Eurasian Journal of Soil Science 2023, 12(3), 257 - 266

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org

# Mapping the sensitivity of land degradation in the Ouergha catchment (Morocco) using the MEDALUS approach

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**Article Info**

Received : 04.12.2022

Accepted : 28.03.2023

Available online : 03.04.2023

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## Abstract

Soil degradation is a global phenomenon affecting the productivity of agricultural land. Due to the low vegetation cover and the aggressive climate, Morocco presents a significant case of soil degradation through erosion and desertification. The Ouergha catchment is highly vulnerable to this scourge. The objective of this study was to assess the sensitivity of land to degradation in the Ouergha catchment area. The MEDALUS approach, widely used in the Mediterranean region, was used to assess the sensitivity of soils to degradation/desertification. This approach integrates four indicators that strongly influence this phenomenon (climate, soil, vegetation and human pressure). The results show that more than half of the study area has a medium sensitivity of land to degradation. The critical areas represent 16.2% and correspond to bare land characterized by steep slopes and absence of vegetation. Low sensitivity areas occupy a limited proportion of 21.9% and correspond to wet summits and conserved forest areas. Climate change could lead to a further increase in areas susceptible to degradation.

**Keywords:** Land degradation, MEDALUS approach, GIS, Ouergha catchment, Morocco.



## Introduction

Soil degradation is a global phenomenon that hinders the productivity of agricultural land (Contador et al., 2009). Several processes such as water and wind erosion, salinity and especially desertification cause this degradation. The United Nations Convention of to Combat Desertification (Paris, 1994), defined desertification as « the degradation of land in arid, semi-arid and dry sub-humid areas as a result of various factors, including the climate variations and human activities. This phenomenon is the result of the interaction of environmental factors (topography, climate, soil and vegetation) and anthropogenic factors such as deforestation, overgrazing and inappropriate management practices (Bouabid et al., 2010; Salvati et al., 2016). The consequences of desertification are often dramatic for poor people in developing countries. It leads to a loss of land productivity (Sepehr et al., 2007), affecting about 40% of the world's land surface. The economic losses of this phenomenon are estimated at 42.3 billion dollars per year (Mokhtari, 2016).

In Morocco, desertification affects approximately 90% of the national territory (Ghanam, 2003). This phenomenon could be aggravated by climate change, characterized by a decreasing trend in precipitation and an increasing trend in temperature (Driouech et al., 2021; Balhane et al., 2022), which leads to a displacement in arid bioclimates, semi-arid and sub-humid towards sub-humid or even humid zones, thus increasing the phenomenon of land degradation. In addition, incompatible human practices implemented locally, such as deforestation and overgrazing, increase the vulnerability of land degradation (Zaher et al., 2021; El Mazi et al., 2022). The Ouergha catchment, largely dominated by semi-arid and sub-humid bioclimates, is more sensitive to land degradation and desertification (Boutallaka, 2019).

doi : https://doi.org/10.18393/ejss.1276119

: http://ejss.fesss.org/10.18393/ejss.1276119

Publisher : Federation of Eurasian Soil Science Societies

e-ISSN : 2147-4249

To deal with this scourge, the scientific community has developed several approaches and methods to assess the sensitivity of land to degradation (Lahlaoi et al., 2017; Prăvălie et al., 2017; Lamqadem et al., 2018; Rabah and Aida, 2019). Some of these approaches are based on the integration of environmental indicators that influence this phenomenon and others combine anthropogenic indicators (Lamqadem et al., 2018). The MEDALUS approach (Mediterranean Desertification and Land Use) is widely deployed to assess the sensitivity of land to degradation/desertification. This approach integrates into the GIS, biophysical and environmental indicators such as soil quality, vegetation cover, climate quality and human indicators. Several studies have applied this method to assess the sensitivity of land to degradation (Sepehr et al., 2007; Contador et al., 2009; Prăvălie et al., 2017; Rabah and Aida, 2019). In Morocco, this approach has been tested in particular to map the sensitivity of soils to desertification in regions characterized by hyperarid, arid and subhumid climates (Bouabid et al., 2010; Lahlaoi et al., 2017; Lamqadem et al., 2018). In northern Morocco, this method has been tested in the Moulouya watershed (Mokhtari, 2016), and in the Upper Ouergha dominated by a subhumid climate (El Ouazani Ech-chahdi et al., 2020).This work aims to assess the sensitivity of land to degradation in the Ouergha catchment, by applying the MEDALUS approach. It also aims to spatialize the degree of severity in order to help decision makers take the necessary measures to maintain the sustainability of natural systems.

## Material and Methods

### Study area

The present study concerns the Ouergha catchment in northern Morocco, part of the Sebou watershed located in the Central Rif, and covering an area of 6150 km$^2$. The altitudes vary from 200 m in its downstream part to more than 2400 m in mountainous ridges. The geological context is dominated by fragile lithological formations composed mainly of marls and shales of the Ktama Unit (Maurer, 1968). The dominant climate is the Mediterranean type (Janati Idrissi, 2010) with rainfall varying between 350 mm the low altitudes to more than 800 mm in the wet slopes. It is characterized by a bioclimatic gradient ranging from semi-arid to humid and cold winter. This catchment has four dams and is considered a water reservoir since it has more than 13% of the surface water of Morocco. It is characterized by a high population density, essentially rural (more than 120 inhabitants/km$^2$). Economic activities are based on agriculture. The principal land uses are cereal crops, tree crops, forest cover and uncultivated land. The population exerts strong pressure on natural resources, in particularly on the forest, the soil and the water, to meet its needs.

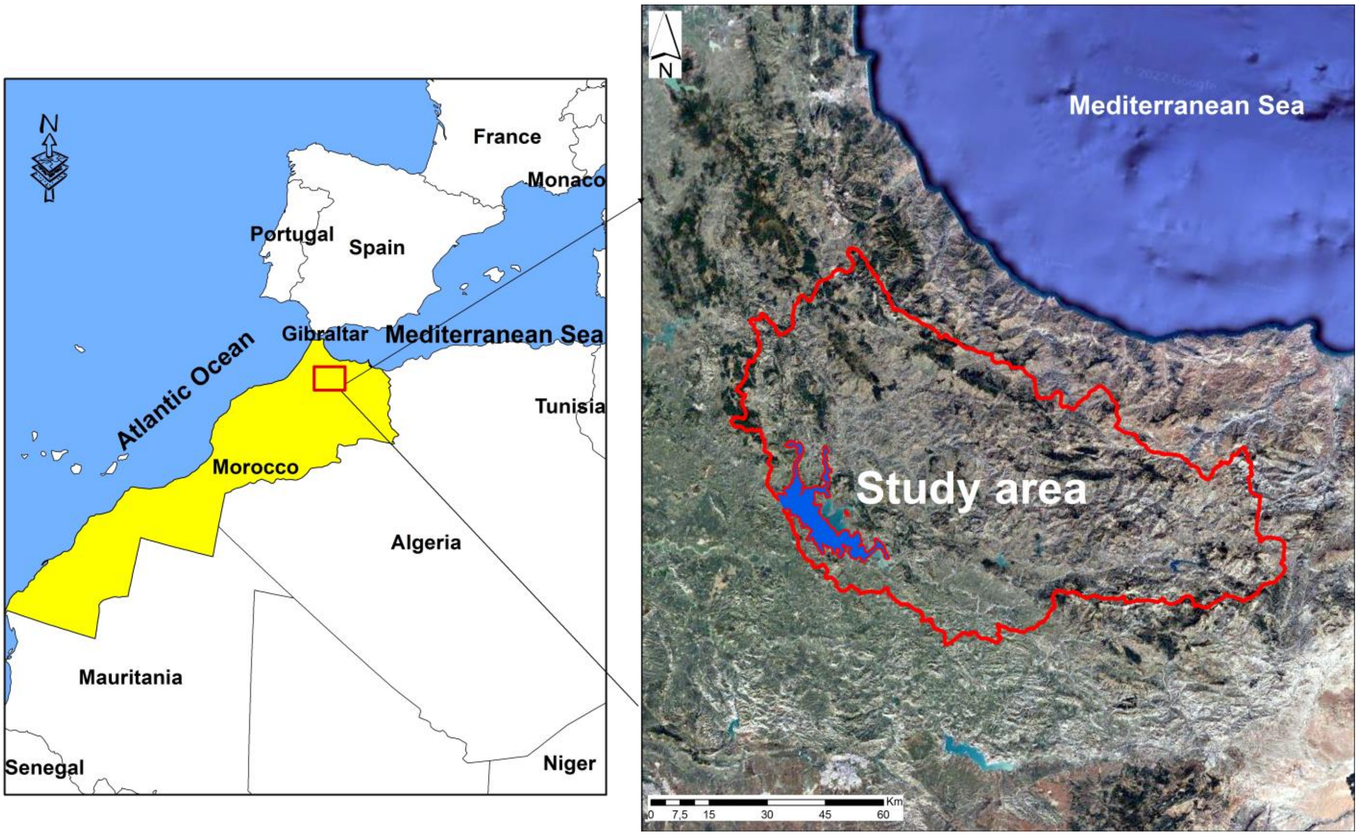


Figure 1. Study area

**Data used**

The data used to produce the map of land sensibility to degradation are:

- The geological map of the Rif at 1:500,000 was used to extract parent materials;
- The soil map at 1:200,000 and soil analyzes carried out as part of the agricultural development studies (department of agriculture) were used to extract texture and depth from soils;
- Series of rainfall data (1980-2015) were collected from the Sebou ccatchment Agency to characterize the quality of the climate;
- The Landsat OLI 8 image (15 September 2017) was collected from the USGS Earth Explorer database ("http://earthexplorer.usgs.gov/"), then processed and analyzed to extract the types of land use. Thus, the 2014 forest inventory map was used to determine the characteristics of forest formations (type, rate of cover, sensitivity to fire);
- The ASTER Global Digital Elevation Model (GDEM) is downloaded from the Earth Explorer website (earthexplorer.usgs.gov), and used to obtain the physiographic aspects of the study area (slopes, slope exposures).
- Demographic data from the 2014 National Population and Habitat Census were acquired from Morocco's High planning Commission. These data are available on the website https://www.hcp.ma.

**Methodological approach**

In this study, the MEDALUS approach was used to assess the sensitivity of land to degradation. This approach is based on the integration of the main biophysical, climatic and anthropogenic indicators influencing this phenomenon (Bouhata and Kalla, 2014; Lamqadem et al., 2018), according to the following formula (Eq.1).

$$SDI = (CQI \times SQI \times VQI \times MQI)^{1/4} \qquad (1)$$

Where SDI is the soil degradation index, CQI is the climatic quality index, SQI is the soil quality index, VQI relates to the vegetation quality index, and MQI is the management quality index. These indicators were combined in the GIS to extract the weighted geometric mean of each indicator (Figure 2).

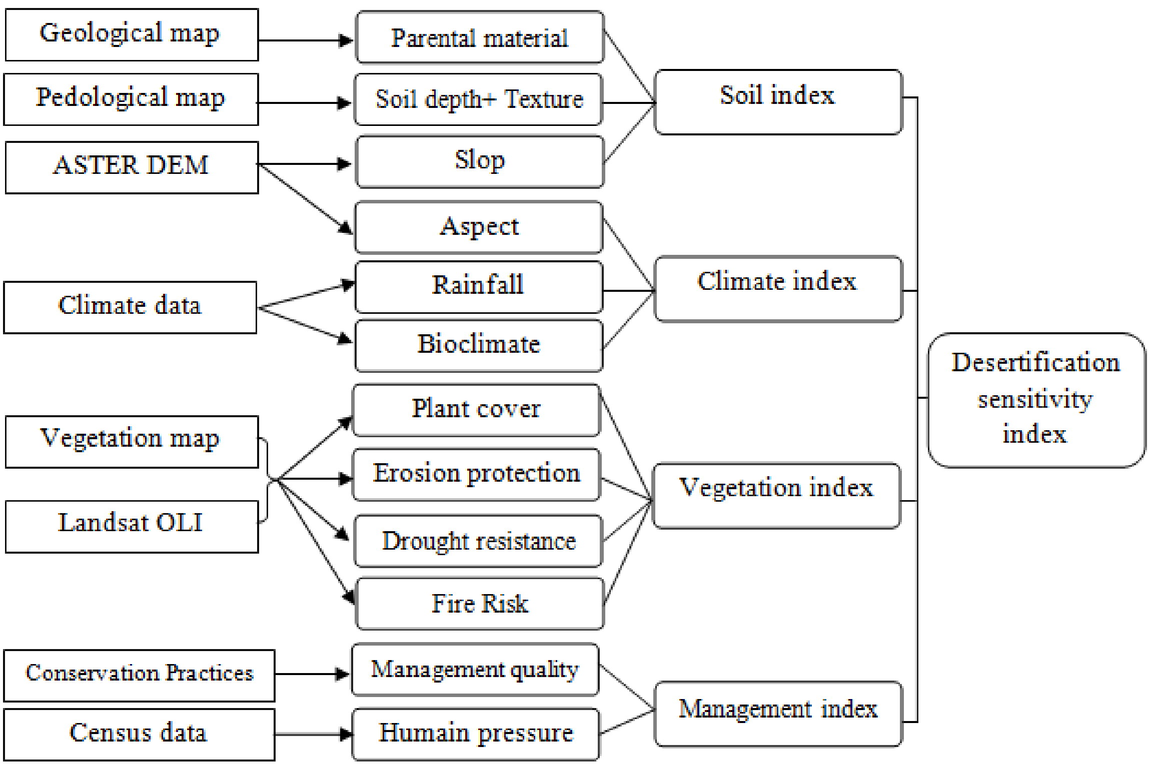


Figure 2. Methodological flowchart

**Climate Quality Index (CQI)**

Climate is an important parameter in the land degradation process (Bouabid et al., 2010). Indeed, rainfall variability, prolonged drought accompanied by extreme climatic events such as heat waves and intense rains can make vegetation cover and land vulnerable to desertification (Lahlaoi et al., 2017). The calculation of the quality of the climate according to the MEDALUS approach is based on three parameters: namely the aridity index, the annual precipitation and the topographical aspect. This index is calculated using the Eq. 2:

$$CQI = (P \times AI \times A)^{1/3} \quad (2)$$

Where P is precipitation, AI is the aridity index, A is the topographical aspect.

The aridity index was developed from the Emberger and Martonne indices, which are widely used to characterize climate aridity in the Mediterranean region (Mokhtari et al., 2013). The precipitation map was prepared based on the spatialization of climate data provided by measuring stations located in the study area and its borders using the IDW technique in Arcmap. The topographical aspect is an important parameter that influences the quality of the climate and the humidity of the soil from based on its sunshine and its location in relation to humid disturbances. The topographical aspect was obtained from Aster GDEM with a resolution of 30m.

**Soil Quality Index**

The Soil factor is a key element in the desertification process (Trotta et al., 2015). The susceptibility of soils to degradation is determined by the cohesion between soil particles, water retention capacity, horizontal depth of soil, soil texture, structure and organic matter content (Lahlaoi et al., 2017). The algebraic expression reflecting the effect of the soil factor is indicated by Eq. 3:

$$SQI = (Pm \times Dp \times T \times S)^{1/4} \quad (3)$$

Where Pm is parent material, Dp is the soil thickness, T is the soil texture, S is the topographical slope.

The geological map of the Rif at 1/500.000 was used to determine the lithological types and classified according to their degree of resistance to water erosion to obtain the parental material. Data relating to soil texture, thickness and organic matter content were extracted from the 1/20.000 soil map and from physico-chemical analyses carried out as part of the Ouergha catchment management study in 1994. The slopes were established from the analysis of an Aster GDEM.

**Vegetation Quality Index (VQI)**

Vegetation cover plays an important role in the process of land degradation. It provides significant protection of the soil against erosion. This protection depends on the type of vegetation and the rate of vegetation cover. Well-maintained forests enrich the soil with organic matter and act as a barrier to precipitation, and reduce land loss. Indicators of land degradation related to vegetation are: fire risk, erosion protection, drought resistance, and vegetation cover (Trotta et al., 2015) . The VQI was determined using Eq. 4.

$$VQI = (Fr \times Dr \times Ep \times Vc)^{1/4} \quad (4)$$

Where Fr is the Fire risk, Dr is the Drought resistance, Ep is the Erosion protection and Vc is the Vegetation cover.

The fire risk index (Fr) is obtained from the study established by Benabid (2007) and the forest inventory map of 2014. The results are validated by our experiences in the field. The sensibility of forest formations to fire depends on the types of vegetation, the density of the strata, mainly the lower strata which play an important role in the spread of flames from the lower strata to tree strata. Soil protection against plant erosion is determined by the types of land use, coverage rates and studies conducted in the region. A classification with the maximum likelihood algorithm of the Landsat OLI images (Thakkar et al., 2017) was used to classify land cover types. The coverage rate is established using the NDVI index of these images (Tucker, 1979).

**Management Quality Index (MQI)**

The anthropogenic factor can be both destructive and positive in the soil degradation process (Boutallaka, 2019). Human pressure on its natural environment and incompatible practices such as deforestation, overgrazing and successive tillage can aggravate the sensitivity of the soil to degradation (El Mazi et al., 2022). On the other hand, soil conservation practices such as reforestation, construction of terraces and residue management are considered as solutions to mitigate the process of land degradation (Laouina, 2013; Eekhout and de Vente, 2022).

In this study, the MQI was calculated from two sub-parameters: namely the human pressure and the quality of the management practices (Eq. 5). The human pressure index is obtained from the population density in each administrative community. The Quality of Development Practices Index was obtained from our field observations and studies carried out on the evaluation of the effectiveness of development interventions.

$$MQI = (\text{Human pressure} \times \text{management quality})^{1/2} \quad (5)$$

## Results and Discussion

The use of the MEDALUS approach permitted to evaluate the sensitivity of soils to degradation and to assess the degree of sensitivity in the Ouergha catchment. The results are presented in maps illustrating the weighting of the indices influencing the land degradation process (climate, vegetation, soil and human factor).

### Climate Quality Index

Climate is a crucial parameter influencing the susceptibility of soils to degradation (Tribak, 2020). This parameter is conditioned by two essential elements (temperature and precipitation). The spatial distribution of bioclimate in the region is characterized by a very high spatial variability due to orographic factors (Boutallaka, 2019). The CQI was obtained by combining three sub-indicators (aspect, precipitation and aridity index). The results were ranked according to the values in the table and spatialized in the map. The Table 1 gives the scores of the different classes of each sub-index. The semi-arid and sub-humid bioclimates are the most dominant. The SW and SE aspects, are the most extensive (51.5%), which are the sunniest and sheltered from humid Atlantic disturbances (Janati Idrissi, 2010). The evaluation of the climate factor based on three sub-indices shows an index oscillating between 1.00 and 2 with an average of 1.38 (Figure 3). The low and very low classes are the most dominant, representing 43.66% of the total area. These zones are dominated by the semi-arid bioclimatic stages with a rainfall less than 400 mm and sub-humid (between 400-660 mm), which extend in the southern and eastern part of the catchment. They also correspond to the SE/SW oriented slopes, which are sunnier, less watered and more exposed to erosion (Tribak et al., 2021). While the good CQI only represents a limited area (13.76%). These are slopes with a humid bioclimate located at high altitude and exposed to humid perturbations that receive a significant amount of precipitation (>660 mm).

Table 1. The climate quality index

| Index | Class | Score | Surface (%) | Description |
|---|---|---|---|---|
| Precipitation (mm) | >600 | 1 | 30,1 | High |
| | 400-600 | 1,5 | 31,5 | Moderate |
| | <400 mm | 2 | 38,4 | Low |
| Aspect | NW/ NE | 1 | 46,98 | Wet |
| | SE/SW | 2 | 51,5 | Dry |
| | Unclassified | - | 1,52 | - |
| Aridity index | Semi-arid | 2 | 38,4 | High |
| | Sub-humid | 1,5 | 30,4 | Moderate |
| | Humid | 1,3 | 31,2 | Low |

### Soil Quality Index

The soil quality index is obtained by combining four sub-parameters (Bouabid et al., 2010). The result of this index is presented in Table 2 and the Figure 4. They show that the study area is characterized by medium to low soil quality, representing respectively 21.2% and 40,81% of the total area. They correspond to areas dominated by friable lithological formations (Schist, Flysch and marl), Stony soils poor in organic matter, and by high topographic slopes which lead a progressive stripping of the arable surface layers (Al Karkouri, 2017). However, the slopes with high soil quality occupy 37.99% of the total area. These correspond to areas of sediment accumulation and lithological formations that are more resistant to erosion (limestone, sandstone, etc.), especially on the gentle slopes. In these areas, the soil thickness is deep and can provide water reserves and optimal conditions for the development and growth of vegetation (Lahlaoi et al., 2017).

Table 2. The soil quality index

| Index | Class | score | Surface (%) | Description |
|---|---|---|---|---|
| Parent material | Coherent | 1 | 17,5 | Limestone, dolomite, sandstone |
| | Moderately | 1,5 | 55,2 | Marl-limestone, shale, Flysch |
| | Soft | 2 | 27,3 | Marl, clay, alluvium and colluvium |
| Soil thickness (cm) | > 80 | 1 | 8,1 | Low |
| | 50-80 | 1,3 | 18,4 | Moderate |
| | 25-50 | 1,6 | 59,2 | High |
| | <25 | 2 | 12,3 | Very High |
| Soil Texture | Balanced | 1 | 38,5 | Low |
| | Fine at mean | 1,3 | 30,1 | Moderate |
| | Fine | 1,6 | 29,6 | High |
| | Rude | 2 | 1,8 | Very High |
| Slopes (degree) | <6 | 1 | 12,7 | Low |
| | 6-18 | 1,3 | 48,4 | Moderate |
| | 18-35 | 1,6 | 35,3 | High |
| | >35 | 2 | 3,6 | Very High |

### Vegetation Quality Index

The results of the Vegetation Quality Index (VQI) are presented in the Table 3 and in the Figure 5. They show that the Ouergha catchment area is dominated by the high and moderate VQI, representing respectively 34.66% and 36.8% of the total area. The moderate quality vegetation corresponds to the fruit plantations. The high quality vegetation is located in the northern part of the basin and corresponds to natural forests developed in the sub-humid and humid bioclimate and irrigated crops in the alluvial terraces. The climax forest is composed of oak, cedar and pine forests that belong to the Mediterranean ecosystem characterized by a high resilience to drought (FAO, 2022). Furthermore, this ecosystem is highly susceptible to forest fires (Mharzi Alaoui et al., 2017), but it is also characterized by a high capacity for regeneration after a fire. The rapid regeneration of vegetation has contributed to the protection of soils from erosion (Laouina et al., 2013; Francos et al., 2019). In addition, areas with low and critical VQI represent 22.16% and 6.37% of the total area respectively. These areas are located in the southern and eastern part of the study area and correspond to bare soil and agricultural land. These occupations are often considered vulnerable to degradation and have low soil protection against erosion and low sensitivity to fire risk.

Table 3. The vegetation quality index

| Index | Class | Score | Surface (%) | Description |
|---|---|---|---|---|
| Fire risk | Low | 1 | 40.4 | Agricultural land, bare land |
| | Moderate | 1.6 | 41.3 | Sub-dense natural forests |
| | High | 2 | 18.3 | Reforestation (pine forest) and secondary training |
| Erosion protection | Low | 1 | 11.8 | Agricultural land, bare land |
| | Moderate | 1.6 | 36.3 | Maquis and matorral |
| | High | 2 | 51.9 | Natural and artificial forests, lawns |
| Drought resistance | High | 1 | 6.0 | Natural and artificial forests |
| | Moderate | 1.6 | 65.1 | Arboricultures, formations secondary |
| | Low | 2 | 28.9 | Agricultural land, Bare land |
| Vegetation cover (%) | >40 | 1 | 4.9 | High coverage |
| | 10-40 | 1.5 | 76.5 | Low coverage |
| | <10 | 2 | 18.6 | Very low coverage |

### Management Quality Index

The Management System Quality Index (MQI) is an indicator of human pressure on the natural environment. In this study, the MQI was calculated by combining two parameters (human pressure and management effectiveness), and has been classified and illustrated in Table 4. These results show that 52.3% of the Ouergha catchment is exposed to high human pressure on the natural environment, and corresponds to heavily populated areas (>160 hab./km$^2$) in the northern part. The areas of moderate human pressure occupy 28.9%, while the areas of low to very low overexploitation, where the population density is less than to 80 hab./km$^2$, are very limited and concern the sparsely populated communes in the southern part of the study region.

The land management systems quality index (Figure 6) shows that the areas of average and good management quality are the most dominant, accounting for 46.2% and 38.4% of the total area respectively. These include dense natural forests and reforestation, as well as erosion control techniques (terraces, dry stone walls). These practices can provide additional ecosystem services, including soil enrichment of organic matter that contributes to the mitigation of degradation (Eekhout and de Vente, 2022). Areas of low management quality occupy 15.4% and correspond to land that has not benefited from management interventions and to cleared land put under cultivation.

Table 4. Management System Quality index

| Index | Class | Score | Surface (%) | Description |
|---|---|---|---|---|
| Human pressure | Very low | 1 | 7,2 | < 80 hab./Km$^2$ |
| | Low | 1,3 | 11,6 | 80-120 hab./km$^2$ |
| | Moderate | 1,6 | 28,9 | 120-160 hab./km$^2$ |
| | High | 2 | 52,3 | >160 hab/km$^2$ |
| Management quality | High | 1 | 38,1 | Reforestation, terraces, managed forest |
| | Moderate | 1,5 | 46,2 | Cultures and forests, agricultural land. |
| | Low | 2 | 15,7 | Abandoned land, cleared land |

### Index of soil sensitivity to degradation

The use of the MEDALUS approach allowed us to assess the sensitivity of land to degradation in the Ouergha catchment. It was developed by combining four indicators (climate, soil, vegetation and human factor) in the GIS using Eq. 1. The results obtained illustrated in the Table 5 and Figure 7. The sensitivity of land to degradation in the Ouergha catchment is classified according to severity, from low to highly critical. Four classes were established according to similar studies (Sepehr et al., 2007; Bouabid et al., 2010; Mokhtari, 2016). Low sensitivity to degradation, (SDI<1.2), medium sensitivity (SDI between 0.2 and 1.4), highly fragile areas (SDI between 1.4 and 1.6) and finally critical areas (SDI between 1.6 and 2).

The low sensitivity areas cover an area of 21.9% of the total area. They cover the northern and north-western part of the basin, and correspond to the humid and sub-humid climatic zones that receive a significant amount of precipitation (Jbel Ouedka, Senhaja Srair, Jbel Tidghin and Jbel khezana, Bab Bard and Bab Taza). As well as the areas protected by high vegetation cover which protects the soil against water erosion (Arrebei et al., 2020; El Mazi et al., 2021). They also correspond to the deep soils in the alluvial terraces which contributed to the supply of a significant proportion of water resources and offer optimal conditions for the development of vegetation. In the south of the basin, there are extensive areas along the valleys and alluvial plains, these lands have a fertile and deep soil. These areas are characterized by low slopes and agricultural activities dependent on irrigation, due to its proximity to valleys. This category is of high quality and has a great capacity to protect the soil against degradation, in particular water erosion.

Table 5. Class areas of each sub-indicator

| Index | Classes | Intensity | Proportion (%) |
|---|---|---|---|
| VQI | 1.00-1.2 | High | 34,66 |
| | 1.2-1.4 | Moderate | 36,80 |
| | 1.4- 1.6 | Low | 22,16 |
| | 1.6-2 | Very low | 6,37 |
| SQI | 1-1.3 | High | 37,99 |
| | 1.3-1.6 | Moderate | 21,20 |
| | 1.6-2 | Low | 40,81 |
| CQI | <1 | High | 13,76 |
| | 1-1.2 | Moderate | 42,58 |
| | 1.2-1.6 | Low | 24,97 |
| | 1.6-2 | Very low | 18,69 |
| MQI | 1-1.3 | High | 34,87 |
| | 1.3-1.6 | Moderate | 46,93 |
| | 1.6-2 | Low | 18,20 |

The areas moderately sensitive to degradation (SDI between 1.2 and 1.4) cover 27.9% of the total area. They are spread out along the edge of valleys and alluvial plains, as well as the slopes with medium to low slopes, and moderately protected by secondary vegetation. Fragile areas with high sensitivity to degradation (SDI between 1.4 and 1.6) occupy 31.7% of the area of the basin studied. They are located in the southern and eastern part. This sensitivity is linked to natural factors such as poor climate quality, soft and low permeability rocks, but also intense land use and poor soil quality, which increase the risk of land degradation (Bouabid et al., 2010). This underlines the urgency of conservation of these areas and integrated planning to reduce the sensitivity of soils to degradation. The slope factor has contributed to the rapidity of rainwater drainage and the strong concentrated runoff, due to the regression of vegetation areas which is characterized by low cover, increasing surface degradation and evolution of water erosion activity especially on bare slopes (Tribak et al., 2021). Areas highly susceptible to degradation (SDI between 1.6 and 2) cover about 16.2% of the total basin area, according to the results of other similar studies. They concern areas characterized by an arid climate or rainfall of less than 500 mm, steep slopes and lack of vegetation, leading to severe soil degradation by water erosion. In addition, anthropogenic action on the environment and incompatible practices implemented locally such as deforestation followed by cultivation and successive tillage increase land degradation (El Mazi et al., 2021). These areas require urgent intervention to minimize the damage.

## Conclusion

The present study focuses on the assessment of land sensitivity to degradation in the Ouergha catchment using the MEDALUS approach. This approach is flexible because it allows the sub-indicators to be modified. Four main parameters, each comprising several sub-indicators, were combined and represented in a GIS to produce a hierarchical map of the degree of sensitivity to degradation. The results revealed that the high and medium degradation sensitivity index prevailed in 59.6% of the total area, and mainly affected the eastern, southern and south-western parts of the basin. The occurrence and amplification of this phenomenon is often the result of a combination of natural and anthropogenic factors.

This sensitivity is expected to increase in the future due to the effects of current climate change (decreasing in precipitation, increasing in temperature), which is leading to a northward shift of the most sensitive dry areas, as well as the concentration of a high-density poor population exerting strong pressure on the natural environment. This underlines the urgency of natural ecosystem conservation and integrated planning to reduce the sensitivity of land to degradation. The study also demonstrates that soil conservation practices, reforestation and terracing are effective measures to mitigate environmental fragility.

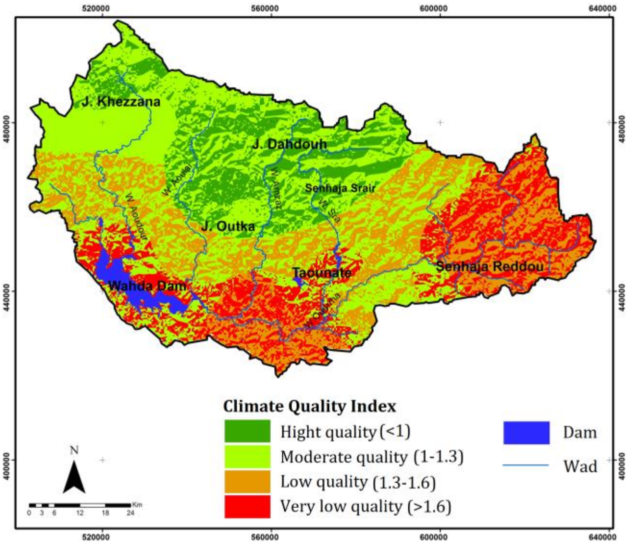


Figure 3. The climate quality Index

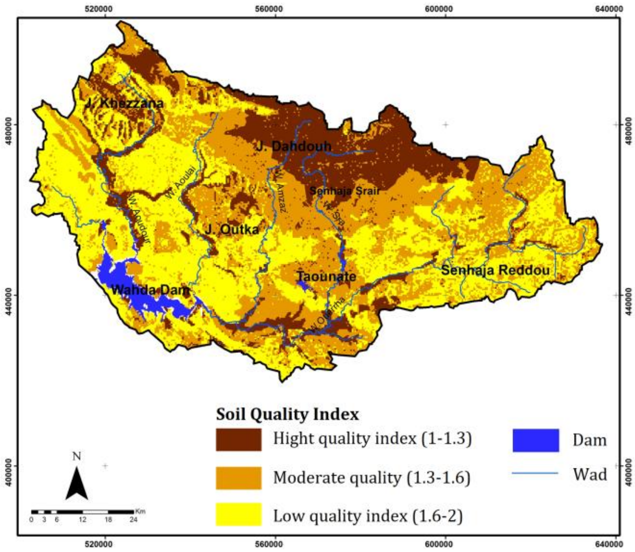


Figure 4. The soil quality Index

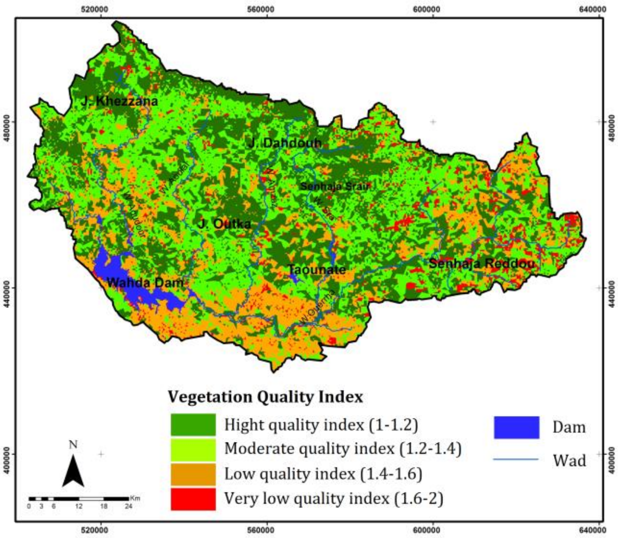


Figure 5. The vegetation quality Index

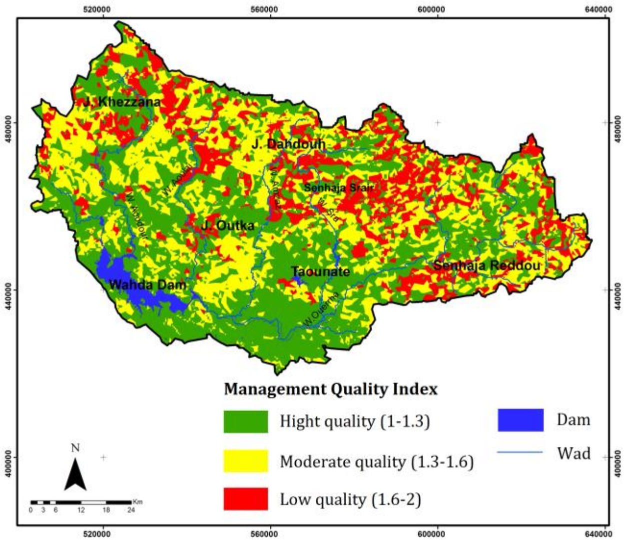


Figure 6. Management Quality Index

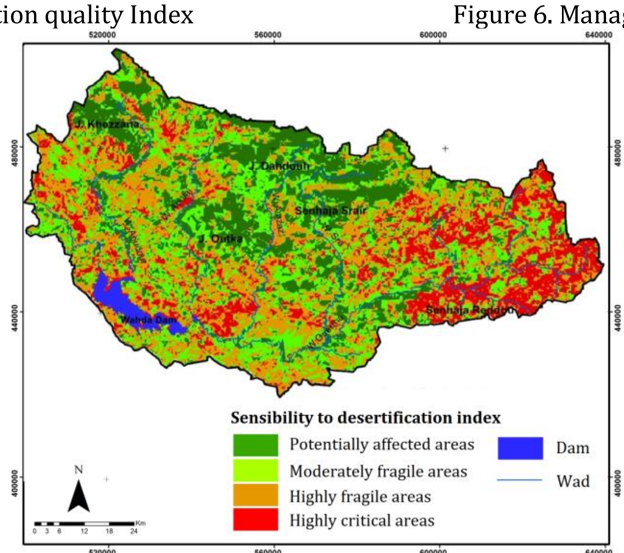


Figure 7. Index of soil sensitivity to degradation in the Ouergha catchment

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