Index integrating soil, vegetation, climate and management qualities to evaluate desertification in the Northwestern coast, Egypt

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Abstract: In Egypt, the phenomenon of desertification is a geographical phenomenon that is related to the decline or deterioration of the land's biological production capacity, which will eventually result in semi-desert conditions, or, in other words, the loss of fertility from productive lands. An understanding of the geographical distribution of environmentally sensitive areas (ESAs) is necessary for sustainable land use in the dry lands. The characteristics of the research region and the Mediterranean desertification and land use (MEDALUS) approach were used to evaluate the environmental sensitivity to desertification on the west-north coast of Egypt. Remote sensing images, topographic data, soils, and geological data are used to calculate desertification indicators.
A hotspot of desertification risk exists on the north coast of Egypt due to soil degradation, climatic conditions, geomorphological and topographic features, soil quality and soil uses in each area. In each of these areas, these variables lead to varying levels and causes of soil degradation and desertification, as well as varying environmental, economic, and social effects. The obtained data reveal that (10.6%, 82.73%) of the west north coast are Sensitive and Very sensitive areas to desertification, About 1.22% of the research area is the moderately sensitive area, while the low sensitive and very low exhibit only (4.21,1.48) %. Remote sensing and GIS are recommended to monitor sensitivity. MEDALUS factors can be modified to obtain more reliable data at the local level.

Keywords: Desertification, Sensitivity, Quality indicators, ESAI, North coast.

Received: January 9, 2023. Revised: October 14, 2023. Accepted: November 15, 2023. Published: December 18, 2023.

1. Introduction

Desertification poses a great threat to global eco-environmental security and human well-being (Yue *et al,2023*). Desertification is the term used to describe land degradation that takes place in environments that are arid, semi-arid, and sub-humid. Desertification can be defined simply as “the making of the desert” or “the production of desert conditions” **(Verstraete, 1986).** However, the United Nations provided the first thorough definition of the word in 1977, which took into account the phenomenon's economic effects. It defined desertification as “the diminution or destruction of biological potential of land which can lead ultimately to desert-like conditions**” (United Nations, 1977).** This definition was modified in 1994, when desertification was defined as “Land degradation in arid, semi-arid, and dry sub-humid areas resulting from human activities and climate variation. encompassing human influences on climate change that go beyond monetary damage (United Nations, 1994). Since then, this last definition has been formally and widely applied to numerous studies on desertification conducted all over the world, providing a variety of perspectives for measuring, analysing, and modelling desertification. **(Kassas, 1995; Li et al., 2016; Cui et al., 2011; Bakr et al., 2012; Lamchin et al., 2016; Liu et al., 2018; Xu et al., 2016; Becerril-Pi˜na et al., 2016; Zhao et al., 2018)**The arid regions are constantly threatened by land degradation and desertification processes, caused by various **reasons** (KERTÉSZ, **2009)**. One of the biggest environmental problems of our day is desertification, according to the United Nations Convention to Combat Desertification (UNCCD). **(Vieira et al, 2022, Yue *et al*,2023).** Significant economic and environmental effects of desertification and land degradation affect 1.4 billion people, 74% of whom are impoverished. In addition, 12 million hectares of agricultural land are lost annually due to desertification and drought. **(United Nations, 2015).** Due to their important roles in food productivity and the social development of communities, arid, semi-arid, and sub-humid regions in particular have attracted growing political and international attention in this issue since 1970. **(Li et al., 2016; Becerril-Pi˜na et al., 2016; Liu et al., 2018; Zhao et al., 2018)**. Taking into consideration the united nation definition definitions, the current study is adopted as: "land degradation in arid, semi-arid, and dry sub-humid areas resulting from human activities and climate variation which can lead to desert-like conditions". Currently, the rate of desertification on the planet is 120,000 km2 per year, and it is predicted that by 2045, this process will have forced the displacement of over 135 million people. **(Fust, 2010).** The "Great Green Wall of Africa," which aims to end land degradation by 2030, has been suggested by countries in the Sahel. Researchers now have a cutting-edge way to track the desertification process thanks to remote sensing technologies. **Zeng et al. (2006)** built an albedo-NDVI feature space and using the findings of linear fitting, calculated the desertification monitoring index (DMI) to analyze the degree of desertification. In comparison to using spectral data alone for level division, this relatively easy method achieved improved accuracy, and it has recently been used to measure desertification across several locations. **(Vorovencii, 2017; Li et al., 2021).**

A range of surface parameters can be used to build DMIs based on linear and point-to-point models, respectively, to acquire the best desertification monitoring model while completely taking into account vegetation cover and surface roughness. **(Wei et al., 2018).** According to some studies, the only variables causing desertification are changes in the soil or vegetation. **(An et al., 2013; Turan et al., 2019),** Indicators affecting the degree of desertification in areas such as soil, climate, vegetation, and management quality can be gathered to create the Environmentally Sensitive Area Index (ESAI). **(Jiang et al., 2019; Uzuner and Dengiz, 2020).**

In multiple testing regions around the Mediterranean region, the environmental sensitivity area index (ESAI) was verified under various environmental conditions at both the local and regional levels. **(Basso et al. 2000; Brandt 2005**). Due to its limited vegetation cover, low drought resilience, steep slopes, and highly erodible parent material, the Mediterranean region is more vulnerable to desertification due to low rainfall and harsh events. **(Ferrara et al. 1999)**. In dry locations, the combination of extreme biophysical and socioeconomic occurrences may result in an irreversible environmental deterioration process. **(Montanarella, 2007).** The Geographic Information System (GIS) is a useful tool for storing, retrieving, and manipulating the enormous quantity of data required to calculate and map various quality indexes related to desertification. **(Gad and Lotfy 2006; Abdel Kawy and Belal 2011).**

This current study aims to how remote sensing is applied to the study of desertification. Therefore, utilizing Mediterranean desertification and land use (MDLUS) indicators in a region along Egypt's north coast, this research was carried out with the intention of offering an early warning approach to desertification risk, focusing on risk management rather than disaster management. The outcome of this study could serve as a template for local land managers to effectively allocate resources for managing and preventing desertification. This approach is thought to be transferable to other dry regions with comparable anthropogenic and environmental variables.

2. Materials and methods

2.1 Location of the study area

According to Figure 1, the study region is situated on Egypt's northwest coast between latitudes 31°0'45 and 30°56'17 north and longitudes 29°23'39 and 27°20'11 east.

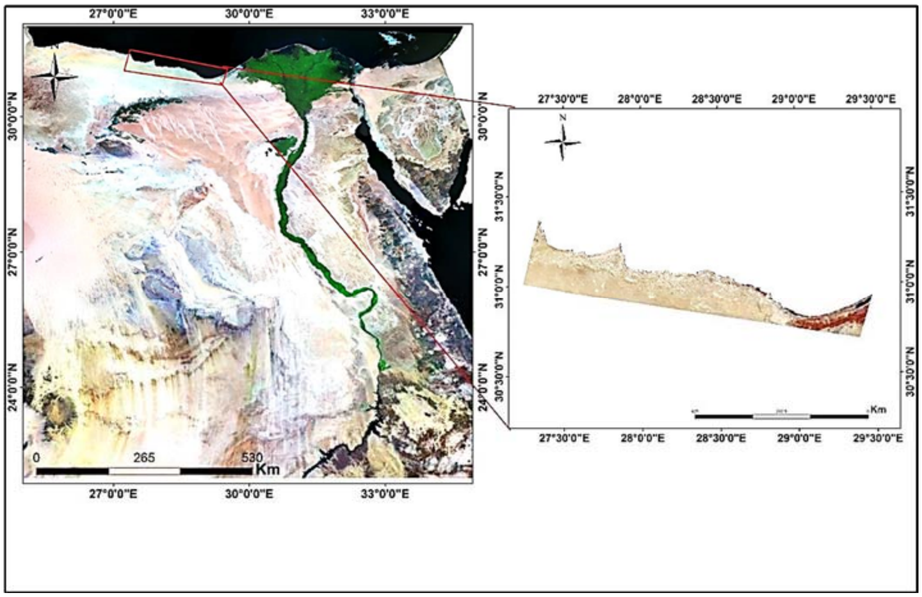

Figure 1: Location of the study area

Figure 2 shows that the study area consists of six main geological units, they are El-Hagif Fm, Gravel, Marmarica Fm, Sabkha deposits, Stabilized Sand Dunes and undifferentiated Quaternary Deposits **(CONOCO 1987).**

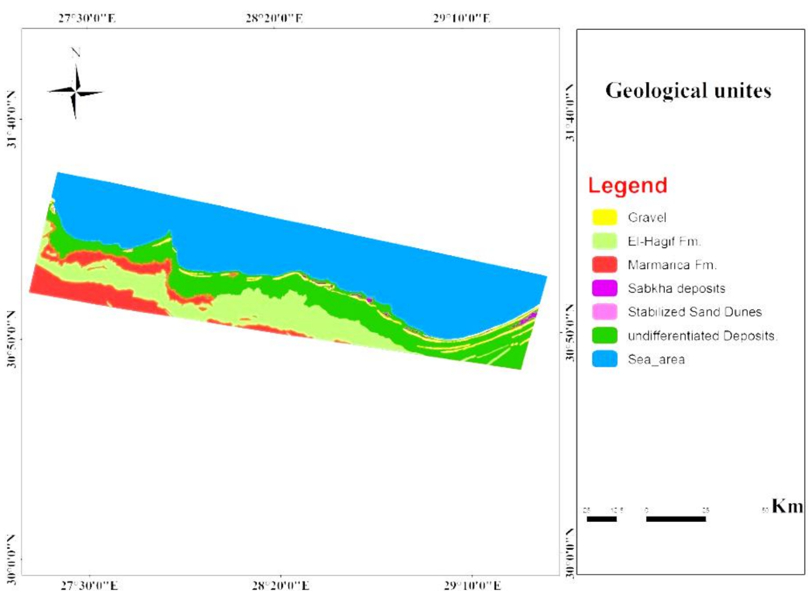

Figure 2: Geology map of the study area CONOCO 1987).

2.2 Climate data

The northern region of Egypt is currently characterized by an arid climate class, which suggests that desertification might take place, according to Pravalie (2016) and Pravalie et al. (2019). The average annual temperature is found to be between 20.12 and 21.12 C, according to the climate data gathered from three surface stations (Matroh, Alexandria, and El-Dabaa). The temperature of the soil regime varies from "Thermic" to "Hyperthermic," and the soil moisture regime is "Torric," as determined by Soil Survey Staff (2014). Wind Speed at 2 Metres (m/s) varies between 3.48 to 4.07 m/s, while the total amount of precipitation per year fluctuates between 330 and 430 mm. An arid climate is indicated by the aridity index, which ranges from 5.72 to 5.89. **(Pravalie et al., 2019)**.

2.3 Remote sensing and GIS work

The primary data source used to build the desertification monitoring model in the research area was the Landsat 8 Operational Land Imager remote sensing pictures, which are accessible at https://glovis.usgs.gov. The images used in this investigation have paths/rows 178/39 and 179/38. The image quality was excellent, as seen by the less than 10% total cloud cover. The visible, near-infrared, and mid-infrared wavelengths, which are made up of six bands and have a spatial resolution of 30 m, were used in this investigation. Geometric calibration and atmospheric correction were carried out with the impact of radiometric distortions and atmospheric disturbances on image quality in mind. Using ENVI 5.3 software, satellite imageries were digitally processed. After that, a supervised classification (maximum likelihood) was carried out after an unsupervised classification (ISO DATA classifier). Slope classes and aspects have been generated from the DEM using ArcGIS 10.8 (ESRI Co., Redlands, USA).

2.4 Modeling desertification in the studied area

Characterization of the original MEDALUS indices

According to Kosmas et al. (1999), the indices are the soil quality index (SQI), the climatic quality index (CQI), the vegetation quality index (VQI), and the management quality index (MQI). The geometric mean algorithm of the parameter scores was used to calculate each index as follows:

$$\text{Index}_X = [S_1 \times S_2 \times S_3 \times S_n]^{1/n}$$

Where n is the number of parameters, S is the parameter score, and x is the index.

The Land Degradation Sensitivity Index (LDSI), which is obtained for the entire study area and is illustrated in Figure 3, is based on these indicators, which were chosen in order to thoroughly characterize susceptibility to land degradation by including characteristics of physical (climate, soil, and vegetation) and anthropogenic (pressures related to land management) characteristics. The UNCCD defined desertification as the degradation of land in arid, semiarid, and subhumid regions; consequently, the ESAI would be indicating the desertification sensitivity index obtained from the conventional MEDALUS approach, according to Tables 1 and 2

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Figure 3: Flowchart of desertification sensitivity assessment (DSAI)

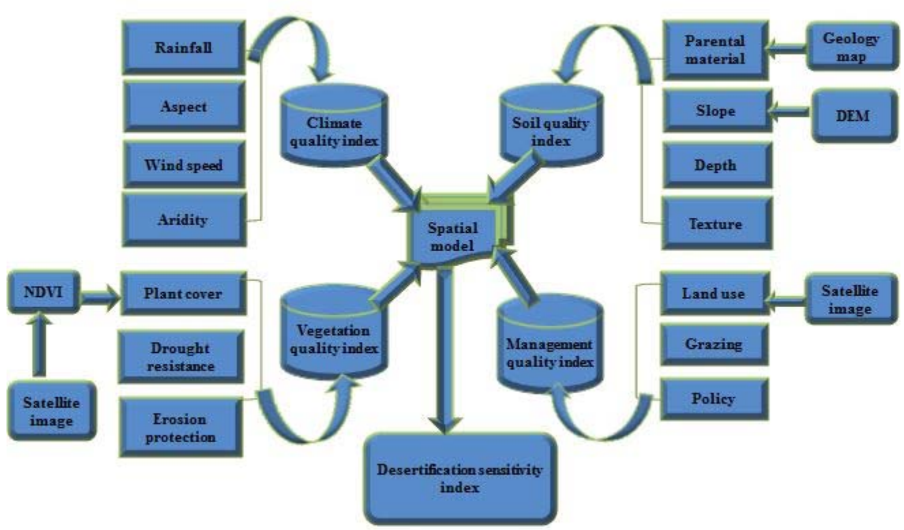

Table 1: Main characteristics of desertification categories

Classes	DSI	Description	Reference
1	DSI <1.2	Non affected areas or very low sensitive areas to desertification	Gad and Lotfy,2008
2	1.2< DSI <1.3	Low sensitive areas to desertification	
3	1.3< DSI <1.4	Medium sensitive areas to desertification	
4	1.3> DSI <1.6	Sensitive areas to desertification	
5	DSI >1.6	Very sensitive areas to desertification	

Table2: Measurable parameters used in developing desertification sensitivity indices (DSAI)

Ind.	Parameter	Data source
CQI	Rainfall	Prăvălie et al ,2017
	Aridity	
	Wind speed	
	aspect	
SQI	Texture	Gad and Lotfy,2008
	Parental material	
	Slope	
	Soil depth	
VQI	Plant cover	Mohamed,2012
	drought	
	erosion	
MQI	Land use	Mohamed,2012
	grazing	
	policy	

2.4.1 Climate quality index

Four factors, including two from the MEDALUS framework (aspect and aridity) and two that were added in accordance with regional specifics (rainfall and wind speed), were used to produce this crucial indicator (Table 3).

Due to its significance in highlighting the availability of water for biological activity, rainfall is regarded as a variable of significant importance for determining the CQI (Table 4) (Kosmas et al., 1999).

According to Salvati et al. (2013), the main contributing factor to land degradation is climatic aridity.

The formula "AI = P/PET" is used to calculate the Aridity Index (AI), where P is the amount of precipitation and PET is the amount of potential evapotranspiration taken from the global database created by Trabucco and Zomer (2009).

Due to its impact on the level of humidity that affects vegetation, slope aspect is regarded as acrucial factor. Understanding the relationship between slope and sunlight and evapotranspiration allows for the realization of this impact. (Kosmas and others, 1999).

Three meteorological stations under the National Meteorology Agency's authority provided data on the wind speed (Table 3).Due to the possibility for the wind deflation process to occur in the region—especially given that it contains the largest sandy soil areas in the nation—wind speed is a crucial component for the process under analysis. By correlating greater intensity values with higher wind speeds, wind erosion was thus indirectly approximated using this methodology (Table 4).

Based on the geometric mean of the sub-indicators' score values, the CQI indicator was calculated using the following formula:

$$CQI = (\text{Aridity Index} \times \text{aspect} \times \text{Rainfall} \times \text{Wind speed})^{1/4}$$

2.4.2 Soil quality index

In the arid, semi-arid, and dry zones, soil is the most important component of terrestrial ecosystems, notably due to its impact on biomass production. Water availability and erosion resistance can be related to soil quality parameters for mapping ESAs (Briggs et al., 1992; Basso et al., 1998). In the current analysis, four soil parameters—namely, parent material, soil texture, soil depth, and slope gradient—were taken into account. On the basis of (OSS, 2004), which was derived from the Medalus project methodology (European Commission, 1999), weighting factors were applied to each category of the attributes that were taken into consideration. The allocated indexes for the various categories of each parameter are shown in Table 3-B. The following algorithm was used to calculate the soil quality index (SQI), and categories are provided in Table 4.

$$SQI = (I_p \times I_t \times I_d \times I_s)^{1/4}$$

Where: The indices of the parent material (I_p), the soil texture (I_t), the soil depth (I_d), and the slope gradient (I_s)

2.4.3 Vegetation quality index (VQI)

The allocated indexes for the various categories of each parameter are shown in Table 3-C. The following equation was used to calculate the Vegetation Quality Index (VQI), which was then divided into groups according to Table 4.

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

Where; the indices of erosion protection (I_{ep}), drought resistance (I_{dr}), and vegetation cover (NDVI) (I_{nd}).

2.4.4 Management quality index

The Management Quality Index, which can be analysed from a two-point perspective (i.e., anthropogenic activity intensity (in crop-lands, pastures, natural, mining, and recreation areas), and agricultural policies aiming to improve restrictive environmental conditions), is one method of evaluating anthropogenic stress on the environment (Kosmas et al., 1999).

The following equation was used to construct the management quality index:

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

In this case, I_l stands for "land use," I_g for "grazing intensity," and I_p for "policy."

Table 3: Characteristics of the parameters (classes and corresponding weights) used for obtaining the (CQI), SQI, VQI and MQI

Indicator	Measurable Parameter	Classes	Description	Score
A (CQI)	Rainfall (mm)	1	650	–
		2	280–650	1.5
		3	280	–
	Aridity Index (mm/mm)	1	Humid (0.65)	1
		2	Dry sub-humid (0.5–0.65)	1.5
		3	Semi-arid (0.5)	–
	Aspect	1	N, NE, NW, V, flat areas	1
		2	S, SE, SW, E	2
	Wind speed (m/s)	1	4.2	1
		2	4.2–5.2	1.5
		3	5.2	2
B (SQI)	Texture	1	Loamy sand, Sandy loam, Balanced	1
		2	Loamy clay, Clayey sand, Sandy clay	1.33
		3	Clay, Clay loam	1.66
		4	Sandy to very Sandy	2
	Parental material	1	Coherent: Limestone, dolomite, non-friable sandstone, hard limestone layer	1
		2	conglomerates, unconsolidated Moderately coherent: Marine limestone, friable sandstone	1.5
		3	Soft to friable: Calcareous clay, clay, sandy formation, alluvium and colluvium	2
	Slope	1	Gentle,	1
		2	Not very gentle	1.33
		3	Abrupt	1.66
		4	Very abrupt	2
	Depth	1	Soil thickness is more than 1 m	1
		2	Soil thickness ranges from	1.33
		3	Soil thickness ranges from	1.66
		4	Soil thickness 0.15 m	2
C VQI	Plant cover	1	NDVI >0.95	1
		2	NDVI 0.65-0.95	1.2
		3	NDVI 0.35-0.65	1.5
		4	NDVI <0.35	2
	Drought	1	Gardens, orchards, rangelands	1
		2	Permanent grassland, annual crops and grasslands	1.5
		3	Bare land	2
	Erosion	1	High	1
		2	Moderate	1.33
		3	Low	1.66
		4	Very Low	2

D (MQI)	Land use	1	Agricultural lands	1
		2	Rangelands	1.3
		3	Poor and degraded	1.66
		4	Bare lands	2
	Grazing	1	Low	1
		2	Moderate	1.5
		3	High	2
	Policy	1	Complete: >75 % of the area under protection	1
		2	Partial: 25–75 % of the area under protection	1.5
		3	Incomplete: <25 % of the area under protection	2

Table 4: Classification of CQI, SQI, VQI and MQI

Parameter	**Class**	**Description**	**Range**
CQI	1	High quality	<1.15
	2	Moderate quality	1.15 to 1.81
	3	Low quality	>1.81
SQI	1	High quality	<1.13
	2	Moderate quality	1.13 to 1.45
	3	Low quality	>1.64
VQI	1	High quality	< 1.2
	2	Moderate quality	1.2 -1.4
	3	Low quality	1.4-1.6
	4	Very Low quality	>1.6
MQI	1	High quality	1-1.25
	2	Moderate quality	1.26-1.5
	3	Low quality	>1.5

3. Result and discussion

3.1 Climate Quality Index (CQI)

The investigated area is an arid region where it receives very little annual precipitation. The major meteorological characteristics that lead to desertification processes are the rainfall, wind speed aspect in addition to the aridity. The result illustrate 100 % of the total area characterized by moderate climatic index where it fills within score range 1.15 and 1.81. It occupies all the area which extens 4584.78 Km^2 , as shown in Table 5 and Figure 4.

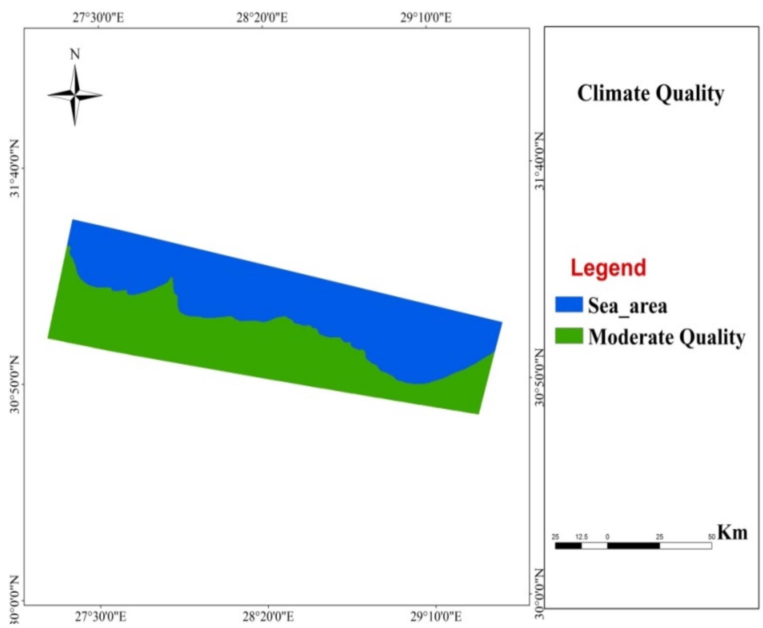

Figure 4: Climate Quality Index Map

3.2 Soil Quality Index (SQI)

To determine the type of parent material, the geologic map was utilized. (Figure 5(A)).this figure shows the study area constitutes only two classes (i.e. Moderate coherent and friable).The friable class is located along the coast covering an area of 1.13–1.45a km, % . as deduced from the GIS system. The topography is represented by slope gradient (Figure. 5(B)) which iscategorized on the basis of the Digital Elevation Model (DEM). The result shows that most of area is assigned by strongly sloping and ranged from 0 to 20 %. This means that the slope in the study area falls into 6 categories according to the FAO classification which are described to flat to very gently sloping, gently sloping, sloping strongly sloping and moderately sloping. The soil texture was assessed on basis of the texture analyses, figure 5 (C) illustrates that soil texture of the study area is ranged between coarse and very like to average. Depth of the study area varies between shallow, moderate and very deep soils as illustrated by figure 5 (D).

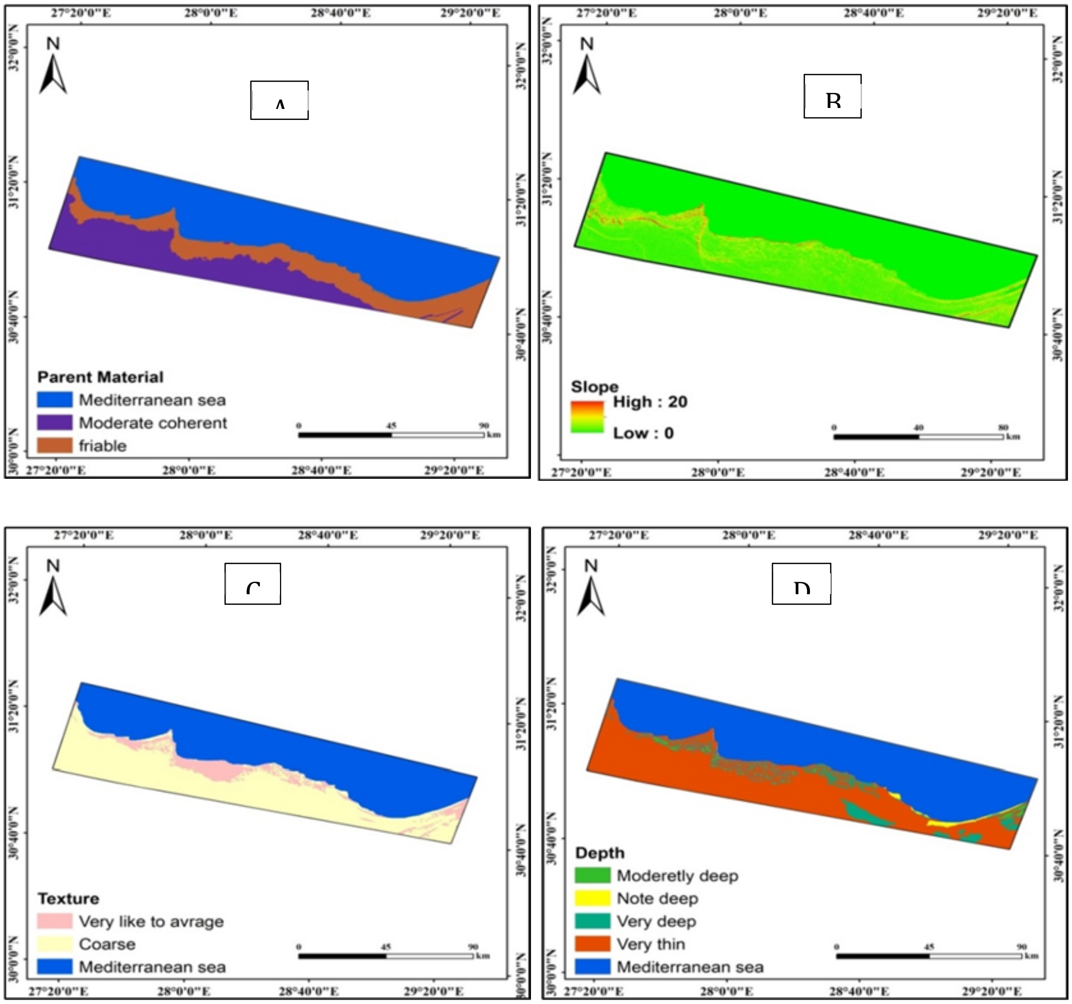

Figure 5: Spatial representation of the selected SQI measurable parameters

Water availability and erosion resistance are two signs of soil quality that can be used to mapEnvironmental Sensitivity Areas (ESAs). Simple soil characteristics including soil texture, parent material, soil depth, and slope gradient can be used to analyse these qualities. The soil quality index (Table 5 and Figure 6) shows that 11.74% (538.43 km^2) of the examined area, located in the northern half, is distinguished by high soil quality. About 3616.59 Km^2 or 78.88% of the total area is covered by the moderate soil quality index. About 9.37% (429.76 Km^2) of the entire area is occupied by the low soil quality index. The depth, the daring condition, the parent material, and the slope are the main limiting criteria of soil quality in the northern section of the research area.

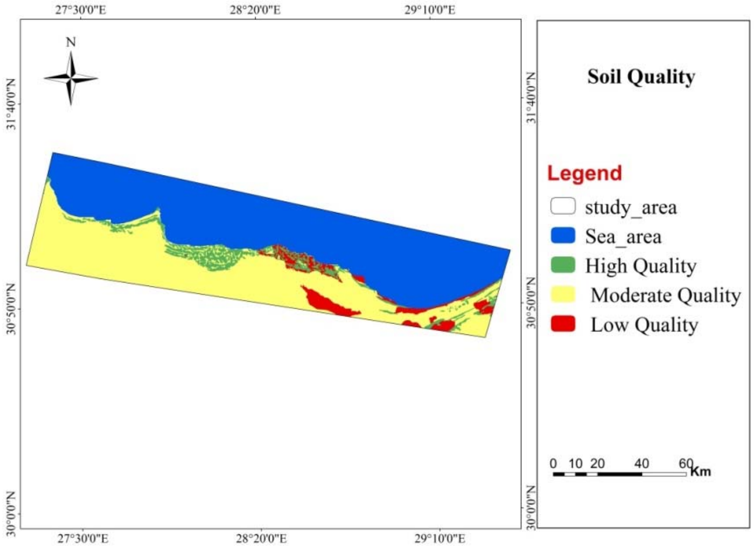

Figure 6: Soil Quality Index Map

3.3 Vegetation quality index

A reliable indicator for determining the North West Coast's classes of desertification susceptibility was discovered to be the Vegetation Quality Index value. The current study takes into consideration soil erosion control, drought resistance, and plant cover type as VQI indicators. The NDVI values, which indicate vegetation cover, were calculated using remotely sensed Landsat photos. Adapted NDVI ratings ranged from 1 to 2, depending on how intense the vegetation index was. The data obtained showed that the study region, which made up around 1.72 and 98.27% of the overall study area (4505.29 Km^2, 79.01 K m^2, respectively), is typified by poor to extremely low vegetation quality index. According to Table 5 and Figure 7, the moderate vegetation quality is predominantly found in the eastern section and covers 0.48 Km^2, or 0.01% of the research area.

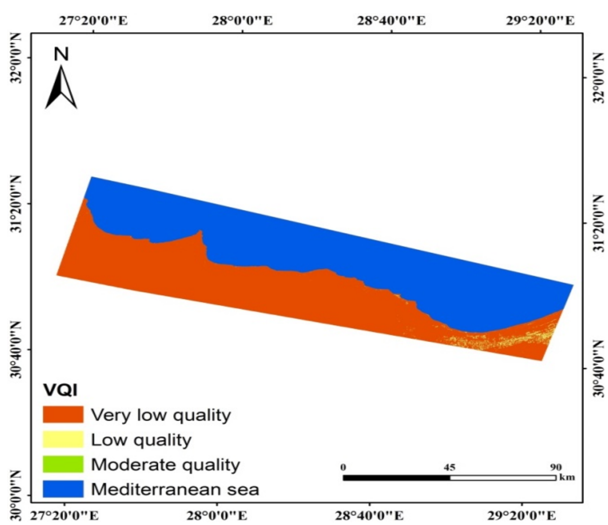

Figure 7: Vegetation Index Map

3.4 Management quality index

In the present study, grazing intensity, policy, and land use factors that were undoubtedly significant in managing the process of desertification were used to suggest the management quality index. The findings show that the research area falls into the moderate and low management quality index categories. It has been determined that (4269.83km^2, or 93.13% of the study area) falls into the low MQI category. (314.95 Km^2, which makes up 6.87% of the total area), has a mediocre quality index as illustrated by Figure 8 and Table 5. It should be noted that the study area suffers from poor land resource management.

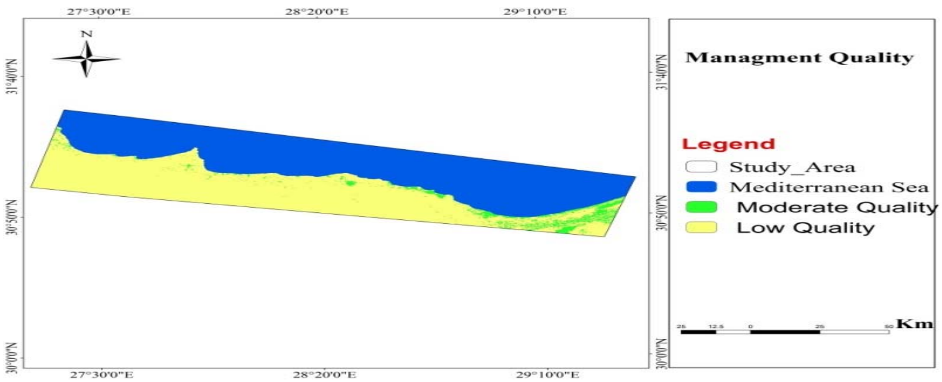

Figure 8: Management Index Map

Table 5: Areas of quality indices classes of Climate, Soil, Vegetation and Management

Indicator	Class	Quality description	Score range	Total area Km2	Total area %
CQI	1	High	1.15	0.00	0.00
	2	Moderate	1.15–1.81	4584.78	100.00
	3	Low	1.81	0.00	0.00
SQI	1	High	1.13	538.43	11.74
	2	Moderate	1.13–1.45	3616.59	78.88
	3	Low	1.45	429.76	9.37
VQI	1	High	< 1.2	0.00	0.00
	2	Moderate	1.2 -1.4	0.48	0.01
	3	Low	1.4-1.6	79.01	1.72
	4	Very low	>1.6	4505.29	98.27
MQI	1	High quality	1-1.25	0.00	0.00
	2	Moderate quality	1.26-1.5	314.95	6.87
	3	Low quality	>1.5	4269.83	93.13

3.5 Desertification sensitive index

To calculate the for desertification ESI, it was necessary to take into account the integration of the climate, soil characteristics, vegetation cover, and management rates. Indicating varying levels of sensitivity to desertification, the values obtained are distributed spatially (Figure 9). The results of this study, which are presented in Table 6, showed that the bulk of the research region, which is located in the south and west, is vulnerable to the processes of desertification, which are typified by severe to extremely severe ESI. These classes represent, respectively, 10.36% and 82.73% (474.91 km^2 and 3793.22 km^2) of the total area. On the other hand, due to the vegetation cover and land usage, the eastern half of the region is very low to low susceptible to desertification. They occupied 67.84 Km^2 and 192.86 Km^2, or 1.48% and 4.21%, respectively, of the total area. Due to the moderately poor soil quality and management, only 1.22% of the land (55.96 km^2) is considered to be Medium Sensitive to Desertification.

Table 6: The area, expressed in absolute and percentage (% of the total study area without sea) values, which corresponds to (DSI), north coast, Egypt

Indicator	Class	Quality description	Score range	Total area (km^2)	Total area (%)
DSI	1	very low sensitive areas to desertification	<1.2	67.84	1.48
	2	Low sensitive areas to desertification	1.2<DSI<1.3	192.86	4.21
	3	Medium sensitive areas to desertification	1.3<DSI<1.4	55.96	1.22
	4	Sensitive areas to desertification	1.4<DSI<1.6	474.91	10.36
	5	Very sensitive areas to desertification	>1.6	3793.22	82.73

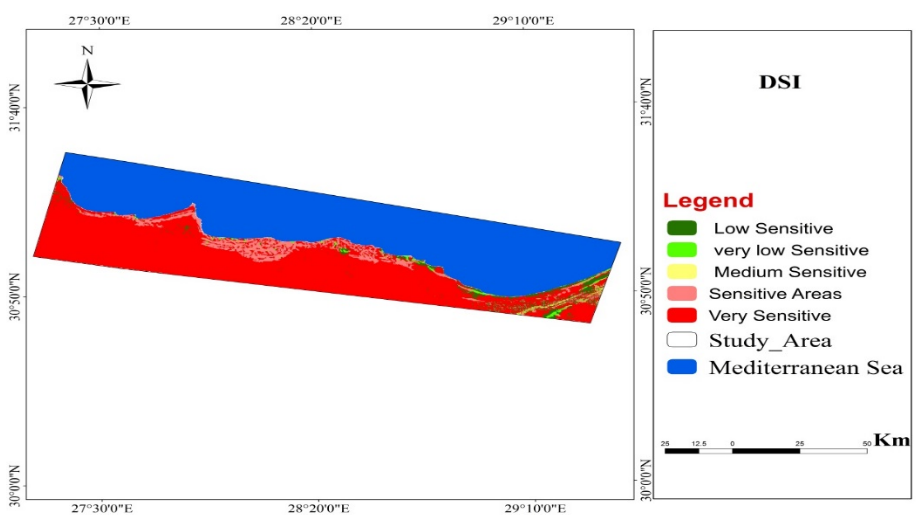

Figure9: Environmentally sensitive areas (ESA's) for north coast, Egypt

4. Conclusions

Desertification is an important geographical phenomena affecting arid regions. The case study discussed in the current article is situated on Egypt's northwestern coast. It is undeniable that identifying the spatial patterns of desertification-prone environmentally sensitive arid regions (ESAs) is a crucial first step in managing sustainable land use. The current paper deals with a case study related to a methodology intended to map and appraise environmentally sensitive areas at risk of desertification. Environmentally sensitive arid areas (ESAs) were calculated using the MEDALUS model in conjunction with field and laboratory investigations. The results indicate that Very Sensitive Areas to Desertification make up 82.73% of the examined area, and Sensitive Areas to Desertification make up 10.36%. Thus, neither the Medium nor the Low vulnerable zones to desertification exceed 1.22–5.69%, respectively. This makes it possible for the land user to recognize and postpone sensitive risk states, supporting the activities required to counter risky desertification processes. The strategy adopted in the current paper is transferable to other Nile basin agricultural regions, the intervening zone of the desert, and prospective oases along the coast. The authors unequivocally advise improving soil and vegetation cover by introducing less water-demanding species, as well as establishing strong stakeholder involvement in order to control wind erosion to mitigate desertification in the study area, particularly in the southern part.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.