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Spatial Modeling of Desertification Sensitivity Using Multiple Environmental Indicators: A MEDALUS-Based Approach in Umm Aqheqih, Eastern Libya

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ABSTRACT

Desertification represents a major environmental challenge in arid and semi-arid regions, where land degradation processes threaten ecosystem stability and sustainable development. This study aims to assess land sensitivity to desertification in the Umm Qahqih area, eastern Libya, using a modified multi-variable Environmental Sensitivity Area Index (ESAI). The study area covers approximately 620 ha, with elevations ranging from 17 to 35 m above sea level. Field investigations were conducted based on 12 representative land units, from which detailed soil profiles and composite samples were collected at variable depths exceeding 90 cm. Soil physical and chemical properties were analyzed, and statistical analyses were conducted to evaluate relationships between selected physicochemical properties and degradation indicators. Significant associations were observed among soil degradation indices, indicating strong physicochemical interactions within the soil system. A spatially explicit desertification sensitivity map was generated using Surfer software. The results revealed pronounced spatial heterogeneity in land sensitivity across the study area, with a mean ESAI value of 1.17 and values ranging from 0.67 to 1.66. Two land units were classified as highly critical (C3), requiring immediate intervention, while 28.9% of the assessed land units were classified within the critical sensitivity classes (C1, C2, and C3), indicating substantial environmental vulnerability. Other critical and fragile units reflected varying degrees of degradation driven by localized soil, vegetation, climatic, and human-induced factors. Non-affected areas were mainly associated with more favorable soil conditions and lower anthropogenic pressure. The findings demonstrate the effectiveness of the modified ESAI model as a flexible and robust tool for identifying priority areas for desertification control. The generated sensitivity map provides a scientific basis for spatially targeted land management strategies and supports decision-making aimed at mitigating land degradation and promoting sustainable land use in eastern Libya.

النمذجة المكانية لحساسية التصحر باستخدام مؤشرات بيئية متعددة: مقاربة قائمة على MEDALUS في منطقة أم أقحيقيح، شرق ليبيا

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الملخص

يُعد التصحر تحدياً بيئياً رئيسياً في المناطق القاحلة وشبه القاحلة، حيث تهدد عمليات تدهور الأراضي استقرار النظم البيئية والتنمية المستدامة. تهدف هذه الدراسة إلى تقييم حساسية الأراضي للتصحر في منطقة "أم قحقيح" بشرق ليبيا، وذلك باستخدام نسخة معدلة من "مؤشر مناطق الحساسية البيئية" (ESAI) متعدد المتغيرات. تغطي منطقة الدراسة مساحة تقارب 620 هكتاراً، وتتراوح الارتفاعات فيها بين 17 و35 متراً فوق مستوى سطح البحر. أُجريت دراسات ميدانية شملت 12 وحدة أرضية ممثلة للمنطقة، حيث جُمعت قطاعات تربة تفصيلية وعينات مركبة من أعماق متفاوتة تتجاوز 90 سم. وقد حُللت الخصائص الفيزيائية والكيميائية للتربة، وأُجريت تحليلات إحصائية لتقييم العلاقات بين الخصائص الفيزيوكيميائية المختارة ومؤشرات التدهور. ولوحظت ارتباطات معنوية بين مؤشرات تدهور التربة، مما يشير إلى وجود تفاعلات فيزيوكيميائية قوية داخل نظام التربة. كما أُنتجت خريطة مكانية لحساسية التصحر باستخدام برنامج "Surfer". وأظهرت النتائج تبايناً مكانياً ملحوظاً في حساسية الأراضي عبر منطقة الدراسة، حيث بلغ متوسط قيمة مؤشر ESAI (1.17)، وتراوحت القيم بين 0.67 و1.66. وصُنفت وحدتان أرضيتان ضمن فئة "شديدة الخطورة" (C3)، مما يستدعي تدخلاً فورياً، في حين صُنفت 28.9% من الوحدات المدروسة ضمن فئات الحساسية الحرجة (C1 وC2 وC3)، مما يعكس هشاشة بيئية كبيرة. وأظهرت الوحدات الأخرى -الحرجة والهشة- درجات متفاوتة من التدهور الناجم عن عوامل محلية تتعلق بالتربة والغطاء النباتي والمناخ والأنشطة البشرية. أما المناطق غير المتأثرة فقد ارتبطت بشكل أساسي بظروف تربة أكثر ملاءمة وضغوط بشرية أقل. وتبرز النتائج فعالية نموذج (ESAI) المعدل

الكلمات المفتاحية:

حساسية التصحر
مؤشر منطقة الحساسية البيئية (*ESAI*)
النمذجة المكانية
تدهور الأراضي

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كأداة مرنة وقوية لتحديد المناطق ذات الأولوية لمكافحة التصحر؛ إذ توفر خريطة الحساسية الناتجة أساساً علمياً لاستراتيجيات إدارة الأراضي الموجهة مكانياً، وتدعم اتخاذ القرارات الرامية إلى الحد من تدهور الأراضي وتعزيز الاستخدام المستدام لها في شرق ليبيا.

Introduction

Land degradation and desertification represent major environmental challenges in arid and semi-arid regions, where climatic variability, limited water availability, fragile soils, vegetation degradation, and increasing human pressure interact to reduce land productivity and ecosystem resilience. Across the Mediterranean region, these processes vary considerably in their intensity and spatial distribution, making the identification of environmentally sensitive areas essential for effective land management and timely intervention. In Libya, the vulnerability of agricultural and semi-arid landscapes is further intensified by low and irregular rainfall, increasing climatic stress, limited soil conservation measures, and human activities that may accelerate erosion and other forms of land degradation [1].

According to the United Nations Convention to Combat Desertification [2], desertification results from the interaction of climatic variations and human activities and should therefore be evaluated through integrated approaches that consider the spatial variability of environmental conditions [2].In this context, Geographic Information Systems (GIS), remote sensing, and spatial modeling have become important tools in engineering [3-5], Tourism [6], mining [7], social [8], political [9,10], environmental [11,12], Agriculture [13,14], etc. In this study we used GIS for identifying areas that differ in their degree of environmental sensitivity and for supporting spatially targeted land management.

Among the established approaches for assessing desertification sensitivity, the Environmental Sensitive Area Index (ESAI), developed within the Mediterranean Desertification and Land Use (MEDALUS) framework, provides an integrated method for combining multiple environmental indicators into a single spatially explicit assessment. The framework traditionally considers the major components of soil quality, climate quality, vegetation quality, and management quality, thereby allowing the combined effects of different environmental pressures to be represented within a common index [15,16].An important advantage of ESAI is its methodological flexibility, which allows individual indicators to be adapted according to local environmental characteristics, data availability, and the specific objectives of a study while retaining the integrated concept of environmental sensitivity.

Previous applications of ESAI have demonstrated its usefulness for evaluating desertification sensitivity across Mediterranean and other dryland environments; however, the relative importance of environmental indicators can vary substantially between locations because of differences in soil characteristics, climate, vegetation cover, hydrological conditions, and land-use practices [17]. Consequently, locally adapted applications are necessary to capture spatial heterogeneity and identify the dominant combinations of factors contributing to land degradation.

Despite the growing application of ESAI at regional and national scales, there remains a need for detailed local-scale assessments in vulnerable agricultural landscapes of eastern Libya, particularly in areas where soil degradation, salinity, water limitations, vegetation decline, and climatic stress occur simultaneously. In the Umm Qahqih area, systematic spatial assessment of desertification sensitivity remains limited, and the interactions among soil, climate, vegetation, and water-related conditions have not been sufficiently integrated within a unified spatial framework. This creates a need for a locally adapted assessment that can identify spatial differences in environmental sensitivity and determine priority areas for land-management intervention.

Therefore, the present study aims to assess the spatial sensitivity of the Umm Qahqih area, eastern Libya, to desertification using a modified Environmental Sensitivity Area Index (ESAI) based on the MEDALUS framework. Specifically, the study seeks to: (1) evaluate the spatial characteristics of the principal soil, climatic, vegetation, and water-related indicators associated with land degradation; (2) integrate these indicators into a modified ESAI framework adapted to the environmental conditions and available data of Umm Qahqih; and (3) produce a spatially explicit desertification sensitivity map and identify areas requiring priority intervention. The main scientific contribution of the study is the application of a locally adapted, multi-variable ESAI approach that integrates field-based soil assessment with climatic, vegetation, and water-quality indicators to provide a more spatially detailed evaluation of desertification sensitivity in an eastern Libyan dryland environment.

Materials and Methods

Study Area

The study was conducted in the Umm Qahqih area, eastern Libya, at approximately 32.17208° N latitude and 23.66351° E longitude Figure (1). The study area covers approximately 620 ha, with elevations ranging from 17 to 35 m above mean sea level. The area is characterized by arid climatic conditions and low and irregular rainfall, with an annual rainfall of approximately 150 mm. These environmental conditions, together with the spatial variability of soil properties, vegetation cover, drainage conditions, and anthropogenic activities, contribute to the vulnerability of the area to land degradation and desertification. The combination of these characteristics makes Umm Qahqih an appropriate case study for evaluating desertification sensitivity using an integrated, spatially explicit environmental index [15,17].

The predominant soils in the study area are Entisols and Aridisols, [18]. These soils generally exhibit limited profile development under dry climatic conditions and are associated with low and spatially variable organic matter accumulation and restricted water availability. Land use is dominated by rain-fed barley cultivation, together with small-scale orchards, vegetable plots, and fallow fields.

Before field sampling, reconnaissance surveys were conducted to delineate and verify the study-area boundaries, examine surface morphology and topographic variability, identify dominant vegetation and land-use patterns, and locate areas representing the principal environmental conditions of the study area. These preliminary observations were used to guide the spatial distribution of sampling sites and improve the representativeness of the field investigation.

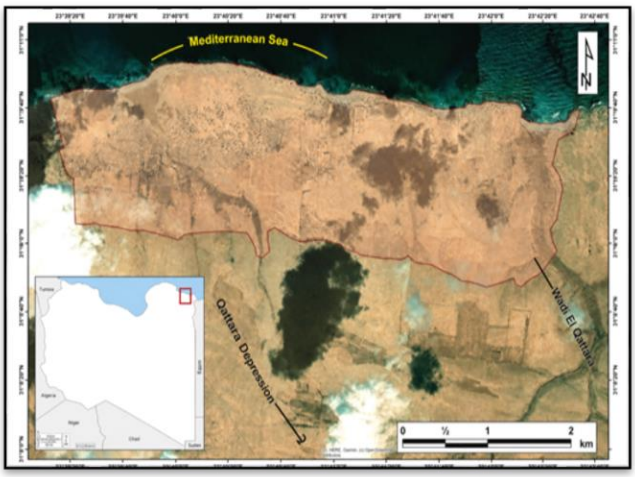


Figure 1: location of study area in Libya.

Field Sampling Strategy

A stratified field-sampling design was adopted to capture the major spatial variations in soil and environmental conditions within the study area. The study area was divided into twelve representative land units/sectors (A1–A12) Figure (2), selected to encompass the observed variation in topography, soil characteristics, vegetation, land use, and drainage conditions.

A total of 26 soil samples were collected from the study area at different depths according to the occurrence and development of soil horizons, with profiles extending to more than 90 cm where soil conditions permitted. In addition, one composite surface-soil sample was collected from each of the twelve land units. Composite samples were obtained using an X-shaped sampling pattern, while zigzag transects were used during field collection to reduce local sampling bias and improve spatial representation.

The sampling strategy was designed to capture both horizontal and vertical variability in soil properties. The twelve land units were subsequently used as the principal spatial units for the environmental sensitivity assessment, whereas the individual soil samples and horizon observations were used for laboratory analyses and statistical evaluation. This distinction is important because the number of spatial assessment units (12) does not represent the total number of analytical soil observations (26 soil samples plus the composite surface samples) Figure (3).

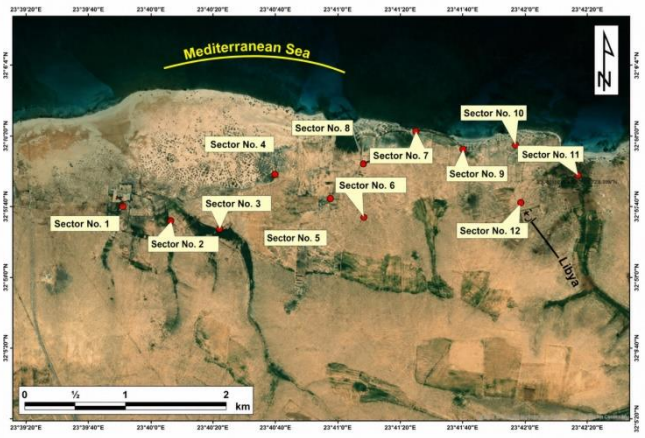


Figure 2: The distribution of soil profiles and sampling sites

Soil and Water Analyses

The collected soil samples were analyzed for a range of physical and chemical properties relevant to soil quality and desertification sensitivity. Physical analyses included particle-size distribution (sand, silt, and clay), bulk density, soil porosity, soil moisture content, aggregate stability, soil depth, rock-fragment content, soil resistance to penetration, drainage condition, and infiltration rate. Chemical analyses included pH, electrical conductivity (EC), total dissolved solids (TDS), soil organic matter (SOM), calcium carbonate ($CaCO_3$), and cation exchange capacity (CEC). These variables were selected because they provide information on soil structure, water retention, salinity, fertility, and the susceptibility of soil to degradation.

Additional field observations included soil colour, texture class, surface condition, vegetation cover, land use, and other environmental characteristics required for the environmental sensitivity assessment.

Water samples were collected from groundwater sources and harvested rainfall used within the study area. Water quality analyses included pH, electrical conductivity, total dissolved solids, chloride (Cl^-), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium-related irrigation indicators, including sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP), where applicable. These measurements were used to evaluate salinity and sodicity hazards and to derive the irrigation-water component of the modified environmental sensitivity assessment.

Laboratory analyses were performed at the Soil and Water Laboratory of Alexandria University, Egypt; the Soil and Water Laboratory of Omar Al-Mukhtar University, Al-Bayda, Libya; and the Natural Resources Laboratory, Faculty of Natural Resources, University of Tobruk, Standard analytical procedures were applied to all soil and water samples.



Figure 3: The field survey and Soil profiles description. by_nor_othmen_6/8/2025 Umm Qahqih.

Environmental Sensitivity Assessment Using the MEDALUS–ESAI Framework

The assessment was based on the Mediterranean Desertification and Land Use (MEDALUS) framework and the Environmental Sensitivity Area Index (ESAI). In the conventional MEDALUS approach, environmental sensitivity is represented through integrated quality indices describing soil, climate, vegetation, and land management conditions. Each environmental variable is first classified according to predefined sensitivity classes and assigned a numerical score, generally ranging from 1.0 (lowest

sensitivity) to 2.0 (highest sensitivity). The corresponding component quality indices are then calculated using the geometric mean of their standardized sub-indicators [15,16]

In the present study, the ESAI framework was modified to account for the specific environmental conditions and data availability of the Umm Qahqih area. The modified framework incorporated four principal components: Soil Quality Index (SQI), Climate Quality Index (CQI), Vegetation Quality Index (VQI), and Irrigation Water Quality Index (IWQI). The inclusion of IWQI was intended to explicitly represent the contribution of irrigation-water salinity and sodicity to land degradation in the study area. The management component (MQI) was not included in the primary modified ESAI formulation because of limitations in the availability of standardized quantitative management indicators and spatially consistent management data.

Assignment of Sub-Indicator Scores

Each selected environmental variable was converted into a standardized sensitivity score before index calculation. The score assigned to each class reflected its relative contribution to environmental sensitivity, with lower values representing more favourable conditions and higher values representing conditions associated with greater degradation risk. The classification thresholds and scores used for each sub-indicator should be presented explicitly in a parameter-weighting table Table (1) to ensure methodological reproducibility.

Soil Quality Index (SQI)

The SQI was developed using the soil variables considered most relevant to land sensitivity in the study area. These included soil texture, soil depth, drainage/percolation characteristics, soil organic matter, electrical conductivity, and other locally relevant physical and chemical properties incorporated into the modified assessment.

The SQI was calculated as:

$$SQI = (\text{soil texture} \times \text{parent material} \times \text{rock fragment} \times \text{slope} \times \text{soil depth} \times \text{drainage} \times SOM \times EC \times pH \times CaCo3 \times CEC)^{1/11}$$

The use of the geometric mean allows a relatively poor soil attribute to contribute proportionally to the integrated soil-quality score rather than being masked by favourable values of other variables.

Climate Quality Index (CQI)

The CQI was derived from climatic indicators influencing water availability and climatic stress. The selected variables included rainfall, aridity, and aspect, according to the modified scoring framework adopted for the study area.

The CQI was calculated as:

$$CQI = (\text{rainfall} \times \text{aridity} \times \text{aspect})^{1/3}$$

Vegetation Quality Index (VQI)

The VQI represented vegetation-related protection against degradation and was derived from the selected indicators describing vegetation condition and sensitivity to environmental stress. These included plant cover, drought risk or drought resistance, erosion protection, and fire risk, where applicable.

The VQI was calculated using the geometric mean:

$$VQI = (\text{fire risk} \times \text{erosion protection} \times \text{drought resistance} \times \text{plant cover})^{1/4}$$

Irrigation Water Quality Index (IWQI)

Because water quality represents an important degradation pressure in the arid agricultural environment of Umm Qahqih, an Irrigation Water Quality Index (IWQI) was incorporated into the modified framework. The IWQI was based on the selected indicators of irrigation-water salinity and sodicity, including pH, electrical conductivity, chloride concentration, and sodium-related hazards.

The IWQI was calculated as:

$$IWQI = (ECw \times SAR \times Cl)^{1/3}$$

Where ESP was used as an additional indicator in the final scoring system, it should be explicitly incorporated into this equation and the corresponding classification table rather than being described only in the laboratory-analysis section.

Final Modified ESAI

The final Environmental Sensitivity Area Index was calculated as the geometric mean of the four component indices:

$$ESAI = (SQI \times CQI \times VQI \times IWQI)^{1/4}$$

The resulting ESAI values theoretically range from approximately 1.0 to 2.0, with lower values representing relatively favourable environmental conditions and higher values indicating increasing sensitivity to desertification. The geometric-mean formulation follows the underlying MEDALUS concept while allowing the fourth component to reflect irrigation-water quality in response to local environmental conditions.

For the optional comparison in which the conventional management component was evaluated, MQI was calculated separately and the corresponding conventional formulation was expressed as:

$$ESAI = (SQI \times CQI \times VQI \times MQI \times IWQI)^{1/5}$$

Classification of Environmental Sensitivity

The resulting ESAI values were classified according to the MEDALUS sensitivity classes. The classification thresholds adopted in this study were:

Table 1: ESAI Classification Thresholds

ESAI value	Class	Sensitivity category
1.00–1.17	N	Non-affected
1.17–1.22	P	Potential
1.22–1.26	F1	Fragile
1.26–1.32	F2	Fragile
1.32–1.37	F3	Fragile
1.37–1.41	C1	Critical
1.41–1.53	C2	Critical
1.53–2.00	C3	Critical

These thresholds correspond to the commonly used MEDALUS/ESAI classification system, in which increasing index values indicate increasing environmental sensitivity to desertification.

Statistical Analysis

Statistical analyses were conducted to characterize the distribution and variability of measured soil properties and to evaluate relationships among selected degradation indicators. Descriptive statistics included the mean, standard deviation, standard error, minimum, and maximum values. Pearson correlation analysis was used to examine the strength and direction of relationships between selected soil properties and degradation-related variables.

One-way analysis of variance (ANOVA) was used to test whether significant differences occurred among the study sites and among soil horizons. Statistical significance was evaluated at the 0.05 probability level. Where appropriate, the assumptions of homogeneity of variance were assessed using Levine's test, and post-hoc comparisons were conducted using the Least Significant Difference (LSD) test.

The statistical analysis was based on the individual soil observations rather than treating the twelve ESAI spatial

units as twelve independent environmental replicates. The twelve land units were used primarily for spatial classification and mapping, while the available soil samples and horizon observations provided the analytical basis for testing differences among sites and depths.

Spatial Analysis and Mapping

Following laboratory and statistical analysis, the measured variables were spatially represented across the study area. The sampling observations were assigned to their corresponding geographic locations, and spatial interpolation was performed using Surfer 10 to generate continuous thematic surfaces for the relevant soil and environmental indicators.

Each thematic layer was subsequently reclassified according to the predefined sensitivity scores and integrated within the MEDALUS–ESAI framework. The resulting component indices (SQI, CQI, VQI, and IWQI) and the final modified ESAI were mapped to identify the spatial distribution of environmental sensitivity and to delineate areas requiring priority land-management intervention.

Methodological Limitation

The relatively small number of spatial assessment units (12 land units) represents an important limitation when interpreting spatial patterns at broader scales. Accordingly, the resulting ESAI map should be interpreted as a detailed assessment of environmental sensitivity within the Umm Qahqih study area rather than as a basis for generalizing desertification conditions across eastern Libya as a whole.

Nevertheless, the sampling design incorporated both horizontal and vertical soil variability, with 26 soil samples collected across the twelve representative sectors. The use of stratified field sampling and multiple environmental indicators was intended to improve the representativeness of the assessment within the study boundary. Therefore, the main value of the analysis lies in identifying relative differences and priority zones within the study area rather than estimating regional-scale population parameters.

Results and Discussions

The results of the Environmental Sensitivity Area Index (ESAI) assessment reveal pronounced spatial variability in land sensitivity to desertification across the Umm Qahqih area, eastern Libya. This heterogeneity confirms that land degradation processes are not uniformly distributed, but rather would be controlled by localized interactions between soil characteristics, climatic stress, vegetation cover, and human activities, as highlighted in previous Mediterranean and arid-region studies [19].

Investigation of degradation-related soil properties

Table (2) shows significant variations in sand, silt, and clay content across the study profiles, while these differences suggest the presence of distinct soil types as indicated by the soil map, the overall textural classification remains consistent. The soils are predominantly coarse-textured, with sandy loam (SL) and sand (S) being the dominant classes throughout the study area. The predominance of sandy soil texture in the study area, characterized by a high average sand content (72.50%), and relatively low proportions of silt (23.08%) and clay (4.41%), indicates the presence of a coarse-textured soil system. The calcium carbonate content was relatively high (33.90%), reflecting the calcareous soil conditions typical of arid and semi-arid environments. The arid coarse soils generally exhibit limited agricultural productivity due to their low capacity to retain water and nutrients., which reduces soil moisture availability for plant uptake, Table (3) shows the significant negative correlation between soil moisture content and sand%, while showed positive relation with clay content.

Unexpectedly the coarse soils under investigation recorded slow final infiltration rates, which ranged between 0.11 to 0.20 cm\hr. Infiltration rate were significantly correlated with the sand and silt contents of the studied soils Table (3). Lower clay and organic matter content, combined with poor aggregate stability, resulted in reduced soil permeability. This likely explains the observed negative correlation between sand percentage and infiltration capacity, as weak structural stability can lead to surface sealing or pore clogging. Also, lands with poor vegetation cover were subjected to a "sieving" effect occurs where raindrops wash fine silt and clay particles downward, in arid regions, the subsequent intense heat may cause this "seal" to dry and harden quickly into a stiff crust Figure (4) [20,21].



Figure 4: Water erosion and surface crusts of semi-arid sandy soils at the study sites

The moderate values of soil resistance to penetration of the study sites (0.75-1.26 MPa) may not reflect a state of soil compaction and physical soil degradation, however, from a structural perspective, the low proportion of clay particles results in weak antiparticle cohesion and poor aggregate stability, making the soil structure relatively loose and unstable. This assumption is confirmed by the results of the The stability test of aggregates larger than 2 mm (WSA%) showed that the low percentage of these aggregates (5.95%) in the soil samples confirms the fragility of the soil. Table (3.4) illustrates that the stability of soil aggregates (>1 mm and 0.5 mm) is positively correlated with clay content,

whereas a negative correlation exists with sand percentage. Consequently, soil texture may be the primary factor undermining soil aggregate stability and resistance to erosion. [22]. $CaCO_3$ content unexpectedly showed a negative correlation Table (3) with WSA > 0.5 and 1 mm. $CaCO_3$ content is among the important factors that determine aggregate stability; however, in this study, the effect of $CaCO_3$ content as a stabilizing factor could have been affected by the higher sand content and lower organic matter content. Previous research has pointed out that the high content of organic matter was the main stabilizing factor for Mediterranean calcareous Rendzinas.

WSA: Water Stability Aggregates index

Table 2: Topsoil physical Properties of the study sites

Property	Mean	Std. Error of Mean	Std. Deviation	Minimum	Maximum	sig	p-value
Sand%	72.50	3.41	11.82	50.00	96.00	0.000	0.00
Silt%	23.08	2.68	9.29	4.00	38.00	0.002	0.00
Clay%	4.41	0.96	3.34	0.00	12.00	0.000	0.00
Bulk Density g\cm3 (B.D)	1.25	0.05	0.17	0.91	1.51	0.000	0.03
Aggregates stability index (A.Gs) St>2mm%	13.69	2.28	13.66	0.00	66.28	0.000	0.07
A.Gs St>1mm%	3.17	0.25	1.49	0.00	6.00		0.06
A.Gs St>0.5mm%	5.22	0.47	2.84	0.00	12.80		0.04
Soil resistance To penetration MPa (S.R.P)	0.96	0.04	0.16	0.75	1.26	0.000	0.02
Water content (W.C%)	2.66	3.66	0.61	0.00	16.55		0.00
Final Infiltration rate cm\hr (I.R)	0.16	0.027	0.008	0.11	0.20	0.000	0.00

Table 3: Descriptive statistics of the physicochemical and physical properties of surface soil samples

Property	Mean	Std. Error of Mean	Std. Deviation	Minimum	Maximum	p-value
pH	7.70	0.11	0.38	7.10	8.20	0.02
EC dS\m	3.32	0.65	3.89	0.17	11.56	0.01
CEC meq/100g	15.63	1.73	5.99	2.05	22.25	0.02
CaCO3%	33.90	4.09	14.18	10.23	52.91	0.02
OM%	1.16	0.16	0.56	0.69	2.71	0.61
ESP%	16.55	2.53	12.39	1.10	43.50	0.00
SAR%	14.90	2.83	13.84	0.69	53.10	0.00
Mg meq/L	26.38	4.61	22.60	2.00	67.00	0.00
Ca meq/L	33.27	6.71	32.85	1.50	111.00	0.00
Na meq/L	109.41	27.93	136.84	0.39	478.31	0.00

Table 4: Soil salinity indicators and classification in the study sites

Sites	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
pH	8.3	7.6	8.0	8.0	8.1	8.5	8.5	8.7	8.5	8.6	7.9	7.9
EC ds\m	1.4	10.8	0.6	0.9	5.4	0.3	0.5	0.3	0.5	0.4	7.4	1.2
ESP %	2.8	8.2	24	15	36	5.1	26.4	25.9	24.8	19.1	7.7	3.8
Soil Salinity Classification	Non	Strongly Saline	Non	Non	Saline-Sodic	Non	Sodic	Sodic	Sodic	Sodic	Moderately Saline	Non

Table 5: Results of Pearson correlation analysis of the relationship between some degradation indicators and some soil parameters

Degradation indicator	Sand	Silt	Clay	$CaCO_3$ %	OM %	EC	TDS	pH
Final infiltration rate (cm h^{-1})	−0.416*	0.496**	0.193	−0.107	0.161	0.245	0.245	−0.403*
Sig. (2-tailed)	0.012	0.002	0.260	0.536	0.348	0.150	0.150	0.015
Water content (%)	−0.353*	0.289	0.389*	−0.184	−0.049	−0.052	−0.052	0.208
Sig. (2-tailed)	0.035	0.087	0.019	0.282	0.776	0.762	0.761	0.223
CEC (meq/100 g)	−0.184	0.200	0.119	−0.151	0.258	0.359*	0.359*	−0.348*
Sig. (2-tailed)	0.284	0.241	0.491	0.378	0.129	0.032	0.032	0.038
Aggregate stability,0.5mm(%)	−0.352*	0.317	0.389*	−0.492**	−0.081	0.037	0.037	−0.170
Sig. (2-tailed)	0.035	0.059	0.019	0.002	0.638	0.829	0.831	0.322
Aggregate stability,1mm (%)	−0.234	0.177	0.338*	−0.383*	0.191	0.013	0.013	−0.201
Sig. (2-tailed)	0.169	0.302	0.044	0.021	0.264	0.939	0.939	0.240
Aggregate stability,2mm (%)	−0.142	0.123	0.131	0.098	0.185	−0.019	−0.018	−0.070
Sig. (2-tailed)	0.409	0.473	0.445	0.569	0.280	0.913	0.917	0.686
Bulk density(g cm^{-3})	0.187	−0.188	−0.156	0.102	−0.089	0.155	0.155	−0.130
Sig. (2-tailed)	0.275	0.271	0.364	0.553	0.606	0.368	0.367	0.450
Soil resistance to penetration (MPa)	−0.209	0.179	0.293	−0.079	0.068	−0.256	−0.255	0.067
Sig. (2-tailed)	0.221	0.296	0.082	0.648	0.695	0.132	0.133	0.697

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

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

Note: Statistics are based on the 12 surface-soil samples (1.1–12.1). EC in dS m^{-1}; CEC in meq 100 g^{-1}. Mg^{2+}, Ca^{2+}, Na^{+}, SAR and ESP were excluded because they are not part of the surface-soil dataset presented in this table.

Low values of soil organic matter (3.2), with an average of 1.16%. Organic matter content according to the study sites

and soil types were not significantly different indicating limited organic inputs and weak biological activity within the soil system. Soil organic matter is considered one of the most important indicators of soil quality and soil health, as it plays a fundamental role in improving soil structure, enhancing aggregate stability, and increasing the soil's capacity to retain water and nutrients. In the coarse-textured soils prevalent throughout the study area, the scarcity of vegetation renders organic matter even more vital for maintaining soil stability and partially compensates for the low clay content.

Consequently, these soils tend to have low resistance to mechanical disturbance and environmental stresses. The weak cohesion between particles also increases the susceptibility of the soil surface to erosion processes, particularly wind erosion, which is a dominant degradation factor in the study area. Field observations revealed several forms of water and wind erosion, such as sheet erosion, rill erosion, and sedimentation near hedges and barriers along the agricultural fields in the area Figure (2).

The average soil pH (7.7) indicates moderately alkaline conditions, and Cation exchange capacity (CEC) values ranged from 2.05 to 22.25 cmol/kg, indicating noticeable variability in the content of clay minerals and soil colloids across the sampling sites. In arid and semi-arid environments, low CEC values often stemming from low clay and organic matter content limit nutrient retention. This results in rapid leaching and diminished fertility, leaving the soil increasingly susceptible to degradation, [35].

Table (4) employs three indicators to evaluate salinity and sodicity across twelve study sites. The results indicate that five sites remained unaffected by salinity, whereas three were classified as saline. Furthermore, four sites exhibited sodicity; these were situated in closest proximity to the coastline, providing a clear spatial correlation for this condition. Conversely, the sites unaffected by sodicity were characterized by two primary factors: their relatively greater distance from the sea and their proximity to active wadi beds. In these locations, consistent intensive surface runoff likely facilitated the leaching of salts, thereby mitigating the accumulation of both salinity and sodicity. However, while salts are present, the soil structure may remain stable until the salts are leached out, at which point it becomes sodic. Sodic soils suffer from poor structure and drainage, which can severely limit their agricultural potential.

According to The U.S. Salinity Laboratory (USSL) system

Table (6) showed that no statistically significant differences ($p > 0.05$) among the three soil horizons for all investigated properties. These findings indicate a high degree of vertical homogeneity in soil characteristics, with no clear evidence of pronounced depth-wise differentiation. Such uniformity may reflect weak horizon development, which is commonly associated with soils formed under relatively stable environmental conditions or limited pedogenic intensity. The lack of vertical variation suggests that soil-forming factors—such as parent material, climate, and topography—have operated in a relatively uniform manner across the profile, restricting the development of distinct diagnostic horizons. Overall, these results are consistent with recent studies indicating that soils in arid and semi-arid environments often display weak profile differentiation and limited vertical variability, primarily due to low weathering intensity, reduced organic inputs, and restricted leaching processes. Under such conditions, soil properties tend to remain relatively uniform with depth, reflecting constrained pedogenic development [24-28].

Table 6: Averages of vertical and significant differences

Properties	Sig.	F	Significance
Sand	0.418	0.907	N.S
Silt	0.657	0.429	N.S
Clay	0.161	1.979	N.S
CaCO3	0.143	2.117	N.S
OM	0.561	0.594	N.S
EC	0.537	0.639	N.S
TDS	0.537	0.64	N.S
pH	0.452	0.822	N.S

Evaluation of land degradation and Spatial Distribution of Desertification Sensitivity (MQI is excluded)

The ESAI classification of the twelve land units (A1–A12) indicates that approximately half of the study area (50%) falls within the critical sensitivity classes (C1, C2, and C3) (Figures 5 to 9). This dominance of critical classes reflects a high level of environmental pressure and suggests that large portions of the area are already functioning close to their ecological thresholds. Similar dominance of critical land units has been reported in other arid environments, where slight increases in stress can trigger rapid land degradation [17].

A single land unit (A2) was classified as C3, representing the highest level of sensitivity. This unit can be considered extremely fragile, where environmental quality is severely

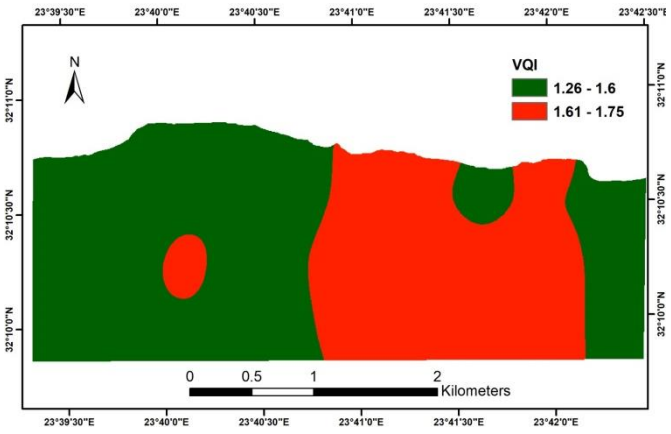


Figure 5: Spatial distribution of vegetation quality index (VQI) in the study area

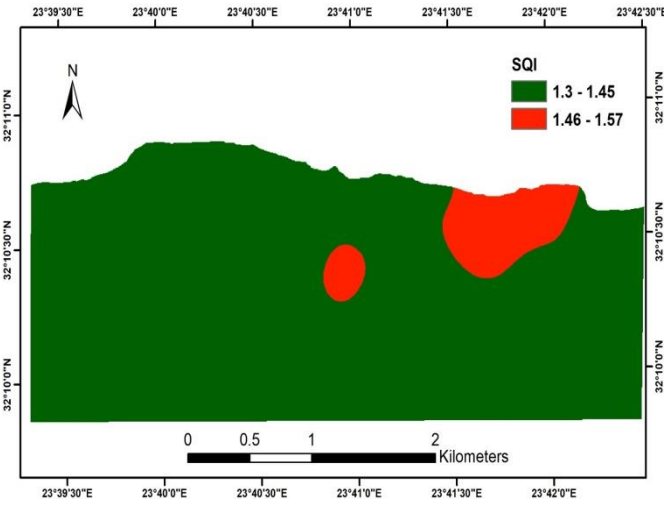


Figure 6: Spatial distribution of soil quality index (SQI) in the study area

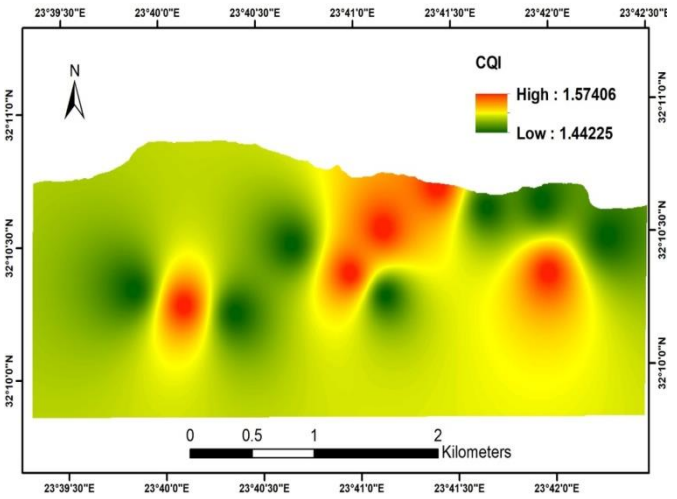


Figure 7: Spatial distribution of Climate quality index (CQI) in the study area

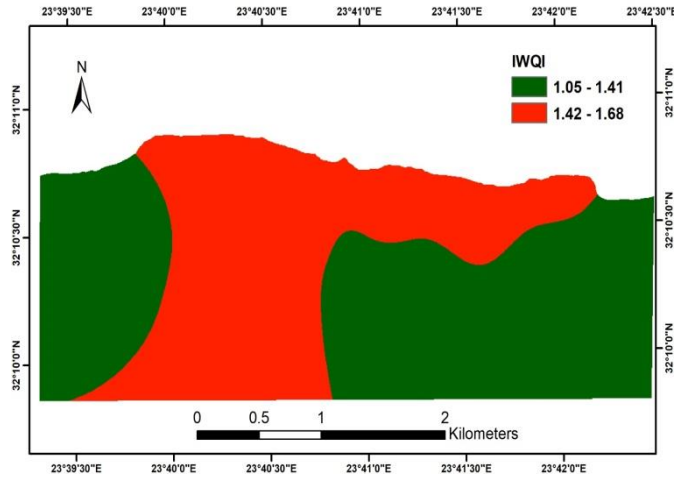


Figure 8: Spatial distribution of Water quality index (IWQI) in the study area

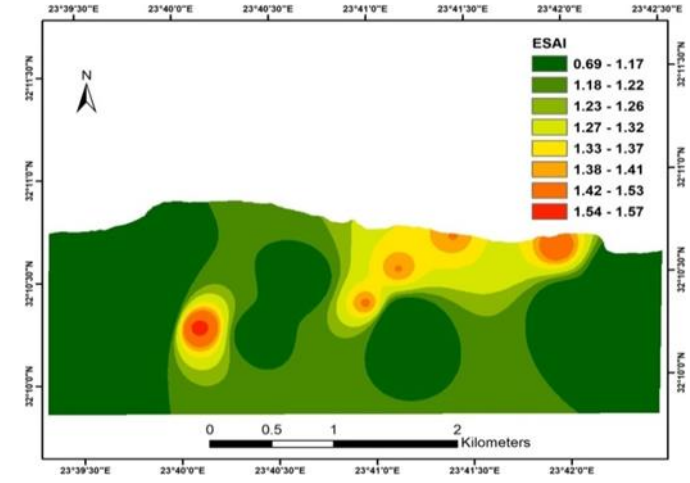


Figure 9: Spatial distribution of environmental sensitivity areas index (ESAI) in the study area

reduced and resilience to further disturbances is minimal. Such areas are often characterized by shallow soils, low organic matter content, high salinity or sodicity, and strong exposure to climatic extremes, making them highly vulnerable to irreversible degradation if no immediate intervention is undertaken [30]. Land units classified as C1 and C2 represent areas with high sensitivity but still retain limited recovery potential if appropriate management measures are applied. These units likely differ in their dominant degradation drivers; for instance, C1 areas may be primarily affected by poor vegetation cover and overgrazing, whereas C2 areas may be controlled by fragile soil texture, high carbonate content, or weak soil structure. This differentiation emphasizes the importance of addressing the specific contributing factors embedded within the ESAI components rather than applying uniform management solutions [15]. The presence of a fragile unit (F1), represented by land unit A9, indicates a transitional condition between stable and critical states. Although not yet severely degraded, this unit lacks sufficient ecological resilience to withstand increasing pressures. Such areas serve as early warning zones, where preventive management can be implemented at relatively low cost compared to rehabilitation efforts in fully degraded lands [14].

In contrast, non-affected units (N), accounting for about 41.7% of the study area, appear to benefit from favorable natural conditions such as deeper soils, better drainage, or relatively denser vegetation cover, as well as reduced human pressure. These areas play a crucial role in maintaining regional environmental balance and can function as protective buffers against the expansion of degradation processes.

Overall, the spatial distribution of ESAI classes in Umm Qahqih indicates that land degradation is unevenly distributed across the study area and reflects the combined influence of several environmental indicators. The results do not point to a single dominant factor controlling degradation; rather, the condition of the land appears to be shaped by the interaction between soil, climate, vegetation cover, and water-related conditions. While local factors such as soil properties and land-use practices may contribute to site-specific variability, the regional semi-arid to arid climate of the Tobruk area also plays a fundamental role in increasing the overall susceptibility of the landscape to degradation. Similar observations have been reported in studies from northeastern Libya, where desertification was found to result from the combined effects of climatic stress and local environmental conditions rather than a single controlling indicator [29, 2].

Evaluation of land degradation and Spatial Distribution of Desertification Sensitivity (MQI is included)

After incorporating the management quality indicator (MQI) into the MEDALUS model, the spatial distribution of the Environmental Sensitivity Area Index (ESAI) classes showed noticeable changes compared with the results obtained without the management factor Figure (10, 11). The updated analysis indicated that approximately 73.7% of the study area falls within the critical class, while 21.1% is classified as non-affected, and only 2.6% fall within the fragile and potential classes, respectively. The increase in the proportion of areas classified as critical reflects the significant influence of land management practices on land degradation processes in the study area.

These results suggest that anthropogenic pressures play an important role in accelerating soil degradation. In particular, overgrazing represents a major driver of land degradation in dryland ecosystems, as continuous grazing pressure reduces vegetation cover and exposes the soil surface to erosion processes. In addition, intensive and traditional tillage

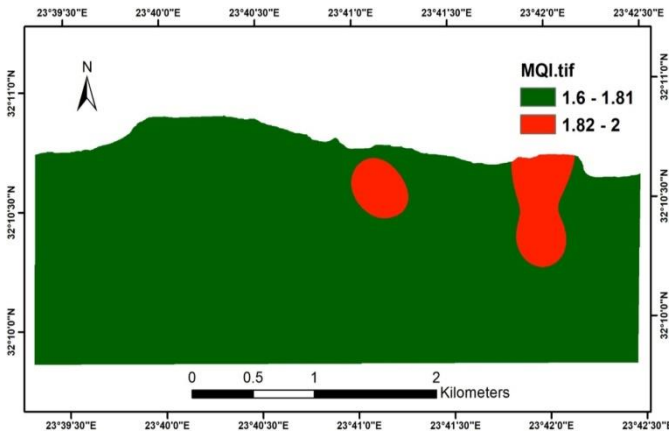


Figure 10: Spatial distribution of the Management Quality Index (MQI) in the study area

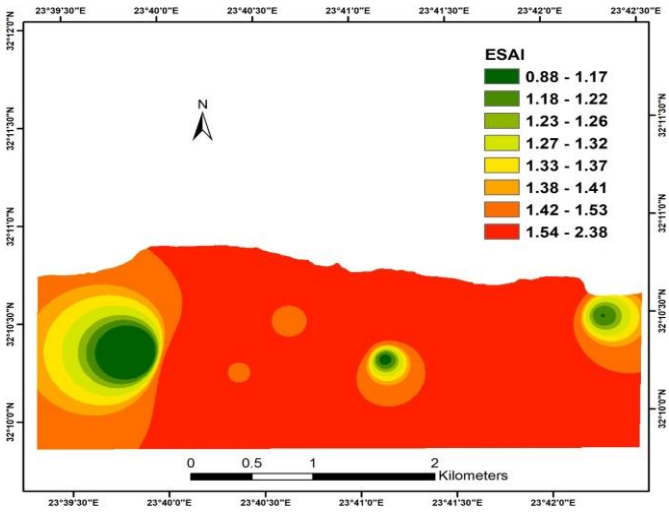


Figure 11: Spatial distribution of environmental sensitivity areas index (ESAI) in the study area

practices contribute to the breakdown of soil aggregates and weaken soil structure, making the soil surface more vulnerable to wind erosion. The limited implementation of soil conservation measures, such as contour cultivation, reduced tillage, and the insufficient presence of windbreaks, further increases the susceptibility of soils to degradation. Similar findings have been reported in dryland studies where unsustainable land management practices significantly increased desertification sensitivity when incorporated into the MEDALUS framework [17,19].

Climatic conditions also play an important complementary role in enhancing erosion processes in areas lacks windbreaks. The study area and its surroundings are influenced by dominant north-easterly to easterly winds, with average speeds ranging between 13–18 km h^{-1} and gusts reaching approximately 21 km h^{-1}. Such wind regimes, particularly under conditions of sparse vegetation cover and loose sandy soils, significantly increase the risk of wind erosion, which is recognized as a major land degradation process in semi-arid environments. Therefore, the observed changes in ESAI classes after including the management factor highlight the combined influence of land management practices and regional climatic drivers, both of which contribute to shaping the spatial patterns of land degradation in the study area.

Conclusions

This study demonstrates the applicability of spatial modelling based on a modified multivariable Environmental Sensitivity Area Index (ESAI) for assessing land sensitivity to desertification in the Umm Qahqih area, eastern Libya. The results indicate that a substantial proportion of the study area falls within the critical sensitivity classes, reflecting the combined influence of soil degradation, climatic stress, vegetation deterioration, irrigation-water quality, and land-management conditions. These findings are consistent with the conceptual basis of the MEDALUS framework developed by [15] and with subsequent applications of ESAI for identifying environmentally sensitive areas in Mediterranean and dryland environments [29,30] . Recent research in northeastern Libya further supports the importance of integrating multiple environmental indicators when evaluating land degradation. For example, [31] reported significant deterioration in several soil-quality indicators following agricultural land-use change in the Al-Jabal Al-Akhdar region, while [32] demonstrated the applicability of NDVI and BSI for detecting desertification patterns in southeast Tobruk. These regional findings reinforce the relevance of a spatially explicit and locally adapted ESAI framework for evaluating environmental sensitivity under the dryland conditions of eastern Libya.

The soil results indicate that the low clay and organic matter contents represent important indicators of declining soil quality in the study area. The predominance of sandy soil materials, together with low organic matter, may contribute to weak soil structure and limited water-retention capacity, thereby increasing susceptibility to erosion and land degradation. The observed salinity and sodicity conditions provide additional evidence of physical and chemical soil deterioration, particularly where irrigation is associated with poor-quality water and inadequate management. This interpretation is consistent with recent Libyan research showing that agricultural land-use change and inappropriate management practices can adversely affect soil-quality indicators. [31] found substantial changes in soil properties under rainfed and irrigated agriculture in Al-Jabal Al-Akhdar, emphasizing the importance of sustainable land-management practices for maintaining soil quality. Similarly, research on irrigation-related salinity in Libya has highlighted the importance of monitoring irrigation-water quality and salinity hazards in agricultural systems [33]. Studies of groundwater quality and soil infiltration in southwestern Libya also emphasize the relevance of evaluating water suitability and infiltration characteristics in agricultural environments [34]. Therefore, the soil and water results obtained in Umm Qahqih should be interpreted as interconnected components of the land-degradation process rather than as independent environmental constraints.

The incorporation of the Management Quality Index (MQI) Figure (11) produced a substantial change in the final ESAI assessment, increasing the proportion of land classified within the critical sensitivity category to approximately 73.7%. This increase demonstrates that management conditions can substantially modify the sensitivity identified from inherent environmental characteristics alone. Importantly, the MQI result has a direct management implication: areas classified as critical after incorporating management pressures should be considered priority zones for intervention because their sensitivity reflects not only climatic and biophysical constraints but also the influence of

land-use practices. Accordingly, management responses should be spatially targeted rather than uniformly applied across the study area. Priority actions should include improving irrigation efficiency and drainage, regularly monitoring soil electrical conductivity and sodicity, applying appropriate soil amendments where required, maintaining or restoring protective vegetation cover, strengthening windbreaks, and implementing soil-conservation measures in erosion-prone locations. The importance of management-based interventions is supported by recent Libyan research showing that inappropriate agricultural practices and insufficient protective vegetation can accelerate soil degradation and erosion [31]. Consequently, the increase to 73.7% should not be interpreted simply as a higher percentage of degraded land; rather, it indicates a larger area requiring management attention and preventive intervention to reduce the likelihood of further degradation.

The spatial distribution of ESAI classes provides a practical basis for prioritizing management interventions rather than applying uniform measures across the entire study area. Critically sensitive units should receive immediate field verification, monitoring, and targeted intervention, whereas fragile and moderately sensitive units should be managed through preventive and conservation-oriented measures. In areas where salinity and poor irrigation-water quality are important constraints, management should emphasize irrigation scheduling, drainage improvement, water-quality monitoring, and the selection of crops or vegetation adapted to saline conditions. In areas affected by erosion or insufficient vegetation protection, priority should be given to maintaining ground cover, establishing appropriate windbreaks, and applying site-specific erosion-control measures. Recent spatial erosion research in Libya has similarly demonstrated the value of GIS-based modelling for identifying areas with different levels of erosion vulnerability and for supporting targeted soil-conservation planning [35]. This spatially differentiated strategy is consistent with the fundamental ESAI concept that environmental sensitivity results from the interaction of multiple environmental and management pressures rather than from a single degradation factor.

Overall, the modified ESAI approach developed in this study provides a useful scientific framework for identifying spatial differences in desertification sensitivity in the Umm Qahqih area. The integration of soil, climate, vegetation, irrigation-water, and management indicators provides a more comprehensive interpretation of land-degradation processes than consideration of individual environmental variables alone. The resulting sensitivity map can serve as a baseline for future monitoring, allowing changes in soil quality, vegetation condition, water quality, and management practices to be evaluated spatially over time. The findings therefore provide a basis for developing targeted desertification-control and sustainable land-management strategies in eastern Libya. The approach may also be transferable to other dryland environments experiencing similar combinations of climatic stress, soil degradation, water-quality constraints, and land-management pressures, provided that the indicator scoring and weighting are adapted to local environmental conditions.

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References

[1] M. Aburas, *Assessment of Soil Erodibility in Relation to Soil Degradation and Land Use in Mediterranean Libya*. Ph.D. dissertation, University of Newcastle upon Tyne, United Kingdom, 2009. https://doi.org/10.13140/RG.2.1.4121.0009

[2] United Nations. "United Nations Convention to Combat Desertification in Those Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa." United Nations, 1994. https://www.unccd.int/sites/default/files/relevant-links/2017-01/UNCCD_Convention_ENG_0.pdf

[3] A. Al-Mousa, and B. Al-Dakhil. "Using Geographic Information Systems (GIS) in Analyzing the Digital Elevation Model (DEM) for Idlib Governorate, Northwest Syria." *Wadi Alshatti University Journal of Pure and Applied Sciences*, pp. 42-52, 2026. https://doi.org/10.63318/waujpas.sp_FISCSDR2026_05

[4] S. Mohammed, et al. "Exploring Promised Sites for Establishing Hydropower Energy Storage (PHES) Stations in Libya by Using the Geographic Information Systems (GIS)." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 3, no. 1, pp. 85-94, 2025. https://doi.org/10.63318/waujpasv3i1_13

[5] E. Najem, and F. Alhadar. "Utilizing Geographic Information Systems to Identify Optimal Locations for Establishing Solar Power Plants in the Sebha Region." *Solar Energy and Sustainable Development Journal*, vol. 14 (FICTS-2024), pp. 36–54, 2025. https://doi.org/10.51646/jsesd.v14iFICTS-2024.442

[6] E. Najem. " Geographical Determinants of Desert Tourism in South-western Libya: A Study in Economic Geography." Fezzan University Scientific Journal, vol. 5, no. 1, pp. 30-55, 2025.

[7] O. Shaltami, et al. "Geological Framework and Exploration Potential of Manganese Mineralization in Libya: A Comparative Study of Nalut–Jabal Nafusa, Wadi Urari and Shati Valley." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 281-286, 2026. https://doi.org/10.63318/waujpasv4i2_32

[8] A. Elesoq, M, Ben Hkoma, and N. Yasser. "Sustainable deployment of Geographic Information Systems (GIS) for primary schools in the Al-Andalus district municipality." *Wadi Alshatti University Journal of Human Sciences*, vol. 2, no. 2, pp. 40-81, 2026. https://doi.org/10.63318/ waujhsv2i2_03

[9] O. Shaltami, et al. "Zionist Entity Settlement Expansion and Agricultural Land Conversion in the West Bank, Palestine (2011–2026): A Multi-Temporal Remote Sensing Analysis."

Wadi Alshatti University Journal of Pure and Applied Sciences, vol. 4, no. 2, pp. 531-536, 2026. https://doi.org/10.63318/waujpasv4i2_60

[10] O. Shaltami, et al. "Spatiotemporal Assessment of Infrastructure Destruction in the Gaza Strip from 2023 to 2026 Using Satellite Imagery and GIS." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 519-526, 2026. https://doi.org/10.63318/ waujpasv4i2_58

[11] H. Algassie, M. Fakroun, M. Miskeen, and I. Gargar. "The Use of GIS and Multi-Criteria Fuzzy Logic to Assess and Identify Flood-Prone Areas in the Greater Ghat Region." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 1, no. 1, pp. 37-47, 2023. https://www.waujpas.com/index.php/journal/article/view/15

[12] O. Shaltami, et al. "Geochemical Approaches to Combating Desertification and Enhancing Sustainable Development in Libya." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 163-169, 2026. https://doi.org/10.63318/waujpasv4i2_19

[13] A. Fadhl, and M. Salih. "The Role of Spatial Technologies in Modeling Changes in Green Spaces in the City of Tobruk: A Study in Applied Geography." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 296-305, 2026. https://doi.org/10.63318/ waujpasv4i2_34

[14] J. Elmbrouk, S. Almuzoghi, S. Mnsur, and A. Ben Gama. "Analysis of Wheat Crop Growth Using Sentinel-2 Satellite Data and NDVI in Al-Dafnia, Misurata, Libya during the 2022-2023 Agricultural Season." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 265-271, 2026. https://doi.org/10.63318/ waujpasv4i2_30

[15] C. Kosmas, A. Ferrara, H. Briassouli, and A. Imeson. "Methodology for mapping environmentally sensitive areas (ESAs) to desertification." in *The MEDALUS Project: Mediterranean Desertification and Land Use Manual on Key Indicators of Desertification and Mapping Environmentally Sensitive Areas to Desertification*, C. Kosmas, M. Kirkby, and N. Geeson, Eds. European Union, 1999, pp. 31–47.

[16] F. Basso, E. Bove, S. Dumontet, A. Ferrara, M. Pisante, G. Quaranta, and M. Taberner. "Evaluating environmental sensitivity at the basin scale through the use of geographic information systems and remotely sensed data: An example covering the Agri basin (southern Italy)." *CATENA*, vol. 40, no. 1, pp. 19–35, 2000. https://doi.org/10.1016/S0341-8162(99)00062-4

[17] S. Bajocco, A. De Angelis, L. Perini, A. Ferrara, and L. Salvati. "The impact of land use/land cover changes on land degradation dynamics: A Mediterranean case study." *Environmental Management*, vol. 49, no. 5, pp. 980–989, 2012. https://doi.org/10.1007/s00267-012-9831-8

[18] T. Caspari, and P. Schad, "World Soil Map according to WRB 2014, derived from the Harmonized World Soil Database." Technical Note, ISRIC – World Soil Information, Wageningen, 2022. https://doi.org/10.17027/isric-wdcssoils-h7aa-qm24

[19] C. Kosmas, O. Kairis, C. Karavitis, C. Ritsema, L. Salvati, S. Acikalin, M. Alcala, P. Alfama, J. Atlhopheng, J. Barrera, A. Belgacem, et al., "Evaluation and Selection of Indicators for Land Degradation and Desertification Monitoring: Methodological Approach," *Environmental Management*, vol. 54, no. 5, pp. 951–970, 2014. https://doi.org/10.1007/s00267-013-0109-6

[20] C. Valentin. "Surface crusts of semi-arid sandy soils: Types, functions and management." in *Management of Tropical Sandy Soils for Sustainable Agriculture*, Food and Agriculture Organization of the United Nations (FAO), 2005.

[21] M. Aburas. "Final infiltration rate as an indicator for soil erodibility prediction." *Al-Mukhtar Journal of Sciences*, vol. 27, no. 1, pp. 136–148, 2012. https://doi.org/10.54172/mjsc.v27i1.264

[22] F. Boix-Fayos, A. Calvo-Cases, A. Imeson, and M. Soto. "Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators." *CATENA*, vol. 44, no. 1, pp. 47–67, 2001. https://doi.org/10.1016/S0341-8162(00)00176-4

[23] R. Lal. "Restoring Soil Quality to Mitigate Soil Degradation." *Sustainability*, vol. 7, no. 5, pp. 5875–5895, 2015. https://doi.org/10.3390/su7055875

[24] R. Lal. "Managing Soil Quality for Humanity and the Planet." *Frontiers of Agricultural Science and Engineering*, vol. 7, no. 3, pp. 251–253, 2020. https://doi.org/10.15302/J-FASE-2020329

[25] Y. Ma, B. Minasny, A. B. McBratney, L. Poggio, and M. Fajardo. "Predicting Soil Properties in 3D: Should Depth Be a Covariate?" *Geoderma*, vol. 383, article 114794, 2021. https://doi.org/10.1016/j.geoderma.2020.114794

[26] B. Zhang, F. Zeng, X. Gao, M. Shareef, Z. Zhang, Q. Yu, Y. Gao, C. Li, H. Yin, Y. Lu, C. Huang, and G. Tang. "Groundwater Depth Alters Soil Nutrient Concentrations in Different Environments in an Arid Desert." *Frontiers in Environmental Science*, vol. 10, article 939382, 2022. https://doi.org/10.3389/fenvs.2022.939382

[27] H. Zhang, Z. Cai, J. Chen, Y. Xu, and F. Zhang. "Sustainable Research of Land Optimization in a Semiarid Sandy Area Based on Soil Moisture Characteristics." *Frontiers in Environmental Science*, vol. 10, article 921345, 2022. https://doi.org/10.3389/fenvs.2022.921345

[28] N. Wang, and T. Zhang. "Soil pore structure and its research methods: A review." *Soil and Water Research*, vol. 19, no. 1, pp. 1–24, 2024. https://doi.org/10.17221/64/2023-SWR

[29] M. Aburas, M. Yousef, and A. Alferjani. "Land degradation at the southern slopes of Al-Jabal al Akhdar, Libya." *Al-Mukhtar Journal of Sciences*, vol. 30, no. 1, pp. 67–79, 2015. https://doi.org/10.54172/mjsc.v30i1.131

[30] M. Aburas, and M. Yousef. "Applying Experimental Mathematical Models to Monitor Soil Erosion and Degradation in Al-Jabal Alkhdar, Libya." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 571-580, 2026. https://doi.org/10.63318/waujpasv4i2_65

[31] J. Alawamy, S. Balasundram, A. Hanif, and C. Sung. "Response of potential indicators of soil quality to land-use and land-cover change under a Mediterranean climate in the region of Al-Jabal Al-Akhdar, Libya." *Sustainability*, vol. 14, no. 1, Article 162, 2022. https://doi.org/10.3390/su14010162

[32] Y. Abdalrahman, and S. Ajiabali. "Desertification rate evaluation using NDVI and BSI indicators in southeast Tobruk, Libya." *Silphium Journal of Science and Technology*, vol. 1, no. 3, 2024. https://j.istc.edu.ly/index.php/sjst/article/view/27

[33] K. Iessa. "Salinity of the agricultural soils in some farms due to the long-term sprinkling irrigation, ALDABWAT agricultural project." *JATAED: Journal of Appropriate Technology for Agriculture, Environment, and Development*, vol. 1, no. 2, pp. 1–9, 2024. https://doi.org/10.62671/jataed.v1i2.22

[34] A. Shaki. "Basic infiltration rate at some farms in Wadi–Al-Hayat area–Southwest Libya." *Libyan Journal of Ecological & Environmental Sciences and Technology*, vol. 4, no. 1, pp. A47–A50, 2022. https://doi.org/10.63359/0qjds806

[35] S. Abdsmod, and F. Abushnaf. "Using the Geographical Information System for Soil Erosion Assessment of the South Tarhuna Area." *The Libyan Journal of Agriculture*, vol. 29, no. 2, pp. 47–57, 2024. https://journals.uot.edu.ly/index.php/ljagric/article/view/1577