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Use of GIS for mapping sensitivity to erosion using the MEDALUS approach: Application in the Boussaada sub- watershed, Algeria.

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ABSTRACT

The sub-watershed of the Oued Bousaâda, covering an area of 2938.36 km², is part of the Hodna watershed, located southwest of Hodna in the high plateaus, and it is characterized by a semi-arid climate and the precipitation is highly irregular. These rains are associated with high variability. Soil erosion poses a serious environmental, agricultural, and social problem that affects and threatens this region. It is necessary to identify the most erosion-sensitive areas in this sub-watershed in order to determine priorities for mitigation actions. The objective of this study is to assess soil vulnerability to water erosion, develop a set of thematic maps (Vegetation Quality Map, Soil Quality Map, etc.), and create a database (DB) using an approach based on the MEDALUS (Mediterranean Desertification and Land Use) model and Geographic Information System (GIS). This mapping model is a tool intended to assist decision-makers in better managing water and soil resources, taking into account the expectations and needs of the rural population. By combining remote sensing with the analysis of factors known to affect the erosion process, such as climate, vegetation, soil, and demographics, a erosion sensitivity map has been created. The erosion risk mapping revealed that more than 75 % of the studied area showed high vulnerability to erosion. This map will be an essential tool for the socio-economic infrastructures of the region.

1. INTRODUCTION

Soil erosion remains the biggest environmental problem in the world; 65% of the planet's soils are facing degradation phenomena, including erosion and desertification [1]. Soil degradation and desertification, including soil erosion, are worsening due to climate change and poor management of agricultural exports [2], [3]. It en compasses a range of phenomena that differ based on regions and local conditions, and their impact can vary. Among these phenomena are vegetation degradation, the expansion of sandy areas, soil impoverishment, the reduction of agricultural crops, and the deforestation of agricultural species [4]. Erosion threatens not only developed countries but even more so developing countries. In Africa, 12.5 million hectares of soil are threatened by water and wind erosion [5]. In Algeria, in the mountainous regions, the constantly increasing erosion leads to a deterioration in the living conditions of the local inhabitants and has disastrous consequences [6]. Annual water losses in dams are estimated to be around 20 millions cubic meters due to siltation [7]. In the long term, this leads to a loss of fertility and a decline in soil biodiversity, while soil is an essential element of agricultural production, which in turn is crucial for the livelihood development of the majority of people who depend on this natural resource [8]. In addition to the socio-economic damage and the floods that threaten populations and infrastructure [9]. Over the past few decades, a variety of methods and approaches have been implemented to examine water erosion [10- 12]. Arid and steppe regions cover more than 600,000 km² north of the Sahara, with approximately 34% in Algeria [13]. Recently, the Algerian steppe has experienced an ecological and climatic imbalance, marked by a pronounced degradation of its fragile environment [14].The climatic variability represents a constant stress for the ecosystems. This pressure intensifies as one moves further south [15]. In recent years, the southern Hodna has undergone a rapid transformation of its landscape due to sand encroachment, a result of major external factors such as erosion and desertification. This situation presents a significant challenge for the region's inhabitants. This situation presents a significant challenge for the region's inhabitants [16]. This degradation is not isolated; consequently, the natural spaces of the region suffer from deterioration and poor conditions, despite their vital importance in human life [3] and their ability to create a microclimate [17]. To estimate the significance of erosion, several methods have been developed, among which the most commonly used in Algeria is the Universal Soil Loss Equation (USLE) (Universal Soil Loss Equation de Wishmeier et Smith 1978), the modified version related of [19] cited by [18], the project for predicting water erosion [19] and the MEDALUS approach (Mediterranean Desertification and Land Use).

The aim of this study is to analyze the various factors, both natural (such as the arid climate with sporadic and stormy precipitation) and anthropogenic (such as overgrazing, deforestation, and forest fires), that contribute to soil degradation in the endorheic basin of Hodna, and by extension, to the weakening of the green belt. The specific objective was to design an erosion sensitivity map using the MEDALUS method and GIS. We will start by describing the physical characteristics of the study area, and then review the methods used. Finally, we will interpret the results and integrate them into the analysis of this phenomenon. This study provides an erosion sensitivity map that greatly facilitates the assessment of degradation status in this basin.

2. MATERIAL AND METHODS

2.1 Study area

It is located in the southwestern part of the Hodna watershed, with an area of 2938.36 km². The Boussaâda

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sub-basin is composed of three sub-basins: Maiter downstream, Boussaada, and Maiter upstream, with areas of 1263.05 km², 1018.81 km², and 1263.05 km², respectively (Fig.1). The sub-basin is located at 35°27'2.4013" North and 34°47'21.0125" South, as well as at 3°35'56.3117" West and 4°31'7.7631" East.

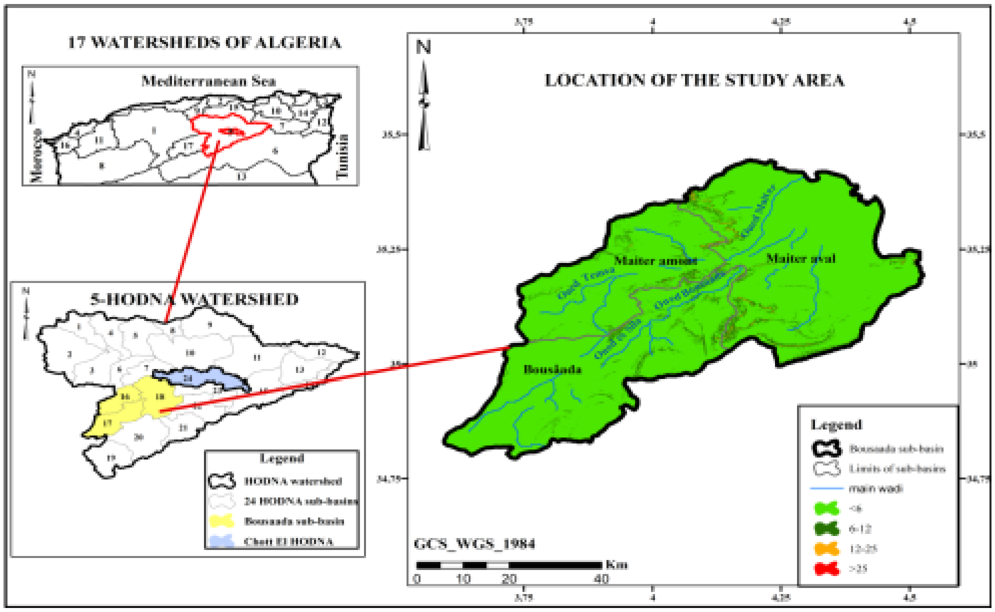

Figure 1 Location of the study area and slope class distribution

Its altitude ranges from 393 to 1644 meters from North to South, with slopes ranging from gentle to moderate, i.e., 6 to 25% (Tab. 1).

Table 1 Morpho-hydrographic characteristics of the Boussaada sub-basin

Characteristic	Symbol	Unit	Value
Watershed area	A	Km²	2938,36
Perimeter	P	Km	317,87
The length of the basin	L	Km	96,8
The width of the basin	I	Km	30,35
Form factor	K	/	1,64
Maximum altitude	H_{max}	m	1644
Minimum altitude	H_{min}	m	393
Average slope	I_m	m/Km	119,88
The length of the main river	L_p	Km	102,8
Drainage density	D_d	Km/Km²	0,16

2.2 Materials and Methods

2.2.1 Data and materials used

To create and enhance our database and prepare the thematic layers required for the MEDALUS model, we used data on several variables influencing erosion, which were gathered from available data in the study area and then incorporated into a GIS where the materials and data required for this study are summarized in Table 2 below. These data are used to calculate the following indices: the Soil Quality Index (SQI), the Climate Quality Index (CQI), the Vegetation Quality Index (VQI), the Anthropogenic Quality Index (AQI), and subsequently the Erosion Sensitivity Index (ESI) (Tab.2 & Fig.2).

Table 2 Materials used

Data/Documents	Software
Landsat 8 TM satellite image (March 2024, 30 m); Digital Elevation Model (DEM) of the Boussaâda sub-basin (Landsat 8 TM) ; Soil map of M'sila, 1/750,000 by [HCDS , DURAND J.H., 1954]; Soil map of Hodna, 1/500,000 by [FAO 1961]; Map of hydro-climatic networks and water quality monitoring; Monograph of the Wilaya of M'sila, 1/500,000 [DPSB, 2020]; Static data of the Wilaya of M'sila [DSA, 2020] ; Climatic data of the Wilaya of M'sila [ANRH, 2020].	Envi 5.4 Arc GIS 10.8 Global Mapper Version 15.1

HCDS–High Commission for Steppe Development.:2020, [DURAND J.H. ,1954].
FAO : Food and Agriculture Organization of the United Nations, 1961.
DPSB–Directorate of Programming and Budget Monitoring-Msila.: 2020.
DSA:Department of Agricultural Services.: 2020.
ANRH-National Agency of Hydraulic Resources. 2020

2.2.2 Applied Methodology - Evaluation of MEDALUS Model Parameters

The study's methodology was based on the MEDALUS model, which assesses erosion sensitivity by calculating the geometric mean of quality indices derived from environmental and human activity factors such as soil, climate, vegetation, and land use planning [20]. These parameters are likely to influence soil degradation [21].

The main objective is to create an erosion sensitivity map. It uses four main variables: soil, vegetation, climate, and human activities, to calculate the Erosion Sensitivity Index (ESI). The MEDALUS model is based on the four main parameters mentioned above: SQI, VQI, AQI, and CQI. Each of these parameters is classified into homogeneous categories relative to its influence on the erosion process. The Erosion Sensitivity Index is expressed by the formula (1):

$$\boldsymbol{ISE} = (\boldsymbol{IQS} \times \boldsymbol{IQV} \times \boldsymbol{IQA} \times \boldsymbol{IQC})^{1/4} \qquad (1)$$

The parameters (SQI, VQI, AQI, CQI, and ESI) were determined using the dataset shown in Fig.2.

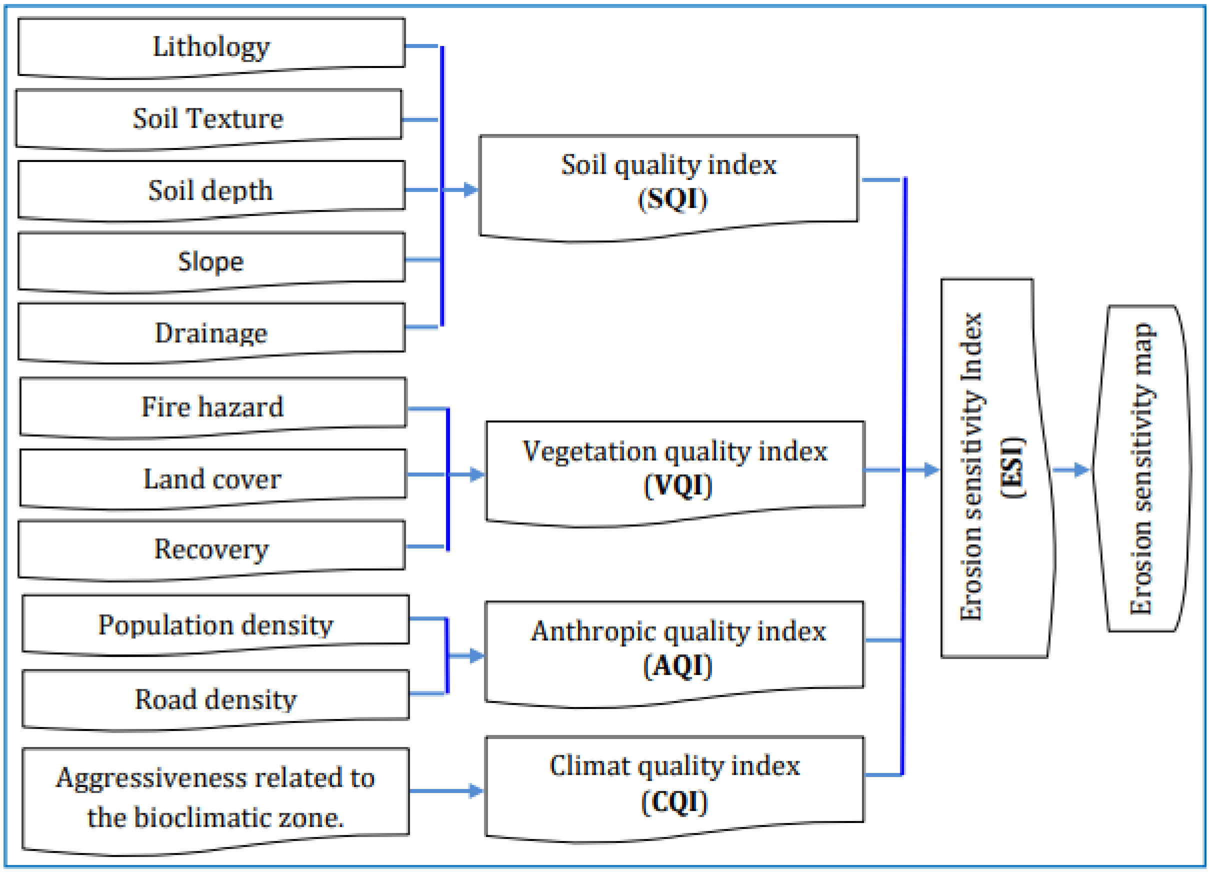

Figure 2 Methodological diagram of the steps followed for calculating the ESI index

The evaluation of soil vulnerability was based on the analysis of four main factors: soil quality, human quality, vegetation quality, and climatic quality.

2.2.2.1 Soil Quality Index – SQI

The variety of soil parameters influencing erosion makes it difficult to account for all of them comprehensively. Therefore, we opted to study a few simple and easily measurable parameters. The Soil Quality Index is calculated based on the following equation:

$$\boldsymbol{SQI} = (\boldsymbol{L} \times \boldsymbol{T} \times \boldsymbol{S} \times \boldsymbol{D} \times \boldsymbol{Dd})^{1/5} \qquad (2)$$

Where L is the lithology index, T is the soil texture index, S is the slope index, D is the soil depth index, and Dd is the drainage density index. The slope map generated from the Digital Elevation Model (DEM) was reclassified according to [23] classification and converted into a soil erosion vulnerability map The slope gradient is classified into four categories based on its influence on soil erosion. Regarding drainage, four distinct classes are defined to assess its effect (Tab. 3).

Table 3 Classes and indices of the SQI parameters.

Erosion factors	Class	Characteristic	Description	Score
Lithology	1	Hard limestone and dolomite, friable limestone	Good	1
	2	Conglomerates	Moderate	1.7
	3	Alluvium, sands and limestone crusts, sebkha	Poor	2

Depth	1	>75	Deep	1
	2	30-75	Moderate	2
	3	15-30	Shallow	3
	4	<15	Very shallow	4
Texture	1	L, LAS, LS	Good	1
	2	A, LA, AL, LAf, AS	Moderate	1.6
	3	SL, S	Poor	2
Slope	1	<6	Very gentle to flat	1
	2	6-12	Gentle	1,2
	3	12-25	Steep	1,5
	4	>25	Very steep	2
Drainage	1	Well drained	Good	1
	2	Medium-drained	Moderate	1,2
	3	Imperfectly drained	Poor	1,5
	4	Poorly drained	Very poor	2

Explanations: L = Loam, SCL = Sandy Clay Loam, SL = Sandy Loam, LS = Loamy Sand, SC = Sandy Clay, SiCL = Silty Clay Loam, C = Clay, SiC = Silty Clay, S = Sand.

2.2.2.2 Climate Quality Index – CQI

Climatic conditions play a crucial role in accelerating erosion processes. Indeed, the parameters that amplify the erosion phenomenon include both the aggressiveness of the climate and the erosivity of precipitation. The CQI estimates the amount of water available for plant growth [24]. The climate aggressiveness related to the bioclimatic zone refers to how climatic conditions influence ecosystems and human activities at different altitudes and latitudes. Bioclimatic zones are areas characterized by specific climatic conditions, affecting vegetation, wildlife, and human activities.

The pluviometric quotient (Q) or Emberger's climatic index is a formula used to characterize the climate of a region, particularly in Mediterranean areas. This index takes into account temperature and precipitation to assess climatic conditions. It helps distinguish between different types of climates in Mediterranean regions, ranging from very dry to very humid, based on the obtained values. The CQI was obtained using the equation (3) below:

$$\boldsymbol{CQI = EB} \qquad (3)$$

Where EB is the score assigned to the bioclimatic zone. The assessment of climate aggressiveness is based on bioclimatic zones. From a bioclimatic perspective (Emberger's climatic index, Q), the study area is characterized by two main types of bioclimatic zones: the Upper Arid zone, which occupies the central and southeastern parts of the study area, characterized primarily by low and irregular rainfall and drought, and the Lower Arid zone, which occupies the south western part of the area (Tab.4).

Table 4 Classes and indices of the CQI parameters.

Erosion factor	**Class**	**Characteristic**	**Score**
Bioclimatic Zones	1	Q > 40 (Upper Arid)	1
	2	Q < 40 (Lower Arid)	2

2.2.2.3 Anthropogenic Quality Index – AQI

The Anthropogenic Quality Index was calculated based on the degree of human-induced impact. The AQI was a combination of two factors: Population Density (Dp) and Road Density (Dr) (formula 4):

$$\boldsymbol{AQI} = (\boldsymbol{Pd} \times \boldsymbol{Rd})^{1/2} \qquad (4)$$

Population density in 2020 was divided into four categories, while livestock density in 2020 was classified into three categories [25], [26]. Land use was divided into two distinct classes, as shown in Tab. 5.

Table 5 Classes and indices of the AQI parameters.

Erosion factors	Class	Characteristic	Score
Population density	1	<15 people/ km²	1
	2	15-20 people / km²	1,33
	3	20-50 people / km²	1,66
	4	>50 people / km²	2
Road density	1	<3 Km/km²	1
	2	3-7 Km/km²	1,5
	3	>7 Km/km²	2

2.2.2.4 Vegetation Quality Index – VQI

The preservation of soil quality is closely related to vegetation, whose impact on land degradation varies depending on its resistance to climatic changes and its ability to prevent soil erosion [24]. The evaluation of the VQI was based on remote sensing methods applied to the interpretation of the satellite image acquired by Landsat 8, with a spatial resolution of 30 meters (formula 5):

$$\boldsymbol{VQI} = (\boldsymbol{CLU} \times \boldsymbol{CV})^{1/2} \qquad (5)$$

Where CLU is Current Land Use data of the study area and CV is Coefficient of Variation of Plant Coverage. The image was analyzed to classify the various types of land use using ArcGIS 10.8. The parameters are evaluated on a scale of indices ranging from 1 (very good quality) to 2 (very poor quality), as shown in Tab. 6.

Table 6 Classes and indices of the VQI parameters.

Erosion factors	Class	Characteristic	Description	Score
Land use	1	Forest-maquis	High	1
	2	Steppe	Medium	1.5
	3	Shrub steppe	Low	1.75
	4	Bare soil and sand, cultivation	Very low	2
Coverage	1	>40%	High	1
	2	10-40%	Medium	1,8
	3	<10%	Low	2

To create the erosion sensitivity map, we calculated four quality indices using the scores assigned to each parameter. Each quality index is derived from the geometric mean of the scores associated with the different parameters of the concerned factor (Tab.7). To finally assess the degree of erosion sensitivity, we multiply the quality indices of the four selected factors.

3. RESULTS AND DISCUSSION

Erosion sensitivity varies according to the quality of each indicator used in this approach (MEDALUS). Since our watershed is located in an arid region, environmental degradation in these areas mainly results from environmental factors, human activity, climatic variations, and factors related to the relief and topography of the land, lithology and soil structure, vegetation cover, and land use.

3.1 Evaluation of land vulnerability factors to water erosion in the Boussada sub-basin

3.1.1 Soil Quality Index

The results obtained from calculating the soil quality index (Tab.7) reveal three distinct categories of soil quality: The category of good-quality soils is relatively limited in the region, representing about 21% of the total area. It is primarily associated with shrub formations and is characterized by soils composed of materials with balanced textures. The moderate-quality category is the most widespread, covering about 64% of the study area. These soils are primarily found under steppe formations and generally have a medium to moderately deep depth. The poor-quality category occupies about 13% of the total area. It is less widespread. These soils are mainly found under shrub steppes and cultivation, primarily in the northeastern part of the sub-basin. These classifications provide crucial information on the distribution and quality of soils in the studied region, which can be essential for land management and planning.

Table 7 Distribution of the three Soil Quality Classes

SQI Classes	**Rank**	**Area (Km²)**	**Area (%)**
High	<1,13	590,57	20,09
Moderate	1,13-1,45	2063,63	70,24
Low	>1,45	284,16	09,67

3.1.2 Climatic Quality Index

The results of the analyses of Climatic quality map primarily highlight three classes of climatic quality distributed (Tab. 8) as follows: The class of good climatic quality occupies nearly 35% of the sub-basin area, corresponding to the upper arid bioclimate. It is situated in the southwestern part of the study area. The class of moderate climatic quality covers approximately 63% of the sub-basin area, located in the northeastern part and corresponding to the lower arid bioclimate.

The class of poor climatic quality represents a very small portion of the total surface area (2.45%) of the sub-basin, situated in the extreme south of the region.

Table 8 Distribution of the three Climate Quality classes.

IQC Classes	**Rank**	**Area(Km²)**	**Area (%)**
High	≤1,49	1021,79	34,74
Moderate	1,49-1,90	1845,58	62,81
Low	≥1,90	71,99	2,45

3.1.3 Anthropogenic Quality Index

The anthropogenic quality index reveals that the majority of the Boussaada sub-basin (78%) exhibits poor quality. This situation is mainly attributed to overgrazing in pastoral lands and urban expansion, which have a negative impact on the quality of developments. Meanwhile, areas of good quality (9%) and moderate quality (12%) correspond to shrub formations and cultivated lands (Tab. 9).

Table 9 Distribution of the three Anthropogenic Quality classes.

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AQI Classes	Rank	Area(Km²)	Area (%)
High	≤1,22	1192,57	40.57
Moderate	1,22-1,44	1623,41	55,25
Low	≥1,44	122,38	04,.18

3.1.4 Vegetation Quality Index

The map of the vegetation quality index (Fig.3) reveals three classes (Tab. 10) distributed as follows: Areas with good vegetation quality are generally found in mountainous forest regions, occupying approximately 39% of the total area, this class is mainly characterized by shrub vegetation forming a significant barrier against erosion, the class of vegetation with moderate quality covers about 15% of the sub-basin area. It is less widespread and corresponds to shrub steppes and cultivated areas and the class of poor-quality vegetation represents nearly 48% of the total area. This is the most widespread class in the Boussaada sub-basin, corresponding to degraded steppes and desertified lands.

Table 10 Distribution of the three Vegetation Quality classes.

VQI Classes	Rank	Area(Km²)	Area (%)
High	≤1,23	19,86	00,67
Moderate	1,23-1,44	919,59	31,30
Low	≥1,44	1998,91	68,03

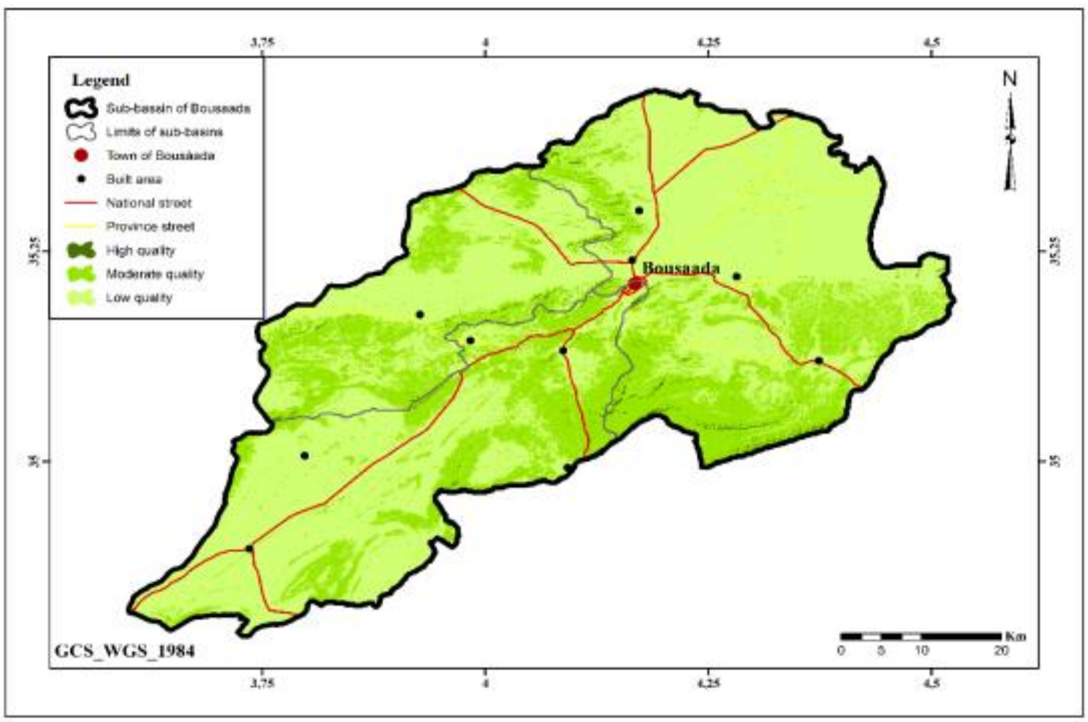

Figure 3 Vegetation Quality map.

3.2 Map of Erosion Sensitivity Index (ESI)

Figure 6 illustrates the map highlighting the erosion sensitivity across different areas of the Boussaada sub-watershed. The application of the MEDALUS method enabled us to evaluate the degree of erosion sensitivity within the Boussaada sub-basin.

Table 11 showed four zones of erosion sensitivity were distinguished: very sensitive, sensitive, moderately sensitive, and non-sensitive.

Table 11 Erosion Sensitivity Index (ESI)

ISE Classes	Rank	Area (Km²)	Area (%)
Non-sensitive	<1,26	615,76	.17.37
Moderately sensitive	1,26 -1,38	360,77	10,18
Sensitive	1,38-1,53	1348,12	38,03
Very sensitive	>1,53	1220,26	34.42

The erosion sensitivity map (Fig. 4) shows that a large part of this sub-basin is classified as highly to very sensitive to erosion, occupying nearly 72% of the total area. This classification is explained by the arid climate of the region and inappropriate land management, which has led to a predisposition to erosion. Areas moderately sensitive to erosion represent approximately 10% of the study area and are mainly located at the northern and southern ends of the sub-basin. Areas less sensitive to non-sensitive to erosion cover only 17% of the mapped area of the Boussaada sub-basin. They are mainly found in mountainous areas where the quality of soil and vegetation is relatively good, reducing their sensitivity to erosion.

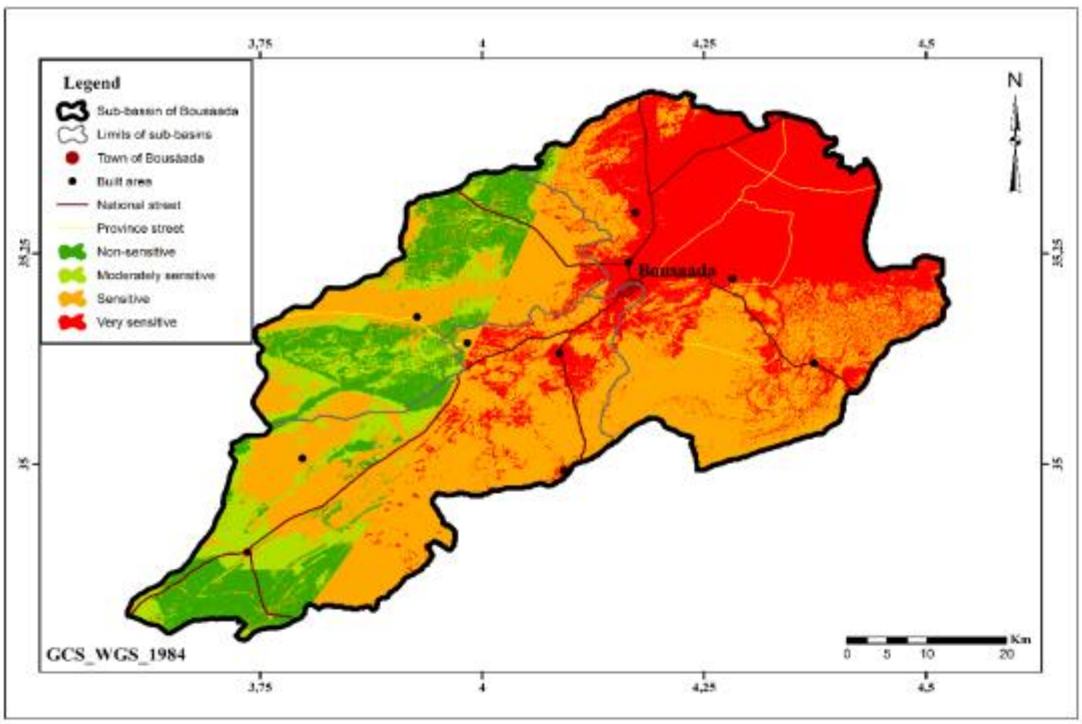

Figure 4 Map of the Erosion Sensitivity Index (ESI) in the Boussaada sub-basin

4. CONCLUSION

Erosion is an irreversible process of soil degradation driven by both human and natural factors. It leads to the deterioration of land suitability for agriculture and livestock, as well as the stability of housing. As a result, it poses a threat to the sustainability of natural resources and the ability of communities to adapt to climate change.

The methodology used in this study is based on the MEDALUS model. The spatial assessment of soil erosion sensitivity is a crucial step for decision-making. The final product obtained is considered acceptable and meets the objective of mapping areas sensitive to erosion, requiring both curative and preventive intervention to combat erosion. The moderate quality class of the soil index predominates, covering approximately 71% of the study area and mainly associated with steppe formations.

The climate index of the sub-basin is characterized mainly by a moderate quality class, encompassing about 63% of its total area, corresponding to the lower arid bioclimatic. Moreover, around 72% of the Boussaada sub-basin's territory exhibits poor anthropogenic quality, significantly impacting development quality.

The majority of the Boussaada sub-basin, about 78%, is characterized by poor anthropogenic quality, which negatively affects development potential. Only 12% of the area shows low sensitivity, located in regions with better land management and healthier vegetation. Approximately 76% of the sub-basin is classified as highly to very sensitive to desertification, resembling a pre-desert state due to its arid climate, low and irregular rainfall, and poor land use practices. Overgrazing, a major contributor to reduced plant diversity, necessitates improved land management to protect and enhance ecological value [25]. One of the most effective strategies adopted is planting forage species to boost pastoral productivity and combat desertification and sand encroachment caused by erosion [26]. The relationship between natural areas and water, a key limiting factor, is crucial but complex, influenced by many difficult-to-address issues [27].

The erosion sensitivity map classifies regions by their level of degradation, providing a vital tool for developing action plans to combat soil degradation from both erosion and desertification [28]. This map is essential for decision-making and environmental management in the region. However, conducting erosion risk mapping with the MEDALUS method and GIS tools presents challenges, particularly in gathering and accessing field data [29].

5. ACKNOWLEDGMENT

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