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ORIGINAL PAPER

Morphological characteristics and development of coastal nabkhas, north-east Kuwait

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Abstract The coastal aeolian nabkhas, in Kuwait, are mostly elongated, with an average length of about 10 m, an average width of 3.7 m, and an average height of 0.65 m. The horizontal component of the nabkha dune (HC: the mean of the length and width of nabkha dune), developed around *Nitraria retusa*, was measured and compared with the height of the shrub. A second-polynomial function was found to best fit the set of data. The fitting identified three trends of the development of the nabkhas. Initially, as the height of shrubs (H) increases, the HC increases linearly until it reaches approximately 10 m. When H exceeds 2 m, the effect of shrub height becomes ineffective in trapping more sediments; that is, reaching an equilibrium condition, before a decrease in shrub height effectiveness occurs. Sediments of the nabkha crest and wings, left and right sides, are subjected to high energy winds, and therefore, they are generally coarser and better sorted than those of the tail or the nose. Minor differences are noted in the textural characteristics and the mineral composition of nabkha sediments and those of other aeolian landforms found in upwind nabkha field; this indicates that the sediments were derived from the nearby sources.

Keywords Shrub · Aeolian sediment · Minerals · Nabkhas

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Introduction

Nabkha is a type of aeolian landform which is commonly developed as a result of aeolian sand accumulation around desert or coastal shrubs; that is, as a result of aeolian erosion and deposition activities (Ardon et al. 2009). Aeolian processes including deflation, transportation and deposition are very active in Kuwait, where they are attributed to the dry, hot, windy climate, the detrital nature of bed rock and its location downwind from the high-deflation area of Mesopotamian floodplain (Khalaf 1993; Al-Enezi et al. 2008). As a result, sand continually drifts along the surface by wind, mainly during the summer season (May–September), to form different aeolian land forms including nabkhas (Al-Awadhi and Misak 2000).

Nabkhas around the same plant in one area may exhibit variable morphological features due to plant morphology (Ahmed et al. 2009). In general, the morphology of nabkhas is controlled by growth patterns of shrub, type of sediment supply and climate (Hesp 1991; Nickling and Wolfe 1994; Khalaf et al. 1995; Tengberg and Chen 1998; Hesp and McLachlan 2000; Wang et al. 2006). Roots and plant debris of the shrubs act to bind and retain sand. This is achieved by the plant putting out new growth after it is partly buried (Dougill and Thomas 2002). Although nabkha dune, being anchored by a plant, does not migrate, it grows along with the plant, both vertically and horizontally (Ardon et al. 2009). Nabkhas are like sand shadows, since they accumulate in the lee-side of isolated shrubs (Cooke et al. 1993). However, due to the complexity of lee-side flow, the flow patterns remain poorly understood with regard to their role in sand transport mechanism and dune maintenance (Walker and Nickling 2002).

As the dune nabkha develops, the shrub is able to keep pace, growing above the active sand surface. Kocurek et al.

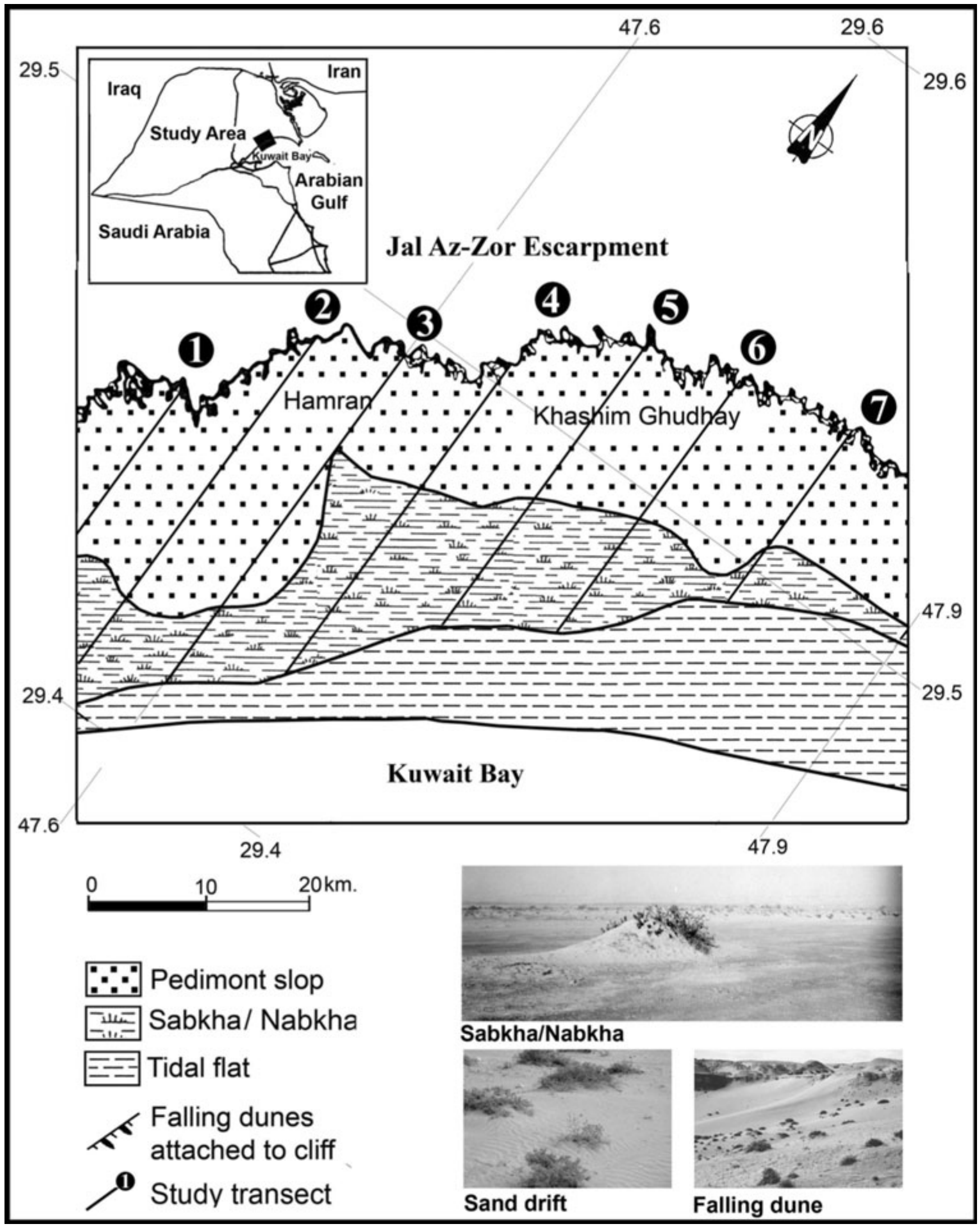

Fig. 1 Geomorphological map of the study area showing the transect lines along which nabkhas and other aeolian landforms were selected for this study. Also, photographs of different aeolian landforms in the study areas are shown

(1995) identified cyclic destructional and constructional phases in a coastal nabkha field, where cycles corresponded to seasonal weather changes. Gile (1975) reported a decrease in number of shrub-coppice dunes in south-western US because of vegetation deterioration due to changes in land use during the last 100 years. Similarly, Omar et al. (2000) showed significant reduction in coastal plant distribution in Kuwait, particularly *Nitraria retusa*, due to human-induced land degradation over the last 30 years.

To provide a better understanding on the features of coastal nabkhas and their development in the north-eastern part of Kuwait, this study presents the results of field and laboratory investigations on the morphological, sedimentological and mineralogical characteristics of the nabkhas, with an emphasis on issues related to their development. In addition, textural characteristics and mineralogical composition of studied nabkhas are compared with other inland aeolian landforms.

The study area

The study area is located within the northern coastal plain of Kuwait Bay (Fig. 1) and downwind of the major mobile sand corridor extending continuously from the north-western border of Kuwait in a SE direction over about 100 km, and with an average width of about 25 km (Al-Awadhi and Misak 2000). Applying a susceptibility model, a map of sand encroachment susceptibility in Kuwait was developed by Al-Hellal and Al-Awadhi (2006). The map showed that the study area is located in a high sand encroachment susceptibility zone with the north-westerly dominant wind direction. Al-Awadhi and Al-Awadhi (2009) estimated the average monthly magnitude of sand transport, in the study area, during a potential sand movement season (April–September) to be about 7,700 kg/m.

The study area is bounded at the north by Jal Az-Zor escarpment (maximum elevation of 165 m), which is intensively dissected by parallel to sub-parallel drainage systems. The coastal plain slopes gently towards Kuwait Bay with an angle <2°. The dominant landform in the coastal plain is consistently sabkha which is covered partially with either sand sheet and/or nabkhas. The coastal nabkhas, in the study area, are developed around plant species such as *Nitraria retusa*, *Tamarix aucheriana*, *Halocnemum strobilaceum* and *Salicornia europaea*, and varying considerably in size and shape and having different ecological properties characterized by lower pH and carbonates percentages, but higher in moisture contents and total dissolved salt levels, in comparison with desert nabkhas (Al-Dousari et al. 2008). The inland area is mainly composed of a residual gravel sheet covered by scattered sand drifts. Falling dunes along Jal Az-Zor escarpment are the most prominent aeolian landform in the study area (Al-Enezi et al. 2008).

Kuwait has a desert climate. As such, the study area experiences a cold, chilly and humid atmosphere in winter due to the cold high Siberian winds and a hot, arid, dry climate in summer, due to the low humid Indian atmospheric pressure belt. Rainfall varies from 28 mm/year (1963–1964) to 260 mm/year (1975–1976), with a yearly average of about 115 mm/year. It has an average evaporation rate of about 6,060 mm/year. Summer is very hot, especially in July and August, with mean temperatures of 37.4 °C and maximum mean temperature of 45 °C (Al-Awadhi et al. 2005). Wind blows from two main directions; from the north-west, and to a lesser extent, from the south-east. The average monthly wind speed ranges from 3 m/s in winter to 4.8 m/s in summer.

Materials and methods

A total of 52 single nabkhas, developed around *N. retusa* plants, were selected along seven transects (see Fig. 1) within the coastal sabkha plain for morphometrical measurements including width, length, tail length, nose length, nabkha sediment height and height of shrub crown. The later parameters are defined in Fig. 2. The morphometrical parameters of the nabkhas were statistically analysed using SAS-JMP version 9 software.

A total of 98 surface sediment samples were collected from the nose, wings, crest and tail of two nabkhas along each transect for textural and mineralogical analyses. For

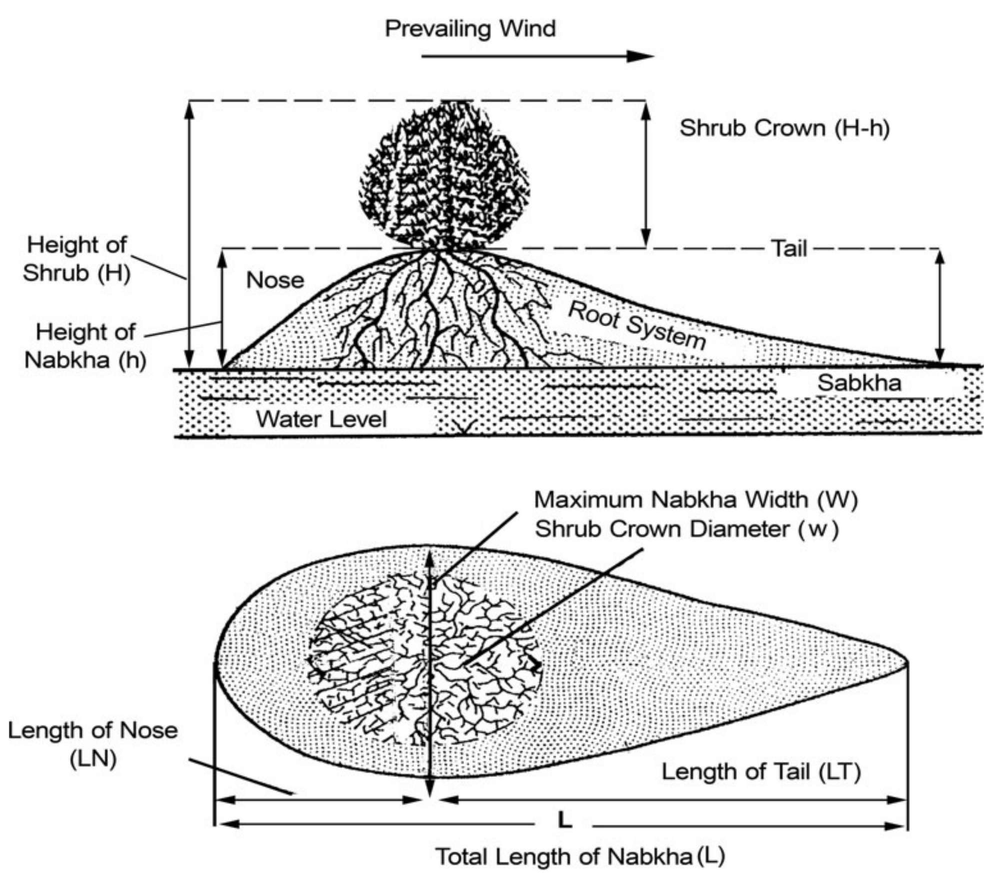

Fig. 2 Schematic diagram illustrating the morphometric parameters of nabkha dunes, (modified after Khalaf et al. 1995)

comparison purpose, additional samples were collected from other surrounding landforms including sabkha, inland sand drifts, inland nabkha, and falling dunes for textural and mineralogical analyses. Grain size analyses of all samples were carried out using standard sieving techniques, and the statistical size parameters were calculated following method of Folk (1974). In order to ensure cleanness of the sand grains, samples were wet sieved on 4 Ø sieve to separate the sand fractions from the mud (silt and clay). Mineralogical analyses of the whole sediment including its sand and mud fractions were carried out using a Siemens D5000 Diffractometer (XRD), equipped with a position sensitive detector. The computer program FIF-FRAC plus (BRUKER AXS, INC, 2004) with ICDD library was used to identify the minerals.

A Q-basic program, based on Fryberger (1978, 1979) method which is a modification of the Lettau and Lettau (1978), developed by Al-Awadhi et al. (2005), was used to calculate patterns of sand movement using wind energy environment of the study area. These include drift potential (DP), resultant drift potential (RDP), resultant drift direction (RDD) and wind index (RDP/DP) for each month. Wind data, at 10 m height, from Mutlaa meteorological station (located 8 km to the west of the study area) was collected for a period from 2006 to 2010. The Fryberger method is designed to give a relative rather than absolute description of the effect of wind energy on sand drift in vector units (VU). However, the wind energy remains a key variable that can be used to examine potential sand drift and aeolian activities in dune fields including nabkha dune (Lancaster 1988; Bullard et al. 1996).

Results

Sand drift potential

Due to monsoonal low-pressure system, the aeolian processes become highly active in the early summer, causing sand drift. Figure 3 presents the monthly sand drift potential (DP) rises in the study area and their resultant drift direction (RDD) based on analysis of monthly average wind speed, using the method of Fryberger (1978, 1979). The data reveal that the annual RDD is consistently towards the SE direction. The monthly DP is estimated at range of 12 VU (vector unit) in November to 106 VU in June, with annual DP equalling to 497 VU. Thus, the study area is classified among the high wind energy deserts, which are defined by Fryberger (1979) as those desert areas with annual DP equal to or greater than 400 VU. Seventy one per cent of the average annual DP occurs during summer period; that is, May–September.

The variations in the sand drift direction (wind direction index) was calculated, and it was found that July had the highest index with a value of 0.87 (unidirectional wind; RDP/DP >0.8). The calculation indicated that December witnesses the lowest directional wind index (RDP/DP = 0.29). The monthly resultant drift direction (RDD) is calculated at ranges from 119° in November to 154° in December, with average RDD equalling to 135°; that is, direction is mainly from NW towards the SE. This coincides with the field observations in which the nabkhas are developed with their long axis parallel to NW–SE; that is, the elongated south-easterly tail and short north-westerly nose are oriented along N21° W, on average.

Nabkhas morphology and morphometry

The nabkhas are mostly present as elongate-shaped mounds having long downwind tail and shorter upwind nose. They are tongue-like in shape and extend with their long axis parallel to the north-westerly wind, where their leeward side gently slopes at angle 18.3°, on average, towards south-east. Their windward side slopes at angle 21.9°, on average, generally towards north-west. However, a few nabkhas have a semi-circular mound-shape.

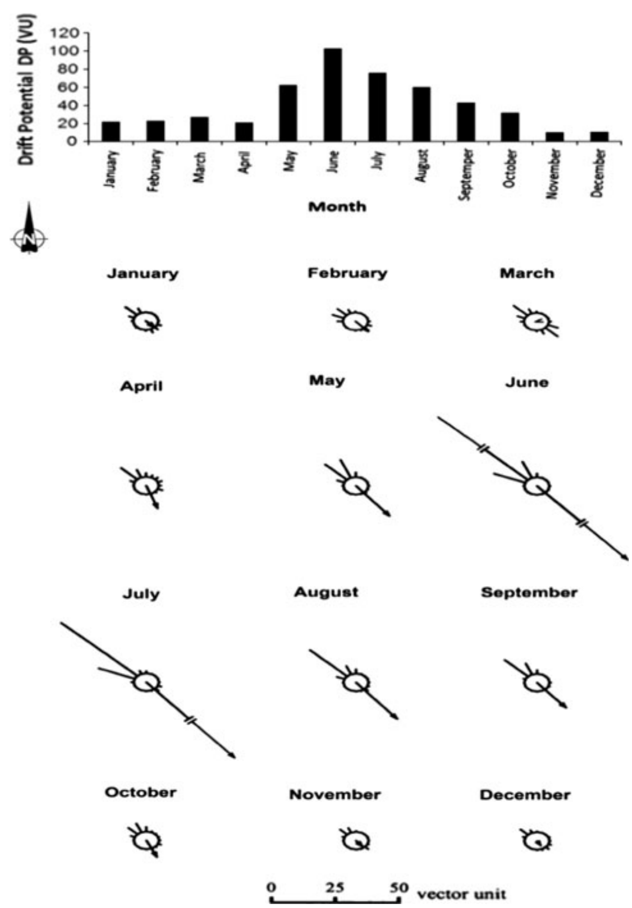

Fig. 3 Monthly drift potential and their resultant drift direction in the study area

Three types of nabkhas were recognized in the study area, namely isolated, compound and complex. Isolated or single nabkha, which were studied, is a sand body developed around single plant specimens. Compound nabkha is commonly formed of two partly overlapped nabkhas forming a saddle like feature. Complex nabkha is a group of nabkhas closing together forming one sand body. The average distance between isolated nabkhas is about 9.5 m. Such distance is strongly related to the nabkha size, that is, the larger the nabkhas, the shorter the distance between them. Variation in distances between nabkha branches for *N. retusa* plants was measured and found to vary in average from 6 to 10 cm. It was also noticed that the higher the density of the shrubs crown of the plant; that is, lower distance between the branches, the greater the volume of trapped sands.

Considerable variation in the morphometrical parameters of the 52-studied single nabkhas was noticed. They vary in length (L) between 5.1 and 15.8 m with an average of 9.98 m. Their width (W) ranges between 1.9 and 5.1 m with an average of 3.7 m. A positive correlation between the width and the length of the nabkhas is recognized through the following relationship (Fig. 4a):

$$W = 0.26L + 1 \quad (R^2 = 0.63;\ p\,\text{value} < 0.001) \qquad (1)$$

The length of the tail is generally greater than that of the nose. It varies between 1.2 and 11.3 m with an average of 7.04 m, while the nose varies in length between 1.2 and 4.9 m with an average of 3.35 m. The height of the nabkhas dune (h) ranged between 0.6 and 1.6 m above their base level with an average value of 0.65 m. Figure 4b shows a non-dimensional relationship (positive weak correlation) between the measured length and width of the nabkha dune, and its height and height of the shrub; that is, the higher the shrub the higher sand accumulation will be

$$H/h = 0.2L/W + 1.2 \quad (R^2 = 0.14;\ p\,\text{value} = 0.02) \qquad (2)$$

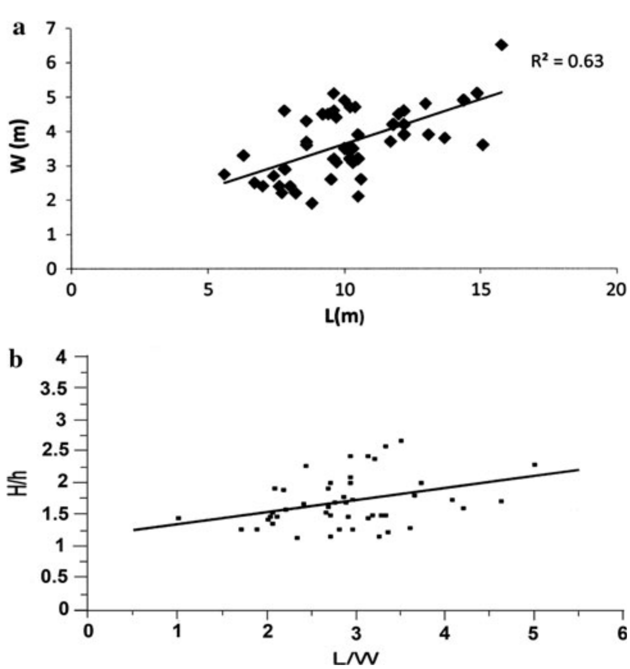

Fig. 4 Scatter plots of nabkha length (L) versus its width (W) (*a*), and non-dimensional relationship of L/W versus non-dimensional relationship of shrub height (H) with nabkha height (h) (*b*)

Table 1 Correlations between the morphometrical parameters of the nabkhas

	H	*L*	*W*	*h*	LT
Shrub height (H)	1				
Dune total length (L)	0.325*	1			
Dune maximum width (W)	0.372**	0.21	1		
Dune height (h)	0.711*	0.118	0.31*	1	
Dune tail length (LT)	0.322*	0.55*	0.344*	0.23	1

** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed)

Table 1 presents the correlations between the morphological parameters of the studied nabkha. It shows that significant correlations (p value <0.05) exist between the height shrub and the dune length, width and height; however, the height of the dune is strongly correlated ($r > 0.7$) with the height of the shrub.

The maximum height of a nabkha shrub (H) is measured to be 2.8 m above the ground with an average height value of 1.78 m; that is, 2.7 times, in average, higher than the height of nabkha dune. Figure 5a indicates that as the shrub increases in height, the dune length of nabkha increases, and the total length may extend, on average, 6.1 times that of shrub height, while the tail length may extend, on average, 3.95 times that of shrub height. Figure 5a, however, reveals that such a relation may become relevant up to a certain height as the shrub grows higher. Figure 5a presents a relationship between the total shrub height (H) and the horizontal component (HC) of the nabkha dune, the latter being the mean of the total length (L) and maximum width (W) of nabkha dune. The data in Fig. 5a were fitted to a polynomial function of order-two, which was found to the best fit compared to other plots in Fig. 5, using the least-square principle method with a constant of $H = 0$, when HC = 0. The relationship between H and HC, as revealed from Fig. 5a, can be described as follows:

$$H = a(\text{HC}) - b(\text{HC})^2 \qquad (3)$$

where HC = $(L + W)/2$, $a = 0.4$ and $b = 0.02$.

Equation 3 was tested using R-square method and was found to be equal to 0.66, and the a and b coefficients were also tested against the height of the shrub and found to be significant (t-probability <0.05); that is, t-probability for a

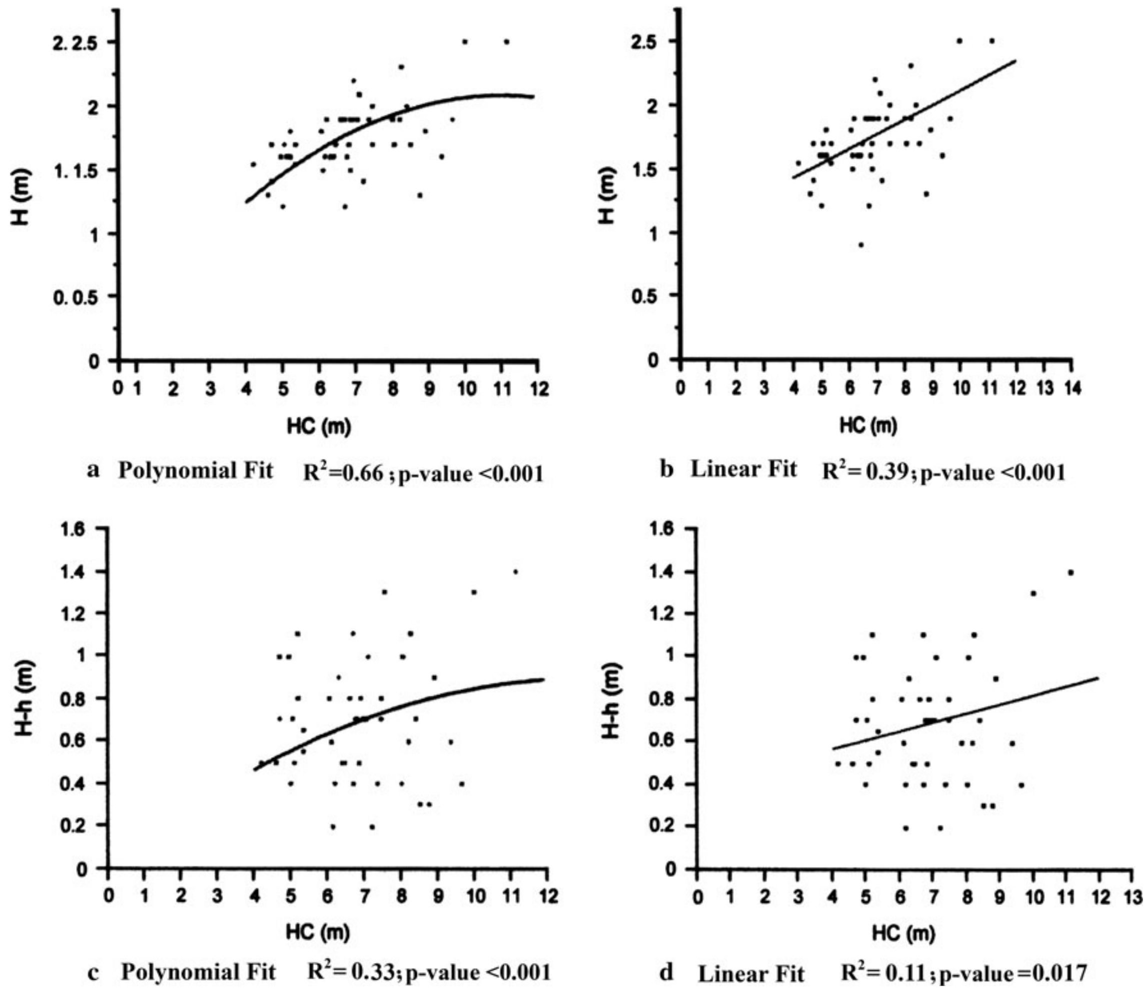

Fig. 5 Different scatter plots of the sizes of *Nitraria retusa* nabkhas in the study area; H and h are the heights of the shrub and dune, respectively; HC is the horizontal component of the dune

and b is equal to <0.0001 and 0.0002, respectively. Analysis of variance for the model (Eq. 3) also showed a p value less than 0.001; that is, significant probability.

A critical point exists due to either biological (growth rate of the shrub) or environmental (interaction between local factors influencing the morphology of nabkha dune) restrains leading to an equilibrium stage in sand accumulation. Such a point can be identified by comparing the rate of growth in the shrub height and horizontal growth of the nabkha dune. A relative rate of growth can be defined as follows:

$$(\mathrm{d}H/\mathrm{d}t)/(\mathrm{dHC}/\mathrm{d}t) = (\mathrm{d}H/\mathrm{dHC}) = a - 2b\mathrm{HC} \qquad (4)$$

Setting relative rate of growth to zero gives an estimate of HC at equilibrium (critical HC; HC_c), as $HC_c = a/2b$; that is, the horizontal component at equilibrium can be calculated as $HC_c = 10$ m. Accordingly, the corresponding equilibrium shrub height (critical H; H_c) can be calculated from Eq. 3, as $H_c = 2$ m.

Textural characteristics

The distribution of the grain size classes of various parts of the nabkha deposits indicates that they are all unimodel, where the medium and fine sand fractions are the most dominant size classes (Fig. 6). However, it is noted that the mud fraction occurs in lesser amounts, particularly in the tail of the nabkhas. It varies from <1 to 7 % with an average of 2.4 %. Sediments in the nabkha nose are relatively more coarser than that in the tail. The texture of both the crests and wings are intermediate between those of the nose and tail. These textural variations are reflected in the size parameters. The average mean size (Mz Φ) of the nabkha sediments is of medium sand (1.22 Φ). It is noted that the Mz Φ of the tail sediment is relatively finer than that of the other parts of the nabkha. Sorting is moderate on average; however, the nose sediments are relatively less well sorted than those of the tail. Those of the crest and the wings are better sorted than those of the nose and the tail.

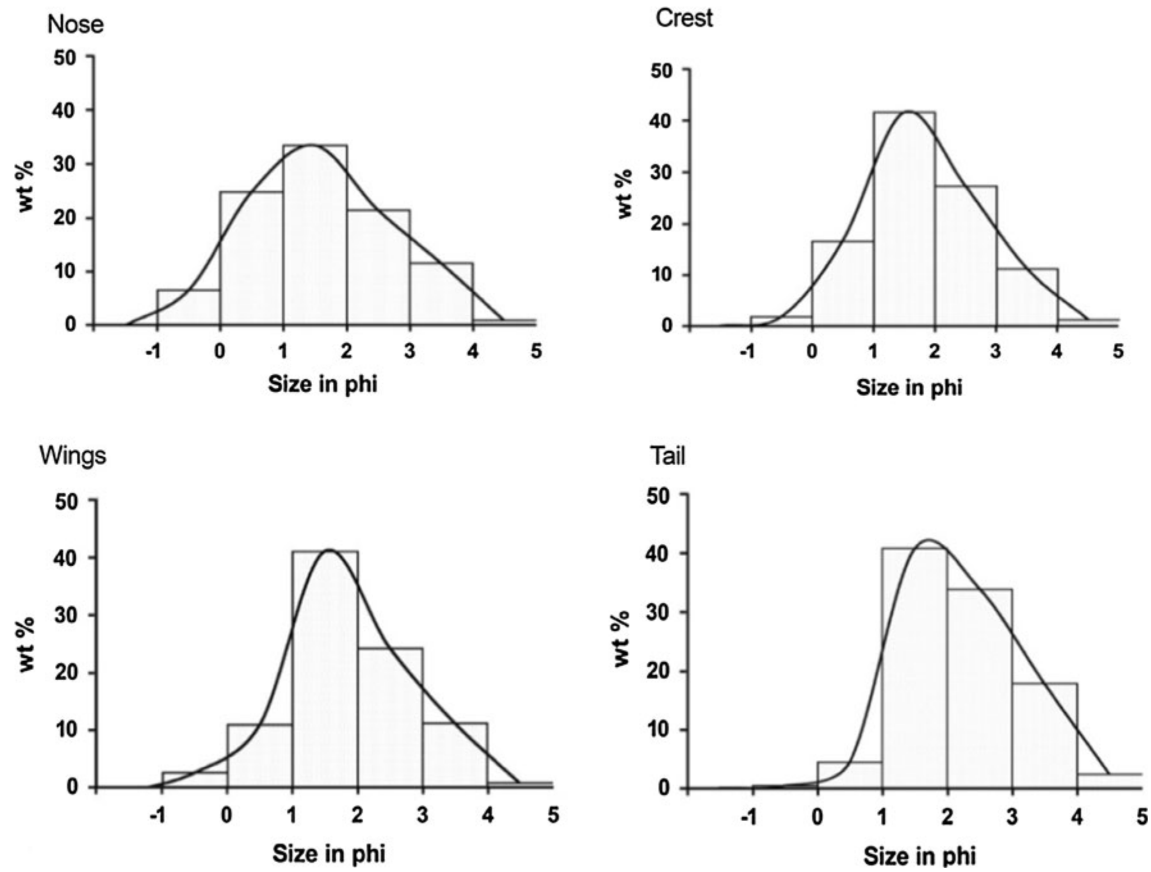

Fig. 6 Average grain size distribution histograms for various positions on nabkha dune

Table 2 Averages of the grain-size statistical parameters (Φ) of the nabkha sediments

Nabkha's part	No. of samples	Mode	Median	Mean	Sorting	Skewness	Kurtosis	Mud (%)
Downwind tail	14	1.92	1.66	1.74	0.81	0.27	0.96	2.3
Upwind tail	14	1.21	1.06	1.22	0.86	0.24	1.03	
Right wing	14	1.42	1.09	1.26	0.85	0.17	1.03	1.6
Left wing	14	1.42	1.17	1.30	1	0.18	0.95	
Crest	14	1.92	1.46	1.50	0.88	0.17	1.04	1.8
Upwind nose	14	1.64	1.20	1.27	0.98	0.16	0.95	1.3
Downwind nose	14	1.14	0.79	0.96	1.07	0.16	1.04	

These sediments are finely skewed and mesokurtic in average (Table 2).

The sediments surrounding the nabkhas, namely falling dunes, inland drifts, sand sheets and sabkha are mostly sand (Table 3). However, the mud fraction occurs in subordinate amount in the sabkha sediments, approximately 1.5 % on average. The falling dune sediments are characterized by a fine sand mode, while the medium sand fraction is the most dominant in the reminder of the sediments. The average mean size of these sediments is medium sand (1.08–1.8 Φ). The increase in the average mean size of the sabkha sediment is attributed to the relative abundance of the gravel fraction. Falling dune and inland drift sediments are relatively better sorted (moderately well sorted) than both the sand sheet and sabkha sediments (moderately sorted). Most of the surrounding sediments are finely skewed and mesokurtic.

Mineralogical characteristics

A slight variation is recognized in mineral frequency percentages in the sand and mud fractions and the bulk sediments in different parts of the nabkhas (Table 4). The bulk sediments of the nabkhas are mostly composed of quartz

Table 3 Averages of the grain-size statistical parameters (Φ) of the sediments surrounding the studied nabkhas

Type of sediment	No. of samples	Mode	Median	Mean	Sorting	Skewness	Kurtosis	Mud (%)
Sabkha sediment	7	1.66	1.40	1.44	1.00	0.17	1.16	0.92
Sand drift	7	1.35	1.12	1.25	0.98	0.15	0.91	0.08
Inland nabkha	7	1.78	1.51	1.57	0.63	0.27	1.01	0.16
Falling dune	7	2.07	1.76	1.79	0.66	0.18	1.08	0.42
Coastal nabkha[a]	98	1.53	1.20	1.32	0.92	0.19	1.00	1.46

[a] Presented values are averages of values in Table 1

Table 4 Mineralogy of nabkha dune and other existing aeolian landforms (%) in study area

Fraction	Position	Quartz	Calcite	Dolomite	Feldspar	Gypsum	Halite	Illite
Coastal Nabkha								
Bulk	Tail	72.96	14.21	2.37	8.48	3.67	2.43	–
	Crest	73.60	12.28	2.28	9.10	2.63	2.88	–
	Nose	83.20	7.43	2.06	5.99	1.97	1.23	–
Average[a]		76.59	11.30	2.23	7.85	2.75	2.18	–
Sand	Tail	73.63	11.63	2.60	8.40	2.50	2.35	10.30
Mud	Tail	43.00	25.13	6.28	9.23	2.57	5.40	10.38
Sand	Crest	68.05	9.58	2.33	13.95	2.60	1.93	7.80
Mud	Crest	39.18	16.65	6.85	18.48	4.10	6.03	9.70
Sand	Nose	85.50	3.68	2.00	6.23	2.00	0.60	7.80
Mud	Nose	35.33	29.13	6.73	10.08	5.80	4.30	11.23
Other landform[a]								
Sabkha sediment		85.50	8.60	1.90	3.88	2.50	–	–
Sand drift		83.65	8.35	1.63	6.38	–	–	–
Inland nabkha		68.28	18.63	1.83	11.28	–	–	–
Falling dune		80.50	8.95	2.00	9.00	–	–	–

[a] Presented values are averages of bulk fraction

and calcite, while feldspar, gypsum, dolomite and halite occur in subordinate amounts. Some differences are noted between the mineral frequency percentages in the sand and mud fractions. Quartz is more frequent in the nabkha's nose sediments. The mineral composition of the surrounding sediments is generally similar to that of the nabkha sediments (Table 4).

Discussion

Despite the importance of the continuous supply of sand, the size variability of nabkhas is controlled chiefly by the total shrub height. The height of nabkha dune, to some extent, is related to the height of the shrub crown, while its length is related to the overall height of the shrub (Khalaf et al. 1995), width of the basal shrub and wind velocity (Hesp 1991). The relationship between the height of shrub and the horizontal component lengths of the nabkha dunes is clarified through scatter plots presented in Fig. 5. Figure 5a reveals that as the horizontal component (HC) grows further, the shrub height (H) effect on sand accumulation appears to stabilize somewhat before decreasing; that is, three phases of nabkha dunes development can be distinguished: a growing, a stabilizing and a degrading phase. Such changes in phases are partly related to the size of the shrub, where the nabkhas are attached and mainly related to sediment supply, and wind regime (Cooke et al. 1993; Tengberg and Chen 1998). Figure 6a also indicates that when H is small, the linear trend in nabkha dune growth (HC) dominates, and as H increases further HC decreases, which may indicate a degrading phase of the nabkha development. Between the two phases, a critical point exists where equilibrium or a stabilizing phase dominates; that is, a balance between the growing phase and degrading phase exists. The HC and H at equilibrium stage, for the Kuwaiti nabkhas, were found to be 10 and 2 m, respectively.

Although research on lee airflow patterns, particularly regarding their relevance in sediment transport and nabkha dune maintenance is mostly qualitative, Leednders et al. (2007) conducted a study to study the effect of single vegetation elements on the pattern of average wind speed and sediment transport. They found that behind shrubs, wind speed near surface was reduced up to approximately seven times the height of the shrub. Field and wind tunnel flow visualizations on the leeward side of non-erodible elements, estimated this distance to be in order of 4–10 times the height of element (e.g., Cooke et al. 1993; Walker and Nickling 2002). Our field investigations showed that the average extent of reduction in erosion or the degree of sheltering by the shrub reaches up to a downwind distance approximately equal to four times the height of shrub. Such variation in estimating this extent of wind reduction behind a non-erodible element is mainly attributed to wind speed and direction, obstacle geometry and atmospheric stability (Walker and Nickling 2002). This means that the nabkha dune does not grow infinitely, but is constrained by shrub growth and sediment supply (Tengberg and Chen 1998); that is, the core of nabkha dune grows to a height at which wind velocity can re-entrain sediment (Cooke et al. 1993). Such an equilibrium condition was explained by the trend of nabkha dune development as the total height of the shrub increases (Fig. 5a). From field observations, it also seems that as the height of shrub increases further, the shrub porosity reduces; that is, a less denser flourishing of shrub, and subsequently, the wind flow over the deposited sediments then becomes more active and erosion takes into place; that is, less trapping wind-laden sands. However, a careful consideration is still needed to explain the degrading phase of nabkha dune.

Variations in the grain size distribution and statistical size parameters of the different parts of nabkha are mostly attributed to the differences of the wind energy distribution around the nabkha shrub, and subsequently over the nabkha dune. Sediments of the nabkha crest and wings are subjected to high energy wind and therefore are generally coarser and more sorted than those of the tail. The latter entrain more fine-grained sediments. According to Leednders et al. (2007), at the sides (wings) of the nabkha dune, wind speed may increase by on average of 6 % by comparison with the back of shrub. A comparison between textural characteristics and mineralogical composition of the nabkha sediments and those of the surrounding sediments indicates that they are mostly derived from the same source. The formation of nabkha could be primarily produced from the local deflated sabkha sediments. Granulometrical analysis of the nabkhas revealed that they are formed from a mixture of sand and mud. The sand fraction could partially result from the deflated sabkha sediments, while the unprocessed deflated sediments from sabkha have resulted in relative abundance of mud fraction, and occurrence of gypsum and clay minerals (illite). However, the slight variation in textural and mineralogical characteristics of nabkha compared with those of different aeolian landforms, existing in the upwind and at a relatively close distance from nabkha field, may suggest a possibility of the role of continuous supply of aeolian sediments to preserve the nabkha formation.

Conclusions

A second-order polynomial equation was found to describe the relationship between the height of a shrub and the horizontal dune component of coastal nabkhas in Kuwait. The relationship distinguishes three phases of the development of nabkha dune as the height of the shrub increases: a growing, equilibrium and a degrading phase; that is, the growth of nabkha dune is restricted to some natural upper limit and constrained by sediment supply and shrub growth. The equilibrium phase occurs at a critical shrub height (2 m) at which wind velocity can re-entrain sediment over the established nabkha dune.

The different parts of nabkha slightly vary in their texture due to difference of the wind energy distribution around the nabkha shrub. A comparison between textural characteristics and mineralogical composition of the nabkha sediments and those of the surrounding aeolian sediments indicates that they are mostly derived from the same source. Entrainment of deflated sediments from a sabkha has resulted in the deposition of quartz, carbonates, gypsum, halite and clay minerals (illite) in nabkha sediments.

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