ELSEVIER

Journal of Arid Environments 72 (2008) 423–439

Journal of Arid Environments

www.elsevier.com/locate/jaridenv

Morphologic characteristics and development of falling dunes, northeast Kuwait

A. Al-Enezi[a,*], K. Pye[b], R. Misak[a], S. Al-Hajraf[a]

[a]*Environmental and Urban Development Division, Kuwait Institute for Scientific Research, P.O. Box 24885, Kuwait*
[b]*Department of Geology, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK*

Received 11 October 2005; received in revised form 29 May 2007; accepted 28 June 2007
Available online 4 September 2007

Abstract

Falling dunes are the most common aeolian landform in northeast Kuwait. They are associated with the Jal Az-Zor escarpment. Comparison of aerial photographs from 1972 and 1992 indicates that these dunes developed recently. This change in a relatively short period is attributable mainly to drought, intensive land use and availability of sand source linked to surface disturbance. Military activities during the two Gulf wars are the main cause of surface disturbance.

The variability in morphology of falling dunes along the dissected escarpment is related to local microtopographic, morphologic and hydrologic characteristics. The length of the falling dunes ranges from 38 to 383 m and their width from 7 to 85 m. They attain a maximum height of 10 m from ground surface.

To discuss the wind energy environment of the study area, Fryberger method was used. The results indicate that falling dunes developed under a high-energy environment, in particular during summer (June–August) when the drift potential (DP) is relatively higher and wind direction has low variability.

Numerical computations using FLUENT 6.0 were employed to simulate both the airflow over the escarpment in 2D with slope angles of 15°, 45° and 90° and the airflow within the vicinity of the valley in 3D. The results indicate that development of falling dunes is significantly affected by slope angle. Steep slope angle favors the development of falling dunes due to the reduction of wind velocity in the wake zone downwind of the escarpment.

Keywords: Escarpment; Falling dunes; Kuwait; Numerical computations; Wadi

1. Introduction

Kuwait witnesses active aeolian processes that are attributable to many physical and human factors. The most significant physical factors are the scarce and irregular rainfall (110 mm annual average), the prevalence of strong northwesterly winds, the availability and variability of sources of mobile sands and Kuwait's location downwind of the deflation area of Mesopotamian floodplain in southern Iraq. Significant human factors involve military operation, e.g. first, second and third Gulf wars in 1980–1988, 1990–1991 and 2000, respectively; quarrying of construction materials; desert camping and recreation and overgrazing. These

*Corresponding author. Tel.: +965 4836100; fax: +965 4815202.
E-mail address: aenezi@safat.kisr.edu.kw (A. Al-Enezi).

0140-1963/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.jaridenv.2007.06.017

Fig. 1. Group of falling dunes along Jal Az-Zor escarpment.

activities caused a catastrophic increase in the supply of drift sands besides large-scale destruction of vegetation (Misak and Omar, 2004).

The interaction of the topography with sand-laden winds is responsible for the development of different types of aeolian landforms. In the literature, these landforms have been termed "sand shadows" or "sand drifts" by Bagnold (1941), "fixed dunes" by Howard (1985), topographically anchored sand dunes by Cooke et al. (1993) and topographically controlled sand dunes by Lancaster and Tchakerian (1996).

Topographically anchored dunes have been reported in desert regions with high relief, such as the Sahara Desert (e.g. Clos-Arceduc, 1967; Mainguet, 1983) and the Mojave Desert, southwest USA (e.g. Clarke and Rendell, 1998; Evans, 1961; Lancaster and Tchakerian, 1996; Tchakerian, 1991, 1999; Zimbelman et al., 1995). In the Middle East, they have been reported by El-Baz et al. (1979) in Egypt, by Tsoar (1989) in northern Sinai in Egypt, by White and Tsoar (1998) in the Negev Desert and by McKee (1979) in Jordan.

Aeolian processes (including deflation, transportation and deposition) are very active in Kuwait, where they are related to the dry, hot, windy climate, the detrital nature of bedrock and its location downwind from the high-deflational area of the Mesopotamian floodplain (Al-Ajmi et al., 1995). As a result, at least 35% of the desert surface of Kuwait is covered by loose, mobile sediments that are continually transported along the surface by wind to form different landforms including falling dunes. The latter are the most common aeolian landform in northeast Kuwait. They are principally associated with the Jal Az-Zor dissected escarpment (Fig. 1). Comparison of aerial photographs of 1972 and 1992 shows that these features have developed recently along the escarpment. This change, over a relatively short period, resulted chiefly from climatic conditions combined with increased availability of sand from human activities under favorable topographic and aerodynamic conditions.

This study presents the results of detailed field investigations on falling dunes in Kuwait. Its main purpose is to elucidate several issues regarding their development, including the factors controlling their distribution and the influence of topography and the wadi system on their morphology and size.

2. Method

In this study, we used existing 1992 aerial photographs (scale 1:29,000) and Landsat^{TM} imagery (scale 1:250,000). The aim of the field surveys was to identify the geographical distribution and morphologic and morphometric characteristics of the falling dunes along the escarpment.

To discuss the wind energy environment of the study area, we used the Fryberger (1978, 1979) method. This method has been the most widely accepted and adopted in world desert environments. The Fryberger method, which is a modification of the Lettau and Lettau (1978), is designed to give a relative rather than absolute

description of the effect of wind energy on sand drift. To apply this method, a Q-basic program was used to calculate the drift potential (DP) in vector units (VU) for 16 directions, resultant drift direction (RDD) and wind index (RDP/DP) for each month at each station. The wind data for calculation were collected from a meteorological station located in Al-Mutla area (western part of the study area) for a period of 4 years (1998–2001) and in accordance with World Meteorological Organization guidelines, i.e. at a height of 10 m. For winds exceeding the threshold velocity, we applied frequencies of direction and velocity-grouped data. After simplifying wind speed data and related calculations, we plotted sand rises.

To simulate airflow over a low-relief escarpment with different slope angles and its impact on the development of falling dunes, we used the computational fluid dynamics (CFD) technique. The approach used in this study was to combine the result from the numerical modelling of the airflow over the escarpment with field observations for verification. Four models of escarpment were designed in a special program called GAMBIT. Three of these models were designed in 2D with slope angles 15°, 45° and 90°. In addition, a 3D model of a typical valley with "W" shape along the Jal Az-Zor escarpment was designed to examine the airflow within the vicinity of the valley and its impact on the development of falling dunes. Numerical computations using FLUENT 6.0 were employed to simulate the airflow over the four models. The key consideration in the numerical model is representing the solid particles as a second continuum flow phase superimposed upon the primary phase, the air, as described by conventional Navier–Stokes equations (Ishii, 1975; Peric, 1985; Gosman, 1999; Alhajraf, 2004). However, considering the air as the continuous phase (carrier phase) and the particles as the discrete phase, the simplest two-phase flow model, known as the homogenous two-phase flow model, was employed in this study. The conservation equations can be expressed as

$$\underbrace{\frac{\partial(\rho\phi_i)}{\partial t}}_{\text{Rate of change in }\phi} + \underbrace{\frac{\partial}{\partial x_j}(\rho u_j\phi_i)}_{\text{Convection term}} = \underbrace{\frac{\partial}{\partial x_j}\left[\Gamma_\phi \frac{\partial \phi_i}{\partial x_j}\right]}_{\text{Diffusion term}} + \underbrace{S_\phi}_{\text{Source term}},$$

where ϕ represents the solution variable to be solved, u, v and w the 3D components of the wind velocity, k the kinetic energy, ε the rate of dissipation of kinetic energy and α_p the particle volume fraction. x_j are the space components x, y, z. The flow governing equations may be formed by substituting the variable ϕ, the diffusion coefficient Γ_ϕ and the source term S_ϕ with the appropriate values (Alhajraf, 2001, 2002).

2.1. Study area

The falling dunes in northeastern Kuwait are all associated with the Jal Az-Zor escarpment that runs parallel to Kuwait Bay for about 80 km (Fig. 2). The escarpment extends from the southwest at Al-Atraf to Bahrat Al-Aujah in the northeast, where it swings to the southeast until it reaches the tip of Kuwait Bay at Ras As Subiyah. According to Taha et al. (1982), the Jal Az-Zor escarpment can be divided into five morphological units: the back slope, crest, scarp, debris slope and coastal plain. The side of the escarpment facing Kuwait Bay where falling dunes are developed has a steep slope, terraces and isolated hills, whereas the backside of the escarpment has gentle slopes with an angle less than 5°.

The wadis cutting the escarpment are prominent morphological features with a dendritic pattern draining toward Kuwait Bay. The wadis are relatively deep near the scarp and become shallower away from the scarp on the back slope. In the center of the study area, between Al-Mutla and Khashim Ghudhay, the wadis are well defined, relatively long and deep with major tributaries. In turn, wadis in the Al-Atraf area and between Al-Mahraqah and Ras As Subiyah are relatively shallow and short.

On the back slope of the Jal Az-Zor escarpment, a bisegmented depression known as the Umm Al-Rimmam depression exists (about 16 km^2). It is mostly rimmed by steep cliff walls about 15 m above its floor. Relatively long and wide wadis dissect the sides of the depression flowing toward the center from all directions. Within the wadis at the northwestern part of the depression falling dunes were also developed.

From a socio-economic point of view, the study area has been used for grazing, which represents more than 75% of its total land use. During the second Gulf war (August 1990–February 1991), the area was used

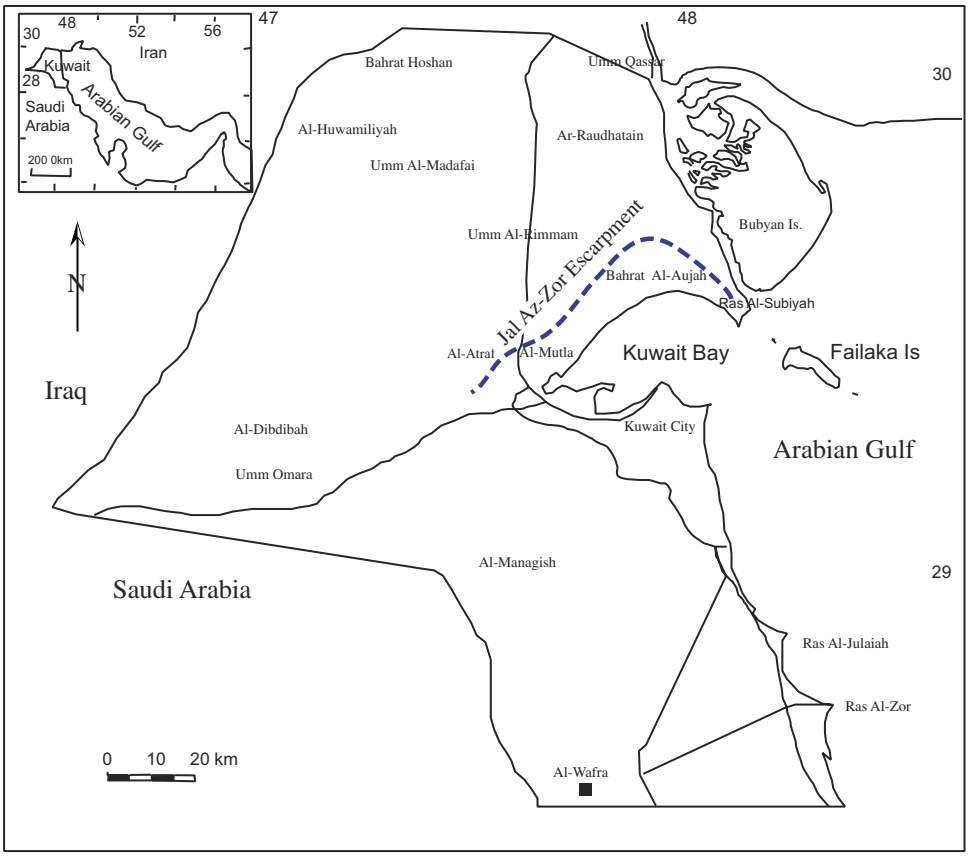

Fig. 2. Location of the study area (labelled by dashed line).

intensively for military purposes. Thousands of ground fortifications were constructed, according to Al-Ajmi et al. (1994), and cover about 100 km^2 in the area of study.

3. Results

3.1. Distribution of falling dunes

Falling dunes are clustered in four principal zones along the escarpment: (1) Al-Atraf–Al-Mutardah, (2) Hamran–Khashim Ghudhay, (3) Al-Mahraqah–Bahrat Al-Aujah and (4) Ras As Subiyah (Fig. 3).

Throughout Al-Atraf–Al-Mutardah zone there are about 112 well-developed falling dunes located mainly in the northeast part of this zone; in particular, between Al-Mutla in the southwest and Al-Mutardah in the northeast. They are closely spaced with a density of about nine dunes per kilometer. This high number of falling dunes in this zone is due to the existence of large wadis with a number of major tributaries where falling dunes have formed inside. For instance, a group of large wadis within this sector contains between five and six falling dunes in each wadi.

Within Hamran and Khashim Ghudhay zone, there are about 60 well-developed falling dunes mainly confined within wadis. They are relatively larger than other zones and closely spaced with a density of seven dunes per kilometer. In general, the largest set of falling dunes occurs at the center of this zone, specifically in Khashim Ghudhay where in the northeast direction the falling dunes become relatively smaller. On the back slope of the escarpment and within the same sand pathway, falling dunes formed within the western and the northwestern wadis of the Umm Al-Rimmam depression. They formed along the cliff of relatively long, wide and shallow wadis oriented perpendicular to the sand-laden winds.

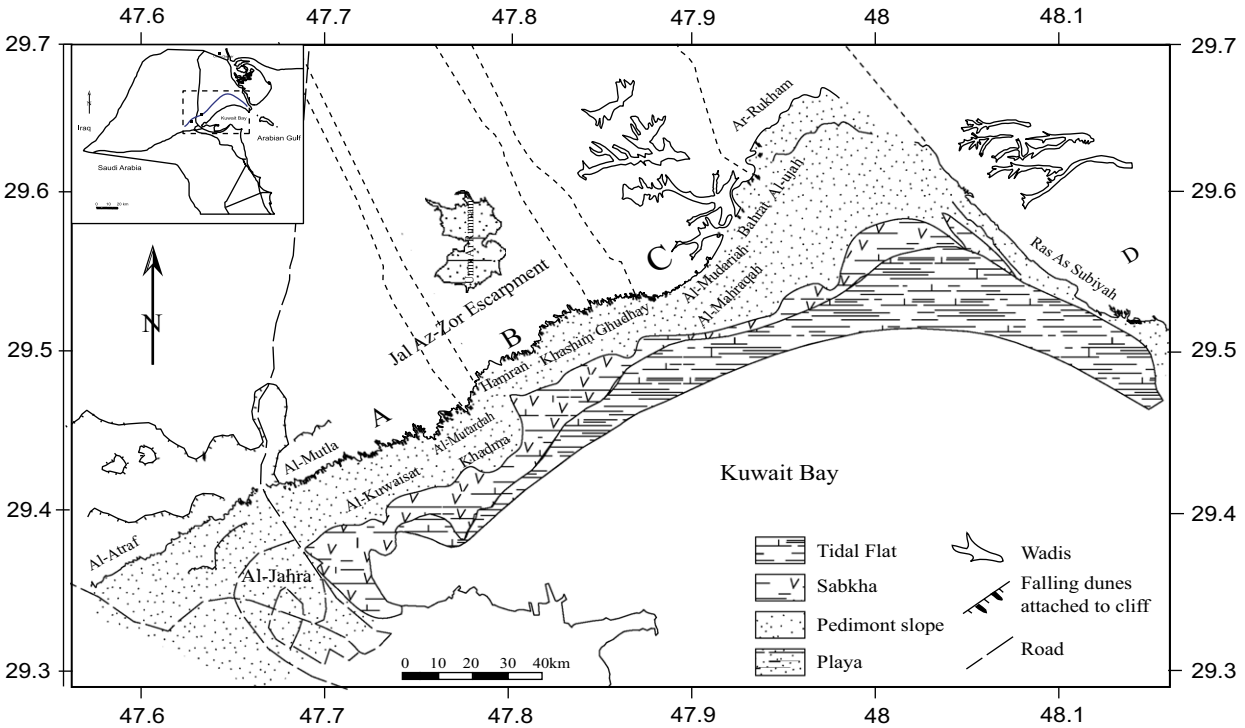

Fig. 3. Geomorphological map of the study area showing the distribution of the falling dunes in the zones: (A) Al-Atraf–Al-Mutardah, (B) Hamran–Khashim Ghudhay, (C) Al-Mahraqah–Bahrat Al-Aujah and (D) Ras As Subiyah.

Falling dunes in the Al-Mahraqah–Bahrat Al-Aujah zone are located mainly at Al-Mahraqah with some at Bahrat Al-Aujah. In between, at Al-Mudariah, they are not developed due to obstruction by the long tributary of wadi Bahrat Al-Aujah. This tributary, which is oriented parallel to the Jal Az-Zor escarpment and stretches perpendicular to the sand-laden wind, acts as a sand collector. It is also related to the low elevation and gentle steepness of the hill slope that prohibit falling dunes from developing in that area.

Near Ras As Subiyah at the extreme northeast, the escarpment changes its orientation, swinging toward the southeast, then changing to a east–southeast direction and decreasing in elevation until it reaches the tip of Kuwait Bay. This orientation greatly influences the formation of falling dunes. In that zone, where the hilly terrain is oriented parallel to the sand-laden winds, only a thin sheet of sand was accumulated on the debris slope of the hill. At the far end, the hilly terrain has been intensively dissected by shallow wadis, forming isolated hills oriented at an angle to the sand-laden winds. On the downwind side of these isolated ridges, eight falling dunes have developed where they break into a series of barchan dunes.

3.2. Falling dune morphometry

The falling dunes vary considerably in the size. They are the largest in the center of the study area, between Al-Kuwaisat and Khashim Ghudhay. In that area, their length ranges between 38 and 393 m and width from 11 to 85 m. The largest falling dune at that site attains a maximum height of 10 m above the ground. By comparison, at the margin of the study area (Al-Atraf–Al-Mutla and Al-Mahraqah–Ras As Subiyah) falling dunes are relatively smaller in size. Generally, between Al-Atraf–Al-Mutla, the length of the falling dunes ranges from 65 to 200 m, and the width varies between 8.5 and 75 m. The maximum height of falling dunes at that site is about 6 m above the ground. On the northeastern margin between Al-Mahraqah and Ras As Subiyah, the length of falling dunes ranges between 38 and 242 m, and the width ranges between 7 and 34 m. The maximum height of the falling dunes at that site is about 6 m.

Despite the importance of the continuous supply of sand, this wide range in the size of falling dunes is controlled chiefly by a combination of the escarpment height and the size of wadis cutting it. Howard (1985) indicates a general relationship between the anchored dunes length and the height of the topography. According to his study, anchored dunes may extend downwind 20 times the height of the topography. In this study, similar relation between the height of the escarpment and the length of the falling dunes was observed. Falling dunes along Jal Az-Zor escarpment extend only 2–11 times that of the cliff height. The influence of the escarpment height on the length of the falling dunes is clarified through bivariate plots showing the relation between both elements (Fig. 4). It can be seen that an increase in escarpment height results in an increase in falling dune length.

The changes in length and width of the falling dunes are partly related to the size of the wadis, where the falling dunes are mostly attached. Along the escarpment, no falling dunes are observed downwind of wadi outlets. The possible explanation is that the airflow within wadis may be modified by topography such that wind regime is not suitable for extending the falling dunes outside the wadi (Bullard and Nash, 1998). Fig. 5 indicates that there is positive correlation between the width of the wadis and the width of the falling dunes. In a similar manner, Fig. 6 shows a close correspondence between the length of the wadis and the length of the falling dunes. These relationships can be seen clearly at the regional scale. Falling dunes at the center of the study area, in particular, between Al-Kuwaisat and Khashim Ghudhay, are larger, owing to their occurrence within relatively longer and wider wadis than other sites in the study area.

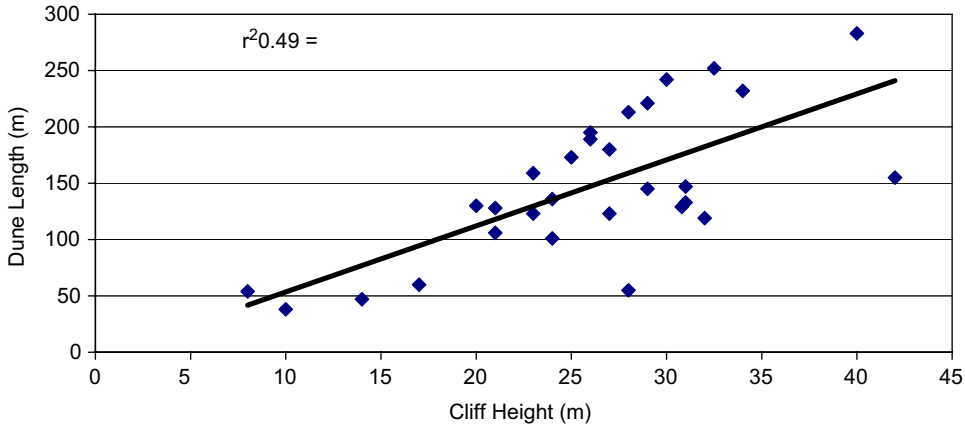

Fig. 4. Bivariate plot of the escarpment height vs length of the falling dunes.

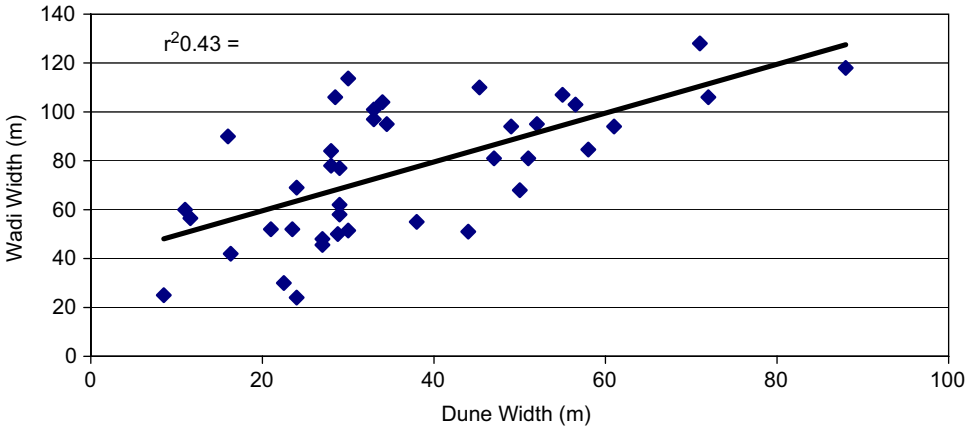

Fig. 5. Correlation between the width of the falling dunes and the wadis along the escarpment.

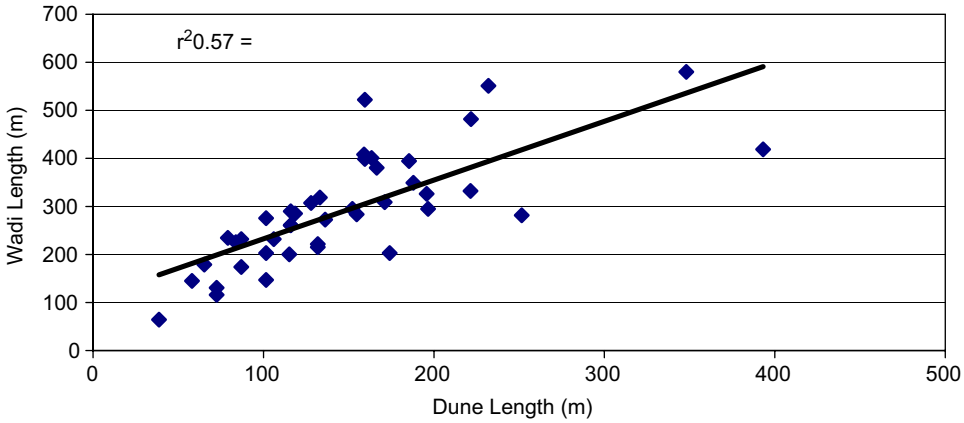

Fig. 6. Correlation between the length of the falling dunes and the wadis along the escarpment.

3.3. Falling dune morphology

Most of the falling dunes along the escarpment accumulate in a simple form, existing as a single finger-like body oriented in the NW–SE direction. Within this general form are slight morphological variations. This variability can be attributed to local changes of the hilly terrain morphology. Based on field observation, there are three major geomorphologic associations between topography and morphology of the falling dunes: (1) falling dunes attached to a cliff headland, (2) falling dunes confined within wadis of different orientations, (3) falling dunes blocked by an isolated hill downwind of the escarpment (Fig. 7).

Most the falling dunes along the escarpment are attached to a cliff headland, where two V-shaped wadis join at a sharp angle. This topographical form has an important role in modifying the morphology of the falling dunes. Tsoar (1989) suggests that if the dunes are attached to cliff headlands they will exhibit a linear pattern with a sinuous or straight crest. This linear pattern is due to the convergence of the airflow around the cliff headlands to reach the falling dunes at both flanks. At some headlands, the attached falling dunes have a sinuous and sharp crest (Fig. 7a). This sinuous type of falling dune is associated mainly with headlands located outside the wadis where the falling dunes are exposed to winds from different directions.

The second form of falling dunes is related to the position of the cliff headland in the wadi. Headlands with a central position cause the formation of symmetrical falling dunes to form with a straight and sharp crest or with a broad ridge depending mainly on the width of both the headland and the size of the wadis. In some areas, headlands are positioned close to the side of the wadi, whose position creates mirror-image falling dunes on the wadi flank. For instance, if the flank of the wadi is straight, the falling dune will form with a straight and sharp crest and steep slipface running parallel to the flank of the wadi (Fig. 7b). Curved falling dunes may develop due to the curvature of the side of the wadi (Fig. 7c). Over these falling dunes, the airflow separates at the beginning of the lee side of the dune and is deflected to run parallel to the side of the wadis and the slipface of the falling dunes forming a sand-free zone in between.

In addition to the influence of the headland, the orientation of the wadis is also important. Three groups of falling dunes were identified, based on the interaction of the sand-laden wind with different orientations of the wadis. The absence of cliff headlands within the wadis oriented parallel to the sand-laden wind causes falling dunes to form along the side of the wadis without a linear pattern (Fig. 7d). With this form of dunes, the wind flows over the dunes parallel to the side of the wadi. However, it may deflect at an angle upslope of the cliff (in some cases, these dunes are called climbing dunes rather than falling dunes as the wind flows upslope of the dune). In some locations, the wadis are oriented at an angle to the sand-laden wind. Thus, the approaching airflow is deflected markedly to become parallel to the wadi's orientation. In these cases a crescent-like falling dune is created with a gentle slope to windward that is attached to the cliff of the wadi and a leeward slipface with a steeper slope (Fig. 7e). The orientation of the wadis perpendicular to the sand-laden winds interferes with the horizontal growth of the falling dunes. Instead, falling dunes either grow vertically and/or throughout

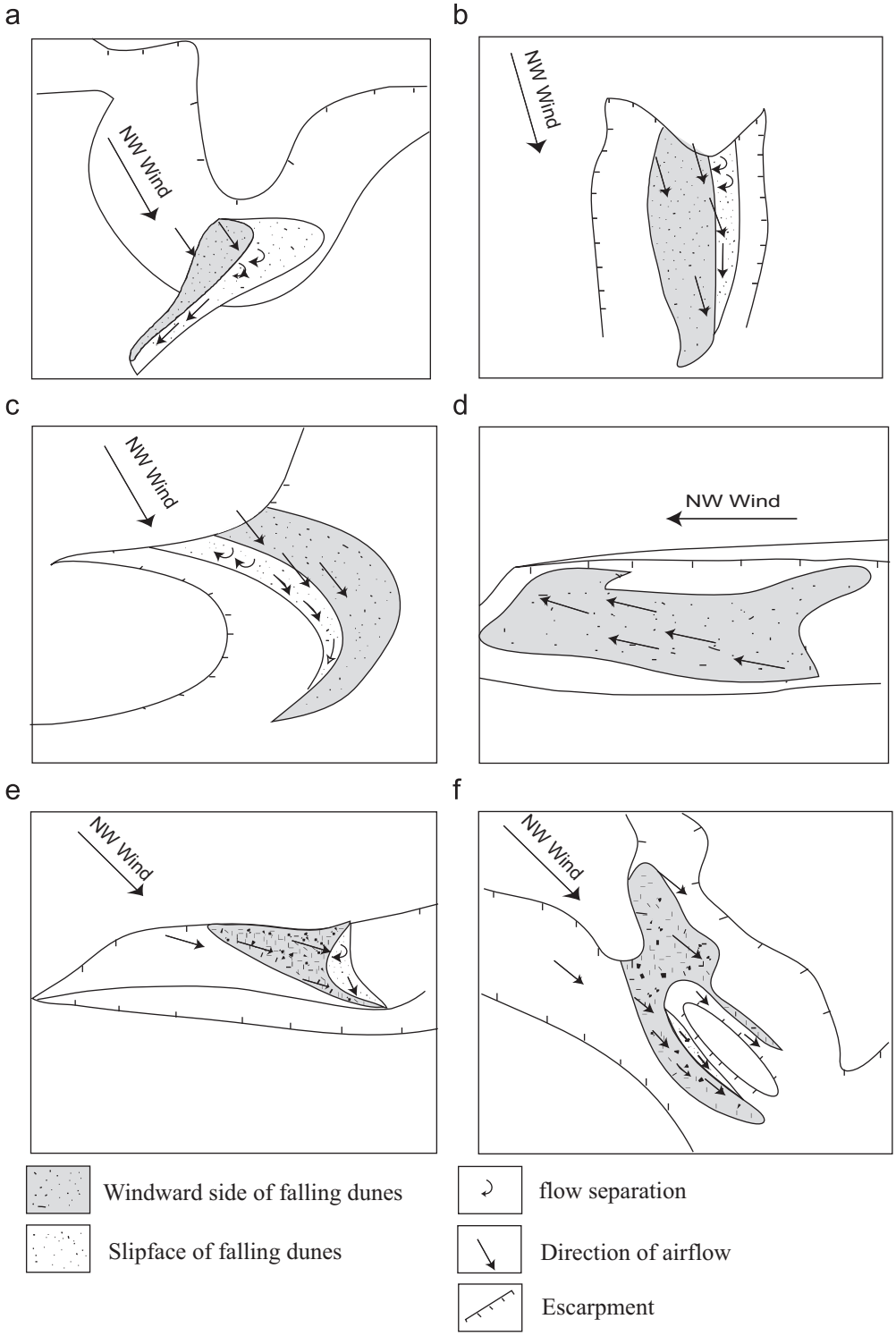

Fig. 7. Different forms of falling dunes related to the effect of topography with emphasis on the airflow over the escarpment and falling dunes. (a) Falling dune with sinuous crest attached to cliff headland outside of the wadi. (b) Falling dune with straight slipface attached to headland close to the side of the wadi. (c) Falling dune with curved slipface attached to headland close to the side of the wadi. (d) Dune without linear pattern located within wadi oriented parallel to the sand-laden wind and accumulated at the side wall of the wadi. (e) Crescent-like falling dune within wadi oriented at an angle to the sand-laden wind. (f) Diverted falling dune around isolated hill downwind of the cliff headland. Direction of the airflow based on field observation.

the whole side of the flank of the wadi, resulting in a dune that is wide in comparison to its length. A typical example of this morphology is the northwestern wadi of the Umm Al-Rimmam depression.

Another common form of falling dune occurs when a dune is blocked from the downwind side by an isolated hill. According to Greeley (1986), such a topography creates a horseshoe vortex surrounding the base of the obstacle. Thus, the falling dune diverges downwind, around the isolated hill (Fig. 7f).

4. Discussion and conclusion

4.1. Development of falling dunes

Falling dunes are the most common aeolian landform in the northeast of Kuwait Desert. They are developed as a result of sand-laden, dominantly northwesterly wind interacting with the Jal Az-Zor dissected escarpment. Comparison of aerial photographs of 1972 and 1992 indicates the recent development of these aeolian landforms. For instance, while in 1972 there were only less than five falling dunes at Al-Mutla, by 1992 the number increased to 29 falling dunes (Fig. 8). During the same period, new fields of barchan dunes and sand patches were developed in different parts of the Kuwait Desert. According to Khalaf (1989), and based on the comparison of Landsat imagery of 1977 and SPOT imagery of 1986, a mobile sand sheet in the southern part of Kuwait extended 35 km in SE direction. In a similar way, Mainguet and Dumay (1998) indicate an expansion of aeolian landforms in the northwest of Kuwait between 1986 and 1990 based on the

Fig. 8. Comparison of serial photographs of 1992 (at the top) and 1972 (at the bottom) along Al-Mutla escarpment. The length of the escarpment from SW and NE is about 5 km. The arrows show some of the falling dunes.

comparison of Landsat and SPOT images. Magaly et al. (1998) demonstrated a sharp increase in the aerial extent of sand sheets in the Kuwait Desert. According to their study, the sand sheet extended by 32% from 1980 to 1992. These changes in the extent of aeolian landforms and, in particular, falling dunes in a relatively short period of time were chiefly the result of a combination of climatic conditions and availability of sand sources due to intensive land use and military operations under favorable topographic conditions.

4.2. Climatic conditions

Increase in aridity is responsible for sand dunes developing in different parts of the world deserts including the Kuwait Desert (e.g. Edward, 1993; Goudie, 1996; Goudie et al., 2000; Lancaster and Tchakerian, 1996; Mainguet and Dumay, 1998; Thomas, 1988; Tchakerian, 1994). During the period 1972–1992, Kuwait experienced irregular rainfall and prolonged drought (rainfall was below the average about 110 mm/year). In 1973, for example, 34.8 mm of rain fell and in 1987–1898 the amount was between 67.5 and 71 mm. During that period, the vegetation cover deteriorated and aeolian processes became highly active. Consequently new sand dunes developed.

Intensive rainfall (reaching 65–105 mm in a single storm, e.g. 1976–1977 and 1993–1994) causes outwash of sandy soils by runoff water, which subsequently contributes to the sand supply. This process is evident in the back slope of the escarpment. During flooding in winter, large amounts of surface and subsurface sediments at the back slope of the Jal Az-Zor escarpment are eroded, which then become available for deflation and reworking by predominantly northwesterly winds.

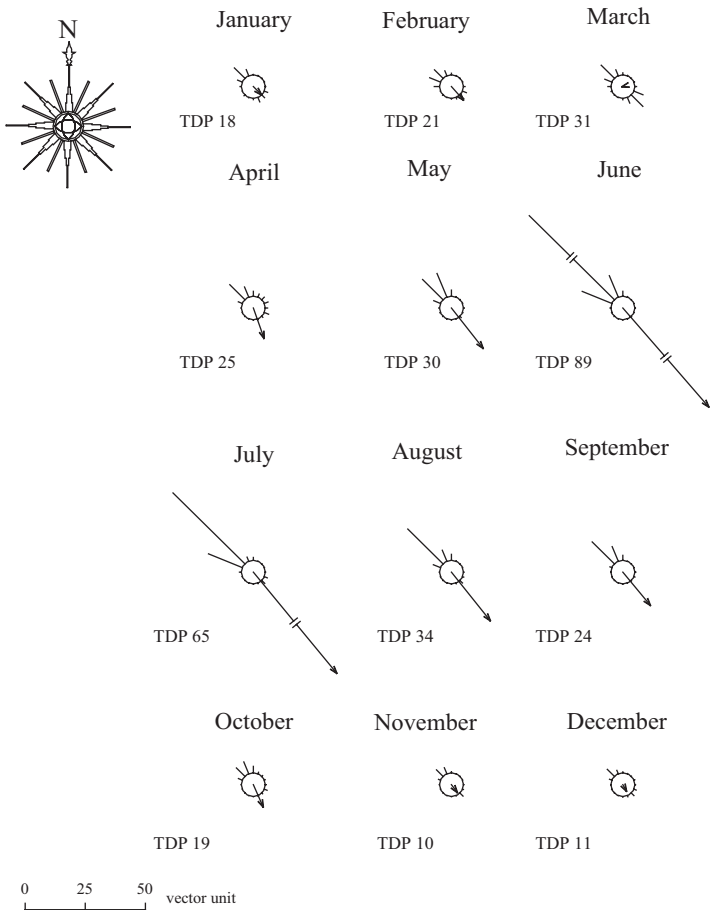

Fig. 9. Monthly potential sand drift rises and their resultant drift direction based on monthly average wind data from Al-Mutla station.

The wind regime is the most important climatic element that influences dune development in Kuwait. Winds are stronger and prevail from the northwesterly quadrant especially in summer (June–August). The wind from this direction is responsible for active aeolian processes (including deflation, transportation and deposition). Fig. 9 presents monthly potential sand drift rises for Al-Mutla station. The annual DP in the studied area indicates a high-energy environment condition (491 VU). Most of this value represents the DP from June to August where the winds are the strongest. Throughout the year, DP reaches it maximum in June (102 VU) and minimum in November (10 VU) (Table 1).

The wind direction in the studied area is less variable in particular during the summer (June–August). The analyzed data reveal that the annual RDD is consistently toward the SE direction and the wind regime has intermediate variability (0.51–0.79) except for July when it has low variability (0.87) according to Fryberger's (1979) classification (see Table 1). The almost unidirectional nature of the effective wind in Kuwait is important in developing falling dunes, which do not survive where there is a large variation in wind direction (Bagnold, 1941; Cooke et al., 1993). Based on the field observations and aerial photographs mapping, it can be seen that the falling dunes in Kuwait are developed parallel to the annual resultant direction of DP, which is commonly toward SE direction.

4.3. Sand supply

Other factors that contribute to falling dunes developing in Kuwait relate to the continuous supply of sand. The enormous increase in sand supply combines with the lack of vegetation capable of impeding sand movement and surface disruption (Al-Awadhi, 2001). Landsat^{TM} image of March 1992 shows a number of aeolian sand pathways in the north of Kuwait extending northwest to southeast toward Jal Az-Zor escarpment. These are the main pathways for sand supply to the falling dunes (Fig. 10). Between Al-Atraf and Al-Mutardah southwest of Jal Az-Zor escarpment, the falling dunes are located downwind of the major sand pathway in the Kuwait Desert. The pathway extends discontinuously over a distance about 90 km from Al-Huwamiliyah on the northwest border of the country to the Jal Az-Zor escarpment. The pathway is obstructed by southwest–northeast trending, low, subparallel elongated, flat-surface ridges. A second sand pathway is located upwind of the falling dunes between Hamran and Khashim Ghudhay. It extends for about 40 km in length and 10 km width emanating from the margin of Kraa Al-Muraw ridge northwest Jal Az-Zor escarpment. This pathway lies within an elongated, shallow depression trending northwest to southeast. Falling dunes between Al-Mahraqah and Bahrat Al-Aujah are located downwind of the sand pathway extending discontinuously from the Kuwait border over about 75 km and with an average width of 12 km. Similarly, microtopography plays a significant role in confining the pathway. The northwestern section of the pathway is associated with the Ar-Raudhatian Plain, while the second section of the pathway is confined

Table 1
Monthly potential sand drift (VU), resultant drift direction and wind direction variability for Al-Mutla station

Month	Drift potential DP (VU)	Resultant drift direction RDD (°)	Wind direction variability RDP/DP
January	22	131.8	0.76
February	23	139.1	0.78
March	27	130.8	0.55
April	21	148.3	0.64
May	63	138.1	0.79
June	103	135.8	0.78
July	76	137	0.87
August	60	137.3	0.74
September	43	137.7	0.79
October	32	146.4	0.64
November	10	117	0.51
December	11	150	0.29
Sum	491	–	–
Average	41	137	0.67

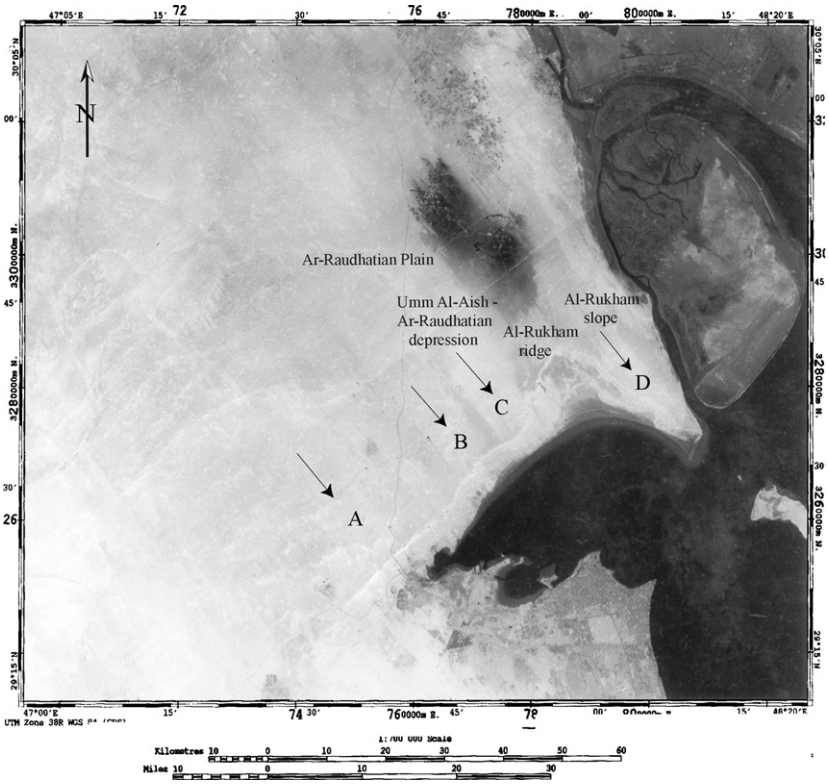

Fig. 10. Landsat^{TM} image of Kuwait, 1995 bands 2, 4 and 7 shows the regional sand pathways: (A) Al-Atraf–Al-Mutardah, (B) Hamran–Khashim Ghudhay, (C) Al-Mahraqah–Bahrat Al-Aujah and (D) Ras As Subiyah. The arrows indicate the direction of aeolian sand pathways.

within an elongated, shallow depression called the Umm Al-Aish–Ar-Raudhatian depression (Fig. 10). Its eastern side is bounded by the Al-Rukham ridge, which causes a slight shift of the pathway at its end. The last group of the falling dunes is located at the extreme northeastern part of the Jal Az-Zor hill. These falling dunes lie downwind of a regional sand pathway associated with the gentle topographical Al-Rukham slope. This pathway forms an irregular discontinuous belt extending from Umm Al-Qassar with a length of about 25 km and a width between 5 and 10 km. Across this belt runs a very shallow dendritic wadi system trending west to east, which obstructs the pathway.

The main sources of the sand supply in Kuwait are from the southern-Mesopotamian muddy floodplain deposits south of Iraq and locally from Al-Dibdibah gravelly deposits in the northern Kuwait Desert (Khalaf et al., 1985; Khalaf, 1989). The socio-economic factors and military operations accelerated the recent development of aeolian landforms including falling dunes in Kuwait.

4.4. Socio-economic factors

The main cause of damage to the Kuwait Desert relates to the increase in socio-economic activities during the last four decades after the oil boom in Kuwait. These changes have affected the desert, where the vegetation cover has been destroyed and the surface sediment disturbed. The main socio-economic factors are the following:

(1) The notable increase in the number of grazing animals (from 230,000 in 1976 to 277,000 and 320,000 in 1980 and 1994, respectively). This situation caused intensive pressure on vegetation cover, now less than 5% in grazed areas whereas it is more than 60% in protected areas.

(2) The accessibility to almost all desert areas after a network of paved roads, completed in the 1980s, contributed to human pressure on local resources (in 1972 Kuwait City–Basra road was the only paved road). This condition accelerated soil and vegetation degradation in the recently accessed areas through various land uses.
(3) The overexploitation of gravel in the 1970s and 1980s. In northern Kuwait, particularly at Jal Aliyah and Kraa Al-Muraw ridges, the surfacial gravelly deposits of Al-Dibdiba formation are being exploited for gravel and used for industrial and building construction and landscaping. The total area of gravel quarries is about 383 km^2, equivalent to 2% of the total area of the country (Al-Awadhi, 2001). As a result of gravel exploitation a huge amount of fine sediment is released from the quarries and deflated by wind. Downwind of these quarries, a major sand pathway extends to Jal Az-Zor hill in a NW–SE direction. This deflated sand is considered to be a source of sand that contributes to falling dune development in some areas along the Jal Az-Zor escarpment.

4.5. Military operations

As a result of the Iraqi invasion and occupation of Kuwait (2 August 1990–26 February 1991), the surface of Kuwait, specially the NE area, has been intensively disrupted by war machinery and a complex system of ground fortification. In the study area, where a huge number of falling dunes formed, some 6,903,383 m^3 of excavated materials were exposed. These materials resulted from the construction of 21,622 ammunition bunkers, 217,786 living bunkers and 23,246 weapon pits (Misak and Omar, 2004). In Ras As Subiyah, more than 75% of the area is changed as a result of sand mobilization caused by Iraqi military activities (Misak and Omar, 2004). About 1,041,742 m^3 of loose sediment was excavated as a result of construction of 4569, 7142 and 3959 ammunition bunkers, living bunkers and weapons pits, respectively (Al-Ajmi et al., 1994). The loose excavated materials from these military fortifications represent the major sand supply source for the falling dunes.

4.6. Topography

Falling dunes in Kuwait have developed as a result of the prevailing northwesterly wind with available sand interacting with the dissected Jal Az-Zor escarpment. Their development is significantly affected by the orientation and slope angle of the escarpment. Fig. 11 shows the airflow simulation of 3D model of wadi cutting Jal Az-Zor escarpment. When the air passes the escarpment, the wind profile, which was in equilibrium with back slope surface, becomes disturbed. The change in topography causes a wake zone to develop downwind of the cliff headland and between trailing vortices, extending parallel to the wadi cliff. The wake zone is wider close to the cliff and becomes thinner downwind. The modification of the airflow downwind of the escarpment is related to reduction of the wind velocity caused by the separation of the flow over the brink of the escarpment (Bowen and Lindley, 1977; Jackson, 1975). At these wake zones, the rate of sand transport is reduced and deposition occurs.

This separation of the flow is influenced to some extent by the slope angle of the escarpment. The field survey showed that well-developed falling dunes are associated mainly with steep-sided escarpment, in particular between Al-Mutla and Al-Mahraqah. In part of the Al-Atraf and Al-Mudariah areas, no falling dunes were developed that related partially to the gentle slope of the escarpment (less than 30°). Fig. 12 shows the streamlined airflow and velocity vector profile at seven sites along the escarpment cross-section with slope angles of 45° and 90°. At the back slope of the escarpment, the streamlines are stably stratified and are concordant with the surface. Downwind, close to the ground and immediately behind the escarpment a re-circulation of air occurs and a wake zone is developed. At the back slope, the field of wind velocity pressure is stably stratified and flow is unaffected. As it reaches the brink of the escarpment, the pressure expands downwind of the escarpment resulting in flow stagnation and velocity reduction. Over the re-circulation zone, the flow accelerates due to streamline compression associated with the decreasing pressure gradient (Bullard et al., 2000). Downwind of the re-circulation zone, the flow velocity and pressure return almost similar to the airflow at the back slope. The length of the re-circulation zone increases as the slope angle increases, as the model shows. Regarding the escarpment with 90° slope angle, the extent of the re-circulation zone was up to

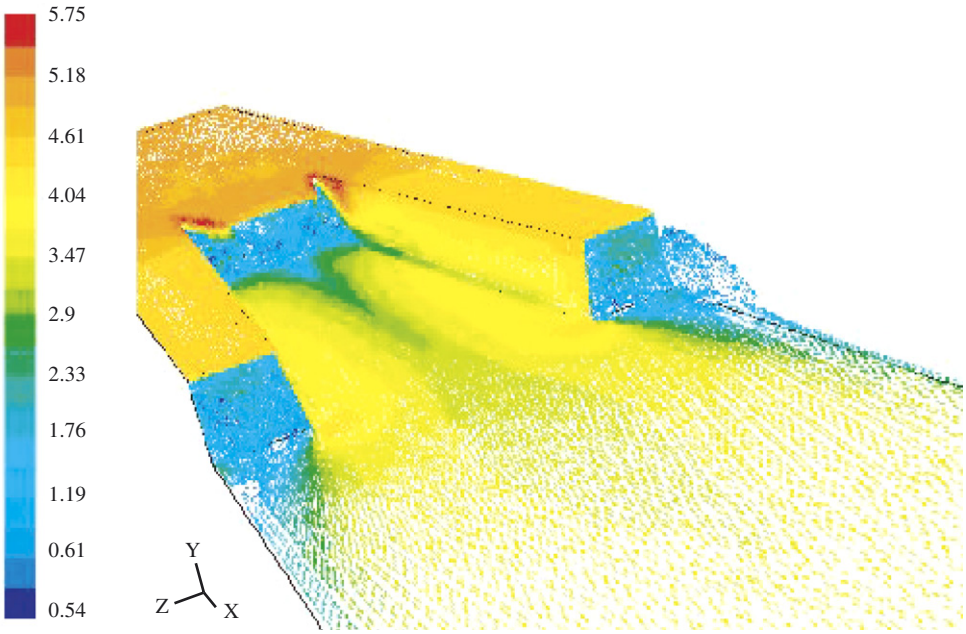

Fig. 11. Velocity vector of wind (m/s) within the vicinity of wadi model along Jal Az-Zor escarpment.

270 m, where it was limited to 250 m in length for escarpment of a 45° slope. Fig. 13 shows the streamline airflow and velocity vector profile at seven sites along the escarpment cross-section with 15° slope angles. In this model, the streamline flow appears to be stably stratified and is concordant with the escarpment profile. However, the model showed no evident re-circulation zone, although the wind velocity reduced. This is related to the fact that the slope angle of less than 30° is predominantly associated with unseparated flow (Scare, 1973).

The development of the falling dunes relates to the orientation of the escarpment and the prevailing northwesterly wind. According to Bagnold (1941) and Cooke et al. (1993), the maximum amount of sand accumulation occurs if the prevailing wind is at right angles to the escarpment. Accumulation is minimum if the escarpment is oriented parallel to the prevailing wind. Along the Jal Az-Zor escarpment, most falling dunes form in the zone where the escarpment is oriented normal to the prevailing northwesterly wind, between Al-Atraf at the southwest to Bahrat Al-Aujah at the northeast. However, at the far northeast of the study area, the escarpment swings to the southeast running parallel to the prevailing wind. In that zone, no falling dunes developed, except at Ras As Subiyah where the escarpment is slightly oriented at an angle with the prevailing wind.

4.7. Future development of falling dunes

In a desert environment like that of Kuwait, the surface sediment and vegetation cover are sensitive elements of the ecosystem that are integrated in equilibrium with natural desert processes (Khalaf, 1989). Therefore, interference with this equilibrium causes environmental and geomorphological changes. These changes include the development of new fields of sand dunes. Based on this study, the future development of falling dunes in Kuwait is controlled principally by changes of sand supply from upwind sources and in some extent to climatic conditions. Since no cyclical climatic changes are observed in Kuwait, it is difficult to predict future development of falling dunes based on climate parameters. However, we can predict that the sand supply will continue.

As previously stated, in Kuwait the falling dunes developed between 1972 and 1992. This related to scanty rainfall, effective and unidirectional nature of wind (northwest wind) and continuous supply of sand

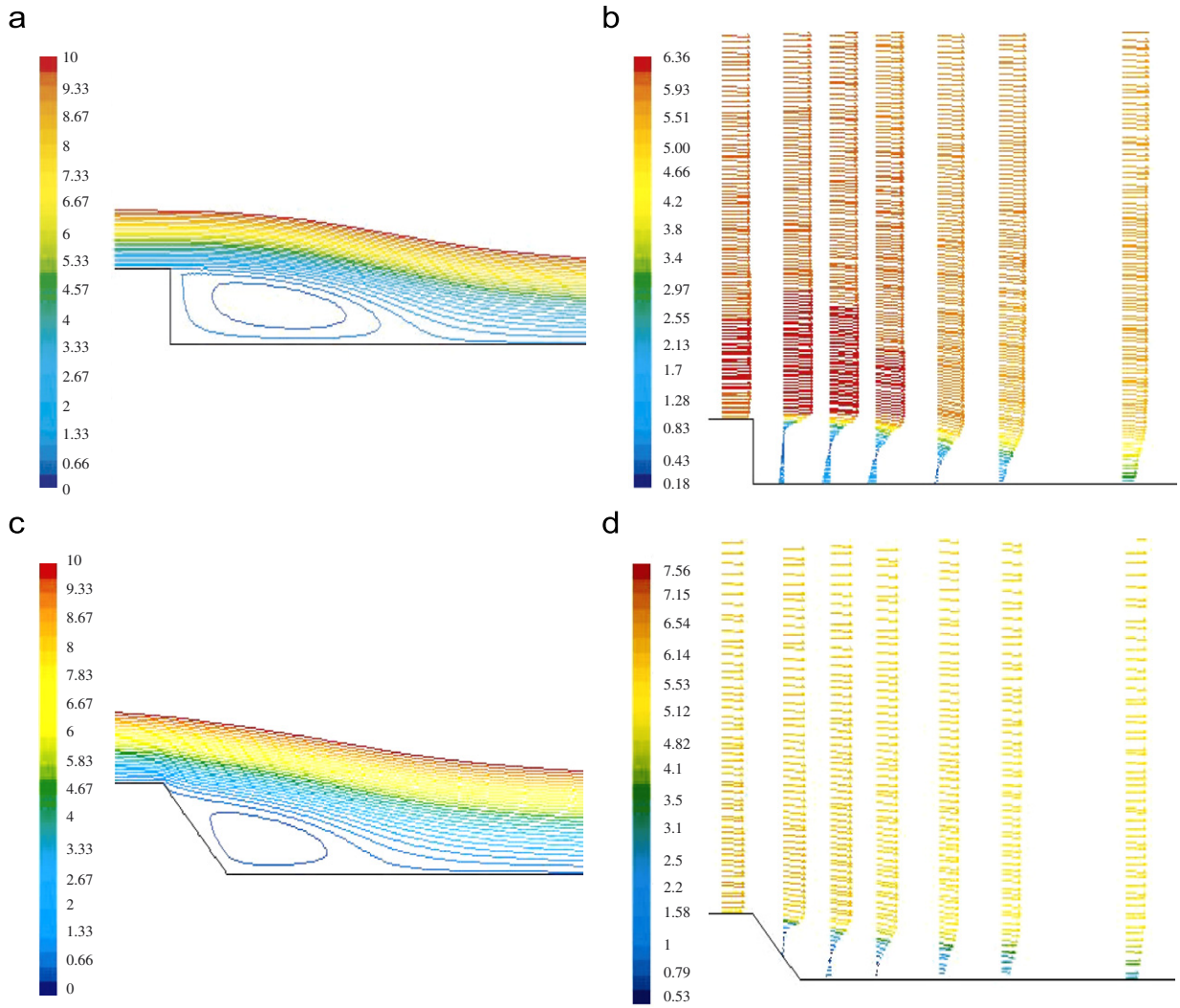

Fig. 12. The 2D view of airflow streamline and velocity vector of wind (m/s) over escarpment with slope angle (a, b) 90° and (c, d) 45°.

through land misuse by human activities. Since 1997, the sand supply toward the Jal Az-Zor escarpment was less. Al-Sudairawi and Misak (1999) indicate that the sand transport at Ar-Raudhatian (30 km northwest of Jal Az-Zor escarpment) was negligible from 13 July to 15 September 1997. Alenezi (2001) reported similar results through measurements of sand transport rate upwind of the escarpment for the period 13 July–15 September 1999. The maximum sand transport measured was 7.4 kg/cm for the whole period of study.

This reduction of sand supply is expected to continue in the future and thus limit the development of further falling dunes and reduce the rate of vertical and horizontal growth of falling dunes. The low source supply of sand that is expected relates to further reduction of human activities in the northern part of Kuwait, including stopping the gravel quarrying that was considered to be a major source of sand to the falling dunes. Other factors relate to the development of new protected areas in northeast of Kuwait. These are the Jal Az-Zor national park (established in September 2000), Ar-Raudhatian As-Sabriyah oil fields and the security zone between the Kuwait–Iraqi border that was established in 1993 (15 km in width). In these zones, the vegetation cover (mainly *Haloxylon salicornicum*) is highly enhanced. The grasses and shrubs act as effective traps for sand transported from the NW to SE.

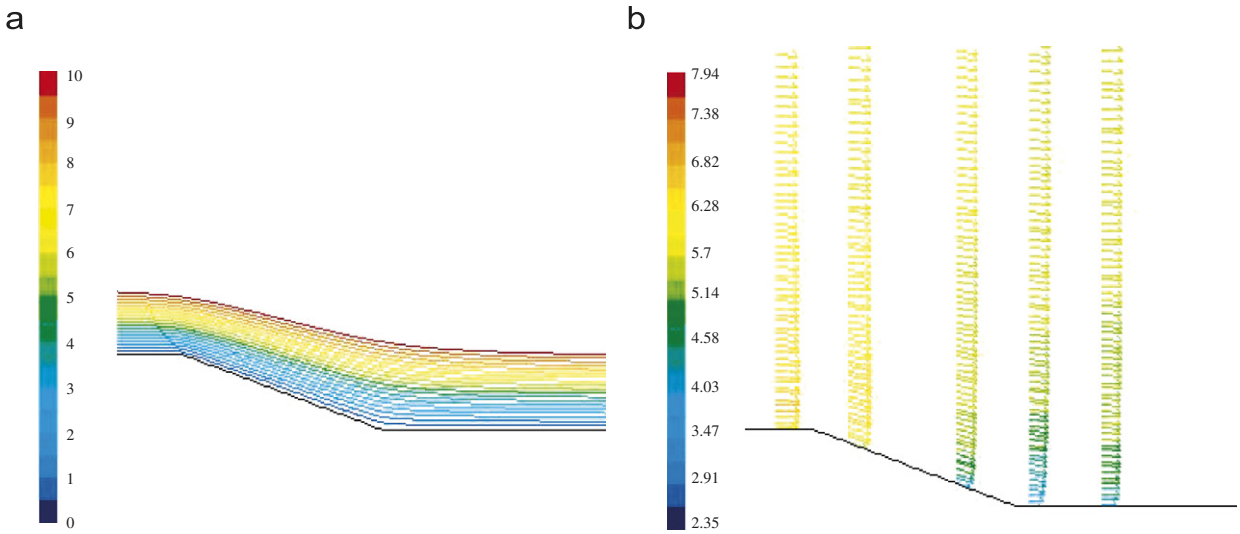

Fig. 13. (a) The 2D view of airflow streamline (kg/s) and velocity vector of wind (m/s) over escarpment with slope angle 15°.

Acknowledgment

This paper was completed with the kind help, advice and support of many experts from Kuwait Institute for Scientific Research and the Department of Geology at Royal Holloway University of London. In particular, we wish to thank K. Spencer, L. Pierce, D. Van Der Wal, S. Yoshida, A. Al-Dousari, S. Blott, D. Croft, J. Richard, S. Saye and L. Wilson from the Earth Surface Processes and Modern Environments Research Group.

References

Al-Ajmi, D., Misak, R., Khalaf, F., Al-Sudairawi, M., Al-Dousari, A., 1994. Damage assessment of the desert and coastal environment of Kuwait by remote sensing (VT001C). Report No. KISR4405, Kuwait Institute for Scientific Research, Kuwait.

Al-Ajmi, D., Misak, R., Khalaf, F., Al-Sudairawi, M., Al-Dousari, A., 1995. Assessment of mobile sand and strategy for its control in Kuwait. Desertification Control Bulletin 26, 44–54.

Al-Awadhi, J.M., 2001. Impact of gravel quarrying and urbanization on earth surface processes in Kuwait. Environmental Geology 41, 365–371.

Alenezi, A., 2001. Morphodynamic and sedimentology of falling dunes northeast of Kuwait. Ph.D. Thesis, Royal Holloway, University of London, unpublished.

Alhajraf, S., 2001. Numerical modeling of drifting sand. Ph.D. Thesis, Cranfield University, UK, unpublished.

Alhajraf, S., 2002. Numerical simulation of sand and snow drift at porous fences. In: Jeffrey, A., Zobeck, T. (Eds.), Proceedings of the Fifth International Conference on Aeolian Research and the Global Change and Terrestrial Ecosystem–Soil Erosion Network, pp. 208–213.

Alhajraf, S., 2004. Computational fluid dynamic modeling of drifting particles at porous fences. Environmental Modelling and Software 19, 163–170.

Al-Sudairawi, M., Misak, R., 1999. Study of sand control at KOC operation areas of southeast, west, north Kuwait (EES-139). Report No. KISR5550, Kuwait Institute for Scientific Research, Kuwait.

Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Chapman & Hall, London, p. 265.

Bowen, A.J., Lindley, D., 1977. A wind-tunnel investigation on the wind speed and turbulence characteristics close to the ground over various escarpment shape. Boundary-Layer Meteorology 12, 259–271.

Bullard, J.E., Nash, D.J., 1998. Linear dune pattern variability of dry valleys in the southwest Kalahari. Geomorphology 23, 35–54.

Bullard, J.E., Wiggs, G.F.S., Nash, D.J., 2000. Experimental study of wind directional variability in the vicinity of model valley. Geomorphology 35, 127–143.

Clarke, M.L., Rendell, H.M., 1998. Climate change impacts on sand supply and formation of desert sand dunes in the south-west USA. Journal of Arid Environments 39, 517–531.

Clos-Arceduc, A., 1967. La direction des dunes et ses rapports avec celle du vent. Comptes Rendus de l'Academie des Sciences, Paris 264D, 1393–1396.

Cooke, R.U., Warren, A., Goudie, A.S., 1993. Desert Geomorphology. UCL Press, London.

Edward, S.R., 1993. Luminescence dating of sand from the Kelso Dunes, California. In: Pye, K. (Ed.), The Dynamics and Environmental Context of Aeolian Sedimentary Systems. Geological Society of London, Special Publication, vol. 75. Geological Society of London, London, pp. 59–68.

El-Baz, F., Breed, C.S., Grolier, M.J., McCauley, J.F., 1979. Eolian features in the western desert of Egypt and some application to Mars. Journal of Geophysical Research 84, 8205–8220.

Evans, J.R., 1961. Falling dune and climbing sand dunes in the Cronese ("Cat") Mountain area, San Beranadino County, California. Journal of Geology 70, 107–113.

Fryberger, S.G., 1978. Techniques for the evaluation of surface wind data in terms of eolian sand drift. USGS Open File Report 78-405, p. 24.

Fryberger, S.G., 1979. Dune forms and wind regimes. In: Mckee, E.D. (Ed.), A Study of Global Sand Seas. United States Geological Survey, Professional Paper 1052, pp. 137–169.

Gosman, A.D., 1999. Developments in CFD for industrial and environmental applications in wind engineering. Journal of Wind Engineering and Industrial Aerodynamics 81, 21–39.

Goudie, A.S., 1996. Desert degradation. In: Goudie, A.S. (Ed.), Techniques for Desert Reclamation. Wiley, London, pp. 1–23.

Goudie, A.S., Colls, A., Stokes, S., Parker, A., White, K., Al-Farraj, A., 2000. Latest Pleistocene and Holocene dune construction at the north-eastern edge of the Rub Al-Khali, United Arab Emirates. Sedimentology 47, 1011–1021.

Greeley, R., 1986. Aeolian landforms: laboratory simulations and field studies. In: Nickling, W.G. (Ed.), Aeolian Geomorphology. Allen & Unwin, Boston, pp. 195–213.

Howard, A.D., 1985. Interaction of sand transport with topography and local winds in the northern Peruvian coastal desert. In: Barndorff-Nielson, O.E., Moller, J.T., Rasmussen, K.R., Willettes, B.B. (Eds.), Proceedings of the International Workshop on the Physics of Blown Sand. University of Aarhus, Aarhus, pp. 511–544.

Ishii, M., 1975. Thermo-Fluid Dynamics Theory of Two-Phase Flow. Eyrolles, Paris.

Jackson, P.S., 1975. A theory for flow over escarpments. In: Proceedings of the Fourth International Conference on Wind Effect on Buildings and Structures, Heathrow, UK, September 1975. Cambridge University Press, Cambridge.

Khalaf, F.I., 1989. Desertification and aeolian processes in the Kuwait desert. Journal of Arid Environments 16, 125–145.

Khalaf, F.I., Al-Kadi, A.S., Al-Saleh, S., 1985. Minerological composition and potential sources of dust fallout deposits in Kuwait, Northern Arabian Gulf. Sedimentary Geology 42, 255–278.

Lancaster, N., Tchakerian, V.P., 1996. Geomorphology and sediment of sand ramps in Mojave Desert. Geomorphology 17, 151–165.

Lettau, K., Lettau, H.H., 1978. Experimental and micrometeorological field studies of dune migration. In: Lettau, H., Lettau, K. (Eds.), Exploring the World's Driest Climate. IES Report 101, Institute for Environmental Studies, University of Wisconsin-Madison, pp. 110–147.

Magaly, K., Abdelgadir, A., El-Baz, F., 1998. Application of geographic information system (GIS) in modeling geomorphologic change in Kuwait's desert. In: Omar, S., Misak, R., Al-Ajmi, D. (Eds.), Sustainable Development in Arid Zones, Assessment and Monitoring of Desert Ecosystem, vol. 1. Balkema, Rotterdam, pp. 333–340.

Mainguet, M., 1983. Dunes vives, dunes fixees, dune vetues: une classification selon le bilan d'alimentation, le regiem eolian et la dynamique des edifices sableux. Zeitschrift für Geomorphologie, Supplementbond 45, 265–285.

Mainguet, M., Dumay, F., 1998. The concept of global wind action system and aeolian sediment balance, keys for aeolian action and desertification. In: Omar, S., Misak, R., Al-Ajmi, D. (Eds.), Sustainable Development in Arid Zones, Assessment and Monitoring of Desert Ecosystem, vol. 1. Balkema, Rotterdam, pp. 127–142.

McKee, E.D., 1979. Introduction to study of global sand seas. In: Mckee, E.D. (Ed.), A Study of Global Sand Seas. United States Geological Survey, Professional Paper 1052, pp. 3–19.

Misak, R., Omar, S., 2004. Military operations as major cause of soil degradation and sand encroachment in arid regions (the case of Kuwait). Journal of Arid Land Studies 145, 25–28 (special issue—Desert Technology VII).

Peric, M., 1985. Finite volume method for the prediction of three-dimensional fluid flow in complex duct. Ph.D. Thesis, Imperial College, London.

Scare, C., 1973. Influence d'une colline sur la vitesse du vent dans la couche limite de surface. Internal Report, Center Scientifique et Technique du Batiment, Nantes, France.

Taha, F.K., Omar, S.A., Clayton, D., Al-Bakri, D., Al-Mutawa, S., Nassef, A.A., 1982. Selection of criteria for national parks, nature reserves in the Kuwait desert. Final Report, KISR, 729AG-40, p. 225.

Tchakerian, V.P., 1991. Late Quaternary aeolian geomorphology of the Dale Lake sand sheet, southern Mojave Desert, California. Physical Geography 12, 347–369.

Tchakerian, V.P., 1994. Paleoclimatic interpretations from desert dunes and sediments. In: Abrahams, A.D., Parsons, A.J. (Eds.), Geomorphology of Desert Environments. Chapman & Hall, London, pp. 631–643.

Tchakerian, V.P., 1999. Dune paleoenvironments. In: Goudie, A.S., Livingstone, I., Stokes, S. (Eds.), Aeolian Environments, Sediments and Landforms. Wiley, New York, pp. 261–292.

Thomas, D.S.G., 1988. Analysis of linear dune sediment–form relationship in the Kalahari dune desert. Earth Surface Processes and Landforms 13, 545–553.

Tsoar, H., 1989. Linear dunes—forms and formation. Progress in Physical Geography 13, 507–528.

White, B., Tsoar, H., 1998. Slope effect on saltation over a climbing sand dune. Geomorphology 22, 159–180.

Zimbelman, J.R., Williams, S.H., Tchakerian, V.P., 1995. Sand transport path in Mojave Desert, Southwestern United states. In: Tchakerian, V.P. (Ed.), Desert Aeolian Processes. Chapman & Hall, London, p. 10.