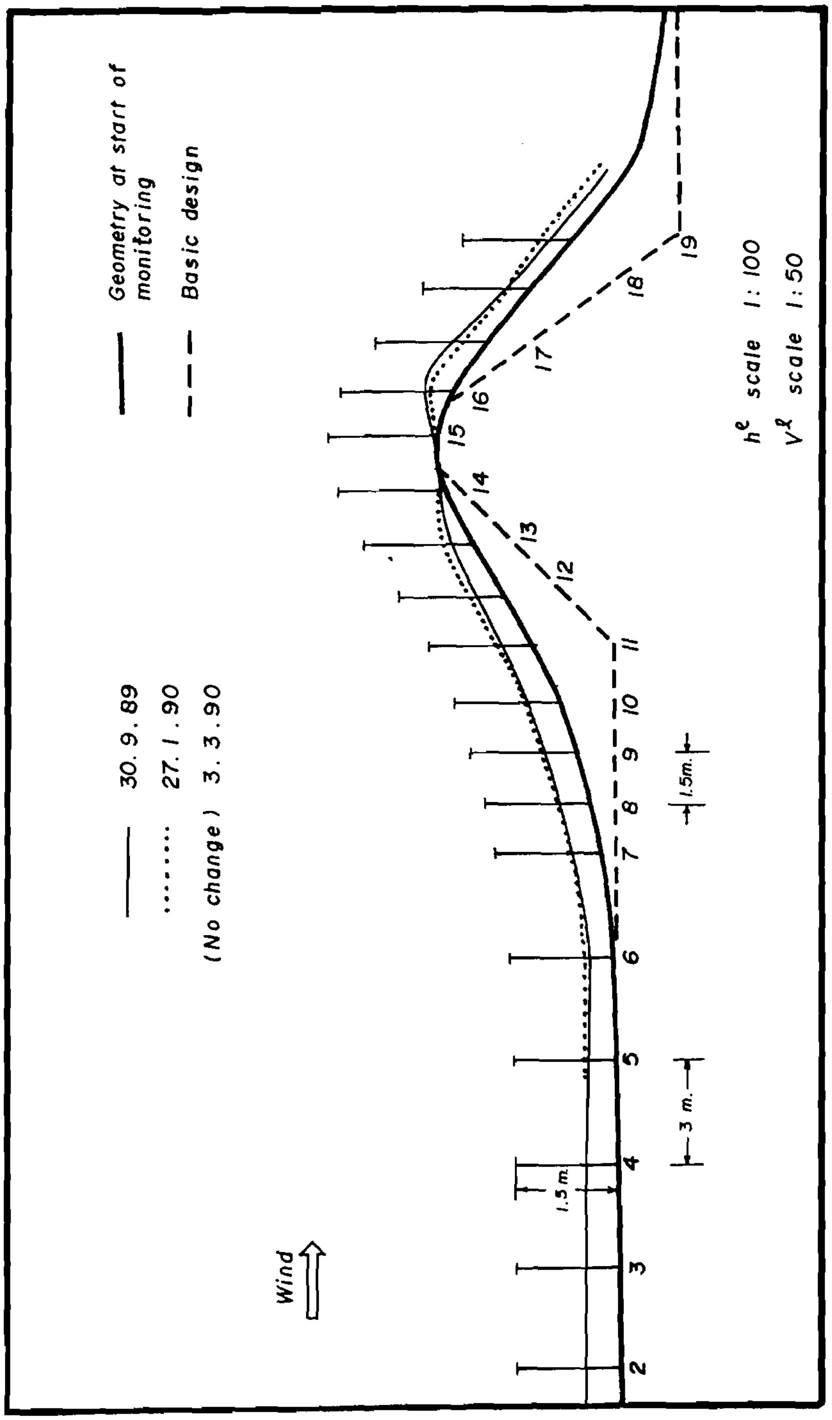


Fig. 7. Trapping sand using sand ridges in western Kuwait.

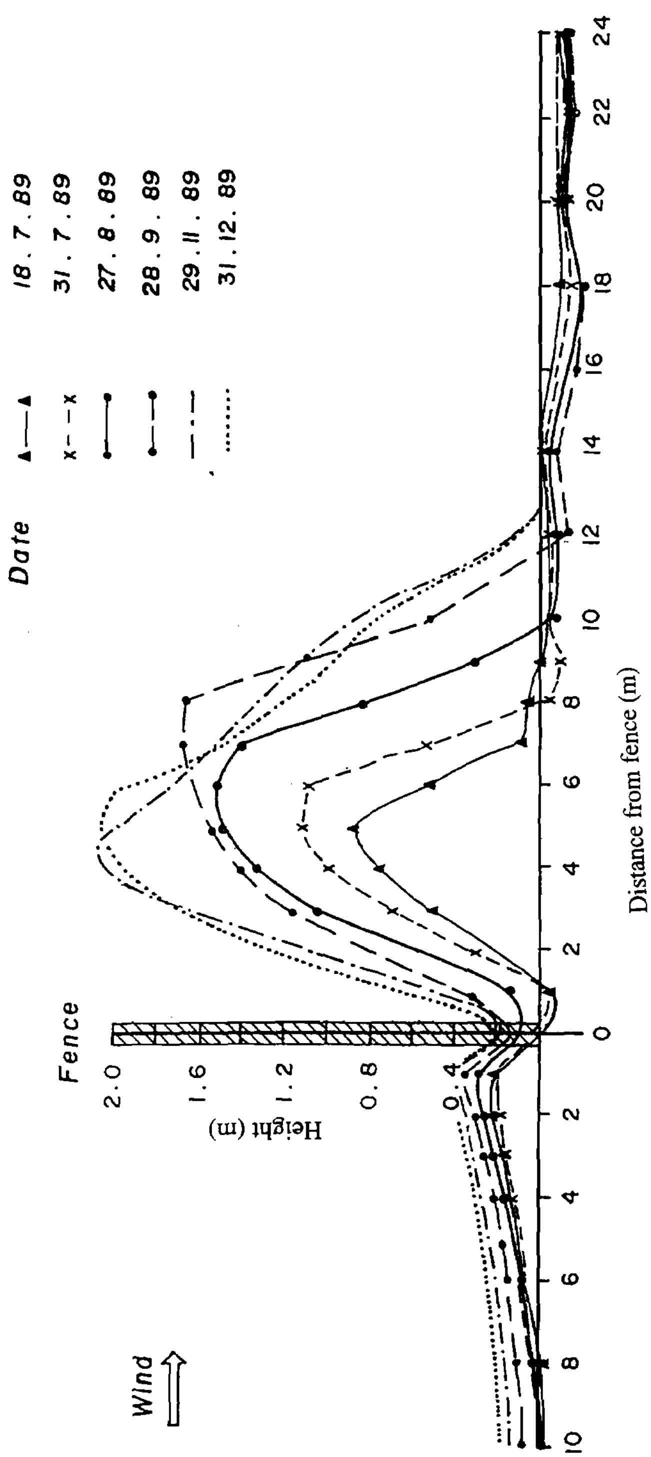


Fig. 8. Trapping sand using a 50% porous fence in western Kuwait.

Chemical stabilizers are widely used to protect artificial sand from erosion. However, due to the short durability of the different stabilizers, this method becomes ineffective after the summer season when high temperatures and wind speeds are recorded. The biological method (planting and afforestation) is considered the best method of sand fixation (Kerr & Nigra 1952), since it is permanent, prevents sand encroachment and is reclaimative. The main drawbacks of this method are the cost and the time needed for plants to grow. Biological control measures adopted at different sites include belts consisting of one to two rows of *Tamarix aphllae, Eucalyptus* sp., and *Acacia* sp. The efficiency of the shelter belts is determined by the height, porosity and type of trees. The height of the trees varies between 3 and 8 m and the porosity is from 25 to 50% in most cases.

The magnitude of the sand encroachment problem for installations and structures in Kuwait is great, and there is widespread awareness of the problem and the need to apply sand control measures. Unfortunately, most control methods adopted in Kuwait so far lack a scientific basis. Thus, an overall plan of action for sand control must be developed.

ENVIRONMENTAL MANAGEMENT

As in other arid regions, Kuwait has diverse environmental constraints, the most significant of which are low, erratic rainfall, prevalence of drought, high wind speeds, extremes of temperature, very high evaporation rates, low moisture retention, scarce vegetation and poor soil fertility. Under these conditions, sand storms become a common weather phenomenon and soil erodibility prevails. Sand encroachment problems are the natural result of erecting constructions in the path of creeping and saltating sand. Therefore, sand encroachment should be considered seriously during the planning and design of major desert development projects. Detailed sedimentological studies should be carried out to determine the nature and occurrence of surface sediments, as well as their textural characteristics and the wind regime in the area, to gain a better understanding of the two main factors of the problem (i.e., sediment and wind), and, consequently, to enable good planning to combat the problem.

The cycle of sand deflation in Kuwait involves detachment, transportation and sedimentation, each of which must be addressed for effective land use management. This can be achieved by (a) treating encroaching sand either by mechanical methods or by using proper mulching techniques, (b) minimizing new sand accumulation using properly designed porous fences, and (c) reducing local soil erosion by considering proper surface management programs including range management and controlling spring camping and off-road vehicles.

To limit the long-term impact of human sand-generating activities, policies and national action programs for controlling mobile sand should be considered. Emphasis should be focused on (a) management and rehabilitation of damaged areas through the establishment of protected areas (priority should be given to the northwestern area of the country), (b) enhancement of the micro-climatic conditions and improvement of soil properties through the planting of drought-resistant trees and shrubs (e.g., *Acacia* sp. and *Prosopis* sp.), and (c) protection of the natural vegetation. It is important that the problems associated with sand be recognized at the early stages of design (Stipho 1992); thus, regular monitoring of aeolian sand transportation and accumulation, changes in the growth rate of natural vegetation, and local variation of wind speed and direction during the year at selected areas is essential. Remote sensing and radar techniques are quite useful in assessing and monitoring aeolian processes in Kuwait.

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تقييم حقلي للعمليات الريحية ووسائل الوقاية من الرمال في الكويت

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خلاصة

إن ندرة الأمطار وعدم انتظام هطولها ، مع وفرة مصادر الرمال وهبوب الرياح القوية من اتجاه الشمال الغربي ، تأثر بشكل واضح على استقرار النظام البيئي الهش في الكويت. ولقد سرّع كل من الاستخدام الخاطيء للأراضي والاستغلال غير العقلاني للغطاء النباتي وللتربة من عمليات التجوية الريحية. وتعد عملية زحف الرمال على المنشآت التنموية من المشاكل البيئية والاجتماعية والاقتصادية . وقد استخدمت عدة وسائل للتخفيف من هذه المشكلة وتتضمن هذه الوسائل تقنيات فيزيائية وبيولوجية وكيميائية . وفي بعض الحالات نفذت برامج وقاية غير ملائمة بيئياً أو اقتصادياً.