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Integration of Sentinel2 Data into a GIS System for the Mapping of Areas at Risk of Degradation by Applying the MEDALUS Model – Case of Sidi Mohamed Ben Abdellah Watershed (Morocco)

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ABSTRACT

Located in the central northwest of Morocco, the Sidi Mohamed Ben Abdellah dam watershed is particularly exposed to soil degradation risk due to a combination of factors such as wide exposure, lithological heterogeneity, and varying climatic conditions. Therefore, the purpose of the conducted study was to create a spatial map of the areas most susceptible to degradation using the MEDALUS (Method for the Evaluation of the Degree of Soil Loss Susceptibility) model to pinpoint the areas that are most vulnerable to the risk of erosion. The MEDALUS model is a commonly used tool for assessing soil degradation and erosion risks. It takes into account physical, climatic, and land use factors to determine the susceptibility of an area to soil loss. To apply the model to the Sidi Mohamed Ben Abdellah dam watershed, the data on factors such as slope, soil type, vegetation cover, and precipitation would be collected, and this information would be used to generate a map of the areas at greatest risk of erosion. This map could then be used to prioritize conservation and management efforts in the watershed and identify the areas that require additional protection or restoration. The map of erosion sensitivity is produced by combining factors that contribute to the phenomenon, such as vegetation cover, climate, relief, pedology, and human intervention. Cross-referencing these factors in a GIS (geographic information system) allows generating an erosion sensitivity map that highlights the most vulnerable areas to this hazard in the region.

Keywords: MEDALUS, erosion, GIS, Sidi Mohamed Ben Abdellah, Sentinel2.

INTRODUCTION

In Morocco, soil degradation is a national concern, as well as a risk threatening the natural resources in the country. The Sidi Mohamed Ben Abdellah basin has been classified among the basins most threatened by soil degradation according to the National Watershed Management Plan (PNABV). Erosion is a significant component of soil degradation, as it occurs when the soil loses its ability to absorb rainfall, causing excess water to flow across the surface and carry away soil particles. This can result in the formation of gullies and ravines. Human activities can exacerbate soil degradation, including overgrazing, intensified agriculture, deforestation, urbanization, and other practices that alter the landscape. Erosion is a natural process that occurs when soil particles are removed from one location and deposited elsewhere by water, wind, or other forces. However, human activities can significantly exacerbate erosion and contribute to soil degradation. Overgrazing, intensive agriculture practices that remove natural vegetation and till the soil, deforestation, and urbanization are some examples of human activities that can increase erosion. Soil erosion can lead to a loss of productive land, reduced crop yields, increased sedimentation in rivers and reservoirs, and even flooding, which can have severe consequences for the environment and human communities.

To address this issue, the Erosion Sensitivity Index (ESI) was developed, inspired by the method used in the Mediterranean Desertification and Land Use project by experts (Arnold et al. 1996). This index uses remote sensing and Geographic Information System tools to identify the areas that are most susceptible to erosion. Other models, such as the Soil and Water Assessment Tools (SWAT), are considered hybrid models that combine empirical and physical measurements collected in the field to assess soil erosion risk. A better understanding of the processes that contribute to soil erosion, and a proactive approach to managing those factors, is necessary to mitigate this problem.

The Erosion Sensitivity Index is a method that utilizes the MEDALUS model to evaluate the susceptibility of soil degradation and erosion. It leverages remote sensing and GIS tools to analyze various factors, including slope, soil type, vegetation cover, and precipitation, to produce a map of the areas that are most vulnerable to erosion. Unlike purely empirical or purely physical models, ESI is a hybrid model that integrates the measurements collected from both field studies and physical measurements, enabling a more accurate assessment of erosion risk while also considering human activities and the physical characteristics of the landscape. Other models, such as the Soil and Water Assessment Tool, are also considered to be hybrid models (Arnold et al. 1996). The SWAT model is a hydrological model that is used to predict the impacts of land use and management practices on water quality and quantity. It combines both empirical measurements and physical measurements to create a detailed simulation of the water cycle in a particular watershed.

Overall, the use of remote sensing, GIS, and hybrid modeling approaches is crucial in identifying and understanding the causes as well as effects of soil degradation and erosion. This information can be used to develop effective conservation and management strategies to mitigate these problems. Morocco has a diverse climate, with variations in temperature, precipitation, and other factors that can greatly affect the risk of soil degradation and erosion. Therefore, it is essential to conduct a comprehensive assessment of the risk of erosion in order to identify and monitor the areas that are most at risk.

This assessment should involve the integration of a wide range of data on factors such as climate, soil, relief, and land use. For example, the data on precipitation, temperature, and evapotranspiration can provide important information on the hydrological conditions in the area, while the data on soil type, depth, and fertility can give insight into the soil's ability to retain water and resist erosion. Similarly, data on relief, such as slope and aspect, can be used to identify the areas that are more susceptible to erosion due to their topography. By combining this information with remote sensing and GIS tools, it is possible to create detailed maps that show the areas that are most at risk of erosion. These maps can be used to prioritize conservation and management efforts in the watershed, as well as identify the areas that may need additional protection or restoration.

Overall, the integration of a wide range of data, in addition to the use of remote sensing, GIS, and hybrid modeling approaches, is necessary to properly identify, quantify and map the areas at risk of degradation in Morocco, especially in the Sidi Mohamed Ben Abdellah dam watershed where the vulnerability to soil degradation is high. The sub-basin of Sidi Mohamed Ben Abdellah is located in the western part of northern Morocco and is bordered by the Sebou watershed to the north as well as the Oued Oum-Rbia watershed to the south. It covers an area of about 10,000 km² and is characterized by a Mediterranean-type climate with high variability in precipitation, temperature, and evapotranspiration.

This sub-basin is particularly exposed to the risk of soil degradation due to a combination of factors such as climate change, demographic development, urbanization, and deforestation. Climate change has led to a decrease in precipitation and an increase in temperature, which can make the soil more susceptible to erosion (Mahe et al. 2011). Additionally, the pressure of demographic development, including urbanization and deforestation, has led to a loss of vegetation cover and an increase in impervious surfaces, which can also contribute to erosion.

The sub-basin of Sidi Mohamed Ben Abdellah is known to be a vulnerable area to soil degradation due to its wide exposure, lithological heterogeneity, and varying climatic conditions. Therefore, it is important to conduct a comprehensive assessment of the risk of erosion in order to identify and monitor areas that are most at risk.

Overall, the sub-basin of Sidi Mohamed Ben Abdellah is an environment highly exposed to the risk of soil degradation. This phenomenon is favored by climate change (Khomsi et al. 2014), demographic development including urbanization and deforestation, and requires detailed analysis as well as proper management to mitigate the erosion problem, and to protect the environment and human communities that depend on it. These dry and arid lands suffer from a strong degradation caused mainly by water erosion; therefore, and in order to reduce the consequences of this degradation, methods of control of erosive processes are necessary.

Several studies have been conducted in the area that includes the Sidi Mohamed Ben Abdellah basin. Geomorphological studies are one type of study that have been conducted in this area, and they focus on studying the landforms and processes that shape the Earth's surface (Beaudet, 1986). These studies can provide important information on the characteristics of the landscape, such as slope, aspect, and soil type, and can help to identify areas that are most at risk of erosion.

Geomorphological studies in the SMBA basin have likely been focused on understanding the different processes that shape the landscape, such as erosion, deposition, and weathering. They might have also been focused on understanding the relationship between the geomorphological characteristics of the area as well as the hydrological and climatic conditions, such as precipitation and temperature. These studies can provide a detailed understanding of the processes that shape the landscape and contribute to erosion. This information can be used to develop effective conservation and management strategies to mitigate the problem of soil degradation and erosion. Overall, geomorphological studies are important tools to understand the landscape and processes that shape it, which can be useful to better understand the risk of soil degradation and erosion in the SMBA basin. They can be used to identify the areas at risk, prioritize conservation and management efforts and develop effective strategies to mitigate the problem.For example, studies on siltation of dams, such as the one by Lahlou (1986), focus on the impact of erosion on the sedimentation in dams, which can reduce their capacity and effectiveness. Studies on logical sediment, such as the one by Ben Mohammadi (1991), focus on the impact of erosion on the sediment transport in rivers and streams. The mapping of soil losses using models such as the USLE and USEL model, such as the one by Ouakil et al. (2021), focus on quantifying the potential soil loss and identifying areas that are most at risk of erosion. It is important to note that the study of soil losses in watersheds requires a multidisciplinary approach that involves various fields such as geology, pedology, hydrology, socio-economics, and climatology. By taking into account the different factors that contribute to soil erosion, it is possible to develop a more comprehensive understanding of the problem as well as effective conservation and management strategies to mitigate it.

Overall, it is beneficial to situate the presented study in relation to the different research axes on soil losses in the SMBA basin, as this allows building on the existing knowledge and developing a more comprehensive understanding of the problem. A multidisciplinary approach that takes into account the different factors which contribute to soil erosion is crucial in identifying and mitigating the problem, as well as protecting the environment and human communities that depend on it. The considered study area is the subject of the application of the MEDALUS model based on a package of different data representing all the factors responsible for the phenomenon:

- The land use map generated from a mosaic of satellite images (SENTINEL2) is a data input that can provide information on the types of land cover present in the study area, such as forests, grasslands, urban areas, and water bodies. This information can be used to understand how different land cover types may affect the phenomenon being studied. For example, if the phenomenon being studied is related to water resources, the land use map can help identify the areas where land cover changes may be affecting water availability or quality. Additionally, the data set of SENTINEL2 is a high-resolution image dataset providing multi-spectral information; it can also help to understand land use changes over time.
- The records of rainfall stations are a data input that can provide information on precipitation patterns in the study area, the records of rainfall can help identify periods of heavy rainfall that may be causing increased erosion.

can also be used to understand the variability of rainfall over time and space, which can help identify the areas that are particularly susceptible to drought or flooding.

Additionally, the records of rainfall stations can also be used to understand the variability of rainfall over time and space, which can help identify the areas that are particularly susceptible to drought or flooding.
- The map of slopes restored from the Digital Terrain Model is a data input that can provide information on the topography of the study area.

STUDY AREA

The study area of the sub-basin of Sidi Mohamed Ben Abdellah is located in the central North-West of Morocco and covers an area of about 10000 km² (Figure 1). The basin is bordered to the north by the Sebou watershed and to the south by the Oum-Rbia watershed, and opens to the west on the Atlantic Ocean.

THE CLIMATE IN THE SUB-BASIN SMBA

The climate of the SMBA watershed is semi-arid, which means that the area receives low to moderate amounts of precipitation and experiences prolonged periods of drought. The semi-arid climate is characterized by a dry season, which lasts for most of the year, and a wet season, which is marked by low rainfall. This type of climate can have a significant impact on the hydrology, ecology and agriculture of the area. The climate in the basin is influenced by both the altitude, especially in the north with altitudes that can reach 1,630 m (Figure 2), and by the opening to the Atlantic Ocean, which ensures both humidification and moderation of temperatures.

The average annual temperatures oscillate in the basin between 15° and 18°C along the coast as well as 15° and 17°C in mountainous areas. In summer, temperatures can reach above 45°C due to the Chergui winds (a hot wind that comes from the Sahara) (Table 1). The SMBA basin is characterized by a rainy season that extends from October to May and a dry season that extends from June to September. The rainy season is characterized by relatively high rainfall and the dry season is characterized by low rainfall. The maximum rainfall is typically observed during the month of December and the minimum rainfall is typically observed in July. In the watershed, there are two types of winds that dominate:
- The winds that generate rain in winter; these are the winds that are the origin of polar air masses covering the Mediterranean areas.
- The winds that are known as Chergui, are hot winds coming from the Sahara and drying the coastal plains (Figure 3).

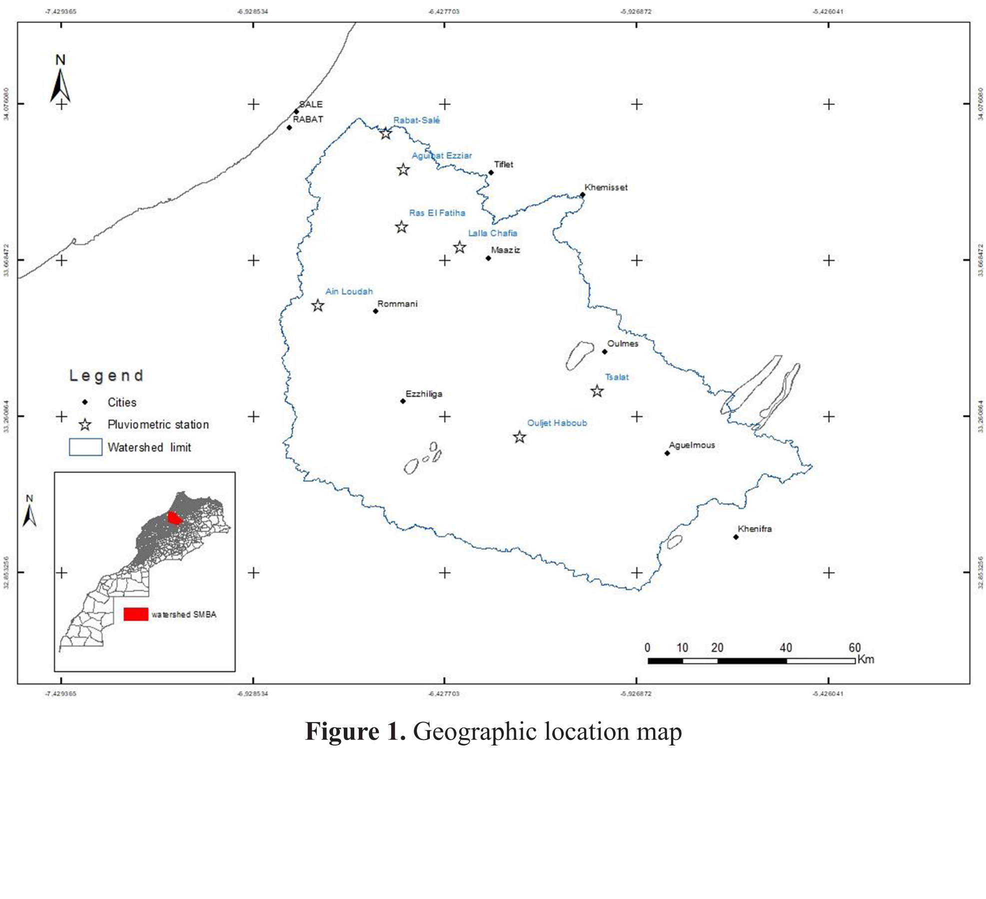

Figure 1. Geographic location map

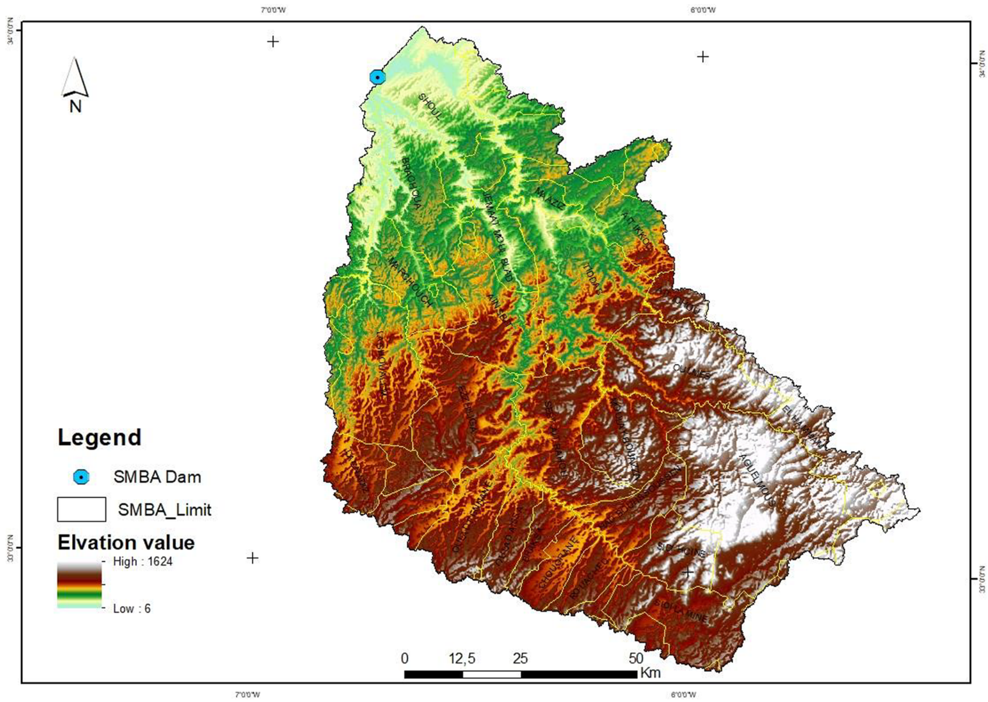

Figure 2. Spatial distribution of elevations in the watershed

Table 1. Average monthly annual precipitation for the period 1980-2009 (SIGMED, 2014)

Stations	Sept	Oct	Nov	Dec	Janu	Feb	March	April	May	June	July	Aug	Annual total
Sidi Jabbour	12.4	29	45.2	48.1	45.4	41.9	36.5	30.3	17.5	6.9	0.9	0.8	314.9
Aguibat Ezziar	9.5	34.8	68.7	76.1	67.8	56.6	46.6	42.7	22.4	6.9	0.5	0.9	433.5
Ras El Fatiha	10.3	31.1	60.5	69.9	59.1	53	45.3	37.4	16.1	5.3	0.8	1.4	390.2
Lalla Chafia	12.1	30.4	49.2	52.8	51	45.4	40.9	40.1	17.6	5.2	0.3	0.6	345.6
Ouljet Haboub	11.9	22	33.3	40.5	30.6	37.6	33.6	28.4	17.6	9.5	3.5	3.9	272.4
Ain Loudah	11	28.7	54.3	56.9	54.3	50.1	38	33.2	16.6	3.9	0.9	1.2	349.1
Tsalat	16.3	34.8	62.7	77.9	67.5	64.7	55.6	42.6	27.9	11.1	5.6	4.6	471.3
Rabat-Salé	8.6	42.8	67.3	104.8	79	61.3	52	55.2	20.4	4	0.2	1.2	496.8
Max	16.3	42.8	68.7	104.8	79	54.7	55.6	55.2	27.9	11.1	5.6	4.6	526.3
Min	8.6	22	33.3	40.5	30.6	37.6	33.6	28.4	16.1	3.9	0.2	0.6	255.4
Monthly average	11.5	31.7	55.2	65.9	56.8	51.3	43.6	38.7	19.5	6.6	1.6	1.8	384.2

Martonne's aridity index

$$I = P/(T + 10) \quad (1)$$

where: P – total annual precipitation, T – average annual temperature.

Rainfall erosivity

The rainfall erosivity factor: is calculated according to the following equation:

$$\text{Log } R = 1.744 \times \text{Log } (\llbracket Pi \rrbracket \text{\^{}}2/P) + 1.299 \quad (2)$$

The equation used to calculate the rainfall erosivity factor (REF). The equation uses two variables, P and Pi, to calculate R, which is the rainfall aggressiveness index in units/year. P represents the average annual precipitation of the observation period in millimeters and Pi represents the average monthly precipitation in millimeters.

The equation also includes a logarithmic transformation. The logarithm is used to compress the wide range of values into a smaller range, making the data more manageable and easier to interpret. According to Martonne's classification, the SMBA basin is characterized as semi-arid, (Figure 4) with a minimum value of 10 and a maximum value of 18.25 in the regions of Rabat-Salé. Martonne's classification is a system used to classify climates

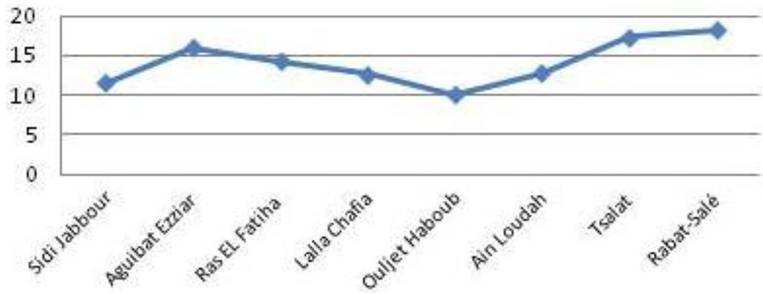

Figure 3. Variation of the Marton index

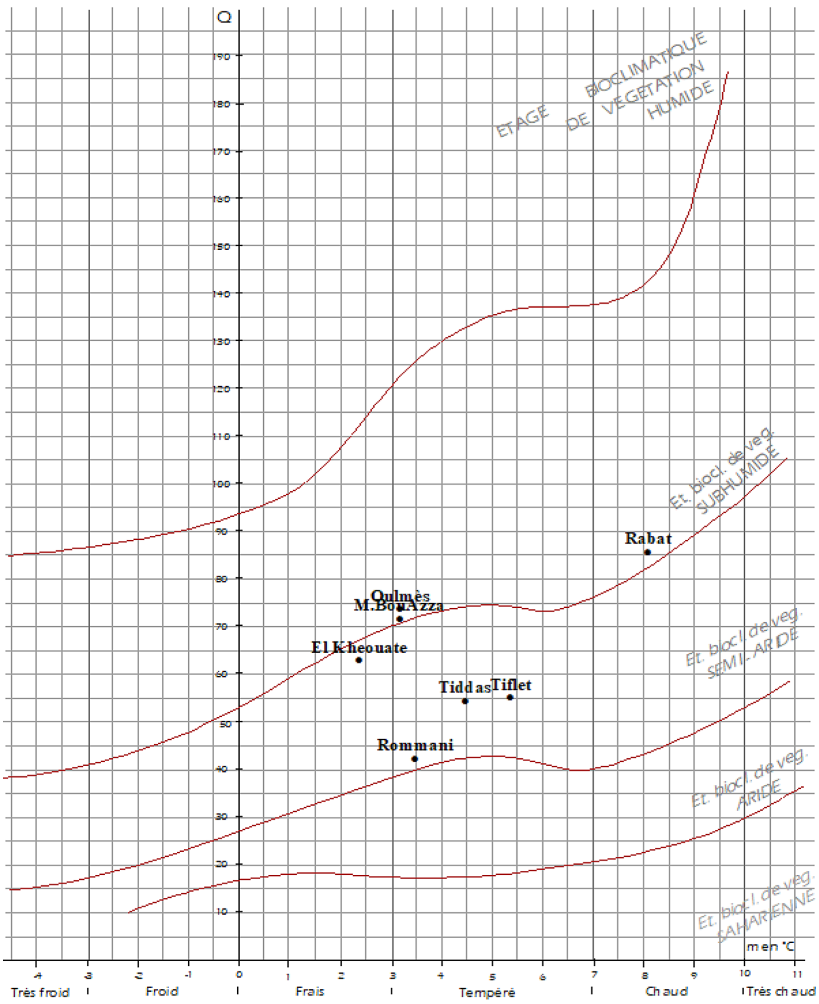

Figure 4. Emberger rainfall quotient

based on the precipitation and temperature of an area. The semi-arid climate is characterized by low to moderate amounts of precipitation and high temperatures, with a dry season that lasts for most of the year. The minimum and maximum values of 10 and 18.25 in the regions of Rabat-Salé indicate that the area experiences relatively low precipitation, which can have a significant impact on the hydrology, ecology, and agriculture of the area. The rainfall erosivity factor (REF) can be used to estimate the potential for soil erosion caused by rainfall, and provide important information to identify the areas that are particularly susceptible to erosion as well as develop strategies for erosion control.

A monthly aridity index can be used to better specify the aridity during the year. The formula provided, $I = 12P/(T+10)$, is one way to calculate the index. The I in the formula represents the monthly aridity index, P represents precipitation (mm) and T represents temperature (°C). This formula takes into account both precipitation and temperature, which are important factors that determine the level of aridity in an area. The formula gives a value of the index between 0 and 1, with values close to 0 indicating a relatively wet climate and values close to 1 indicating a relatively dry climate. The monthly aridity index can be useful to identify the period of the year that are more arid and the regions that are more affected by the aridity. To better specify the aridity during the year, a group of scientists uses a monthly aridity index given by the following formula:

$$I = 12P/(T + 10) \quad (3)$$

The results of the calculation of the monthly aridity index for the SMBA watershed indicate that the months of June, July, and August form an "arid" season with an accentuated severity in July, where the temperature registers 24.5°C. September is considered an arid month with a semi-arid tendency due to its relatively higher precipitation compared to June, July, and August. The other months are less arid due to their relatively high rainfall. The months of December, January, and February are the least arid with indices between 34.82 and 39.13, this is due to the relatively high amount of rainfall that marks this period of the year. To properly relate the vegetation cover to the climate, it is important to know the length of the dry season. According to Gaussen's determination, any month with total rainfall equal to or less than twice the average monthly temperature expressed in degrees centigrade is a biologically dry month (Bagnouls and Gaussen, 1953) (Figure 5). This information can be used to understand how vegetation is affected by the aridity and precipitation patterns of the area, as well as make decisions related to land use and conservation.

Geology of the study area

In the latter case, the main geological characteristics to be considered are the lithology and the tectonic structure of the bedrock. The Bouregreg watershed as a whole belongs to the Moroccan central massif. The latter is the most northerly and the most important of the Hercynian basement bulges of Atlantic Morocco. The SMBA watershed belongs as a whole to the Moroccan Central Massif (in its entirety, it occupies 90% of the Moroccan Central Massif and covers a whole geological structure. Thus, from upstream to downstream of the basin (Table 2) (Ben Mohammadi, 1991) and (Figure 6), it is possible to distinguish between.

The anticlinorium of Kasba Tadla-Azrou. It constitutes the upper part of the Bouregreg watershed. It is in fact a real mosaic of faulted anticlines of unequal magnitude where rocks outcrop from the Precambrian to Devonian and between which are spread the discordant and synclinal depressions of the Carboniferous (Termier, 1936; Bouabdelli, 1989). The Permian continental strata of Khenifra cover in angular unconformity the central-eastern part of this complex set.

The Fourhal Synclinorium is a synclinal trough that extends from the north of Boujad to the Causse d'Agourai. It exposes the sandstones and shales of Viséan, Namurian, and Westphalian ages to erosion (Tahiri, 1991). Its eastern flank is pierced by the granitic intrusion of Ment. The Khouribga-Oulmès anticlinorium is located at the heart of the Bouregreg watershed. It has a NE-SW orientation and

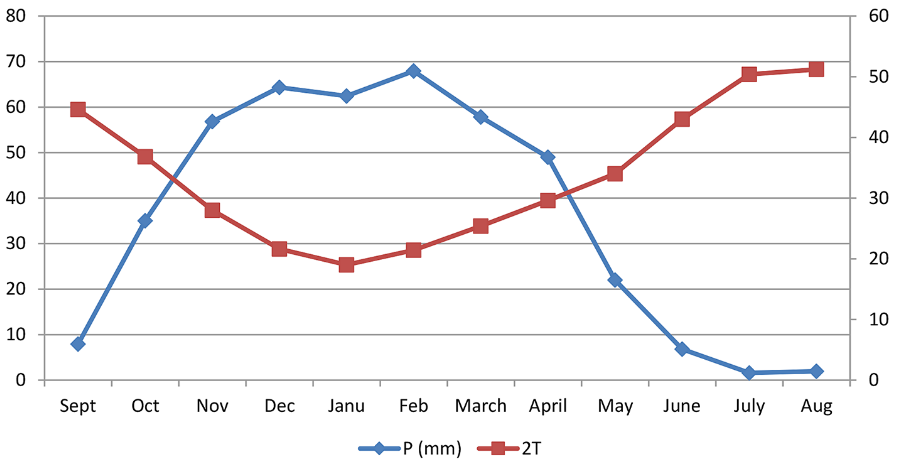

Figure 5. Ombrothermic diagram

Table 2. Results of the planimetry of the lithological formations of the Bouregreg watershed

Formations lithologiques	Superficie en Km²	Pourcentage
Schiste	7066	72.1
Quartzite	942	9 .6
Grès et Calcaires	502	5.1
Granites	470	4.8
Argiles et basaltes	413	4.3
Marnes	407	4.1

Source: Ben Mohammadi (1991) cité par Moshine (2009).

is characterized by predominantly schistose and quartzite layers from the Ordovician and Silurian periods. Overlying these layers, there are some detrital and/or carbonate scarps from the Carboniferous era (Piqué, 1979; Chakiri, 1991; Tahiri, 1991). Within this region, several granitoid massifs are present, including Zaër, Oulmès, and Moulay Bou Azza. The Khémisset-Rommani synclinorium is a substantial synclinal structure primarily composed of schistosandstone layers from the Lower Carboniferous period (Tournaisian and Viséan) as well as clay and basalt from the Triassic period. Occasionally, it undergoes erosion where anticlines expose Devonian formations (Chakiri, 1991; Zahraoui, 1991). The Rabat-Tiflet anticlinorium is a notable geological structure oriented in an East-West direction, characterized by the exposure of cataclastic granite and Caledonian metamorphic rocks due to tectonic faults (Piqué, 1979; El Hassani, 1990).

DATA AND TOOLS

The objective of the study was to apply the MEDALUS model for mapping areas at risk of degradation. To achieve this, a dataset was used to enrich the database and prepare the necessary parameters (indicators) for implementing the model. To effectively assess and manage erosion risks, it is necessary to analyze and integrate various factors that contribute to erosive processes, such as terrain topography, soil erodibility, and land use. The Sentinel 2 acquisitions downloadable from the Glovis database (https://glovis.usgs.gov) represent the raw material for the mapping of land cover in the study area, for this purpose, a classification oriented on the series of images in R-V-B-IR mode (combination of four bands) was applied. For

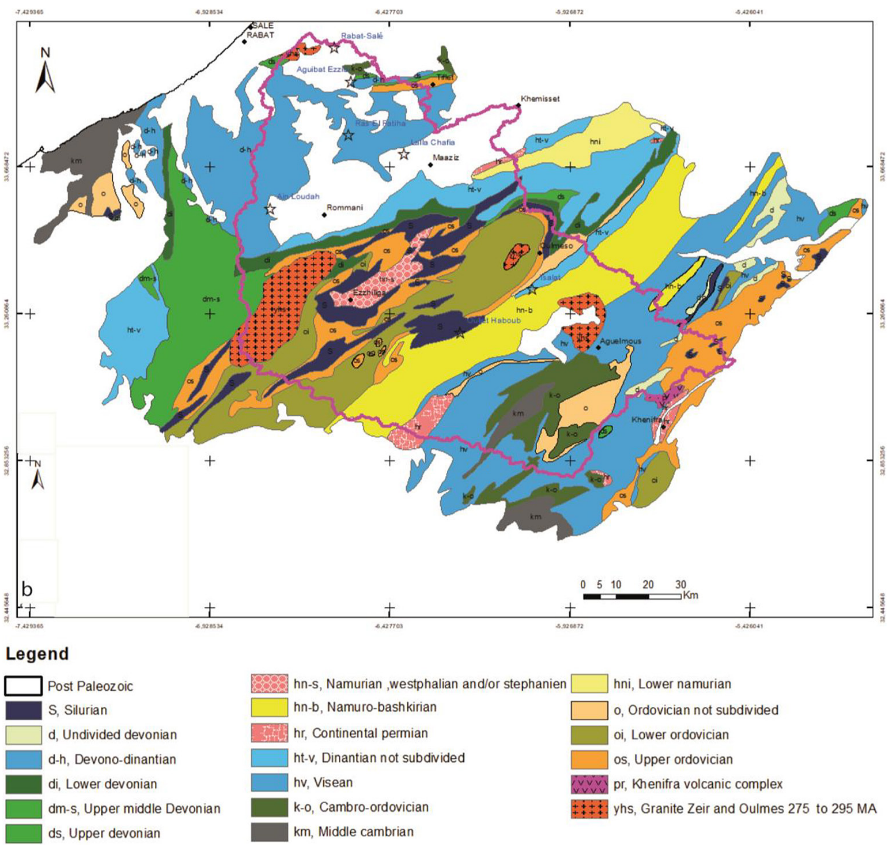

Figure 6. Geologic map

the morphological study of the considered area, the downloadable Digital Terrain Model Raster available on the Internet was used, which represents the raw material, also with a resolution of 30 m. The GIS allows integrating the different factors and applying mathematical equations on the values in order to produce a risk map (map of sensitivity to erosion). For data processing and analysis, various tools and software were used (Table 3).

Application of the MEDALUS model for the mapping of the areas at risk of degradation

The MEDALUS method used in the framework of the DISMED project (2003) for the purpose of producing a desertification sensitivity map for the Mediterranean countries, is based on the integration of four factors (soil, vegetation, climate, land use) (Figure 7). The choice of the MEDALUS method was based mainly on the amount of data required and the simplicity of implementation; it is a reasonable method which is both qualitative and quantitative.

$$ISE = (IQS * IQV * IQC * IQA) \quad (4)$$

where: ESI – erosion sensitivity index, SQI – soil quality index, IQC – climate quality index, AQI – development quality index.

RESULT AND DISCUSSION

The climate quality index (CQI)

The climatic conditions act on the acceleration of the erosive process. Indeed, its quality (climate) is evaluated by using the parameters that influence the availability of water which are the amount of precipitation, exposure and aridity. The quality index of the climate is obtained by crossing the three layers of information, namely the exposure (EXP), the total precipitation (PP) and the aridity index (IA) (Figure 8).

$$\mathrm{IQC} = (\mathrm{EXP} \times \mathrm{PP} \times \mathrm{IA})^{1/3} \quad (5)$$

The exposure map is produced from the Digital Terrain Model, the rainfall data recorded at the weather station and regarding the aridity, the Global Aridity Index and the potential evapotranspiration were adopted, which are both modeled using the data available in WorldClim Global Climate Data and in https://cgiarcsi.community. This choice is justified on the one hand by the recommendation of this index used by the United Nations, which proves its universality, and on the other hand by the ease of its use. It is noted that 30% of the area of the considered zone has good climatic conditions, and that the rest about 70% meets average conditions this result reflects the effect of the three parameters (Rainfall, Aridity and exposure).

Soil quality index

The soil quality index (SQI) is obtained by crossing the data of parent materials (PM), the slope of the land (Slope), and the evolution of the soil horizons in order to compensate for the lack of data on depth (ES), and texture (TEXT) according to the following equation:

$$\mathrm{IQS} = (\mathrm{RE} \times \mathrm{ES} \times \mathrm{TEXT} \times \mathrm{Pente})^{1/4} \quad (6)$$

The intersection of the layers allowed the derivation of the soil quality map (SQI). In addition, it should be noted that the index expresses soil quality in terms of susceptibility to desertification, rather than the inherent quality of the soil in terms of agronomic suitability (Figure 9). The result of SQI shows that most of the land in the basin is of average quality compared to its vulnerability to degradation (60%). Upstream, the quality of soils is moderately good; this is due to the good coherence of parent materials and the texture favoring infiltration.

The vegetation quality index (VQI)

For the elaboration of the vegetation index map, the data of the Sentinel 2 satellite were used; the S2 acquisitions obtained were corrected in order to produce an image with four bands (R,V,B,PIR) ready for the treatment. The image produced was

Table 3. Data and materiel used

Data	Softwar
Satellite Image Sentinel 2 (RVBPIR) Precipitation data Bioclimatic static recording Geological map Soil map	Geomatica 2018 Erdas Emagines 2015 Arc Gis 10.8

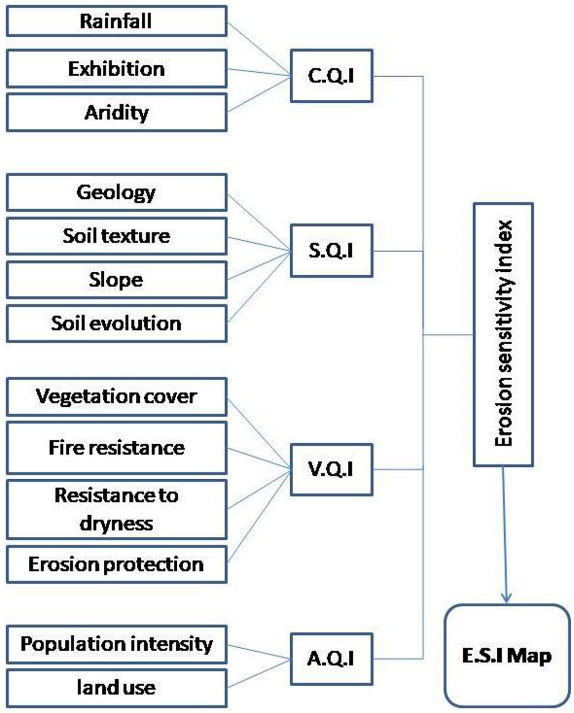

Figure 7. Methodology of application of the MEDALUS model

used to deduce the land cover by adopting a supervised classification. This classification is based on the knowledge of a set of land points for which the land cover is known (ground truth); using the statistical algorithm of maximum likelihood, it can identify groups of spectral signatures to obtain a number of classes of land cover with the best possible statistical separability (Figure 10). The land use map reflects the variety of classes in the basin, the cork oak occupies this space of the lower level of the Bouregreg basin with formations of clear or dense forests and matorrals of variable density; also, the presence of spaces of cereal cultivation was noted. This variety plays a very important role for the immobility of the soil and its resistance to the risk of degradation. The elaboration of the vegetation quality index is based on the integration of a set of factors (land use, resistance to drought, resistance to forest fire and protection systems against erosion in agricultural areas) (Figure 11). This map is obtained after reclassification of the vegetation data from the land cover map and the integration of the different parameter acting on the quality of the vegetation cover according to the Medalus standards. The table shows the weighting of the vegetation cover according to the MEDALUS standards (Table 4).

The management system quality index (MSQI)

One of the most interesting aspects of the Medalus model is the integration of socio-economic parameters in the study of land degradation. Thus, the quality index of the land management system was calculated on the basis of three parameters, namely the intensity of agricultural land use (IUTA), the intensity of rangeland use (IUTP) and the population pressure (DP) (Table 5). The map of the quality index of the management system is obtained by multiplicative crossing of the three indices DP, IUTA, IUTP. The result allowed classifying the considered area in three classes (Good; Average; Low); it can be noted that the majority of the land marks a remarkable absence of anti-erosion management systems.

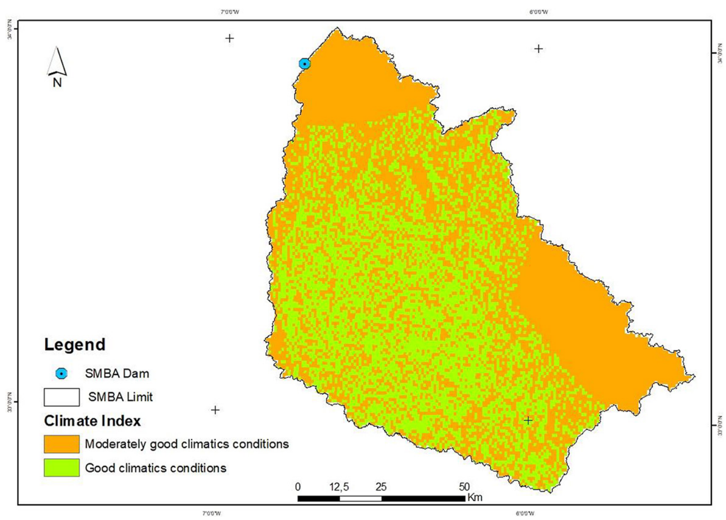

Figure 8. Climate quality map

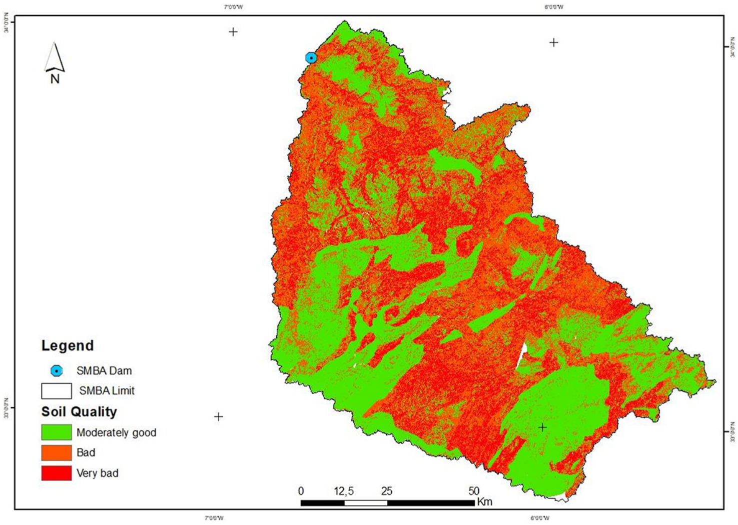

Figure 9. Soil quality map

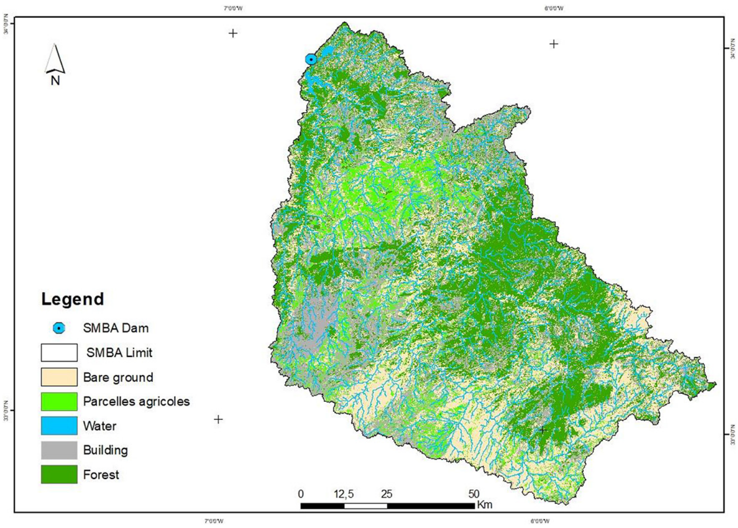

Figure 10. Land use map

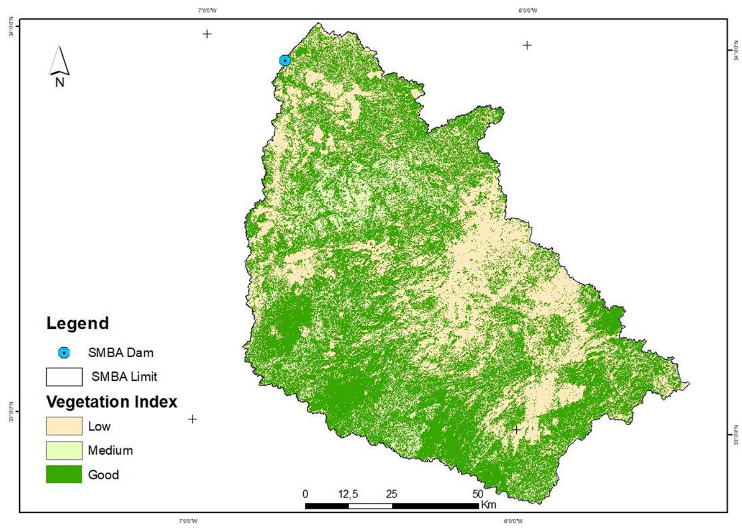

Figure 11. Vegetation quality index map

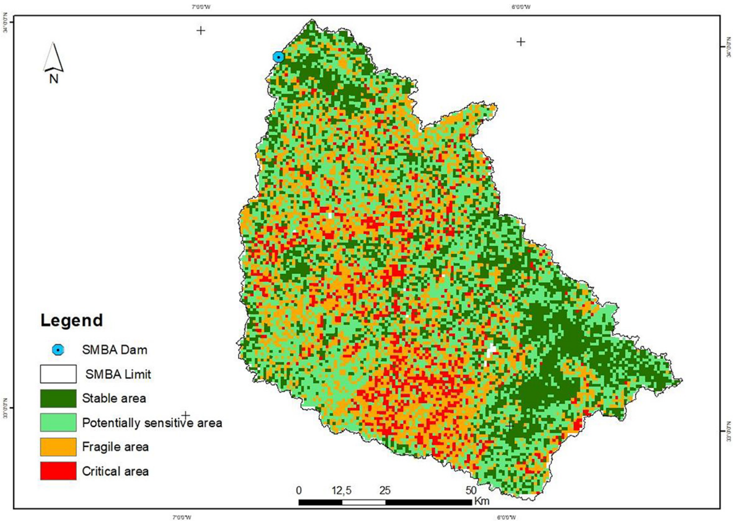

Figure 12. Desertification sensitivity map

Table 4. Vegetation cover weighting according to the MEDALUS standards

Classe	Description	Score
1	Good	1
2	Medium	1.66
3	Low	2

Table 5. Anthropic pressure according to the MEDALUS laws

Class	Description	Index
1	Extreme (>1000 hbts/km²)	2
2	High (1000>D>100 hbts/km²)	1.66
3	Medium (100>D>50 hbts/km²)	1.5
4	Low (50>D>25 hbts/km²)	1.45
5	Very Low (D<25 hbts/km²)	1.25

Table 6. Medalus desertification sensitivity classification standards

Class	Description	Index	Surface %
1	Stable	<1.17	25.89
2	Potential	1.17–1.23	37.72
3	Fragile	1.23–1.38	26.79
4	Critique	>1.38	9.58

Elaboration of the map of sensitivity to desertification

The desertification sensitivity map compiled from the four indices related to soil (SQI), vegetation (VQI), climate (CQI) and management system (SAQI) was reclassified according to the standards of the Medalus model (Figure 12). According to the value of the Desertification Sensitivity Index, 4 sensitivity classes were obtained, as presented in the table below (Table 6).

Desertification sensitivity map

According to the results obtained, just 25% of the land is more or less stable, generally the forest areas and areas at low altitude; the remaining 75% is exposed to the risk of degradation (Figure 12). It should be noted that the intense migration of the population to cities (urbanization) and the undirected use of land (overgrazing) have accentuated the degree of sensitivity of soil to desertification.

CONCLUSIONS

The Sidi Mohemed Ben Abdellah basin is situated in the humid region of Morocco, and it falls under the category of a semi-arid basin. Rainfall plays a crucial role in shaping the variations in land use within the area. Unfortunately, unfavorable climatic conditions have led to the degradation of vegetation cover, resulting in increased soil erosion risk. Additionally, rapid population migration to urban areas and unregulated land use practices further exacerbated the sensitivity of the soil to desertification. The land use map generated from processing Sentinel 2 satellite imagery classifies the area into 5 distinct categories. The first category comprises water bodies, covering 10% of the region, while vegetation covers approximately

25%. Human activities have led to the division of land into agricultural areas, occupying 15% of the total area, and built-up areas, represented by 20%. Lastly, barren land constitutes the largest class, accounting for 40% of the mapped area.

The geomorphology of the area is characterized by altitudes ranging from 1600 to 6 meters, extending from East to West. The presence of delicate soils makes it more susceptible to erosive processes. Spatial remote sensing and geographic information systems serve as vital monitoring tools to track changes in land cover. These technologies aid in comprehending erosion phenomena, allowing for the implementation and monitoring of adaptive strategies. The results obtained from these monitoring efforts reveal a concerning trend: the percentage of degraded land is consistently increasing. This degradation can be attributed not only to disruptions in the climatic regime, such as shifts in temperature and precipitation patterns, but also to unregulated land use practices resulting from rapid demographic changes and population migration to urban areas.

Addressing this issue requires a comprehensive and multidisciplinary approach to effectively control the erosion phenomenon. Implementing adaptive strategies becomes essential to mitigate further degradation and promote sustainable land management practices.

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