Environ Geol (2006) 49: 960–967
DOI 10.1007/s00254-005-0134-8

ORIGINAL ARTICLE

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Assessment of sand encroachment in Kuwait using GIS

Received: 20 June 2005
Accepted: 26 November 2005
Published online: 13 December 2005

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Abstract Assessment of sand encroachment in Kuwait using Geographical Information System (GIS) technology has been formulated as a Multi-Criteria Decision Making problem. The Delphi method and Analytical Hierarchy Process were adopted as evaluating techniques, in which experts' judgments were analyzed for objectively estimating and weighting control factors. Seven triggering factors, depicted in the form of maps, were identified and ordered according to their priority. These factors are (1) wind energy; (2) surface sediment; (3) vegetation density; (4) land use; (5) drainage density; (6) topographic change and (7) vegetation type. The factor maps were digitized, converted to raster data and overlaid to determine their possible spatial relationships. Applying a susceptibility model, a map of sand encroachment susceptibility in Kuwait was developed. The map showed that the areas of very high and high sand encroachment susceptibility are located within the main corridor of sand pathway that coincides with the northwesterly dominant wind direction.

Keywords Delphi · AHP · Susceptibility model · GIS · Landuse planning · Geography · Arid climate · Wind · Kuwait

Introduction

Sand deposition in Kuwait might have initiated from ancient rivers and deltas 3.3 million years ago and might have ended one million years ago (Al-Sarawi 1988). Since then, down dip breaching upstream of the alluvial fan has reduced flow, and consequently sediment load, resulting in degradation, and subsequent erosion of the fan surface. The alluvial fans have resulted from stream flooding and are composed of stacked depositional units (Al-Sarawi 1988).

During the early Holocene, silts and clays from reworked Kuwait Group sediments accumulated in depressions, leaving colluvial deposits upslope. Desert deposits subsequently invaded this landscape after the last glacial period (Al-Sarawi 1988; Al-Sulaimi and El-Rabaa 1994).

Aeolian deposits have been studied in relation to natural conditions, soil characteristics, vegetative cover and transport rate in Kuwait (e.g., Khalaf et al. 1984; Al-Nakshabandi and El-Robee 1988; Omar et al. 1989; Khalaf 1989; Khalaf and Al-Ajmi 1993; Al-Awadhi and Misak 2000). Aeolian deposits are predominant, covering more than 50% of the surface of Kuwait, and occur in the form of sand sheets, sand dunes, sand drifts, and wadi-fill (Khalaf 1989).

Aeolian sand encroachment in Kuwait has become a serious economic and social problem and is recognized by the extensive deterioration of the natural vegetative cover and increase in mobile sand activity (Khalaf 1989; Omar 1990; Khalaf and Al-Ajmi 1993; Al-Awadhi and Misak 2000). In Kuwait, sand activity is recognized by the development of new barchan dunes (Al-Dabi et al. 1997; Al-Awadhi et al. 2000) and the changing of immobile sand sheets to mobile sand sheets due to excessive uncontrolled human activities and misuse of land (Al-Awadhi et al. 2003). Economic losses caused by sand encroachment have been evaluated by Al-Awadhi and Misak (2000) for most of the desert developments of Kuwait. For example, severe sand movement at the periphery of agricultural areas in the southern part of the country has resulted in the complete failure of farms due to the adoption of mechanical (fences) and biological (belts of one or two rows of trees) sand control measures which lack a scientific basis (Al-Nakshabandi and El-Robee 1988).

Sand encroachment problems in Kuwait are a natural result of erecting constructions in the path of sand movement. Therefore, sand encroachment should be considered seriously during the planning and designing of major desert development projects. To enable good planning to combat sand encroachment problems in Kuwait, this paper aims to identify all possible factors controlling sand encroachment and to produce a map representing susceptibility to sand encroachment by using Geographical Information System (GIS) technology and by utilizing the knowledge of local experts. Delphi and Analytical Hierarchy Process (AHP) methods were used for quantifying and ranking the controlling factors.

Factors controlling aeolian sand movement

By exploiting the knowledge of local experts, seven factors controlling sand encroachment in Kuwait were identified for analysis.

Wind

The prevailing winds in Kuwait blow from the northwest and, to a lesser extent, from the southeast. The winds from other directions are less frequent and of shorter duration (Khalaf and Al-Ajmi 1993). During summer, the prevailing northwesterly wind, which reaches a maximum speed of 29 m/s in June, transports sand and fine particles from the Mesopotamian flood plain in southern Iraq towards Kuwait (Al-Awadhi and Misak 2000).

During the period between 1998 and 2001, wind data from eight meteorological stations were analyzed by Al-Awadhi et al. (2005a) to examine sand drift potential by wind in Kuwait. They found that the average annual sand drift potential (DP) is about 354 vector units (VU), which puts Kuwait among the intermediate wind energy deserts (DP between 200 and 400 VU), according to Fryberger's (1979) classification.

Surface sediments distribution

The Kuwait desert comprises about 80% of the total area of the country; the majority of this ecosystem is vulnerable to wind erosion and sand encroachment due to the aridity of the area (Al-Awadhi and Misak 2000). Several types of sediments, including aeolian deposits, residual gravel deposits, playa deposits, alluvial fans, and coastal deposits, overlay the surface of Kuwait.

Generally speaking, six forms of aeolian sand deposition are recognized by Khalaf et al. (1984) and Khalaf and Al-Ajmi (1993): (1) smooth sand sheets, flat to slightly rippled, that are normally covered with a thin veneer of coarse sand or fine gravel and cover extensive areas of southern Kuwait; (2) rugged and vegetated sand sheets that result from sand trapped around vegetation and occur in shallow wide depressions surrounding playas in the western and southern part of Kuwait; (3) active or mobile sand sheets that are thin blankets of well-sorted sand and have been deposited over other surface sediments; (4) wadi fill sands that developed by accumulation of sand in dry, shallow courses, usually covered with vegetated sand drifts; (5) barchan sand dunes that occur mainly in the northern part of Kuwait and are oriented in a northwest to southeast direction; and (6) sand drifts that frequently occur as accumulations on the lee side of shrubs—the larger the shrub, the larger the sand drift.

Vegetation type and vegetation density

The vegetation of Kuwait's desert is very sparse and is dominated by woody shrubs with annual forbs, herbs and grasses. The vegetation structure and density is dynamic and is dependent on rainfall, landform characteristics, and biotic factors (Taha and Omar 1982). Landform characteristics are particularly important as they influence the redistribution of rainwater and surface sediments by directing them towards lower elevations or runoff areas (Halwagy and Halwagy 1974). Areas within the drainage systems (wadis) support denser vegetation in the wet season than the drier upper slopes.

The natural vegetative cover in the Kuwait desert is almost completely denuded except in those areas that have restricted access, such as military zones, petroleum industry locations, and conservation sites. In these restricted areas, vegetative cover is still maintained (Al-Awadhi et al. 2005b). Studies by Halwagy et al. (1982) and Omar (1990) indicate that vegetation within protected areas may attain a potential ground cover of about 25–50% under normal climatic conditions. However, under present grazing pressure and land use, vegetation cover outside protected areas rarely exceeds 5%.

Vegetation communities in Kuwait are described in detail in a number of publications (e.g., Halwagy et al. 1982; Halwagy and Halwagy 1974; Omar 1990, 1991). Omar et al. (2001a) differentiated six major plant communities in the Kuwaiti desert: *Cyperus conglomeratus*, *Rhanterium epapposum*, *Zygophyllum qatarense*, *Halaxylon salicornica, Panicum turgidum* and *Stipagrostis plumosa*.

Land use

Fine sediments may be exposed to surface winds, and new sand supply bodies may be created in areas affected by land degradation due to land pressure or misuse. As stated by KISR (1999) and Omar et al. (2001b), some 19 types of land use are identified in the highly fragile desert ecosystem of Kuwait. Rangeland that is used for grazing by livestock and recreational activities such as camping and hunting, are the predominant land use affecting almost three-quarters of the degraded land. Military maneuvers, oil operations, and gravel quarrying affect the rest of degraded land. The unused land in Kuwait covers only 18% of the country area.

Drainage system

Regional topography has played a significant role in the morphometrical characteristics of the drainage basins in Kuwait; its northern part has well-developed drainage networks while such networks are very scarce in the southern part of the country. The drainage systems vary in pattern and dimensions and they are more abundant in the northwestern part of Kuwait desert; the most dominant pattern is subparallel dendritic (Al-Sulaimi et al. 1997). Drainage basins in the north, developed on the gently sloping northeast plain, and are relatively large in area and characterized by fine texture, low relief, and high density. They are centripetal drainage network basins that flow from all directions towards a shallow depression. These basins are elongated in the NW–SE direction. The drainage basins developed within the northwest undulating terrain are also elongated but less dense and have coarse texture. Drainage basins associated with the local topographic changes are very small in area, have course texture, very high relief ratios and very high density (Salman 1979; Al-Sulaimi et al. 1997; Kwarteng et al. 2000).

In spite of low average annual rainfall (115 mm), Kuwait experiences high intensity rainfall, usually in excess of 20 mm/day during the wet season from October to March (Al-Awadhi et al. 2005b), resulting in surface runoff loaded with considerable amounts of transported sediment within the drainage systems. During dry seasons, these systems act as local sand supply sources.

Topographic change

The surface topography of Kuwait is a rather flat to gently rolling desert plain, broken by occasional low hills, scarps, and wadis. The main impact of change in landscape on the sand movement rates is the modification of wind flow characteristics and associates aerodynamics.

The landscape slopes gently in a NE direction from about 280 m asl near the Wadi Al-Batin valley in the extreme southwestern corner of the country towards the Arabian Gulf coast (sea level) in the east. The continuous northeastern slope in the northern part of Kuwait is interrupted by a very wide, shallow inland depression with inland drainage patterns in the north, followed by a very gentle dome-shaped elevation acting as a local watershed. The Jal Az-Zor escarpment (65 km long) is the most predominant topographic feature; it extends along the north and west of the Kuwait Bay with a local relief of 125 m. Wadi Al-Batin is a large valley forming a natural western border between Kuwait and Iraq, with an average width of 7–10 km, a depth of up to 57 m, and a length of about 775 km (75 km of it lies in Kuwait and the rest in wadi Ar-Rimah in Saudi Arabia). Al-Ahmadi Ridge is a topographic feature paralleling the coastline south of Kuwait City, with a height of 125 m asl and a crest that extends for 6 km. Isolated hills in the south, such as the Warah hill and Al-Burqan hills, are roughly circular in shape and stand about 30–50 m above the surrounding plain (El-Baz and Al-Sarawi 2000).

- These factors detailed above were ranked and the following maps were compiled: Wind energy map (WE), in term of potential sand flux, (after Al-Awadhi et al. 2005a)
- Surface sediment map (SS) (after Khalaf and Al-Ajmi 1993),
- Vegetation density map (VD) presented as a normalized difference vegetation index (NDVI) image computed using bands 3 and 4 of mosaicked Landsat image of Feb-Mar, 2001 (source: Kuwait institute for Scientific Research),
- Land use map (LU) (after Omar et al. 2001b),
- Drainage density map (DD) (after Kwarteng et al. 2000),
- Topographic change map; contour interval 5 m (TC), and
- Vegetation type map (VT) (after Omar et al. 2001a).

Evaluating techniques

Assessment of sand encroachment potential in Kuwait using GIS can be considered a multi-criteria decision making (MCDM) problem. Multiple-criteria evaluating methods (e.g., Liu and Wei 2000) can be used to objectify subjective decisions. Weighting methods like Delphi and AHP are commonly used methods that apply objectively to subjective decision-making problems in a way that allows qualitative comparisons to be quantified and ranked.

Delphi process

The Delphi method is a process of collecting and distilling consensus knowledge from a group of experts using a series of questionnaires, interspersed with controlled opinion feedback. It is originally conceived as a method for predicting future events by consulting panels of experts in a particular field of interest (Brooks 1979).

The Delphi process has four necessary features (Dalkey 1972; Brooks 1979): (1) anonymity; (2) iteration, i.e., submission of a questionnaire over a series of rounds, allowing the members to change their opinions; (3) controlled feedbacks between rounds, i.e., the results of each round are analyzed by a central researcher and the responses for each given statement are fed back to all members of the Delphi group; and (4) statistical aggregation of group response, i.e., expresses the degree of consensus of the group on a particular issue.

Questions raised in the Delphi method for assessing sand encroachment problems in Kuwait were selected on a scientific basis to follow the requirements of the GIS application to be used and to avoid any personal interest. The questions emphasized: (1) selecting factors involved in sand encroachment; (2) establishing priorities for the triggering factors; and (3) weighting and setting numerical values for the sub-factors of the selected factors.

Six experts were chosen to participate in the Delphi panel; an expert here is considered to be an individual who has recognized expertise and can provide a valuable opinion on the questions related to the triggering factors and sub-factors of sand encroachment. The experts were chosen from Kuwait Institute for Scientific Research (KISR) and from Kuwait University (KU). All of the experts had good knowledge in sand encroachment phenomena and were already involved in several projects related to sand movement. Four rounds, which allowed discussion and answering of the questionnaire, were carried out to meet the objective of the study. The first two rounds required the experts to justify sand encroachment triggering factors and their ranking, followed by two rounds to weigh the sub-factors for the pre-selected factors with respect to a common scale (Table 1).

Table 1 Scale of weighting factors

0	No weight
10	Extremely low
20	Very low
30	Low
40	Low to moderate
50	Moderate
60	Moderate
70	Moderate to high
80	High
90	Very high
100	Extremely high

Table 2 Quantifying of the factors controlling sand encroachment and weighting

Wind energy (WE)	
0–100	20
> 100–200	40
> 200–300	60
> 300–400	80
> 400	100
Surface sediment (SS)	
Gravel Lag, Coastal plain deposits, Playa deposits	30
Siliciclastic Granule Lag, Pebbly and Granule Lag rich in calcretic debris, Deflated rugged sand sheet, Barchoanoid ridges	50
Fall dunes	60
Smooth sand sheet	80
Barchan dunes	90
Active sand sheet	100
Vegetation density (VD)	
High density of vegetation	20
Medium density of vegetation	40
Low density of vegetation	60
Very low density of vegetation	80
Land use (LU)	
Agricultural area, unused land, national park (wooded park)	10
Power stations	30
Cemetery, oil field, scrap yard	40
Build-up and industrial area, Water reservoir	50
Refuse disposal areas/landfill	60
Racetrack	70
Encampment, intensive animal farms, military area	80
Range land	90
Quarry area	100
Drainage density (DD)	
No drainage (bare drainage)	25
Low density of drainage system	50
Medium density of drainage system	75
High density of drainage system	100
Topographic change (TC)	
Very low change	20
Low change	40
Medium change	60
High change	80
Very high change	100
Vegetation type (VC)	
Agricultural area	0
Urban area	10
Panicultural areas (Panicetum)	30
Haloxyletum, Rhanterietum, Halophyletum	40
Stipagrostietum, Zygophylletum	50
Cyperetum, Centropodietum	60
Bare area	100

Table 3 AHP scale of pair-wise comparison

Verbal judgment of preference	Numerical rating
Extremely preferred	9
Very strong to extremely preferred	8
Very strongly preferred	7
Strongly to very strongly preferred	6
Strongly preferred	5
Moderately to strongly preferred	4
Moderately preferred	3
Equally to moderately preferred	2
Equally preferred	1
For inverse comparison	Reciprocals

Table 4 AHP calculations to determine weight of criteria for sand encroachment

	WE	SS	VD	LU	DD	TC	VT	Relative weight (w)
WE	1	2	6	6	7	8	9	0.37
SS	0.5	1	4	5	5	7	9	0.26
VD	0.166	0.25	1	2	3	7	8	0.12
LU	0.166	0.2	0.5	1	4	5	9	0.11
DD	0.14	0.2	0.33	0.25	1	5	7	0.07
TC	0.125	0.14	0.14	0.2	0.2	1	9	0.05
VT	0.11	0.11	0.125	0.11	0.14	0.11	1	0.02
Sum	2.21	3.90	12.10	14.56	20.34	33.11	52.0	1.00

The results for each round were analyzed by the junior author of this paper, and the responses for each given statement were returned to all members of the Delphi group. Statistical aggregation of group response was done at the end of rounds 2 and 4 as final steps to achieve the consensus of the results. The results are presented in Table 2.

AHP method

The purpose of AHP theory is to make a contribution towards unity by modeling the MCDM problems (Saaty and Vargas 1991). This is done by means of pair-wise comparisons of the factors to indicate the strength with which one factor dominates another. The pair-wise comparisons are arranged in a matrix, referred to as a reciprocal matrix. The principal diagonal elements of a reciprocal matrix have the property of unity, reflecting the fact that a factor when compared with itself should obviously produce a judgment of "equal importance". Table 3 shows the scale of absolute magnitudes that was used to indicate a relative judgment preference of one factor over another.

The questions for the pair-wise comparison were formed in terms of which is the more preferred or desired factor in order to satisfy the sand encroachment problem in Kuwait. An inverse comparison relationship

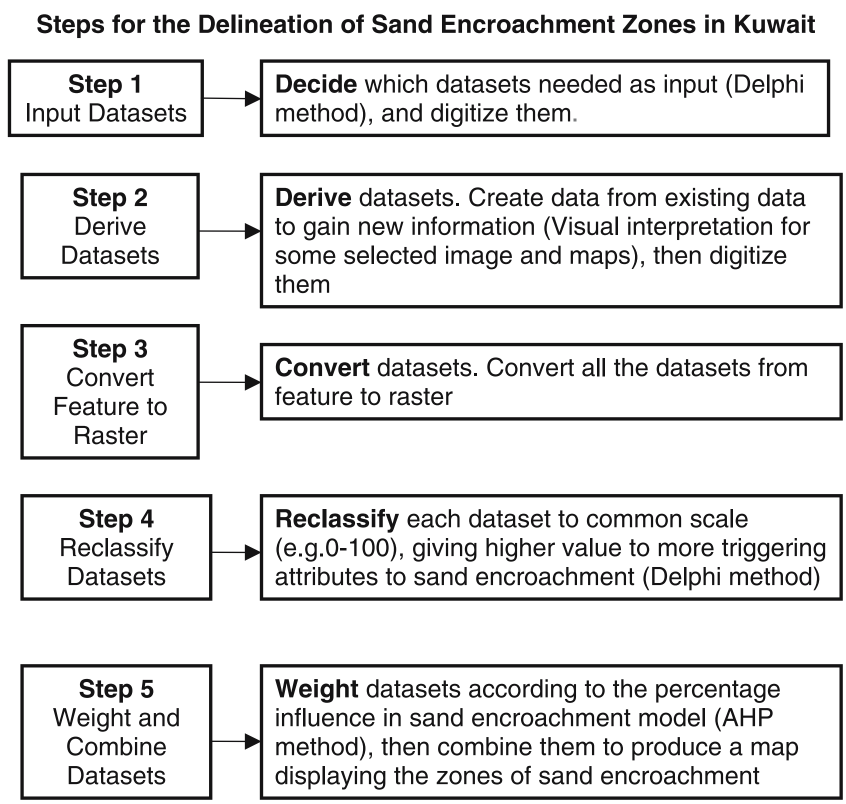

Fig. 1 Steps for the delineation of sand encroachment zones in Kuwait

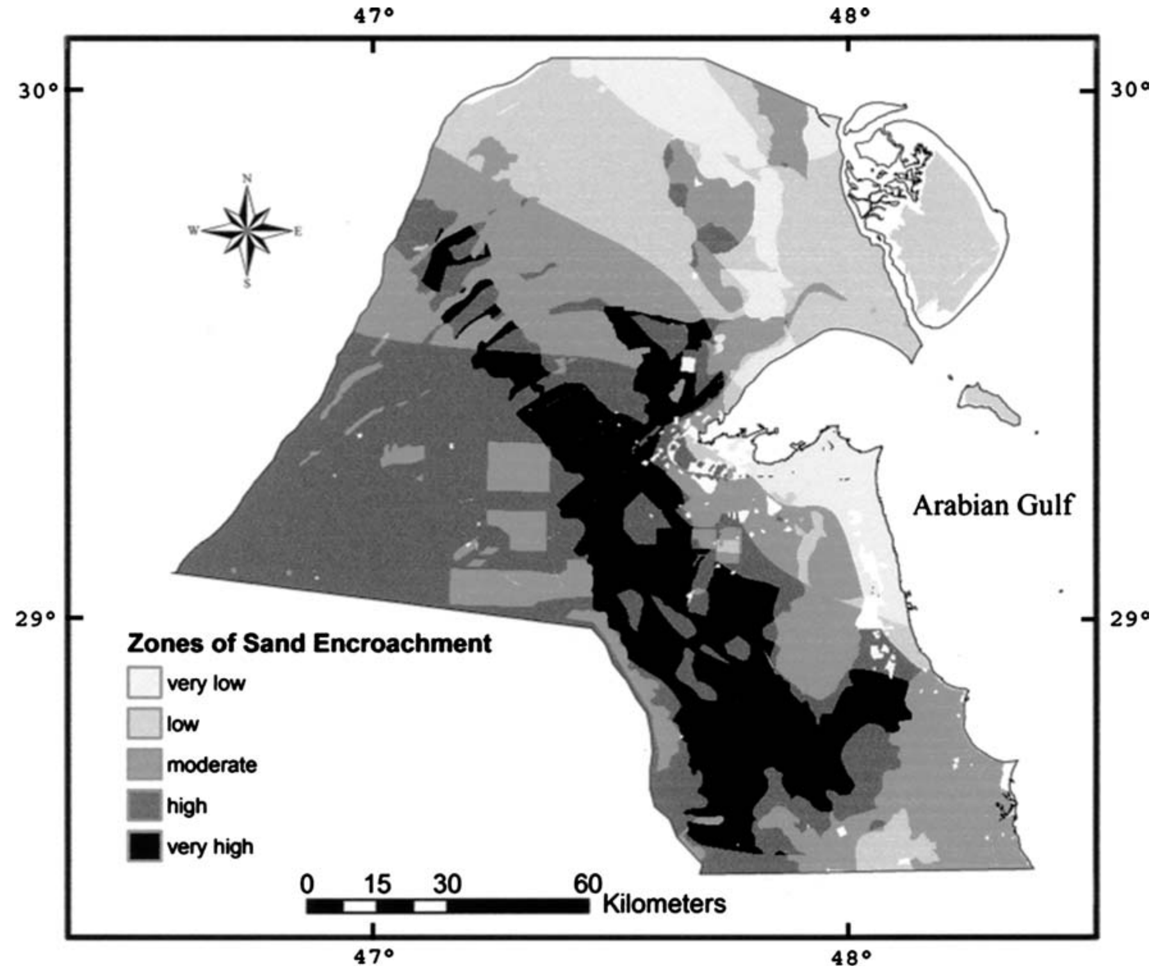

Fig. 2 Map of sand encroachment susceptibility in Kuwait

was then applied to calculate the reciprocal or positive response. Once the matrix was completed, the values of each column were summed. Then the value of each factor was divided by the sum value of the column, and the arithmetic mean values then derived for each row. These values, presented in Table 4, represent the weights calculated to reflect the relative importance of the various factors considered.

Results

Five general steps (Fig. 1) were applied using a proposed integrated GIS-suitability model to delineate the zones of sand encroachment susceptibility in Kuwait. Such delineation was achieved by combining the reclassified raster layers (maps representing the triggering factors) and by applying the following model of sand encroachment:

$$E = \sum_{i=1}^{n} W_i X_i, \tag{1}$$

where E is the sand encroachment ranking value, n number of controlling factor, W_i is a weight factor, and X_i is a triggering factor.

Replacing each weight factor by its value from Table 4:

$$\begin{aligned} E = {} & 0.37X_1 + 0.26X_2 + 0.12X_3 + 0.11X_4 \\ & + 0.07X_5 + 0.05X_6 + 0.02X_7, \end{aligned} \tag{2}$$

where X_1 Sand drift potential (Wind energy) (WE), X_2 Surface sediment type (SS), X_3 Vegetation density cover (VD), X_4 Land use type (LU), X_5 Drainage density (DD), X_6 Topography change (TC), X_7 Vegetation type (VT).

Raster Calculator, a spatial analyst function tool in Arc View8 software that is capable of weighting reclassified raster layers and combining them, was applied to evaluate the zones of sand encroachment susceptibility using Eq. 2. The sand encroachment susceptibility map was then produced and classified into five classes based on natural breaks method; i.e., identifying peak values. Accordingly, the following susceptibility classes for sand encroachment were named:

$0 \leq E \leq 43$	very low sand encroachment,
$43<E \leq 54$	low sand encroachment,
$54<E \leq 65$	moderate sand encroachment,
$65<E \leq 76$	high sand encroachment,
$76<E \leq 100$	very high sand encroachment.

The resulting map (Fig. 2) indicates that the very high and high classes of sand encroachment in Kuwait constitute 40 and 19% of the land area, respectively, the moderate classes account for 23%, followed by the low and very low classes at 13 and 5%, respectively. Comparing the resulting map with the land use map of Kuwait shows that most of the vital desert installations are located within the zones of very high and high sand encroachment, which are located within the main corridor of sand pathway, as presented by Al-Awadhi and Misak (2000). The map also shows that the pattern orientation of the zones of sand encroachment is mostly parallel to the northwesterly dominant wind direction.

Conclusions

Employment of the Delphi method and the AHP in combination with GIS techniques, proved quite useful in evaluating factors controlling sand encroachment and in producing a sand encroachment susceptibility map for the study area. Such a map can be useful for planners and decision makers in making judgments on whether vital major desert development projects should be carried out, avoided, or shifted to other areas to minimize cost and problems associated with sand movement, especially at the early stages of construction and land use planning. The methodology employed in this study which focuses on the Kuwait desert may also be useful in reflecting similar sand encroachment processes for other arid and/or desert regions of the world, such as China (Gobi desert), the Southwestern United States (Sonora desert), and parts of Africa (Sahara and Kalahari deserts).

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