

Integrating GIS and the MEDALUS Model for Soil Erosion Risk Assessment in Arid Mediterranean Landscapes: A Case Study from the Soubella Sub-Catchment, Hodna, Algeria

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Abstract Soil erosion represents a major environmental challenge, particularly in arid and semi-arid regions where natural factors and human activities intensify land degradation. This study evaluates the Soubella sub-catchment's susceptibility to water erosion using the MEDALUS (Mediterranean Desertification and Land Use) model. The assessment is based on four key quality indices Soil Quality Index (SQI), Climate Quality Index (CQI), Vegetation Quality Index (VQI), and Anthropogenic Quality Index (AQI) derived from remote sensing, GIS analysis, and field observations. Spanning 1837.33 km², the study region features diverse topography, with elevations ranging from 376 to 1871 meters and an average slope of 19.02 m/km, indicating moderate terrain. The climate is semi-arid, characterized by high temperatures, limited rainfall, and pronounced spatial and temporal variability. Average annual precipitation at the Soubella dam site is estimated at 289 mm. The findings reveal a distinct spatial classification into three erosion sensitivity levels: non-affected (27.5%), sensitive (16.1%), and highly sensitive (56.4%). The resulting erosion sensitivity map highlights the spatial distribution of vulnerable areas, demonstrating the significant roles of climate, topography, and land use in soil degradation. These insights are crucial for developing targeted and sustainable land management strategies to mitigate erosion risks in the region.

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1. Introduction

Soil erosion is one of the most critical environmental concerns globally, with around 65% of the world's soils affected by degradation processes such as erosion and desertification (Fadl et al., 2022). This degradation is increasingly intensified by climate change and unsustainable agricultural practices (Achim et Ouillon, 2016; Seghiri et al., 2022; Bensefia et al., 2024).

These phenomena vary in form and intensity depending on regional and local conditions. Their main impacts include vegetation decline, soil depletion, desert expansion, reduced crop yields, and loss of agricultural tree cover (Madani et al., 2023). Although developed countries are also affected, soil erosion poses a greater threat to developing nations. In Africa, around 12.5 million hectares are vulnerable to wind and water erosion (Pushpam & Vuola, 2015).

In Algeria, especially in mountainous areas, increasing erosion is severely degrading living conditions and leading to major environmental impacts (Meddi et al., 2005). Erosion causes an annual loss of about 20 million cubic meters of dam storage due to siltation (Remini, 2000). It gradually depletes soil fertility and biodiversity, thereby reducing agricultural productivity, which is essential for local livelihoods (Dakiche

et al., 2016). Additionally, it increases flood risks, threatening communities and infrastructure (Roose et al., 2010). Over the years, several methods have been developed to assess water erosion, including the Universal Soil Loss Equation (USLE) (Cherif, 2008), its modified version by Foster et al. (1987), the Water Erosion Prediction Project (Tra Bi, 2013), and the MEDALUS model (Plaiklang et al., 2020).

The Algerian steppe, particularly the southern Hodna region, is facing severe ecological and climatic disruption, marked by advancing sand encroachment and intensified by erosion and desertification (Liazid, 2013; Abdesselam & Halitim, 2014). This widespread degradation threatens vital natural areas essential for local livelihoods and microclimate regulation (Seghiri et al., 2022; Ouzir, 2023). To evaluate soil erosion intensity, several methods have been applied, notably the MEDALUS model, widely used in Algeria (Plaiklang et al., 2020).

This study focuses on identifying the main factors driving soil degradation in the endorheic Hodna basin, considering both natural (arid climate, irregular rainfall) and human-induced (overgrazing, deforestation, fires) pressures. Using the MEDALUS model and GIS tools, it aims to produce an erosion sensitivity map. The approach includes describing the region's

physical context, presenting the methodology, and analyzing the results. The findings will offer a valuable tool for assessing land degradation in the Hodna basin.

2. Methods

Study area

The Soubella sub-catchment (code 05-11) is a subdivision of the Hodna Basin (code 05, NAHR), covering an area of 1837.33 km². Situated to the north of the Magra municipality, it lies roughly 340 km to the southeast of Algiers and approximately 60 km east of M'Sila wilaya. The sub-catchment falls within the geographic coordinates 35°51'32"–35°23'52" N and 4°48'9"–5°31'18" E (Figure 1), and extends from the southern flanks of the Hodna Mountains in the north to the northern edge of Chott El Hodna in the south, and borders the Bou Taleb Massif to the center-west.

Elevation in the area ranges between 376 and 1871 meters, with an average slope of 19.02 m/km, indicating a moderately

rugged landscape, as presented in Table 1. The region experiences a semi-arid climate, with mean temperatures ranging from 14.2 to 17.6 °C (Hasbaia et al., 2017) and average annual precipitation of approximately 289 mm (NAHR, 2020). Rainfall distribution follows a bimodal pattern, characterized by dry summers and peak precipitation occurring during autumn and winter (Seddiki et Khemissa, 2021).

Data and materials used

To build the database and produce the thematic layers needed for the MEDALUS model, a range of erosion-related variables were gathered from existing sources and incorporated into a GIS environment. These data were then used to compute several key indices, namely the Soil Quality Index (SQI), Climate Quality Index (CQI), Vegetation Quality Index (VQI), Anthropogenic Quality Index (AQI), and the overall Erosion Sensitivity Index (ESI), as summarized in Table 02 and illustrated in Figure 2.

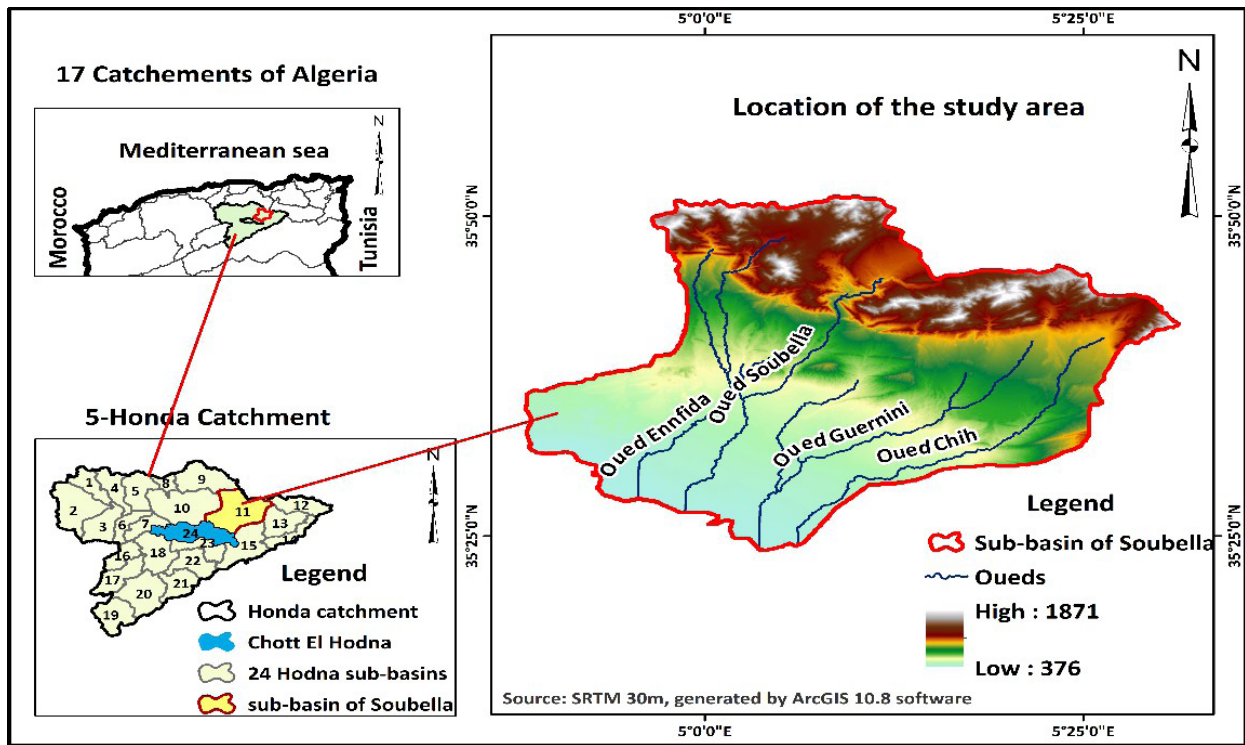


Figure 1. Geographical Location and Elevation Profile of the Soubella Sub-Catchment (Khodour et al., 2025)

Table 1. Hydro_Morphological characteristics of the Soubella sub-basin.

Features	Value
Sub-basin area (A)	1837,33 Km ²
Perimeter (P)	231,275 Km
Sub-basin length (L)	96,62 Km
Sub-basin width (I)	19,02 Km
Factor of Form (K)	1,51/
Maximum altitude (Hmax)	1871 m
Minimum altitude (Hmin)	376 m
Medium slope (Im)	19,02 m/Km
Length of main river (Lp)	53.61 Km
Drainage density (Dd)	0,15 Km/Km ²

MEDALUS Model to Analyze Erosion Risk

This study employs the MEDALUS model to evaluate erosion sensitivity by computing the geometric mean of several key quality indices related to soil, climate, vegetation, and land use (Plaiklang *et al.*, 2020). These factors, identified by Fadl *et al.*, 2022, are recognized as major drivers of soil degradation. The indices applied in this model were derived from a multi-source dataset (Figure 2).

Each of the four factors was evaluated using a specific quality index, with scores ranging from 1 (representing low sensitivity) to 2 (representing high sensitivity). These scores were subsequently classified into five levels of desertification sensitivity: very low, low, moderate, high, and very high (Table 03). The 1–2 scoring scale applied to the different parameters follows the MEDALUS methodology used for mapping Environmentally Sensitive Areas (ESAs) to desertification (Kosmas *et al.*, 1999).

In Algeria, soils are increasingly affected by degradation in both quality and extent, which threatens agroecological sustainability (Morsli *et al.*, 2013). Soil erosion sensitivity was evaluated based on four key factors: lithology, soil texture, slope, and drainage conditions. These variables were derived from digitized thematic maps and Digital Elevation Models (DEMs) and subsequently integrated into a Soil Quality Index (SQI) to identify areas most vulnerable to degradation. Lithological and soil texture information were obtained from existing geological and pedological maps, which were digitized and converted into raster layers within the GIS environment. Topographic parameters, particularly slope, were extracted from the DEM using terrain analysis tools, while drainage conditions were derived from the hydrographic network generated from the same elevation model. Each variable was then reclassified and assigned a ranking value reflecting its relative contribution to soil degradation processes. The

Table 2. Materials used

						Programs
Image satellite	Satellite	Sensor	UTM Zone	Acquisition Date	Cloud Coverage	Envi
	LANDSAT_9	OLI_TIRS	31	10-05-2024	0.02	5.4
DEM	Digital Model Elevation (DEM) of the Soubella sub-basin (SRTM).					
Cartographic data	Title			Scale	Support	ArcGIS
	➤ Map hydro-climatological and water quality monitoring network [ANRH., 2005]			1/500000	Scan	10.8
	➤ Surface geological map of Africa (geo7_2ag), published on June 21, 2021 [Publication Date 2021-06-21]			1/5000000	Download	Global Mapper
Further data	➤ Monography of the M’Sila and Setif provinces [DPSB. 2020]. ➤ Statistical data from the M’Sila and Setif provinces [DSA. 2020]. ➤ Climatic data for the province of M’sila [ANRH. 2020].					15.1

Image satellite : ID :LC09_L1TP_195035_20240510_20240510_02_ T1. Satellite data extracted from the USGS (United States Geological Survey) website.

DPSB–Directorate of Programming and Budget Monitoring-Msila.: 2020.

DSA: Department of Agricultural Services.: 2020.

ANRH: National Agency of Hydraulic Resources (NAHR. 2020)

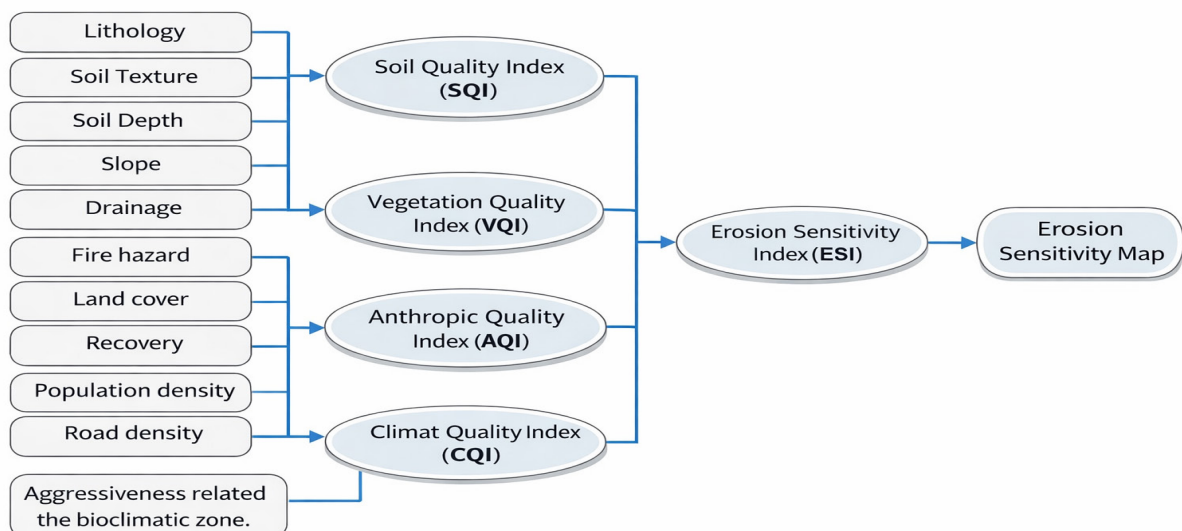


Figure 2. Schematic Illustration of the ESI Index Computation Process

Table 3. Classification of Parameters and Index Values for SQI, CQI, AQI, and VQI

Index	Erosion Factor	Class	Features	Description	Score
SQI	Lithology	1	Blue marls, sandstone arls,sandstones, limestones, diatomites, gypsummarls, carbonates marl-limestone	Good	1
		2	Sandy clays, carbonates, and sandstones. sandy marls, alluvium marls, limestones, and clays	Moderate	1,7
		3	Clayey-carbonate, clayey-sandstone	Poor	2
	Texture	1	L,CL	Good	1
		1	C	Moderate	1.6
	Slope	2	< 6	Very gentle	1
		3	6 – 12	Soft	1.2
		4	12 – 25	Steep	1.5
			>25	Very steep	2
	Drainage	1	Well drained	Good	1
		2	Medium-drained	Moderate	1.4
		3	Imperfectly drained	Poor	2
	Depth			Deep	1
		1	< 75	Moderate	2
		2	30 – 75	Shallow	3
		3	15 – 30	Very shallow	4
CQI	Bioclimatic Zones	1	Q > 40	Upper Arid	1
		2	Q < 40	Lower Arid	2
AQI	Population density	1	<15 people / km ²	Good	1
		2	15-20 people / km ²	Moderate	1.33
		3	20-50 people / km ²	Poor	1.66
		4	>50 people / km ²	Very poor	2
AQI	Road density	1	<3Km/km ²	Good	1
		2	3-7Km/km ²	Moderate	1.66
		3	>7Km/km ²	Poor	2
AQI	Fire hazard	1	Baresoil,steppe	Low	1
		2	Crop,shrubsteppe	Medium	1.3
		3	Scrub-forest	High	2
AQI	Erosion protection	1	Scrub-forest	High	1
		2	Shrubsteppe	Medium	1.3
		3	Steppe	Low	1.6
		4	Baresoil,cultivation	Very low	2
VQI	Drought resistance	1	Bare soil	High	1
		2	Steppe	Medium	1.4
		3	Shrub steppe	Low	1.7
		4	Forest and scrub, cultivation	Very low	2
VQI	Recovery	1	> 40 %	High	1
		2	10-40 %	Medium	1.8
		3	<10 %	Low	2

Explanations:L=Loam,CL= ClayLoam,C= Clay. Source: Personal work inspired by studies from KOSMAS et al.,1999 and BASSO et al., 2012.; Khoudour et al., 2025.

standardized layers were subsequently combined using a spatial overlay procedure in ArcGIS to compute the Soil Quality Index (SQI), which provides a spatial representation of soil susceptibility to erosion and degradation across the study area.

$$SQI = (Lithology * Texture * Solpe * Drainage * Depth)^{1/5} \quad (1)$$

Erosion poses an increasing threat to Algeria’s arid and semi-arid ecosystems, where the progressive and often irreversible loss of vegetation cover highlights the urgent need for strengthened conservation strategies (Cheramat et al., 2013).

Vegetation status was evaluated using indicators including fire risk, erosion protection capacity, drought resistance, and recovery potential (Equation 2), derived from processed Landsat 9 satellite imagery. Image processing involved area

extraction and atmospheric correction to improve data reliability. After preprocessing, spectral indices were calculated from the satellite bands to characterize vegetation conditions across the study area. In particular, the Normalized Difference Vegetation Index was used to assess vegetation density and vigor, allowing differentiation between dense vegetation, sparse vegetation, and bare soil.

A land cover map was generated by visual classification of remote sensing indices, particularly NDVI, enhancing image interpretation and facilitating the extraction of key information. Based on the classified land cover and vegetation density levels, each area was assigned ranking values corresponding to the different vegetation indicators (fire risk, erosion protection capacity, drought resistance, and vegetation recovery potential). These indicators were then combined according to Equation (2) to compute the Vegetation Quality Index (VQI) for each spatial unit within the basin.

These data enabled the calculation of the Vegetation Quality Index (VQI), providing an effective representation of vegetation vulnerability to erosion. The resulting VQI layer was subsequently classified into three vegetation quality classes using the Jenks Natural Breaks Classification method in the GIS environment, allowing the identification of areas with high, moderate, and low vegetation quality. This integrated approach supports informed decision-making for the conservation and sustainable management of fragile ecosystems.

$$VQI = (\text{Fire risk} * \text{Erosion protection} * \text{Drought resistance} * \text{Recovery})^{1/4} \quad (2)$$

Algeria's Mediterranean climate, influenced by maritime conditions, topography, and altitude, is characterized by intense and irregular rainfall (Achite et al., 2006). Climatic vulnerability was assessed using annual precipitation and the aridity index (Equation 3), with data obtained from the National Agency for Hydraulic Resources (NARH) and climate platforms such as Infoclimat (<https://www.infoclimat.fr/>).

Meteorological data from available stations were compiled and spatially interpolated in the GIS environment to generate continuous climatic surfaces representing the spatial distribution of precipitation across the study area. The aridity index was calculated by combining precipitation and temperature-related parameters to evaluate the degree of climatic dryness and water availability.

These indicators were used to compute the Climate Quality Index (CQI), which reflects the region's sensitivity to erosion. Each climatic parameter was standardized and assigned a ranking value according to its influence on erosion processes. The ranked layers were then integrated using spatial analysis tools in ArcGIS to generate the Climate Quality Index (CQI) map, which highlights areas where climatic conditions increase susceptibility to land degradation and soil erosion.

$$CQI = \text{Bioclimatic zones} \quad (3)$$

Human activities play a significant role in intensifying erosion processes, highlighting their increasing contribution to soil degradation (Harkat et al., 2011). This impact was assessed using indicators such as population density, livestock density, and land use (Equation 4), with data obtained from institutions including DAS (Direction of Agriculture Service)

and DPBM (Direction of Population and Buildings of M'sila). The collected statistical data were spatially processed and converted into thematic layers within the GIS environment. Population and livestock data were normalized to obtain density values, while land use information was derived from the classification of satellite imagery and existing land cover maps.

These parameters were used to calculate the Anthropogenic Quality Index (AQI), which quantifies the extent of human influence on land degradation. Each indicator was reclassified and assigned a ranking value according to its potential impact on soil degradation. The standardized layers were subsequently combined using spatial overlay analysis in ArcGIS to generate the Anthropogenic Quality Index (AQI) map. The resulting values were then classified into three anthropogenic quality classes representing different levels of human pressure on the environment.

$$AQI = (\text{Population density} * \text{Road density})^{1/2} \quad (4)$$

The Erosion Sensitivity Index (ESI) was calculated by combining the Soil, Vegetation, Climate, and Anthropogenic Quality Indices, as expressed in formula (5).

$$ESI = (\text{SQI} * \text{VQI} * \text{CQI} * \text{AQI})^{1/4} \quad (5)$$

Each of the component indices (SQI, VQI, CQI, and AQI) was standardized and weighted according to its relative contribution to erosion processes before integration. The combined raster layer represents the overall susceptibility of each spatial unit within the Soubella sub-basin to soil degradation and erosion.

The results were mapped using ArcGIS 10.8, enabling the spatial visualization of vulnerable areas and the identification of high-risk zones within the Soubella sub-basin. To facilitate interpretation and support decision-making, the ESI values were classified into three categories representing low, moderate, and high erosion sensitivity. This classification was performed using the Natural Breaks (Jenks) classification method, which identifies optimal thresholds by minimizing variance within classes and maximizing variance between classes.

This method allows the classification to reflect the natural distribution of the data rather than applying arbitrary thresholds. After classification, the spatial extent of each sensitivity class was calculated as a percentage of the total study area, producing quantitative results suitable for comparison and reporting (e.g., Table 8). The use of the Natural Breaks (Jenks) classification is widely adopted in spatial environmental analyses because it provides a more realistic representation of spatial variability compared to simple equal-interval classifications.

3. Results and Discussion Soil Quality Index (SQI)

The distribution of soils according to their quality in the Soubella sub-basin is presented in Table 04, revealing clear spatial variability. A large proportion of the area (62.6%) consists of high-quality soils, indicating a good state of conservation and satisfactory fertility. In contrast, 28.9% of the territory is affected by significant degradation, characterized by low organic matter content, severe erosion, and physico-chemical deterioration. The intermediate class, representing

8.5% of the area, corresponds to soils in a transitional state and therefore requires restoration measures to prevent further degradation. Figure 3 illustrates the spatial distribution of soil quality within this catchment.

Climatic Quality Index (CQI)

The distribution of climatic quality in the Soubella sub-basin is presented in Table 05, based on an index that integrates aridity and rainfall variability. The majority of the area (78.13%), mainly located in low-altitude zones, experiences unfavorable climatic conditions that increase the risk of erosion. Only 4.67% of the high-altitude areas benefit from favorable climatic conditions, while 17.20% of the mid-altitude zones exhibit moderate vulnerability. These results highlight a strong relationship between elevation and climatic degradation, as illustrated in Figure 04.

Anthropogenic Quality Index (AQI)

The distribution of anthropogenic quality classes is presented in Table 06, assessing the impact of human activities on land degradation. The majority of the area (58.9%) is subjected to strong human pressure, while 27.9% benefits from relatively more sustainable land-use practices. The remaining 13.2% exhibits a moderate level of human impact. These results highlight the importance of implementing integrated land

management strategies to mitigate degradation, as illustrated in Figure 5.

Vegetation Quality Index (VQI)

Table 07 categorizes vegetation quality based on factors such as plant cover, fire risk, erosion protection, and drought resistance. The analysis reveals that 48.5% of the land has low-quality vegetation, primarily in low-lying areas affected by aridity, limited rainfall, and degradation from desertification, overuse, and drought. In contrast, 26.2% of the territory exhibits high-quality vegetation, mainly in higher-altitude areas with more favorable climatic conditions. The remaining 25.3% falls into the moderate category, reflecting partial degradation. These findings emphasize the urgent need for vegetation restoration in vulnerable lowland zones to improve resilience against erosion and climate change (Figure 6).

Map of Erosion Sensitivity Index (ESI)

The ESI cartographic analysis identified three erosion sensitivity zones—non-affected, sensitive, and highly sensitive—closely associated with environmental conditions and human activities (Table 8 & Figure 7). These results, in line with M’hamdia et al. (2016), highlight the decline of vegetation driven by both climatic and anthropogenic pressures.

Table 4. Distribution of the three Soil Quality Classes

Class	Description	Rank	Area(%)
1	High quality	≤1,13	62.6
2	Moderate quality	1,13-1,45	8.5
3	Low quality	≥1,46	28.9

Source: Personal analysis in Arc gis software

Table 05. Distribution of the three Climate Quality Classes

Class	Description	Rank	Area(%)
1	Highquality	≤1,22	27.9
2	Moderatequality	1,23-1,44	13.2
3	Low quality	≥1,44	58.9

Source: Personal analysis in Arc gis software.

Table 6. Distribution of the three Anthropogenic Quality Classes

Class	Description	Rank	Area(%)
1	High quality	≤1,22	27.9
2	Moderate quality	1,23-1,44	13.2
3	Low quality	≥1,44	58.9

Source: Personal analysis in Arc GIS software

Table 7. Distribution of the three Vegetation Quality Classes

Class	Description	Rank	Area(%)
1	Highquality	≤1,23	26.2
2	Moderatequal	1,23-1,44	25.3
3	Low quality	≥1,44	48.5

Source: Personal analysis in Arc gis software.

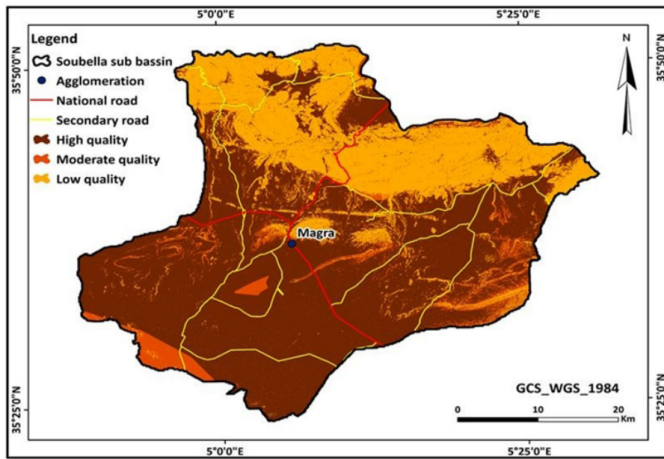


Figure 03. Distribution of soil Quality

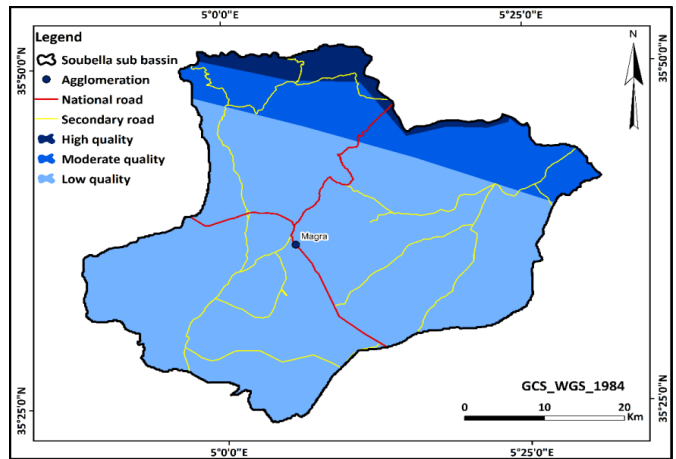


Figure 04. Distribution of climate Quality

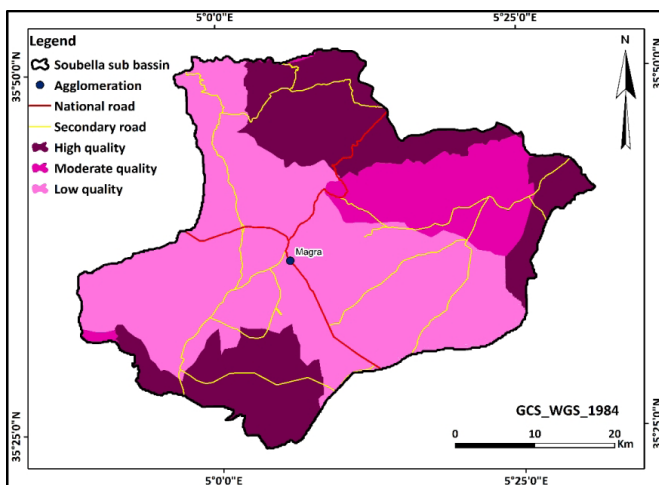


Figure 05. Distribution of Anthropogenic Quality

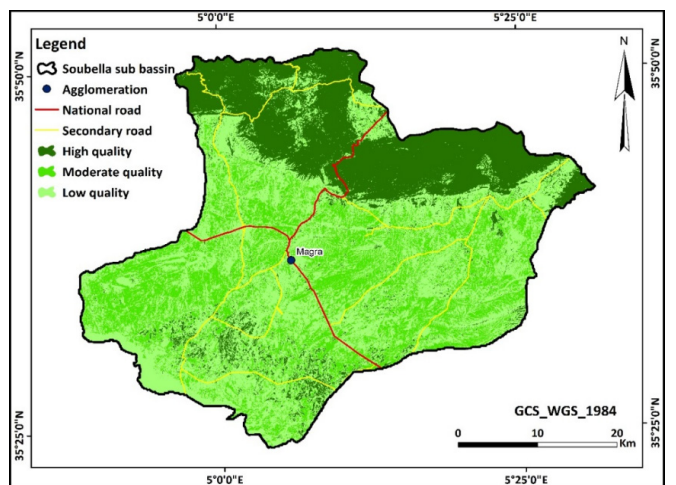


Figure 06. Distribution of Vegetation Quality

Source: The maps were generated by the authors using multiple data sources listed in Table 2. (original)

Table 8. Erosion sensitivity classification according to the ESI.

Class	Description	Rank	Area(%)
1	Non-affected	≤1,37	27.5
2	Sensitive	1,38-1,53	16.1
3	Very sensitive	≥1,53	56.4

Source: Personal analysis in ArcGIS software.

Highly sensitive zones cover 56.4% of the area and are characterized by aridity, irregular rainfall, and high climatic variability, which weaken ecosystem resilience. Poor vegetation affects 48.5% of the land, reducing erosion protection and soil regeneration. Human activities—including overgrazing, deforestation, and urbanization—impact 58.9% of the territory. Although 62.6% of the soils are of high quality, 28.9% remain degraded (Fredj *et al.*, 2024; Figures 7 & 8).

Sensitive zones cover 16.1% of the area and exhibit moderate degradation. Located mostly at intermediate altitudes, they experience milder climatic conditions (17.2%) and moderate human pressure (13.2%) compared to highly sensitive zones. Vegetation is slightly degraded but still provides some erosion control. These observations, consistent with Djoukbal *et al.* (2024), highlight noticeable erosion and regional disparities,

underscoring the need for targeted mitigation and sustainable management to reduce desertification risk (Figure 8).

About 27.5% of the land is classified as non-affected or insensitive to desertification. Primarily at higher altitudes, these areas benefit from favorable climate and dense, resilient vegetation, offering strong erosion resistance. This aligns with Boudjemline and Semar (2018), who reported lower degradation in mountainous regions of the Hodna area, while lowlands and high steppe plateaus are more vulnerable due to rainfall variability, altitude, and human or livestock pressure. Similarly, Djamil *et al.* (2023) emphasized that erosion threatens vulnerable zones, causing vegetation loss, soil degradation, reduced agricultural productivity, and deforestation—effects most pronounced in the highly sensitive areas identified in this study.

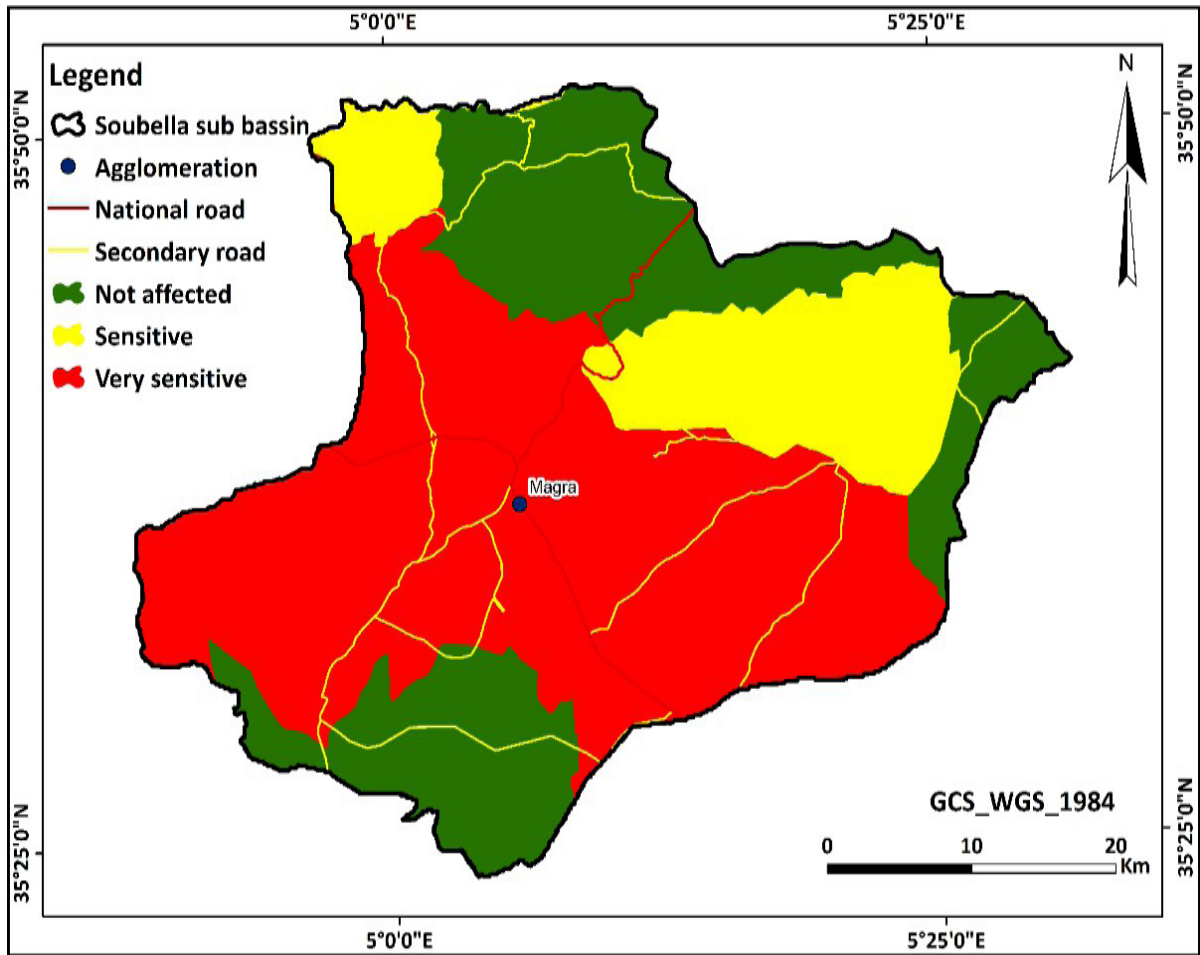


Figure 07. Erosion Sensitivity map of the Soubella Sub-catchment, Hodna

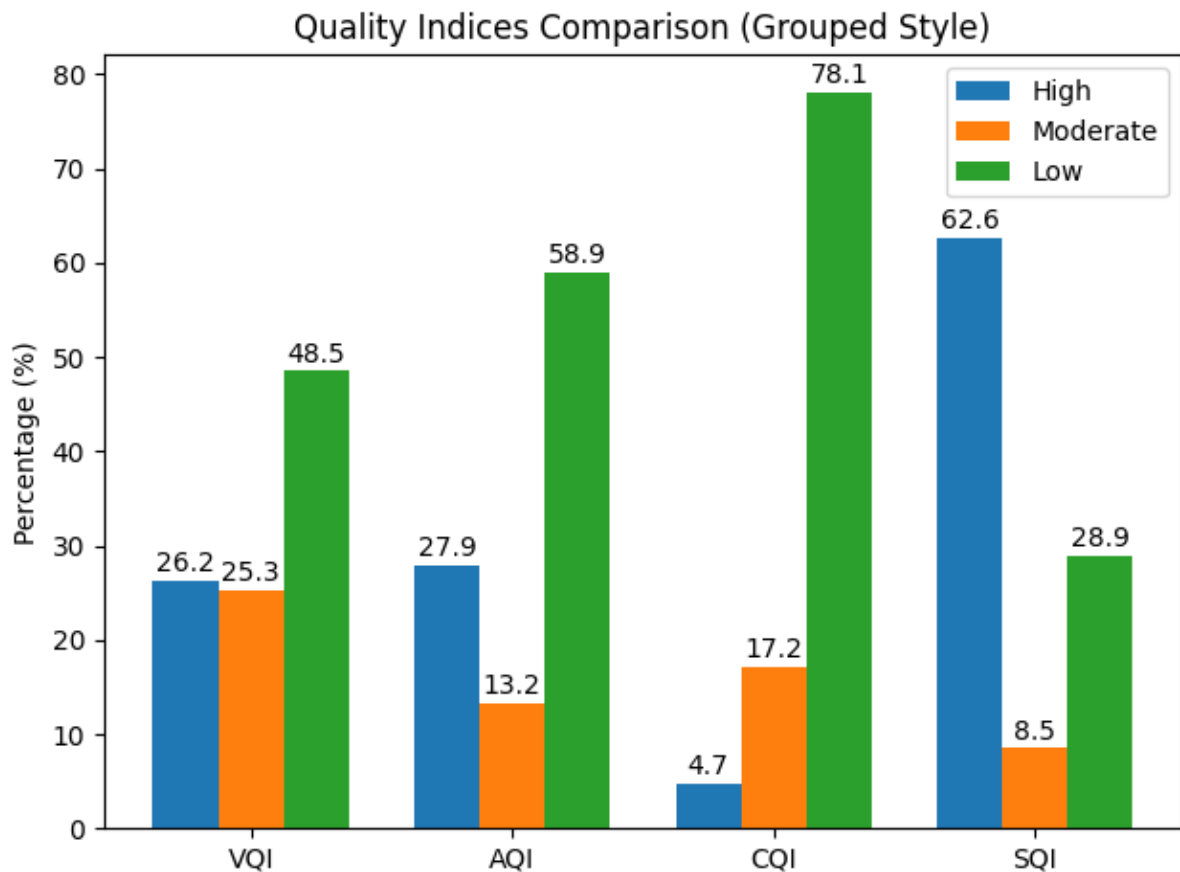


Figure 8. Demonstrates the influence of individual quality indicators on erosion vulnerability. (Personal analysis in Arc GIS software).

So, the distribution of various indices was crucial in determining erosion sensitivity levels. Highly sensitive zones, marked by adverse conditions, are the most at risk, whereas non-sensitive areas, with more favorable environments, show greater resilience to erosion.

4. Conclusion

The present paper evaluated erosion sensitivity in the Soubella sub-basin (Algeria) using an integrated approach that combines the MEDALUS model with geomatics tools. The findings reveal a varied spatial distribution of vulnerability, shaped by climatic, ecological, and human factors. The most erosion-prone areas—representing the majority—are marked by harsh climatic conditions, degraded vegetation, and intense human activity. In contrast, less affected zones, mainly at higher altitudes, benefit from dense vegetation and more consistent rainfall, increasing their resilience. The study highlights the critical interplay between climate, ecological conditions, and human pressure in driving erosion. It underscores the need for targeted management strategies, especially in vulnerable areas. By offering a scientific foundation, this work supports the development of conservation and ecosystem restoration policies in arid and semi-arid regions, promoting sustainable land management tailored to local conditions to mitigate erosion impacts on communities and natural resources. The erosion sensitivity map produced in this study serves as a vital tool for identifying and prioritizing areas requiring intervention. Highly sensitive regions should be targeted with conservation efforts such as reforestation, sustainable agricultural practices, and improved land management. Areas with moderate soil quality, which make up a substantial part of the study area, require preventative measures to preserve soil health and prevent further degradation. So, that GIS-based approach, integrated with the MEDALUS model, offers valuable guidance for informed land management, supporting strategies to combat soil erosion, enhance productivity, and mitigate land degradation.

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