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ORIGINAL PAPER

Spatial assessment of desertification in north Sinai using modified MEDLAUS model

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Abstract This study aims to use spatial analyses and a geographic information system (GIS) to assess the environmental sensitivity for desertification in the north Sinai Peninsula, Egypt. Based on the Mediterranean Desertification and Land Use (MEDALUS) approach and the characteristics of the study area, a regional model was developed using GIS. Five main indicators of desertification including soil, climate, erosion, plant cover, and management were considered for estimating the environmental sensitivity to desertification. A spatial analyst extension Arc-GIS 10 software was used for matching the thematic layers and assessing the desertification index, of which the map of environmentally sensitive areas of the north Sinai Peninsula is produced. The obtained data reveals that 65 % of north Sinai is characterized by very severe sensitivity to desertification while the low sensitive one exhibits only 1.2 %. The moderately sensitive area occupies approximately 23 % of the study area. ETM+ and SPOT images are recommended to monitor sensitivity. The MEDALUS model was developed under the Egyptians to assess desertification sensitivity.

Keywords North Sinai Peninsula · GIS · Remote sensing · Desertification sensitivity · MEDALUS

Introduction

Desertification is land degradation in arid, semiarid, and dry sub-humid areas resulting from various factors including climatic variations and human activities (UNEP 1992). According to Kosmas et al. (1999), the Mediterranean Desertification and Land Use (MEDALUS; European Commission 1999) methodology identifies regions that are environmentally sensitive areas (ESAs).

The environmental sensitivity areas index (ESAI) was validated at both the local and regional scales in several testing areas of the Mediterranean region under different environmental conditions (Basso et al. 2000; Brandt 2005). There are two major causes of desertification, namely natural–physical and human-induced factors resulting from different activities. Human factors are seen as more important than the physical and many aspects considered as feedback mechanisms for physical factors (Herrmann and Hutchinson 2005). Desertification is the result of complex interactions among various factors, including climate change and human activities (UNCCD 2005b). In more than 100 countries, about 1 billion of the world's population of six billion is affected by desertification (Adger et al. 2001). The environmental sensitivity of an area to desertification is a complex concept to rationalize since, depending on the context, it can be caused by many different factors operating in isolation or in association (Rubio 1995; Thornes 1995; UNEP 1992). An ESA can be considered, in general, as a specific and delimited entity in which environmental and socioeconomical factors are not balanced or are not sustainable for that particular environment. The Mediterranean region is found in a different sensitivity status to desertification for low rainfall and extreme events due to low vegetation cover, low resistance of vegetation to drought, steep slopes, and highly erodible parent material (Ferrara et al. 1999). In dry areas, land degradation coupled with extreme biophysical and socioeconomic phenomena may turn into an irreversible process of environmental degradation, that is decortications (Montanarella 2007). The Geographic Information System (GIS) is a valuable tool to store, retrieve, and manipulate the huge amount of data needed to compute and map different quality indices to desertification (Gad and

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Lotfy 2006; Abdel Kawy and Belal 2011). The ESAI procedure makes the methodology suitable for different scale approaches and even for (small) changes in the set of input variables. Furthermore, the adaptability of the ESAI to different socio-environmental contexts makes the index applicable at the level of the whole Mediterranean basin (Luca and Sofia 2011). The presence of calcium carbonates and gypsum content in soil drastically change soil chemistry, thereby changing the chemical processes that occur and the community of organisms that colonize the soil (Soil Survey Staff 1975). Calcium carbonate and gypsum contents are basic soil data widely used by soil surveyors to describe soil types and are also pertinent properties used to quantify vulnerability to erosion (Le Bissonnais 1996). Therefore, the first goal of this research is to modify the MEDALUS methodology to include calcium and gypsum contents as predictor factors for soil quality index under Egyptian conditions as well as considering normalized differential vegetation index (NDVI) as an indicator factor for vegetation cover. The second aim of this study is to apply the modified MEDALUS methodology using spatial analyses and GIS to assess and map the desertification sensitivity in the north Sinai Peninsula depending upon the soil's characteristics, climatically data, vegetation, and management practice.

Materials and methods

Location of the study area

The studied area is located at the northern part of the Sinai Peninsula and lies between longitudes 32°30′ and 34°25′ east and latitudes 30°50′ and 31°20′ north as shown in Fig. 1. Eight main geological units of investigated area are Nile silt or Nile deposits, Quaternary deposits, Sabkha

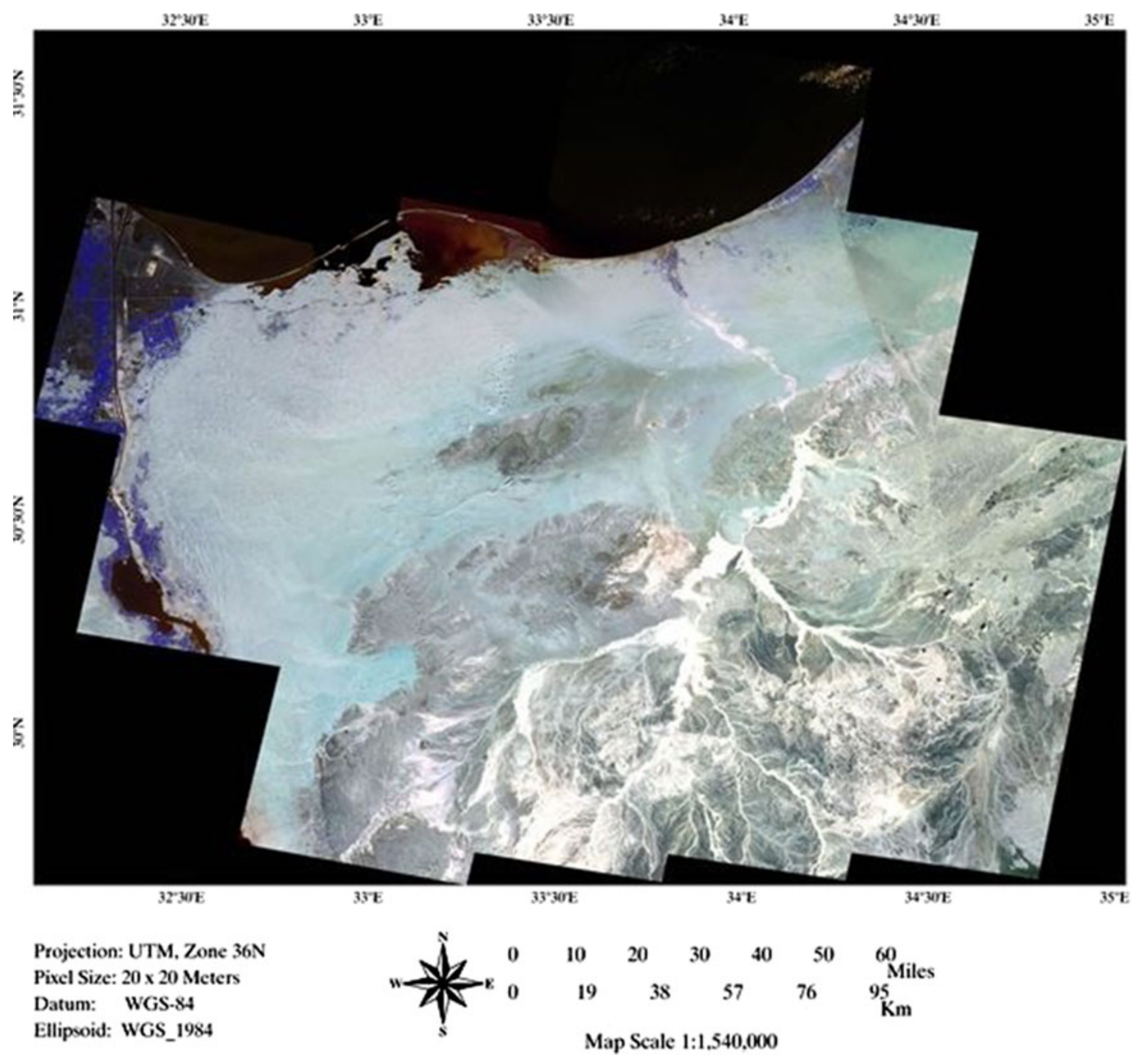


Fig. 1 Location of the study area

Table 1 Classes and factors assigned weighting index affecting desertification process

Indicators		Description	Classes (threshold)	Index
Soil quality index	Soil depth	Very deep	Depth >1 m	1.0
		Moderately deep	Depth <1 to 0.5 m	1.33
		Shallow	Depth <0.5 to 0.25 m	1.66
		Very shallow	Depth <0.15 m	2.00
	Soil texture	Loamy sand, Sandy loam	1	1.0
		Loamy clay, clayey sand, sandy clay	2	1.2
		Clayey, clay loam	3	1.6
		Sandy to very sandy	4	2.0
	Slope gradient	Gentle	<6 %	1.0
		Not very gentle	6–18 %	1.33
		Abrupt	19–35 %	1.66
		Very abrupt	>35 %	2.0
	Calcium carbonate[a]	Non-calcareous	<5 %	1.0
		Slightly calcareous	5–10 %	1.2
		Moderately calcareous	10–20 %	1.5
		Strongly calcareous	>20 %	2.0
	Gypsum[a]	Slightly gypsiric	<5 %	1.0
		Moderately gypsiric	5–15 %	1.2
		Strongly gypsiric	15–60 %	1.5
		Extremely gypsiric	>60 %	2.0
	Electrical conductivity	Very low	<4 dS/m	1.0
		Low	4–8	1.2
		Moderately	8–16	1.5
		Moderately high	16–32	1.7
		High	>32	2.0
	Rock fragments	Very stony	>60 %	1.0
		Stony	60–20 %	1.3
		Bare to slightly stony	<20 %	2.0
	Drainage	Well drained	1	1.0
		Moderately drained	2	1.2
		Poorly drained	3	2.0
Climate quality index	Rainfall (mm)	High	>300 mm	1.0
		Moderately	150–300 mm	1.33
		Low	>150 mm	1.66
	Evapotranspiration (mm)	Low	<1,500 mm	1.0
		Moderately	1,500–2,000 mm	1.5
		High	>200 mm	2.0
	Aridity index (P/ETp)	Semi-arid	AI≥1	1.0
		Arid	AI 0.1–1	1.5
		Hyper-arid	AI <0.1	2.0
Management quality index	Land use	Agricultural lands	1	1
		Rangelands	2	1.3
		Poor and degraded	3	1.6
		Bare lands	4	2
	Grazing intensity	Low	<1	1.0
		Moderate	1–2.5	1
		High	>2.5	1.5
				2

Table 1 (continued)

Indicators		Description	Classes (threshold)	Index
	Policy and management	Complete: >75 % of the area under protection	1	1.0
		Partial: 25–75 % of the area under protection	2	1.5
		Incomplete: <25 % of the area under protection	3	2.0
Erosion quality index	Wind erosion	Very low	1	1
		Low	2	1.2
		Moderate	3	1.5
		High	4	1.7
		Very high	5	2
	Water erosion	Very low	1	1
		Low	2	1.2
		Moderate	3	1.5
		High	4	1.7
		Very high	5	2
Vegetation quality index	Erosion protection	High	1	1.0
		Moderately	2	1.33
		Low	3	1.66
		Very low	4	
	Drought resistance			1.0
		Gardens, orchards, rangelands	1	1.5
		Permanent grassland, annual crops and grasslands	2	2.0
		Bare land	3	
	Normalized different vegetation cover	High	NDVI >0.95	1.0
		Moderate	NDVI 0.95–0.65	1.2
		Low	NDVI 0.65–0.35	1.5
		Very low	NDVI <0.35	2

[a] Calcium carbonates and gypsum contents according to FAO (2006)

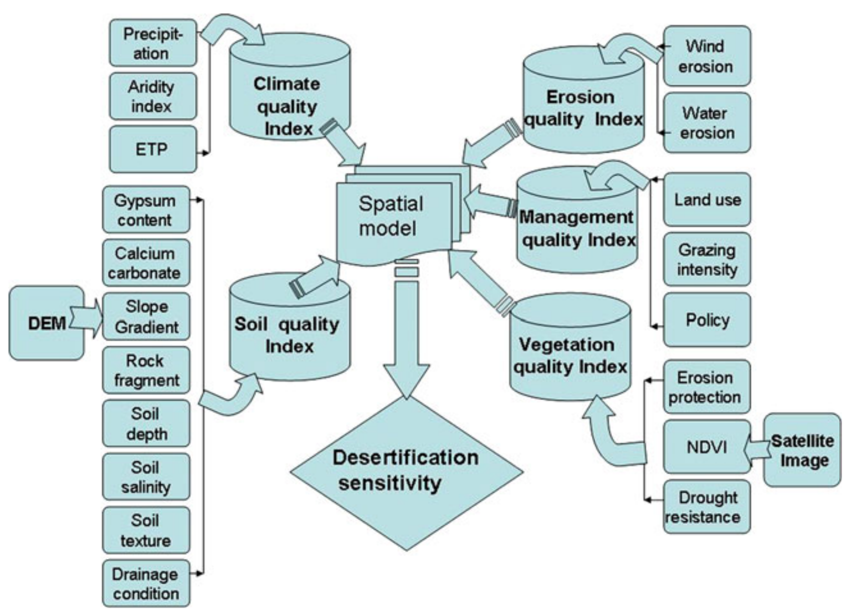


Fig. 2 Flowchart of mapping environmental sensitivity

deposits, Sand dunes, Stabilized dunes, Wadi deposits, Pliocene deposits, and Plio-pleistocene deposits (CONOCO 1987). The main geomorphic units of north Sinai are the northern coastal plain, morphotectonic depression, wadis, and northern piedmont plain (Dames and Moore 1981). Soils of north Sinai were classified into two orders: Aridisols and Entisols (Hassan 2002). The studied area has typically arid and semi-arid climatic conditions. The mean temperature ranged from 27.8 °C to 14.4 °C and 25.9 °C to 13.4 °C in the Port Said and El-Arish stations, respectively. The average annual rainfall at Port Said is 73.6 mm and increases up to 100.7 mm at El-Arish. According to USDA (2010), the soil temperature regime of the area could be defined as thermic and the soil moisture regime as torric, except for the soil that has a high water table where the soil moisture regime could be considered as aquic. The natural vegetation in the studied area is very poor, and the most striking feature in the area is its barrenness. However, some ephemeral grasses and desert shrubs appear during the rainy season in the wadis and in the hollows between sand dunes. Halophytic plants are also observed particularly in the wet and salt-affected areas, from studies on plant communities in the studied area (Dames and Moore 1981). El Salam canal is considered one of the main sources of irrigation water; it feeds the northern part of the investigated area. The source of this water is Nile water, Bahr Hadous and Serw drains, with a mixing ratio of 1:1 (Mohamed 2006).

Digital image processing

The studied area was represented by 16 SPOT satellite images dated from 2011. The SPOT images were geometrically corrected. A rectification method (image to map) followed. The geometric model used in the rectification process was a second-order polynomial, and the resampling method is the nearest neighbor method. A mosaic process was elaborated to overlay the SPOT images. ASTER Digital Elevation Model (DEM) images were used as the source data for elevation heights of the study. DEM has been derived from ASTER images. Slope and aspect were

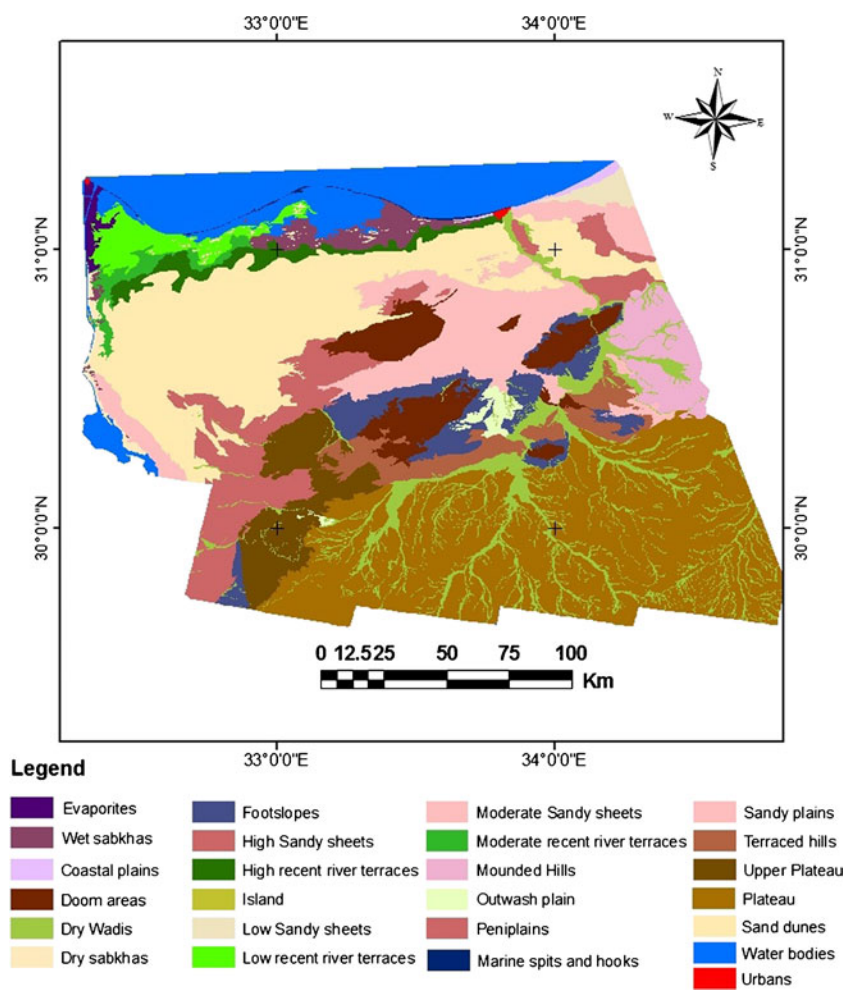


Fig. 3 Geomorphologic map of north Sinai

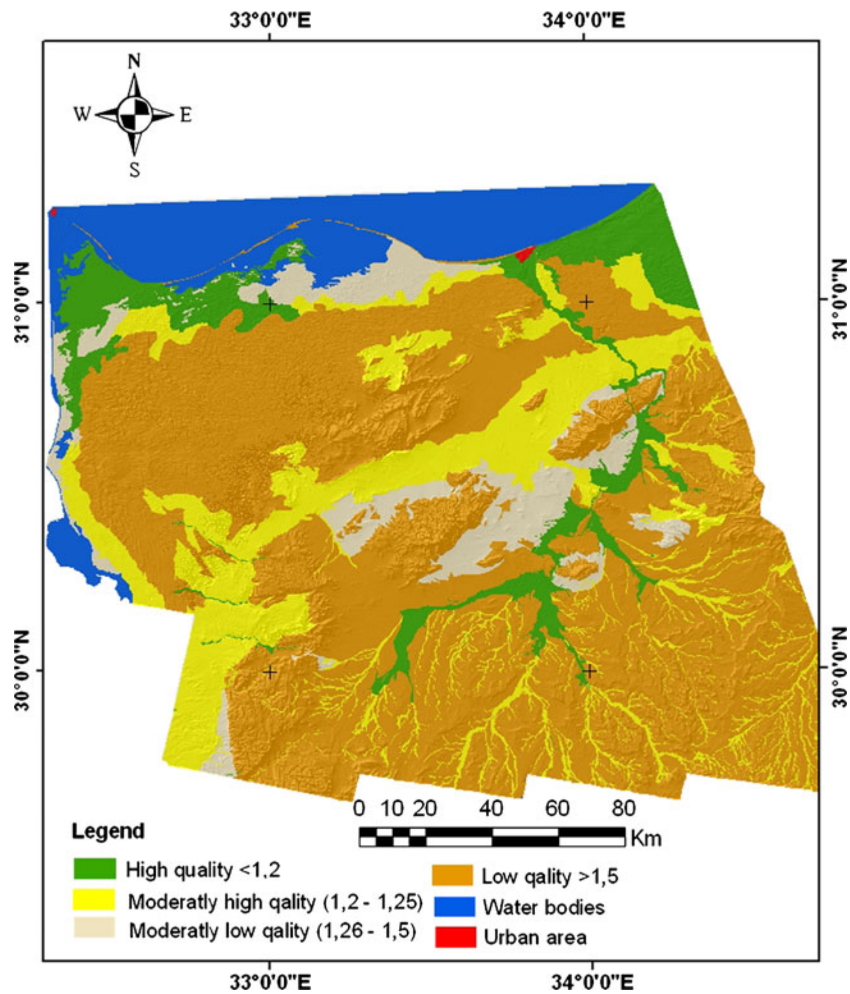


Fig. 4 Soil quality index classes of the studied area

derived from DEM as a factor of soil quality index. The mosaic image was draped over DEM to get the feel of natural 3D theme to get a better understanding of the physiographic units and to facilitate extracting these units.

Fieldwork and laboratory analyses Field studies and ground truth were carried out to identify the geomorphologic units. Morphological description of 25 soil profiles representing the different geomorphic units and the laboratory analyses were carried out using the soil survey laboratory methods manual of the soil survey staff (2002).

Desertification sensitive spatial modeling Five thematic indicators quantifying the environmental quality in terms of climate, soil, vegetation, land management, and erosion (Kosmas et al. 1999; Sepehr et al. 2007)

$$\mathrm{DSI} = (\mathrm{SQI} \times \mathrm{VQI} \times \mathrm{CQI} \times \mathrm{MQI} \times \mathrm{EQI})^{1/5},$$

where SQI is the soil quality index, VQI is the vegetation quality index, CQI is climate quality index, MQI is the management quality index, and EQI is the erosion quality index.

Soil quality index The following equation was used to assessment soil quality index depending on GIS spatial model.

$$\mathrm{SQI} = \left(\mathrm{I_t} \times \mathrm{I_d} \times \mathrm{I_s} \times \mathrm{I_r} \times \mathrm{I_e} \times \mathrm{I_c} \times \mathrm{I_g} \times \mathrm{I_{dr}}\right)^{1/8},$$

where I_t is the index of soil texture, I_d is the index of soil depth, I_s is the index of slope gradient, I_r is the index of rock fragment, I_c is the index of calcium carbonate content, I_g index of gypsum content, and I_{dr} is the index of daring condition.

Table 2 Soil quality index of the studied area

SQI class	Score	Area %	Area (ha)
High quality	<1.2	12	426,417
Moderate quality	1.2–1.25	13	483,919
Moderately low quality	1.25–1.5	7	237,832
Low quality	>1.5	58	2,071,674
Reference terms (urban water bodies)	–	11	377,802
Total	–	100	3,597,644

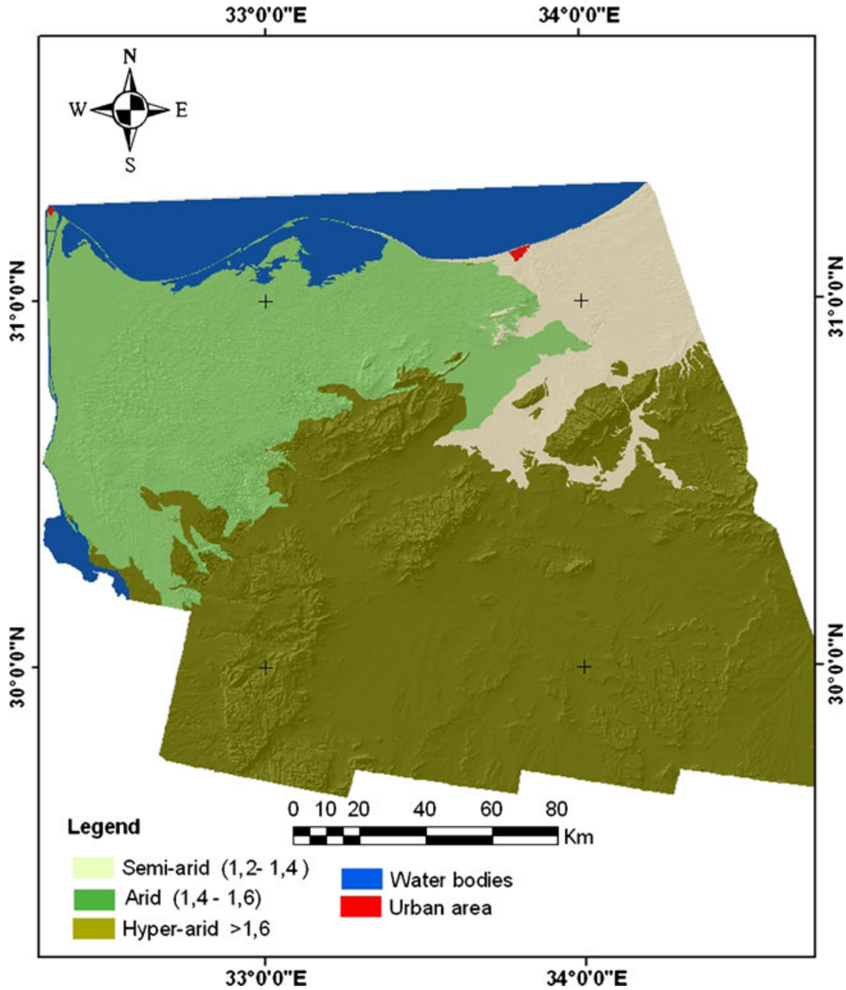


Fig. 5 Climate quality index classes of the studied area

Climate quality index Climate quality is calculated according to the following equation:

$$\mathrm{CQI} = (\mathrm{I_r} \times \mathrm{I_e} \times \mathrm{I_a})^{1/3},$$

where I_r is the index of rainfall, I_e index of evaporation, and I_a is the index of aridity.

The climatic elements were collected from Port Said and El-Arish meteorological stations from 1985 to 2009.

Vegetation quality index Vegetation quality index was calculated according the following equation:

Table 3 Climate quality classes of the studied area

CQI class	Score	Area %	Area (ha)
Semi-arid	1.2–1.4	9	309,111
Arid	1.4–1.6	24	824,296
Hyper-arid	>1.6	56	1,923,358
Reference terms (urban water bodies)	–	11	377,802
Total	–	100	3,597,644

$$\mathrm{VQI} = \left(\mathrm{I_{ep}} \times \mathrm{I_{dr}} \times \mathrm{I_{nd}}\right)^{1/3},$$

where I_{ep} is the index of erosion protection, I_{dr} is the index of drought resistance, and I_{nd} is the NDVI index of vegetation cover.

Management quality index Management quality index was calculated according to the following equation:

$$\mathrm{MQI} = \left(\mathrm{I_l} \times \mathrm{I_g} \times \mathrm{I_p}\right)^{1/3},$$

Table 4 Vegetation quality classes in the studied area

VQI Class	Score	Area %	Area (ha)
High quality	<1.2	0.8	27,624
Moderate quality	1.2–1.4	1.2	–
Low quality	1.4–1.6	10.5	377,294
Very low quality	>1.6	77.5	2,792,908
Reference terms (urban water bodies)	–	11	377,802
Total	–	100	3,597,644

where I_l is the index of land use, I_g is the index of grazing intensity, and I_p is the index of policy.

Erosion quality index Erosion Quality Index was calculated on the basis of the following equation:

$$EQI = (\text{Wind erosion} \times \text{Water erosion})^{1/2},$$

ESA was calculated depending on the MEDALUS criteria (Table 1). Calcium carbonates and gypsum contents, according to FAO (2006), as well as NDVI, were considered in the current work; the value "1" was assigned to areas of least sensitivity, and the value "2" was assigned to areas with the most sensitivity. Desertification-sensitive spatial modeling (DSSM) has been established using Arc GIS 10; for identification of the desertification sensitivity degrees, some of the necessary components contributing to this operation are: (1) transforming all features to raster layers, (2) all raster layers have been classified, (3) if the spatial statistics model have been done depending upon the DSI equation suggested by Kosmas et al. (1999). A sensitivity score system was then applied based on the estimated degree of correlation between the various factors (Fig. 2).

Results and discussion

Geomorphologic of north Sinai

The results of geomorphologic unit extraction indicates that within the north Sinai Peninsula area there are major landforms, namely, the coastal plains, sabkhas, dunes, alluvial fans, basins, wadis, alluvial plains, river terraces, and plateau. Physiographical units are shown in Fig. 3.

Soil quality index

Soil quality indicators for mapping ESAs can be related to water availability and erosion resistance. These

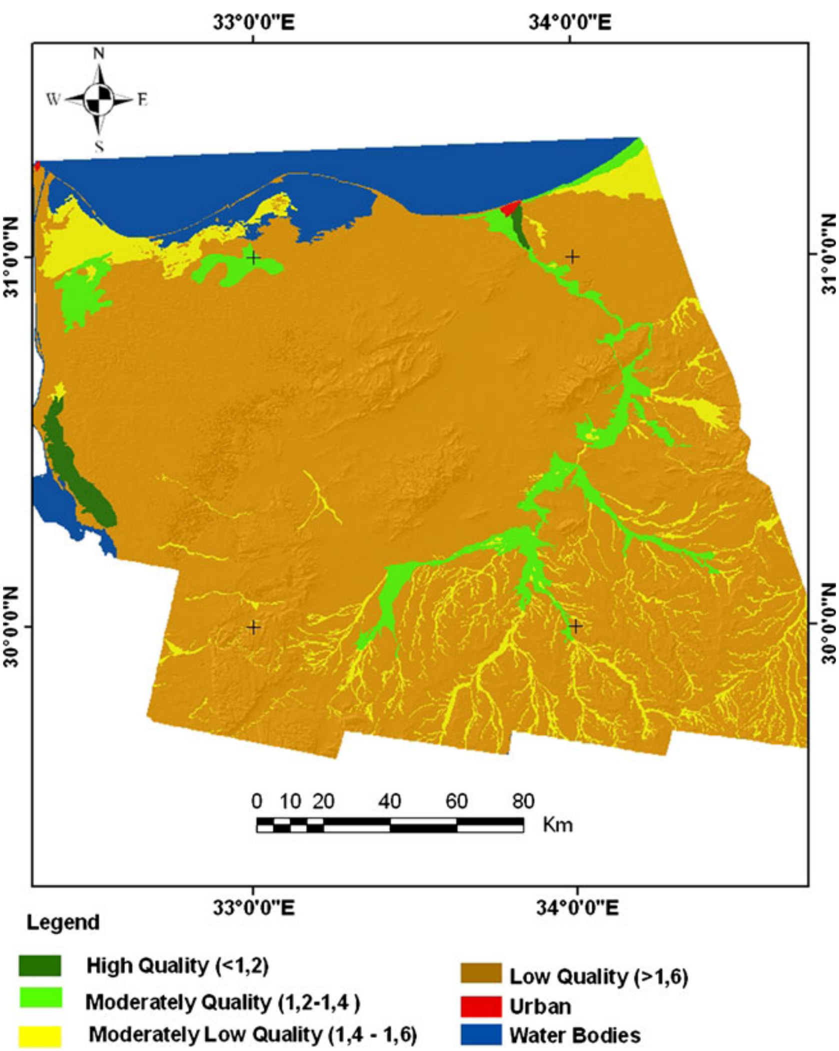


Fig. 6 Vegetation quality index classes of the studied area

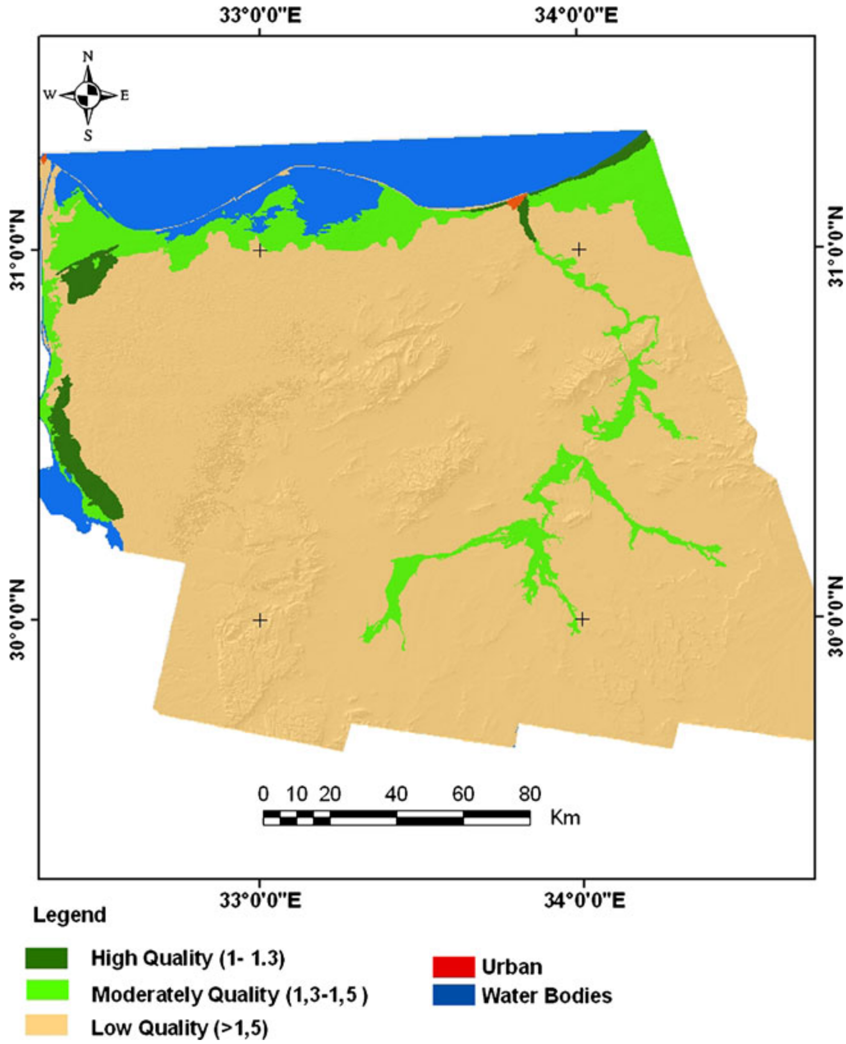


Fig. 7 Management quality index classes of the studied area

qualities can be evaluated by using simple soil properties such as soil texture, parent material, rock fragment cover, soil depth, slope grade, drainage conditions as well as calcium carbonate and gypsum contents. The results indicate that 12 % (42,616 ha) of the studied area is characterized by high soil quality, located at the northern part of the studied area. The moderate soil quality index occupies an area of about 721,750 ha representing 20 % of the total area. The low soil quality index occupies an area about 58 % (2,071,674 ha) of the total area as shown in Fig. 4 and Table 2. The limited factors of soil quality in the northern part of the study area are salinization and daring condition as well as calcium carbonate content.

Climate quality index

The rainfall, evaporation, and aridity are the main climatic attributes which contributes to the desertification processes. The result illustrated 56 % of the total area characterized by low climatic index (hyper arid). It occupies an area of about 1,923,358 ha as shown in Table 3 and Fig. 5. The area located at the northwest of the study area is characterized by arid conditions which represent 24 % of the total area while the area located at the northeast of the investigated area is characterized by semi-arid conditions due to high amounts of rainfall which reached up to 250 mm/year.

Table 5 Climate quality classes in the studied area

MQI class	Score	Area %	Area (ha)
High quality	1.0–1.3	4.1	148,362
Moderate quality	1.3–1.5	5.5	200,070
Low quality	>1.5	79.4	2,890,011,652
Reference terms (urban water bodies)	–	11	377,802
Total	–	100	3,597,644

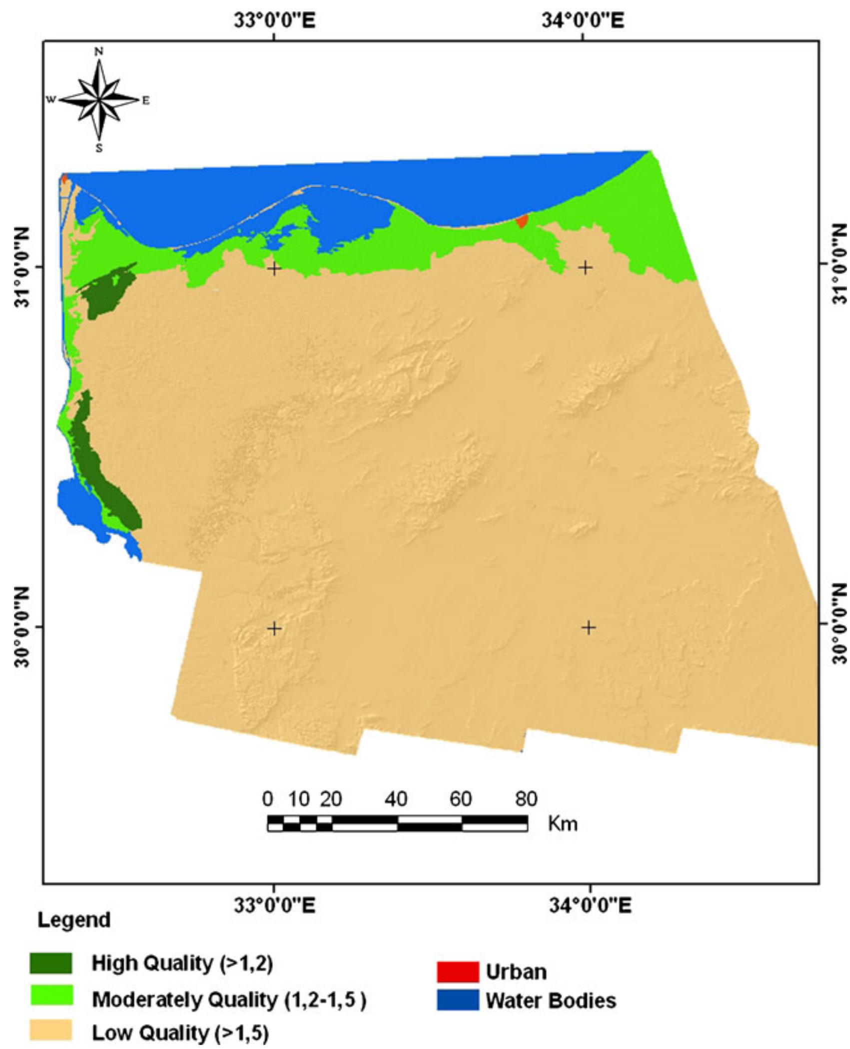


Fig. 8 Erosion quality index classes of the studied area

Vegetation quality index

Vegetation quality index is an essential factor for assessing the degree of desertification sensitivity in north Sinai. The erosion protection to the soils, drought resistance, and plant cover are the major factors effecting vegetation quality in the studied area. Remotely sensed images were used to derive NDVI as a good indicator for vegetation cover. Therefore, NDVI was adapted rating values ranging from 1 to 2 depending on the intensity of the vegetation index.

The obtained data revealed that the areas characterized by high vegetation quality occupied about 0.8 % of the total area (27,624 ha), the moderate vegetation quality index occupied an area of about 1.2 % of the investigated area (39,356 ha). An area of about 10 % of the total area was characterized by low vegetation quality index while 77.5 % of the total area was characterized by very low vegetation quality index, as shown in Table 4 and Fig. 6.

Management quality index

Management quality index included land use, grazing intensity, and policy, which were clearly important factors controlling the desertification process. The result indicated that about 79.5 % of the total area is suffering from mismanagement of land resource, over-grazing, and inappropriate land use systems.

Table 6 Erosion quality classes in the studied area

EQI class	Score	Area %	Area (ha)
Low quality	<1.2	1.2	40,581
Moderate quality	1.2–1.6	3.8	137,360
High quality	>1.6	85	3,059,241
Reference terms (urban water bodies)	–	11	377,802
Total	–	–	3,597,644

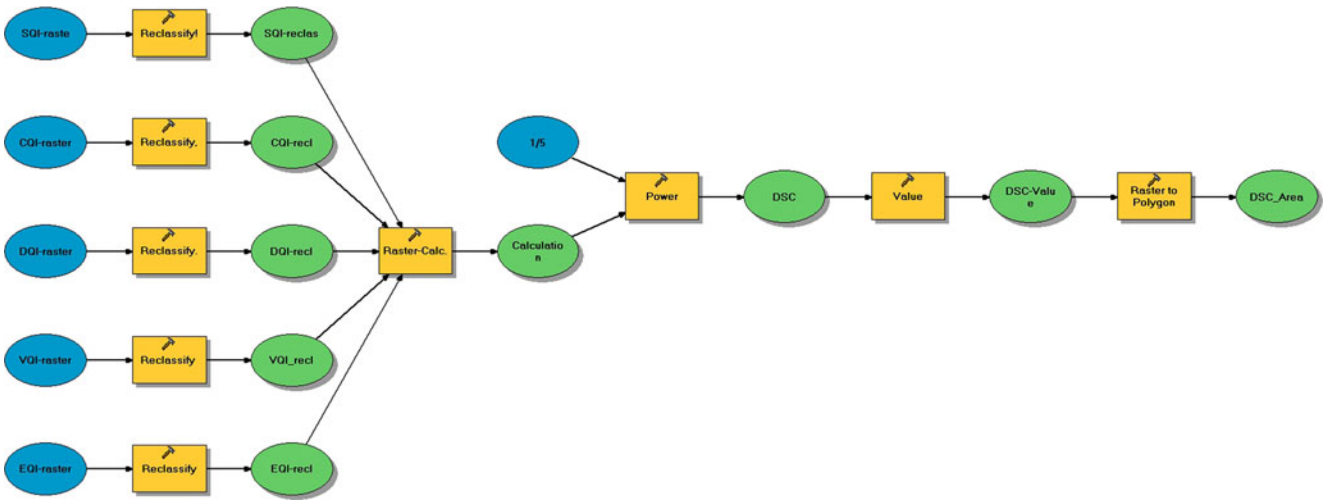


Fig. 9 Flowchart of the designed desertification sensitive spatial modeling

The areas of moderate quality index represents about 5.5 % of the total area while 4.1 % of the total area is characterized by a high quality index as shown in Fig. 7 and Table 5.

Erosion quality index

Erosion plays an important role in desertification sensitivity in the northern Sinai region, which is characterized by a high erosion quality index due to the effect of morphology and relief, wind velocity, soil characteristics, and plant cover.

The results indicate that the areas characterized by high erosion quality index occupied an area about 85 % of the total area while the area which is characterized by moderate and low quality represents about 4 % of the total area, it is associated with the cultivation area as shown in Fig. 8 and Table 6.

Desertification-sensitive spatial modeling

The integration of soil parameters, climate condition, vegetation cover, management, and erosion rates were considered to derive DSSM; Fig. 9 shows the model process. The results obtained revealed that 65 % of the studied area which is located at the middle and southern part of the studied area suffers from desertification sensitivity and can be classified as very severe due to mismanagement, topographic condition, land use, as well as climate condition, as shown in Table 7 and Fig. 10. Of the investigated area, 17.5 % is severely and 5.3 % is moderately affected by desertification. On the other hand, almost 1.2 % of the total study area was low sensitive to desertification due to the vegetation cover and land use.

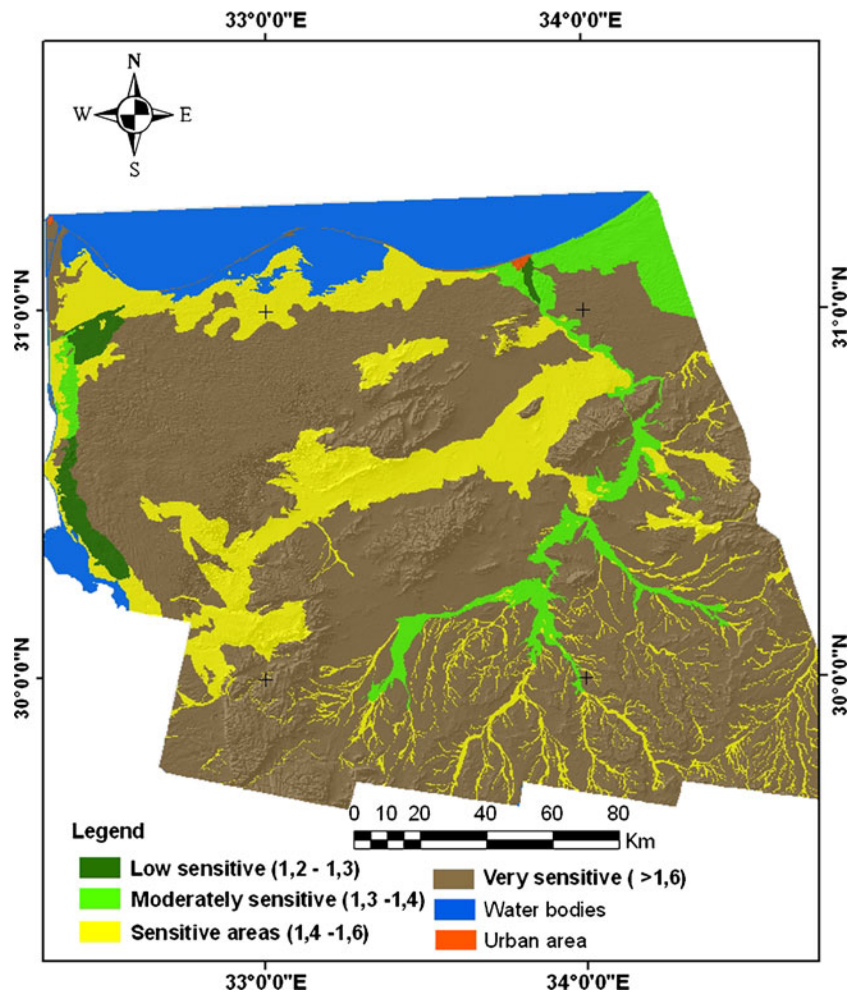
Table 7 Environmentally sensitive areas based on DSSM model

DSI class	Score	Area %	Area (ha)
Low sensitive areas	1.2–1.3	1.2	43,746
Moderately sensitive areas	1.3–1.4	5.3	188,973
Sensitive areas	1.4–1.6	17.5	643,513
Very sensitive areas	>1.6	65	2,360,168
Reference terms (urban water bodies)	–	11	377,802
Total	–	100	3,597,644

Conclusions and recommendations

DSSM based on remote sensing data and GIS tools is very important in identifying areas where sensitivity is increasing over time. The soil quality index was developed under Egyptian conditions using calcium carbonate and gypsum content as important factors, as well as the other factors mentioned above, in the MEDALUS methods for desertification sensitivity. This work covered the highlights and overviews on high-severity areas in the north Sinai peninsula where it shows a part, about 80 %, of the studied area which is susceptible to desertification due to low vegetation cover, soil quality, mismanagement, climate condition, and wind erosion, although the area located east of Arish was characterized by good climate quality where the rate of rainfall reached to 250 mL/year. Therefore, the north Sinai area needs great efforts from the Egyptian government to overcome these phenomena through using effective management and policies to combat desertification.

Fig. 10 Environmentally sensitive map of north Sinai



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