ISSN 2522-9400 **European Modern Studies Journal** Vol 7 No 2
available at www.journal-ems.com
DOI: 10.59573/emsj.7(2).2023.22

Mapping of Soil Losses in the Gheralla Watershed (Eastern Pre-Rif Morocco) Using the RUSLE Model and GIS

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Abstract. Water erosion has become one of the main natural hazards encountered in the Mediterranean mountains. Population growth, land clearing and overgrazing lead to the degradation of the vegetation cover and, consequently, to the increase of the erosive risk, which affects the soil productivity and accelerates the silting up of the dam. The Gheralla watershed is an elongated mountainous basin in the Perif region of northern Morocco and is strongly affected by soil erosion. The objective of this study is to map the erosion risk in order to help decision makers to take the necessary measures. Erosion drivers according to the RUSLE model were integrated into the GIS and combined according to the Universal Soil Loss Equation (RUSLE). The results show that the erosive risk in this basin is critical. Soil losses are estimated at 62.5 t/ha/year. The conclusions are intended for managers for a better management of natural resources, taking into account the agricultural vocation of the area and the need to preserve the hydraulic infrastructure downstream.

Keywords: Soil erosion, RUSLE, GIS, Remote sensing, Gheralla watershed, Morocco

Introduction

Water erosion is a global phenomenon that leads to soil degradation and negatively affects the fertile surface horizons of agricultural land (Li et al., 2022). Soil erosion contributes to about 84% of soil degradation worldwide (Oldeman, 1994). This hazard affects about 1100 million hectares of cultivated land worldwide (Brown, 1984). About 10 million hectares of cropland are lost annually by soil erosion, reducing the amount of arable land available for food production (Pimentel, 2006). Soil erosion is linked to natural factors, in particular the aggressiveness of the climate and the predominance of a fragile lithology (Tribak, 2020). Incompatible human practices, such as deforestation, successive ploughing and exploitation of sloping land, increase the risk of erosion (Eekhout & de Vente, 2022). The Mediterranean region, characterized by a very aggressive climate due to the concentration of precipitation in time and space, is highly threatened by water erosion (FAO, 2022). Soil degradation caused by erosion is projected to increase under climate change, especially the frequency of extreme precipitation events.

The Moroccan territory presents an environment conducive to the risk of water erosion (Jazouli et al., 2019; Lamane et al., 2022; Laouina et al., 2013). Their consequences are multiple: stripping of arable layers, reduction of land productivity, silting of dams, etc. (Heush, 1970). A study of 20 million hectares of land upstream of dams showed that about 25% of this land is exposed to severe water erosion (MADREF, 2001). Specific soil degradation by water erosion exceeds 2 t-ha/year (MAMVA, 1993), with 60% of eroded land concentrated in the Rif mountains (Heusch, 1970). Climate change is expected to greatly increase the erosive risk (Eekhout & de Vente, 2022; Elaloui et al., 2022). Climate projections predict that the Moroccan territory, as everywhere in the Mediterranean rim

countries, will experience a downward trend in annual precipitation and the succession of severe droughts (Driouech et al., 2021), and an upward trend in extreme precipitation (Al Karkouri, 2017; Yadari & Idrissi, 2021). This precipitation causes rapid flooding of valleys and urban areas (Janati Idrissi, 2010), and increases the erosive risk in sloping hillsides, leading to silting of downstream dam reservoirs (Tribak et al., 2021). The increase in extreme precipitation often generated by Atlantic disturbances (Hanchane, 2016), leads to an increase in excess surface runoff by infiltration, and consequently, promotes erosion by runoff and gullying. The degradation of arable land by soil erosion is more directly affected by incompatible human practices implemented locally such as deforestation, successive tillage and exploitation of sloping lands (Grovel, 1996; Al Karkouri, 2017; Zaher et al., 2021). On the other hand, water and soil conservation practices such as reforestation, terraces construction and residue management are often considered as a solution to mitigate soil loss through erosion (Laouina et al., 2013). Thus, these practices can provide additional ecosystem services, including carbon sequestration that contribute to climate change mitigation (Eekhout & de Vente, 2022). The Gherrala watershed located in the eastern Pre-Rif presents a very vulnerable environment and is prone to erosive processes due to the combination of physical (steep slopes, aggressive rainfall, no vegetation cover, predominance of soft rocks... etc.) and anthropogenic factors (overexploitation, grazing, clearing, etc.). In this basin, erosion takes several forms, generates enormous soil losses, and exceeds the tolerance threshold, which has contributed to the acceleration of the silting of the Idriss I dam downstream.

To address this problem, the scientific community has developed methods and models to quantify and classify erosion-prone areas in order to determine priority areas for intervention. The Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978) is the most widely used mathematical model for predicting sheet soil erosion in the world. The integration of the factors of this model into the GIS allowed the identification of the impact of each factor on soil losses, the ranking of the relative importance of erosion areas and the quantification of soil losses (Sadiki et al., 2004). This model was used in many studies of Morocco (Aroussi et al., 2011; Faleh et al., 2012; Chadli, 2016; Jazouli et al., 2019; Meliho et al., 2020; Tribak et al., 2021; Okacha et al., 2023). The objective of this study is to (i) map the causal factors of water erosion using GIS and spatial remote sensing, (ii) quantify soil losses by integrating the universal soil loss model of Wischmeier and Smith (1978) (iii) hierarchise the degree of vulnerability in order to help decision-makers to take the necessary measures for a better sustainability of natural systems.

Materials and Methods

Study Area

The Gheralla watershed is located in the eastern Prérif in northern Morocco (Figure 1). The shape of Gheralla is elongated with an N-E S-W direction; it is characterized by a complicated topography whose altitudes vary between 1236 m at the upstream and 525 m at the outlet. This area is a tributary of Oued Lahdar that is in turn a tributary of Inaouene River, and administratively it covers the territorial Had M'sila community.

The Gheralla watershed, which crosses the rural commune of Had M'ssila, is a tributary of the Lahdar River. The hydrological regime is generally perennial upstream and seasonal and episodic downstream. The dominant climate is semi-arid Mediterranean and is characterized by irregular and brutal rainfall. The heaviest rainfall is concentrated in a few days of the wet season or even in a few hours; the succession of exceptional rainfall events constitutes a real source of risk threatening the study area. The predominantly rural population of the area has declined considerably in recent decades. The study area has

experienced intense pressure on natural resources, particularly through forest clearing and the expansion of the agricultural domain where the local population depends on food crops and pasture as their main agricultural activities. Several types of land use coexist, including forest (Aleppo pine and holm oak), degraded matorral, annual crops, fruit crops (apricots, almonds, figs, etc.), olive groves and fallow land.

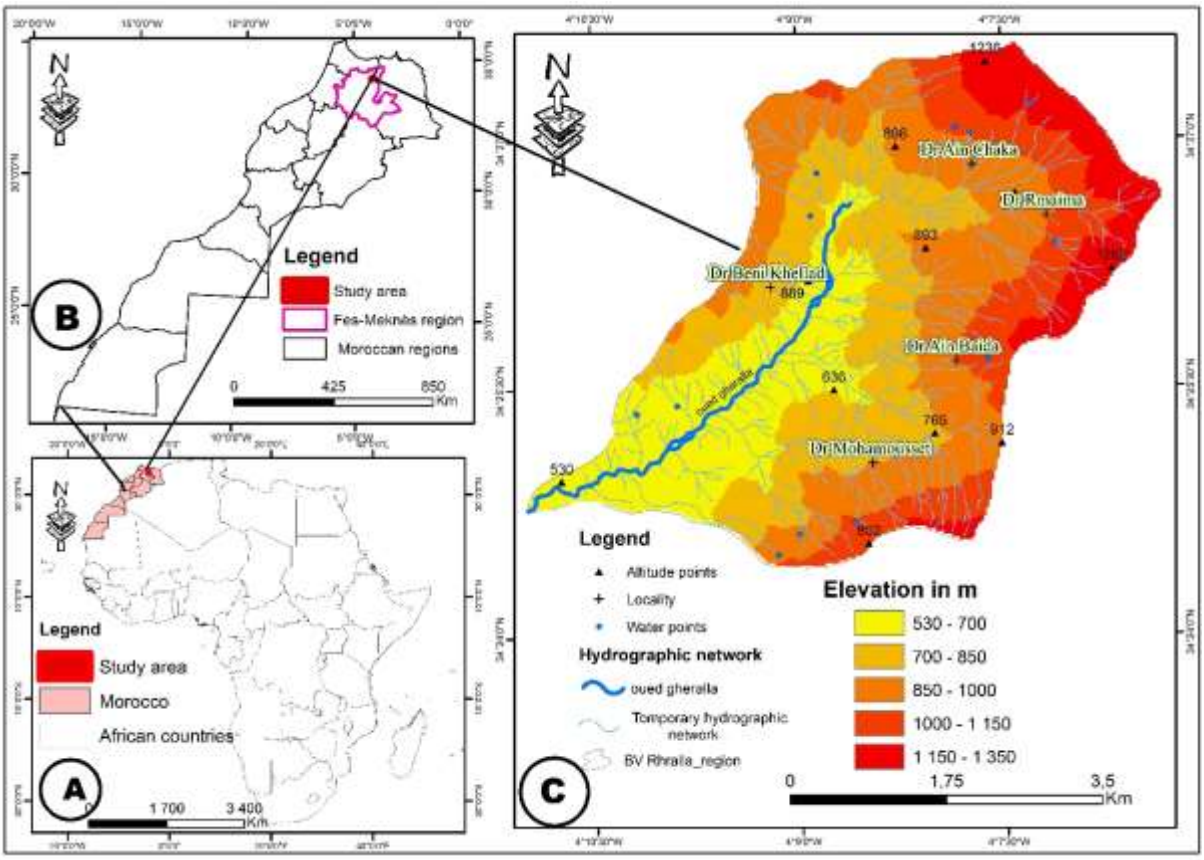

Figure 1. Study area

Data

The data used to map the soil loss are as follows:

- The topographic map (Tainaste 1:50000) and digital terrain elevation model (DEM) downloaded from the site https://earthexplorer.usgs.gov/ and subsequently used to extract the physiographic factors of the study area (altitude, slopes, LS factor);
- Series of rainfall data (1980-2017) were collected from the Sebou basin Agency to characterize the rainfall erosivity factor;
- The soil map of Tainaste (1:50000) as prepared by the Department of Agriculture in 1996 and the physico-chemical analyses were used to produce the soil erodibility map;
- The land use/cover map (LULC) has been produced by Processing Landsat images (OLI 8, date 13/05/2021) with a spatial resolution of 30 m, downloaded from the website https://earthexplorer.usgs.gov/. The accuracy of the classification was confirmed by field observations and the use of Google Earth images;
- The land conservation and management map has been produced based on our field observations.

Methodology

In this study, the estimation of soil loss in the studied catchment was based on the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (1978). Five factors generating sheet erosion were developed and spatialized in maps. These factors were combined according to the following formula (Eq. 1).

$$A=R*K*LS*C*P \qquad \text{(Eq. 1)}$$

Where A is the annual soil loss rate in t/ha^{-1}/year^{-1}. R is the rainfall erosivity index. K is the soil erodibility index. LS is the topographical factor representing the slope (s in %) and the length of the slope. C is the vegetation cover index. P is the conservation and management practices (Figure 2).

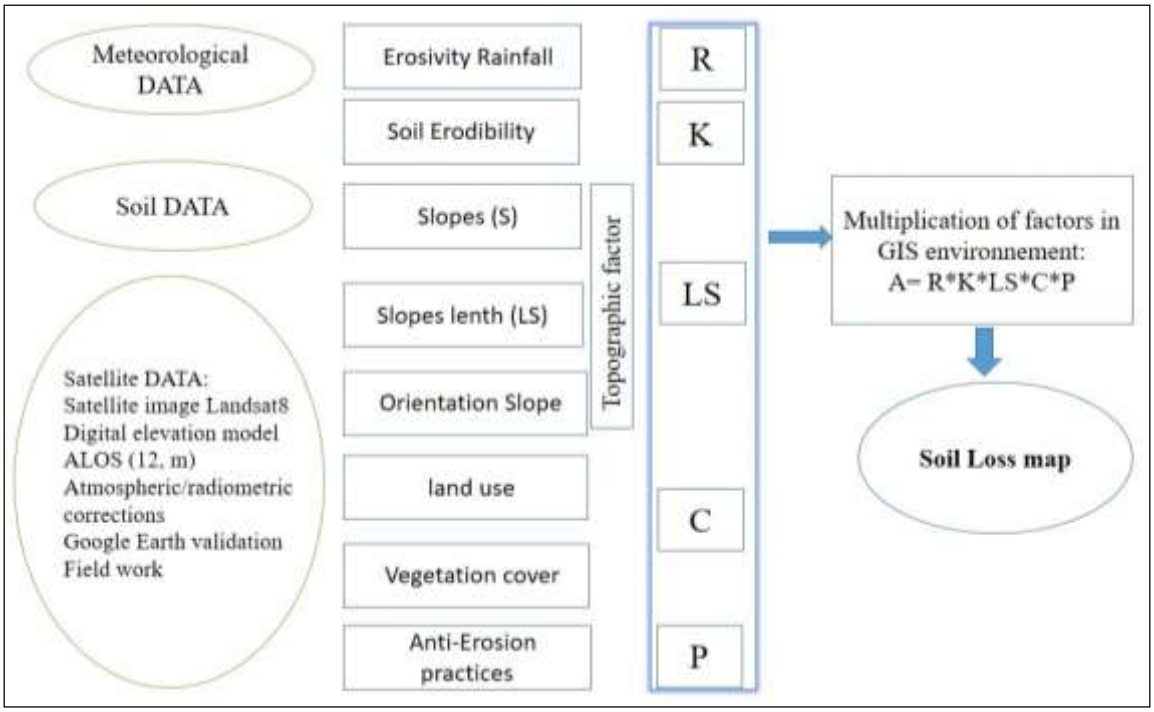

Figure 2. Methodological flowchart

The rainfall erosivity is considered as a factor for accelerating water erosion, surface erosion is related to the intensity of precipitation and the high volume of fragmentation of soil elements is proportional to the intensity of precipitation and not to its quantity. Among the existing formulas for the calculation of the rainfall erosivity factor (R), we used the one of Rango and Arnoldus (1987), which takes into account monthly and annual rainfall according to the following formula (Eq. 2):

$$\log R = 1{,}74 \log\left(\frac{Pi^2}{P}\right) + 1{,}29 \qquad \text{(Eq. 2)}$$

Where R is the rainfall erosivity. Pi is the monthly precipitation. P is the annual precipitation. The soil erodibility factor is the erosion rate determined experimentally under standard conditions (Wischmeier & Smith, 1978). The calculation of this factor according to the RUSLE equation combines four parameters, namely organic matter, soil texture, soil structure and permeability. The calculation of soil erodibility was based on the formula developed by Wischmeier and Smith (1978) according to the following equation 3.

$$K = \left\lfloor 2{,}1*10^{-4}(10-OM)*M^{1{,}14} + 3{,}25*(S-2) + 0{,}25*(P-3) \right\rfloor / 100 \qquad \text{(Eq. 3)}$$

Where OM is the organic matter content of the soil. M is the texture calculated by the following formula: (% fine sand + silt) × (100 - % clay). S is the soil structure. P is the permeability percentage.

The physico-chemical analyses of the soil (organic matter, clay, sand, silt and structure) were taken from the report on the study of the soils of the North-East region drawn up by the Directorate of Agriculture (SETE) and from analyses carried out at the geo-environmental analysis laboratory (LAGEA-DD, USMBA). The permeability is obtained from field measurements obtained by some studies in the region (Abahrour et al., 2009; Trbak et al., 2009).

The topographic factor (LS) is a key factor in erosion intensity and is defined as the length and slope steepness. The (LS) factor is calculated from the DEM and the slope length and slope steepness according to the following formula (Eq. 4).

$$LS = \left(L/22.13\right)^{m}.\left(0.065 + 0.0456(s) + 0.006541(s)^{2}\right) \qquad \text{(Eq. 4)}$$

Where LS is the length and slope factor (dimensionless). L is the length of the slope in (m). S is the slope steepness in (%) and m is a parameter that varies with the slope.

The C-factor used to determine the density of vegetation cover, the relative efficiency of major cropping systems and soil management. In order to be able to assess the different vegetation cover units in the Gheralla watershed, it is necessary to map land use based on fieldwork and data use. The Landsat (2021) imagery (OLI-8) was used to classify the land cover. This image was radiometrically corrected using the FLAASH model in ENVI software. 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).

The P factor represents soil protection and anti-erosion practices that reduce the speed of runoff and thus reduce the risk of water erosion. It varies according to the development carried out. The values of this factor generally vary between 0.5 in the developed and protected areas and 1 where the protection and development of soils and slopes are almost absent.

Results

The use of the RUSLE Model approach permitted the mapping of soil loss and the hiearachisation of the degree of degradation in the Gherrala watershed. The results are presented in the form of maps illustrating the weighting of indices influencing the soil degradation process.

Rainfall Erosivity Factor (R)

The erosion factor is calculated from monthly and annual rainfall data from the Had Msila rainfall station. The results are presented in Figure 3-R. The average value of R is 68.28. This value is slightly higher than that found by several authors in Morocco. Indeed, Faleh (2004) reported that the average value of R in the Aknoul catchment is 54. Thus, this value oscillates between 40 and 50 for the Boussouab basin in the Eastern Rif (Sadiki et al., 2004) and between 40 and 56.3 for the Telata watershed in the pre-Rif area (Abahrour, 2009). This means that the study area has a slightly higher climatic aggressiveness than the other regions of the Rif, due to its direct exposure to Atlantic wet disturbances. The frequency of extreme rainfall events, often of thermo-convective origin, constitutes a factor generating erosion. Thus, these rains, which can exceed 80 mm/day in certain showers (Tribak, 2020), occur at the end of the study period or at the beginning of autumn, making the environment very sensitive to erosion due to the long summer period.

Soil Erodibility Factor (K)

The soil erodibility factor is calculated by using the formula developed by Smith. The results are shown in Figure 3-K and their areas are presented in Table 2. They show that soil erodibility increases with the value of the (K) factor. In general, the value of the (K) factor is

high; there will be a high susceptibility of the soil to erosion. Soil erosion susceptibility values vary from 0.27 for calcimagnesic soil to 0.46 for isohumic soil, due to the difference in organic matter content and soil texture. These parameters change according to the type of land use and exploitation mode (Roose, 1992). Isohumic soils are very sensitive to erosion when their K-factor is higher than 0.46% due to their low organic matter content (0.95%) and their high content of fine silt and sand (58.60%). Tribak, (2020) shows that studies that fine silt and sand rich soils are very susceptible to water erosion. While calc-magnesian soils recorded low K values, due to their moderate OM content (1.44%) and moderate clay content (29.20%).

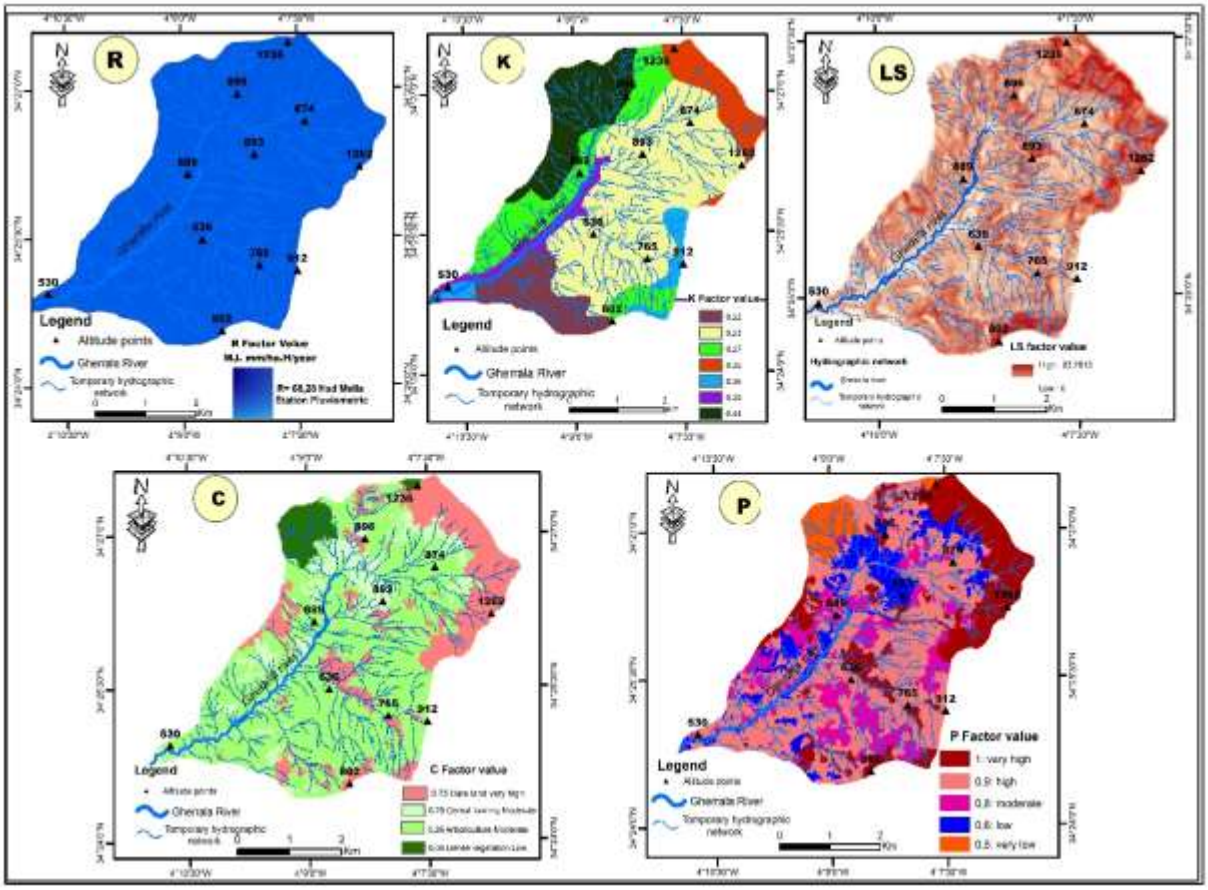

Figure 3. Spatial distribution of soil erosion factors in the Gherrala watershed (R: Rainfall erosivity. K: Soil Erodibility. LS: Topographical factor. C: Vegetation cover index. P: Conservation practices.

Topographic Factor (LS)

The LS factor is a topographic index that represents the morphology of the terrain. It is calculated from the Digital Terrain Model by superimposing maps of slope lengths and slope gradients. The slope has an important influence on the process of water erosion. It aggravates the effect of rainwater runoff. The results obtained for LS vary between 0 and 82.26. The highest values are located in the upstream part of the Gheralla basin and on hills with very high slopes (Figure 3-LS). The values that are considered low are assigned in the downstream part near the outlet of Gheralla and in the streambeds.

Vegetation Cover Factor (C)

This factor represents the effect on soil losses. Several types of land use coexist in the Gheralla watershed, there are forests (*Pinus halepensis, Pinus pinaster, Quercus rotundifolia, Tetraclinis articulata, Arbutus unedo*... etc.), degraded Matorral, annual crops (hard and soft wheat, barley and beans), fruit crops, olive trees and wasteland. The results of the C factor obtained for the Gheralla watershed are given in Figure 3-C. It varies according to the change in land use and cover rate. It varies from 0.08 as the minimum value for dense forest to 0.75 as the maximum value for bare land.

Soil Conservation Practices Factor (P)

The local populations of the study area have been able to set up and develop or improve certain traditional techniques allowing to gain cultivable surfaces and to stabilize the degradation processes. These interventions vary from one region to another depending on the material possibilities of the farmers and the spatial difficulties (slope, lithological nature, etc.).

P-factor map shows that uncultivated lands are affected by all forms of water erosion due to the absence of human exploitation that can protect the soil, followed by annual croplands that experience irrational overexploitation leading to the aggregation of surface formations during the first autumn rains (Figure 3-P).

Soil Losses

The soil loss map was obtained by combining 5 factors controlling erosion risk (climatic aggressiveness, vegetation cover, soil erodibility, LS). Soil losses were classified according to the loss tolerance of the land established in the USA. This classification assumes that, on average, soils can tolerate losses of up to 7.41 t/h/year and still allow a high level of agricultural production. Above 20 t/h/year, the loss is high and the soils severely degraded, which can affect production. Based on this classification, four classes of soil losses were established; low losses (<7 t/h/year), medium losses (between 7 and 20 t/h/year), high losses (between 20 and 32 t/h/year) and critical losses (> 32 t/h/year). The distribution of these classes in the catchment area is presented in the map (Figure 4) and the proportions of each class are given in Table 1.

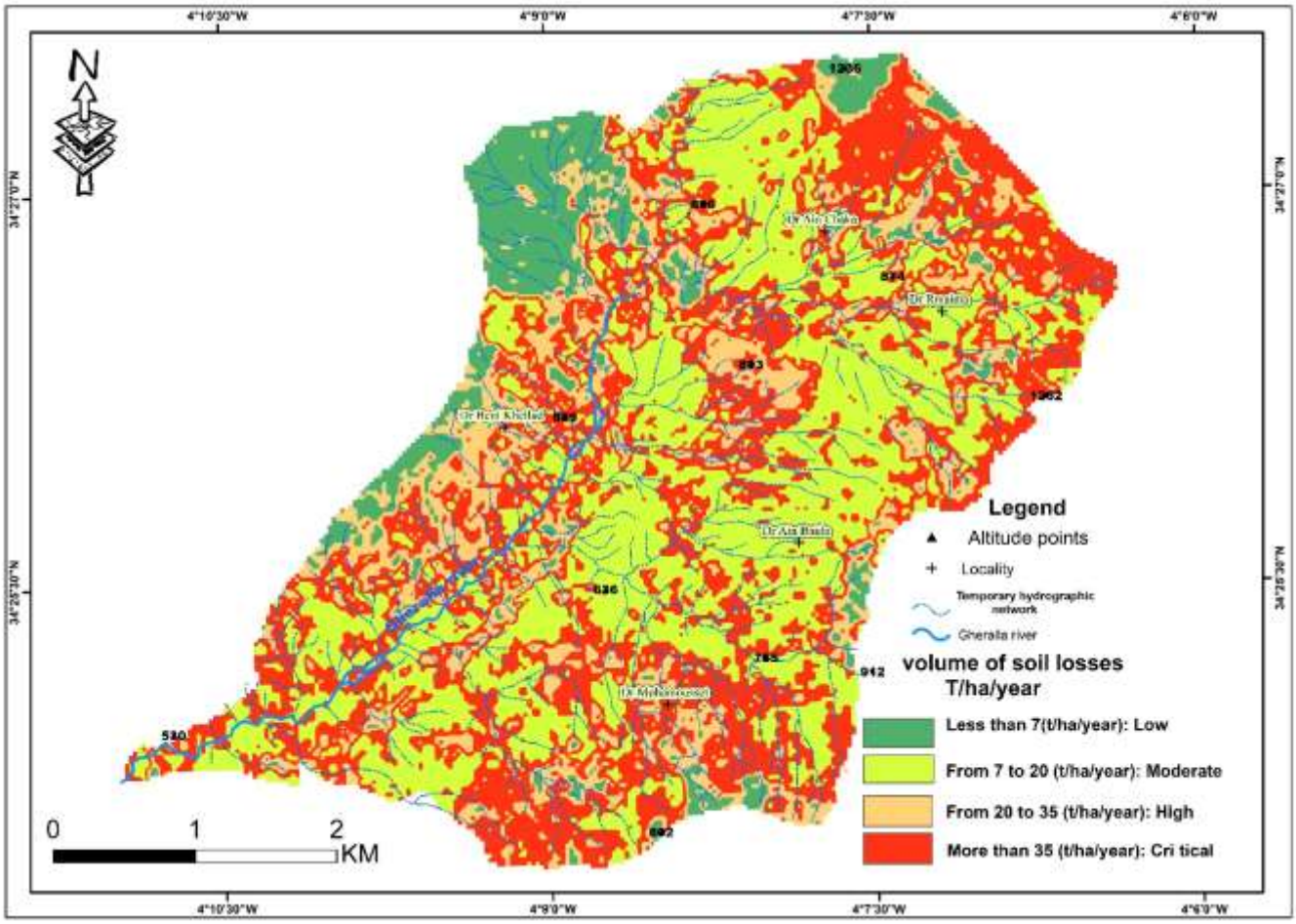

Figure 4. Spatial distribution of soil losses in the Gheralla watershed

Table 1. Proportion of each soil loss category

Erosion class	Soil loss (t/h/year)	Area km^2	Area %
Low	<7	1,97	8,89
Moderate	7-20	8.51	38,30
High	20-35	3.57	16,08
Critical	>35	8.15	36,70
Total	-		100

The soil loss is enormous and exceeds the tolerance threshold. The average of this loss is estimated at 62,2 t/h/year and oscillates between 7 t/h/year as minimum value and 125 t/h/year as maximum value. The spatial distribution of soil loss classes in the study area shows that the areas weakly affected by sheet erosion are the most extensive with 8.89% of the total surface area of the study. The critical and highly endangered areas that require priority interventions cover 36.70% and 16.08% of the total catchment area respectively, while the moderately affected areas occupy 38.30% (Table 1).

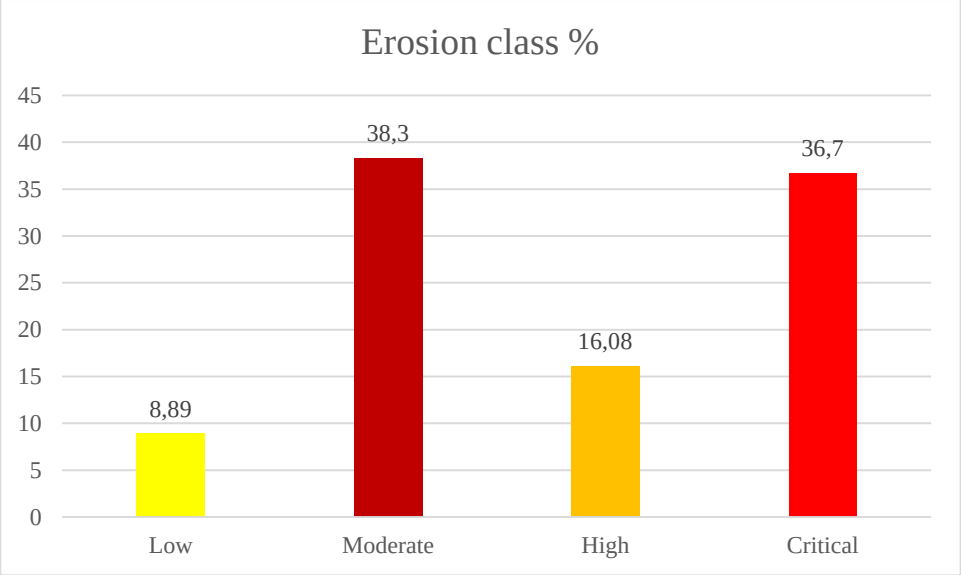

Figure 5. Rate of each degree of soil losses in the Gheralla watershed

Discussion

This study focuses on mapping the causal factors of erosion and quantifying soil losses in the Gheralla basin in the eastern pre-Rif based on the universal soil loss equation. Five causal factors of water erosion (Rainfall erosivity, Soil Erodibility, Topographical factor, Vegetation cover index, Conservation and management factor) were integrated in the GIS to elaborate the soil loss map. The estimated soil loss averaging 62.2 t/hr/year in this study is consistent with other studies conducted in the same context of the Rifan Mountains characterized by aggressive climate, friable lithology, and low vegetation cover. Indeed, Tribak et al. (2012 a) reported that soil losses reached 61,42 t/h/year in the Telata watershed in Northern Morocco. In the same context, Sadiki et al. (2004) recorded that the average soil loss is 55.35 t/h/year. Thus, Benzoughagh et al. (2020) found that the Inaouen watershed is characterized by medium climatic aggressiveness and medium to highly eroded soil with a loss ranging from 50 to 150 t/h/year. Soil loss amounts to 38 t/h/year in the Nekor catchment where the land is moderately resistant and vegetation cover is high (Okacha et al., 2023).

In order to find correlations between soil loss and causal factors 80 random points were generated by the GIS tool. The values of slope, LS factor, soil erosion, C factor, were extracted for each point, and then a regression analysis was performed. The relationship between soil erosion and vegetation cover shows a significant correlation (R^2: 0.58%), and revealed that vegetation cover plays an important role in reducing soil erosion. Three classes of NDVI were established; low cover (NDVI <0, 25), moderate cover (0, 25<NDVI<0, 45) and high cover (NDVI > 0, 45). These classes cover respectively 76, 14%, 14, 6% and 9, 60% of the total surface of the study area. More than 75, 4% of critical soil loss corresponded to the low NDVI class, while 44, 9% of low losses were recorded in the high NDVI. Several studies have reported that high soil loss corresponding to low NDVI (Khademalrasoul & Amerikhah, 2020; Meliho et al., 2020). The distribution of erosion according to soil types shows that low erosion values is found above the conserved forest areas (1,76 t/h/year) and in the matorrals (1,85 t/h/year). The vegetation cover presents good soil protection against the destructive forces of raindrops that cause soil sealing, crusting and erosion (Al Karkouri et al., 2000; Sabir et al., 2004; Zaher et al., 2021). Bare land occupies about 16.35% of the study area, with high losses (81,73 t/h/year). This is due to low soil OM and low vegetation cover. This land has a considerable tendency to increase due to the abandonment of the land by the local population because of its low agricultural productivity. The estimated average loss for

cereal land, which occupies the average of the study area (49.9%), is the 38.28 t/h/year. These lands are subject to successive ploughing which mineralizes OM and weakens soil stability and makes the soil very sensitive to erosion (Moussadek et al., 201; Bensaleh et al., 2012; El-Ommal & Tribak, 2023).

Table 2. Relationship between soil erosion and land use in the Gheralla watershed

Land use	Area %	Soil loss classes t/h/year (area %)			
		Low	Moderate	High	Very high
Forest	3,99	2,51	1,48	-	-
Matorral	1,69	1,02	0,27	0,15	0,26
Olive trees	12,65	5,58	1,49	4,18	1,40
Crops and plantations	15,11	8,92	1,40	3,61	1,17
Annual crops	50,12	26,14	5,19	12,82	5,96
Bare soil	16,43	0,71	0,13	0,75	14,84

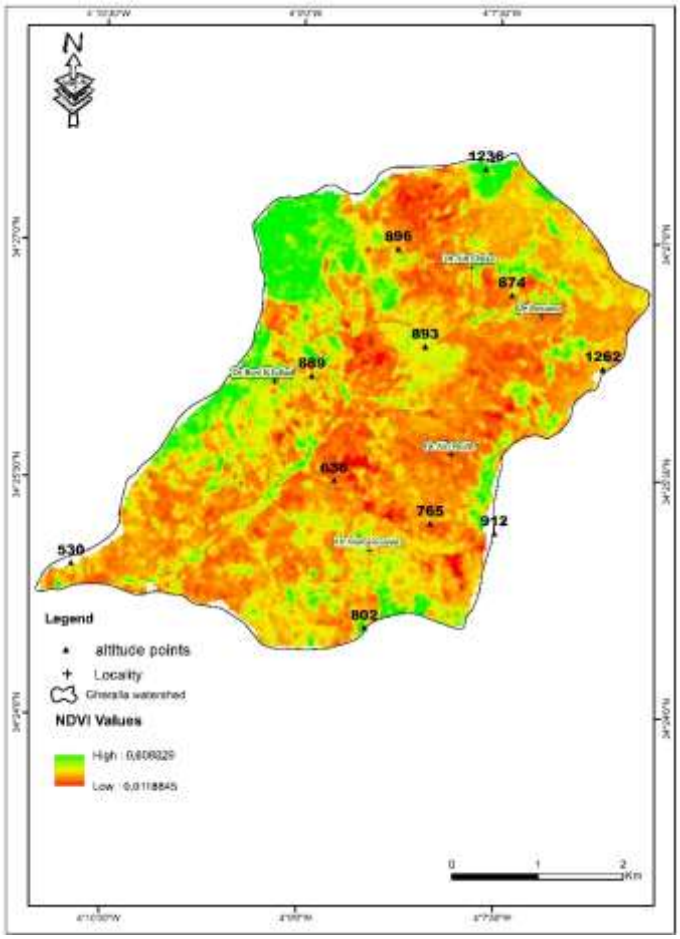

Figure 6. NDVI values

Table 3. Relationship between soil erosion and slope degree in the Gheralla watershed

Slop degree (°)	Area %	Soil loss classes t/h/year (area %)			
		Low	Moderate	High	Very high
<5	5,10	2,08	1,12	1,16	0,75
5-15	23,98	23,64	6,09	9,78	8,11
15-25	36,71	15,70	3,44	8,60	8,98
25-35	17,51	2,27	3,52	6,38	5,34
> 35	16,71	0,21	2,05	9,31	5,14

The analysis of the relationship between soil erosion and the degree of slope shows a high positive correlation coefficient (R^2: 0.62). More than 16% of the catchment area has a slope greater than 35%, of which 9.31% is affected by high erosion and 5.14% by critical erosion (Table 3). On slopes with a low gradient, the proportion of high and critical loss is low, at 1.16% and 0.75 respectively. There is also a strong correlation between the LS factor and soil loss (R^2:0.59). This finding implies that steeply sloping areas with high values of the LS-factor are very vulnerable to soil erosion, especially in areas without vegetation (photo 1 and 2). These results are consistent with studies conducted in other regions (Arrebei et al., 2020; Naimi et al., 1998; Okacha et al., 2023).

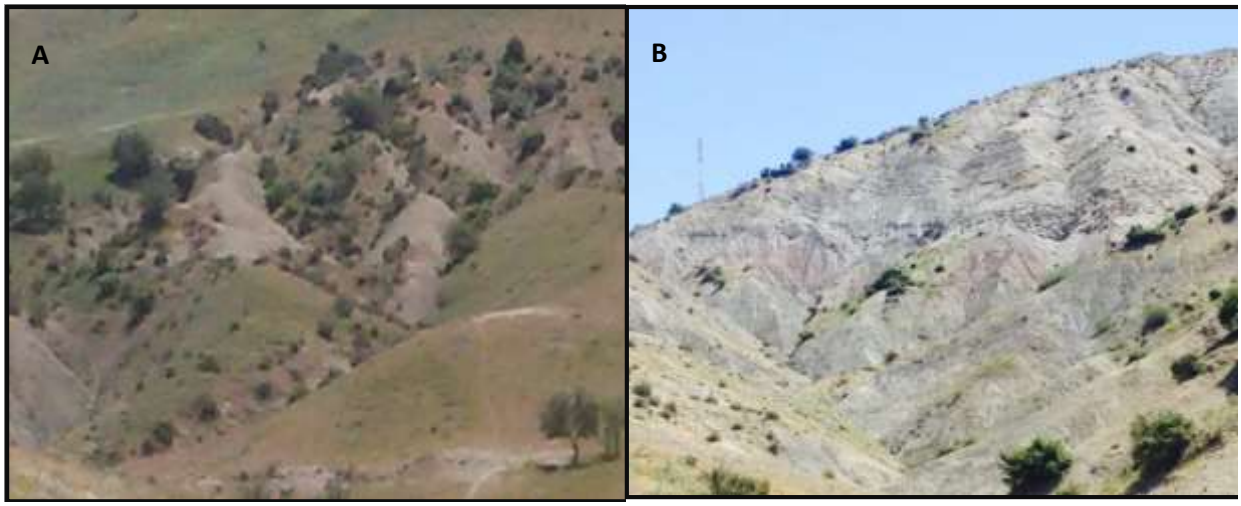

Figure 7. Soil completely denuded by erosion, A: U-shaped gully flank firewood, B: the steep slopes and appearing as badland

However, the Universal Soil Loss Equation (RUSLE) has some limitations. It only applies to sheet erosion, since the energy source is rainfall. It never applies to linear erosion or mass erosion. It considers the erosion factors as independent, whereas there are many interactions between them. Impossibility to estimate land loss over a short period of time (season or single rainfall event). Despite these shortcomings, it remains a management and planning tool for decision makers. These limitations can be corrected and the GIS should be integrated and adjusted. This allows mapping of erosion risk areas requiring priority intervention strategies.

Conclusions

The results obtained by applying the RUSLE model to map erosion in the Gherrala watershed indicate that this watershed is strongly affected by sheet erosion. The average soil erosion estimated for this basin was 62.2 t/h/year with a variation of 7 t/h/year to 125 t/h/year.

The spatial distribution of erosion implies that this area is subject to critical erosion and exceeds the tolerance threshold. The high and critical erosion classes occupy 36.7 % and 16.08 % of the total area respectively. The vulnerability of the soil in this area to erosion is due to the climatic aggressiveness, dominance of erodible soils, low vegetation cover and steep slopes. These losses contribute to the silting up of dams and deprive the soil of its production potential.

In this context, a set of measures should be put in place to reduce soil conservation against water erosion. This should prompt decision makers to seek viable solutions focused on safeguarding and rehabilitating forest ecosystems, planting bare slopes, and socio-economic development.

Conflict of Interest

The authors declare that there is no conflict of interest.

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