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Quantification de l'érosion des sols par le modèle USLE dans le bassin versant de l'Oued Za (Nord-Est du Maroc)

Quantification of soil erosion by USLE model in the Oued Za watershed (northeastern Morocco)

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Abstract. The watershed of Oued Za, is the main tributary of the Oued Moulouya (the most important Moroccan river, which flows into the Mediterranean Sea). The Oued Za drains three large distinct units forming a watershed with an area of 15884 km2. This watershed is characterized by a semi-arid climate, scarce and irregular rainfall combined with low vegetation cover, which causes water erosion. The main objective of this study is to integrate thematic maps of different factors of the Universal Soil Loss Equation (USLE) into a Geographic Information System (GIS) with their databases. The results indicate that for the Oued Za watershed, the average soil loss is 2.91 t/ha/year. The methodology and results provide a decision support system for stakeholders in the region.

Keywords: Soil erosion, Oued Za, USLE, GIS, Eastern Morocco.

Résumé. Le bassin versant de l'Oued Za est le principal affluent de l'Oued Moulouya (le plus important oued marocain qui se jette dans la mer Méditerranée). L'Oued Za draine trois grandes unités distinctes formant un bassin versant d'une superficie de 15884 km2. Ce bassin versant est caractérisé par un climat semi-aride, des précipitations rares et irrégulières combinées à une faible couverture végétale, ce qui provoque l'érosion hydrique. L'objectif principal de cette étude est d'intégrer les cartes thématiques des différents facteurs de l'équation universelle de perte de sol (USLE) dans un système d'information géographique (SIG) avec leurs bases de données. Les résultats indiquent que pour le bassin versant de l'Oued Za, la perte moyenne de sol est de 2,91 t/ha/an. La méthodologie et les résultats fournissent un système d'aide à la décision pour les parties prenantes de la région.

Mot-clés : Erosion des sols, Oued Za, USLE, SIG, Maroc Oriental.

INTRODUCTION

Soil loss due to erosion is a global problem, especially affecting natural resources and agricultural production (Bakker *et al*. 2005, Ighodaro *et al*. 2013, Parveen & Kumar 2012, Pimentel 2006).

Water erosion is a very frequent phenomenon in the countries of the Mediterranean region and it takes considerable proportions of the soil (Khali Issa *et al*. 2016). In Morocco, water erosion is the main cause of degradation of the soil and the environment. It affects, with varied intensities, about 40% of land in Morocco (FAO 1990). Annual soil loss exceeds 20-ton ha−1 year−1 in the Mountainous regions of northern Morocco and varies between 10- and 20-ton ha−1 year−1 in the Pre-Rif regions and 5- and 10-ton ha−1 year−1 in Middle and High Atlas regions (MAEF 2001). Several natural and anthropic factors contributing to the initiation and development of erosion processes: a fragile ecosystem due to the aggressive climatic and irregularity of rainfall, and fragile geological substrates especially in the northern and eastern regions.

Assessing soil erosion risk in the watershed requires mapping and analyzing the many factors involved in the erosive process: rainfall aggressiveness, slope degree and length, soil erodibility, vegetation cover, and erosion control practices. Each factor behaves differently in different parts of the watershed. We chose the USLE method (Wischmeier & Smith 1978), which is the most widely used for the quantification of surface erosion. This choice is dictated by the fact that the data necessary for the application of USLE are available for the Oued Za watershed. The aim of the study is to elaborate a set of thematic maps presenting the results of the analysis of the different factors involved in the erosion phenomenon, as well as potential erosion maps. In addition, the identification of erosion factors and areas vulnerable to soil erosion could be very useful to assess the expansion and degree of risk and, ultimately, to develop measures and soil conservation and water management plans.

METHODOLOGY

The empirical formula of Wischmeier & Smith (1978) $A = R^* K^* LS^* C^* P$ is used to estimate the soil loss rate. It is the mathematical model combined with GIS techniques, often used in the world to quantify soil loss. It is based on five (05) explanatory factors of water erosion. These factors are: R is the rainfall erosivity factor; it corresponds to the annual average of the sums of the products of the kinetic energy of the rain by its intensity in 30 consecutive minutes; it is expressed in (MJ.mm/ha.h). K is the soil erodibility; it depends on the granularity, the quantity of organic matter, the permeability and structure of the soil; it is expressed in (t. h/MJ.mm). LS is a unitless factor that represents the slope degree (S in %) and the slope length (L in m). C is a unitless factor that represents the effect of vegetation cover, P, a unitless factor, is a ratio that takes into account anti-erosion cultivation techniques such as contour plowing (Fig. 1).

The analysis and evaluation of each of these factors require several analysis and processing operations to obtain maps of the erosion factors of Oued Za. The integration of these maps in the Geographic Information System (GIS) allowed the evaluation of the erosion rate at all points of the watershed and the elaboration of the synthetic map of soil losses according to the methodological flow chart (Fig. 1).

For the R factor, we used the climatic data of nine (9) weather stations: Ain Bni Mathar, Guenfouda, Guefait, Oued Za dam, Laayoune Taourirt, Melga El-Ouidane, Melloulou Geurcif, Tendrara, by interpolating the data of R under ARCGIS software sing the command (Raster interpolation) in order to obtain a raster map of factor R.

Rainfall is the driving force behind erosion, the R coefficient requires knowing the distribution of rainfall over the entire watershed area. To calculate this factor there are different methods. For this study it is calculated according to an equation developed by Wischmeier & Smith (1978) and modified by Rango & Arnoldus (1987), it only concerns the annual and monthly rainfalls to determine the R factor:

$$\text{Log } R = 1.74.\ \text{Log} \sum (Pi^2 / P) + 1.29$$

Where:

- R is the rainfall erosivity factor (MJ-ha-1 .h-1. yr-1),
- Pi is mean monthly precipitation (mm), i from 1 to 12,
- P is mean annual precipitation (mm).

Rainfall erosivity values over the period 2000 to 2017 interpolated using the Geostatistical Analyst command on ARCGIS software to obtain a raster map for the R factor.

Topographic factor (LS) is the slope length gradient factors comprising L, slope length, and S, slope steepness (Panagos *et al.* 2015). LS-factor map was produced in the ARCGIS environment from the digital elevation model (DEM). The equation derived by Mitasova *et al*. (1996) was adopted:

$$LS = [(Flow.Ass \times Résolution) / 22.1]^{0.4} \times [((pente \times 0.01745) / 0.0896]^{1.4} \times 1.4$$

Where flow accumulation is a raster of accumulated flow to each cell and grid size is the length of a cell side.

The soil erodibility factor (K) represents the effect of soil properties and soil profile characteristics on soil loss. K is strongly related to the physical properties of the soil, plays an important role in soil conservation strategies (Shabani *et al*. 2014), and reflects the rate of soil loss per rainfall erosivity index (Parveen & Kumar 2012).

The C factor is a dimensionless factor representing the effect of vegetation cover on erosion (Prasannakumar *et al.* 2012). This factor ranges from 0 (densest cover) to 1 (no ground cover). It can be estimated from the Normalized Difference Vegetation Index (NDVI) using satellite imagery Landsat 8.

$$NDVI = (PIR - RED) / (PIR + RED)$$

Where:

- NDVI: Normalized Difference Vegetation Index,
- PIR: The intensity of light in the near infrared,
- RED: The intensity of light in red channels.

The following formula proposed by Van der Knijff *et al*. (2000), Van Leeuwen *et al*. (2004) and Prasannakumar *et al*. (2012) was used to generate the C-factor from the NDVI values.

$$C = exp\ [-a \times NDVI / b - NDVI]$$

Where:

- a, b are parameters determining the shape of the NDVI-C curve with a = 2 and b = 1

The factor P describes the soil-conserving human actions that are practiced to counteract water erosion. Contour, alternate strip or terrace cropping, bench reforestation and ridging are the most effective soil conservation practices (Koussa & Bouziane 2018, Benzougagh *et al*. 2020).

STUDY AREA

The watershed of Za is the main tributary of the Oued Moulouya (the most important Moroccan river that flows into the Mediterranean Sea). It is located in the eastern region of Morocco (Fig. 2), covering an area of approximately 15884 km² and a perimeter of 970 km. It is delimited by the horsts chain to the north, the Rekkam plateau to the west and the high plateau to the south.

The dominance of soft lithological facies, composed of essentially poorly evolved soils from alluvial and/or colluvial contributions, characterizes the region, where the texture is silty to sandy-silty, leading sometimes to a strong threshing, the fine and coarse structures follow one another according to the edaphic conditions (surface crust). The soils are very poor in organic matter.

The geographical location, the spatio-temporal distribution of rainfall, the diversification of the relief forms, confer to the Za watershed a diversification in the plant material well appreciated. Indeed, there is a need to find species characteristic of different ecosystems and a well-defined spatial distribution.

Due to its position, the Oued Za watershed enjoys a Mediterranean climate of semi-arid type. The average annual rainfall for the period 1980-2017 varies from one station to another.

The average temperatures are around 15 to 20°C. The coldest month is January – February, where the average temperatures are around 5°C in Ain Bni Mathar and 10°C in Taourirt. The hottest period of the year is obviously the summer, especially the months of July and August.

The altimetry in the study area varies between 283 m and 1800 m (Figs. 3–4), with an average of 1201.85 m. The low altitude is located at the outlet of the watershed which is the Hassan II dam, while the highest altitude is 15 km (as the crow flies) north of the dam, just before Jbel Boukhwali where the summit rises to 1728 m.

The morphometric parameters evaluated in the study site (Tab. 2) show that the compactness index of Gravelius KG is equal to 2.16. It reflects a relatively elongated shape and

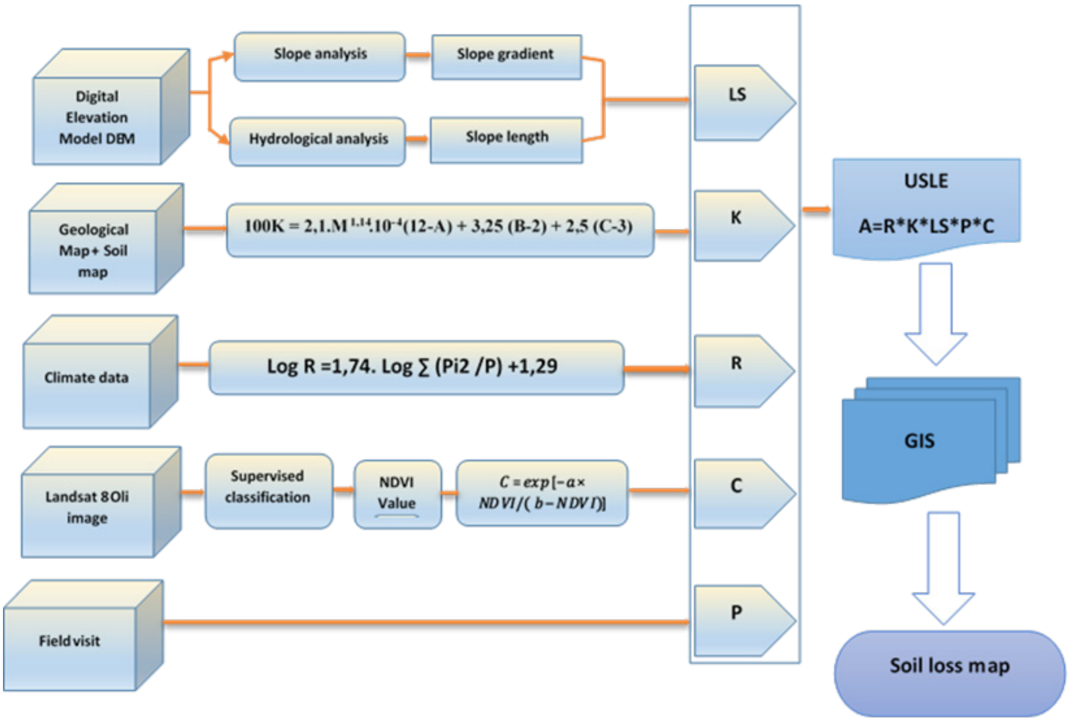

Figure 1. Methodological flowchart of the integration of the Universal Soil Loss Equation in the GIS.

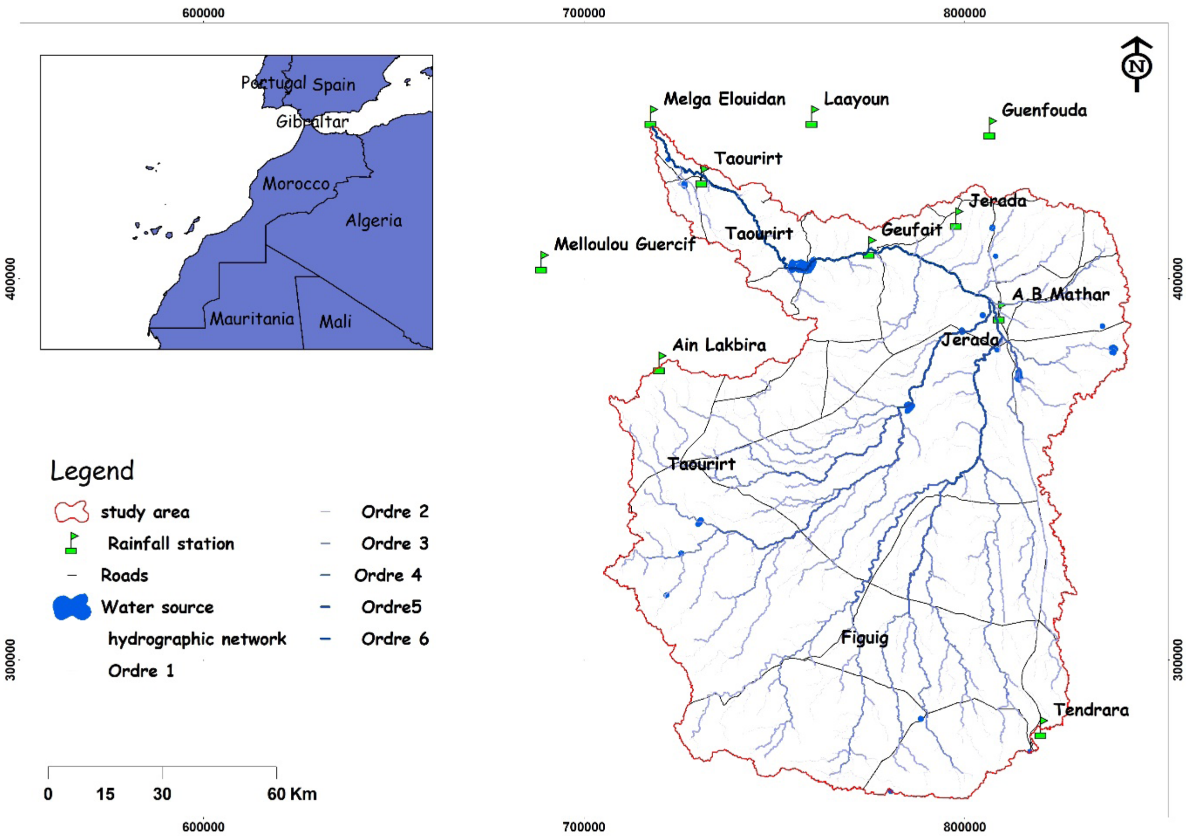

Figure 2. Map of localization of the Za watershed.

Table 1. Average annual rainfall of the Za watershed.

Stations	X (m)	Y(m)	Average annual rainfall (mm)
Taourirt	731447	427010	193
Ain Bni Mathar	809200	391300	241,8
Guafait	775100	408275	216,7
Tendrara	821248	299450	138,9
Guenfouda	806750	439600	251,8
Melga El Ouidane	716937	442370	182.1
Laayoune	765422	446578	269.6
Melloullou Guercif	689000	404400	182.2

favors low peak flows. The dimensions of the equivalent rectangle are: length L=450.17 Km and width l= 35.28 Km.

Table 2. Morphological characteristics of the Oued Za watershed.

Watershed area (km^2)	15884
Watershed perimeter (km)	970
Length of the equivalent rectangle (km)	450.17
Width of the equivalent rectangle (km)	35.28
Mean altitude (m)	1201845.41
Stream length (km)	90.94
Minimal altitude (m)	283
Time of concentration (h)	0.73
Mean slope (%)	20.20
Median elevation (m)	1400
KG Index	2.16

From a geological point of view, the watershed is formed by Paleozoic formations that represented essentially by shales and coal beds. They outcrop partly in the Mekam buttonhole (N-W) and Jerada in the North. The marly and basaltic formations of the Permo-Triassic outcrop on the periphery of the primary massif. The Jurassic series, which then begins with the Lias which is deposited either normally on the Triassic or in discordance (absence of the Triassic in the northern part of the horsts). It occurs as limestone and dolomitic limestone. The Lias constitutes the aquifer of the captive water table of Ain Béni Mather. The Cretaceous begins everywhere by a conglomerate formed of bedded banks, followed by sandstone, continental red marl and oolitic limestone. The Tertiary is constituted by continental formations: alternating clay, sand and flinty lacustrine limestone. The Quaternary occupies huge areas largely covered by superficial deposits and crusts (Fig. 5).

The northern part of the watershed has been affected by soft then brittle tectonics that played a role since the Jurassic and played again during the Atlas orogeny. It is responsible for a Horst and Grabens structure. The middle post-Westphalian phase is responsible for the folding of the Jerada area into a large complex syncline.

The part that encompasses the Highlands can be subdivided into three structural units parallel to the Horst chain: the collapse of the Oued EL Haï or the Jurassic basement. The platform of the Ain Bni Mathar area or the Jurassic roof is everywhere close to the surface and the collapse of the Oued Charef, Graben that extends south of the platform of Ain Bni Mathar.

RESULTS AND DISCUSSION

The cross-referencing of the maps of the main factors, involved in soil water erosion, provides a map of soil loss at any point in the watershed. The application of the Wischmeier & Smith (1978) formula, taking into account the numerical values of the five factors, gives the soil loss for each point of the watershed.

Climatic aggressiveness R-factor

This factor representing climatic aggressiveness is determined in the Wischmeier & Smith equation:

$$R = K^{*} EC^{*} I_{30}$$

Where:

- K : Coefficient depending on the system of measurement units,
- EC : Kinetic energy,
- I_{30} : Is the maximum intensity of rainfall in 30 min.

The unavailability of data for the two terms EC and I30 rejects the use of this method, leading us to use other relationships involving data available from stations located in or near the watershed. That is, monthly and annual averages. The two authors (Rango & Arnoldus 1987) integrated these two data in the formula represented below:

$$\text{Log } R = 1.74. \text{ Log } \sum (Pi^2 / P) + 1.29$$

Where:

- Pi: Monthly mean precipitation (mm),
- i: from 1 to 12 (January to December),
- P: Annual mean precipitation (mm).

The R-factor values calculated for the nine rain gauge stations have been used to produce the erosivity map of the study area, by the application of the kriging interpolation method in ArcGIS 10.3 software.

The monthly and annual precipitations used in the calculations are averages between 2000 and 2017 from the rainfall stations distributed in the catchment area of the Za watershed, used to calculate the R factor (Tab. 3).

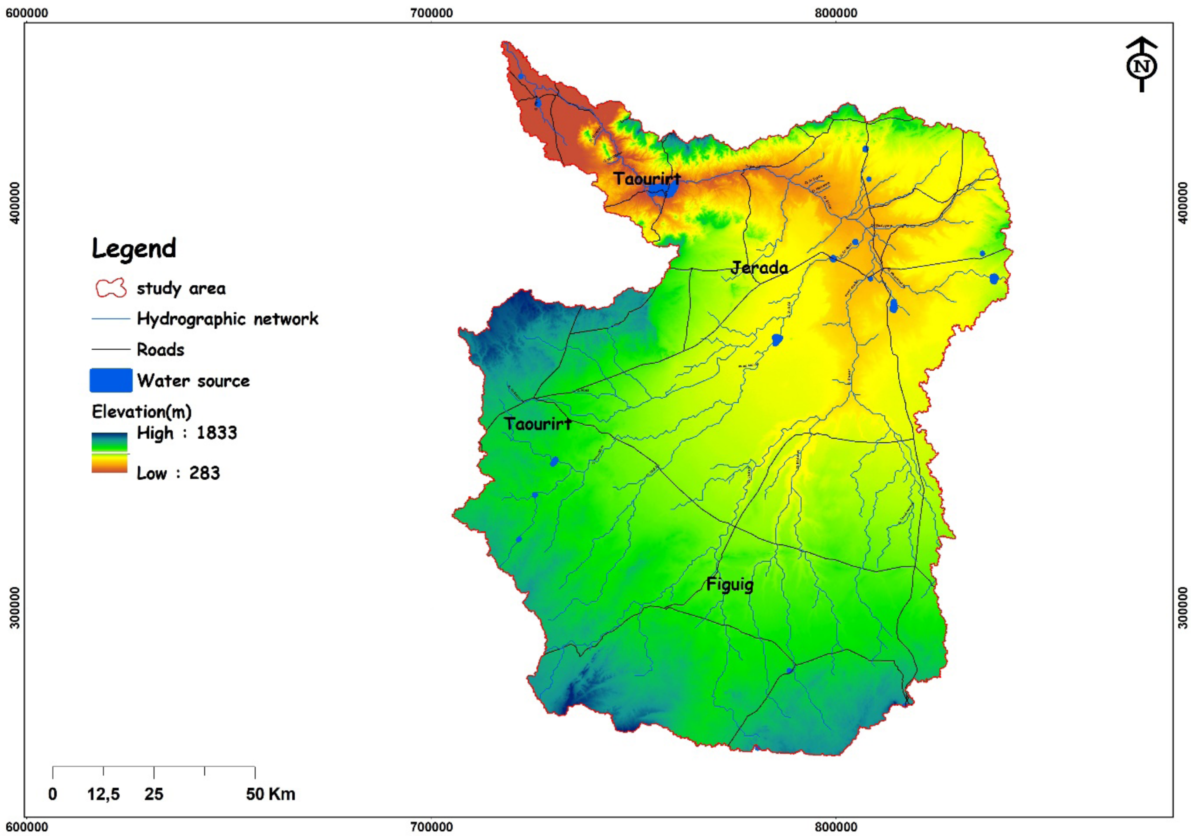

Figure 3. Map of altitudinal heights from a DTM at 30 m resolution.

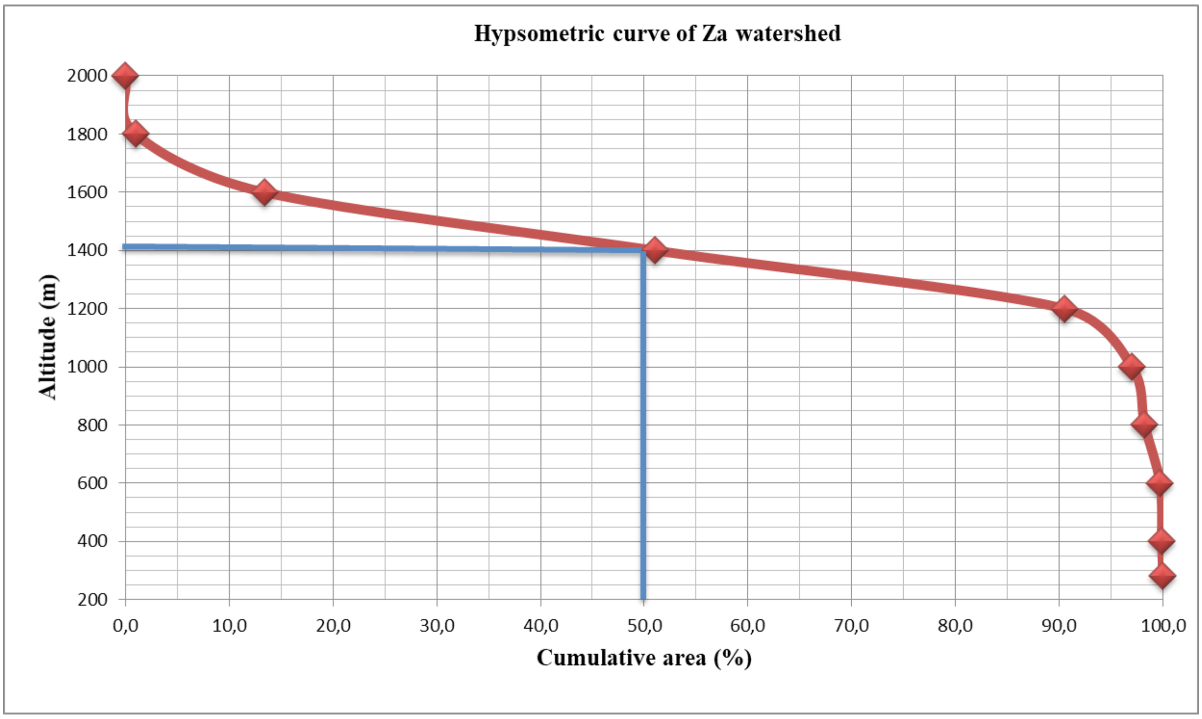

Figure 4. Hypsometric curve of the Za watershed.

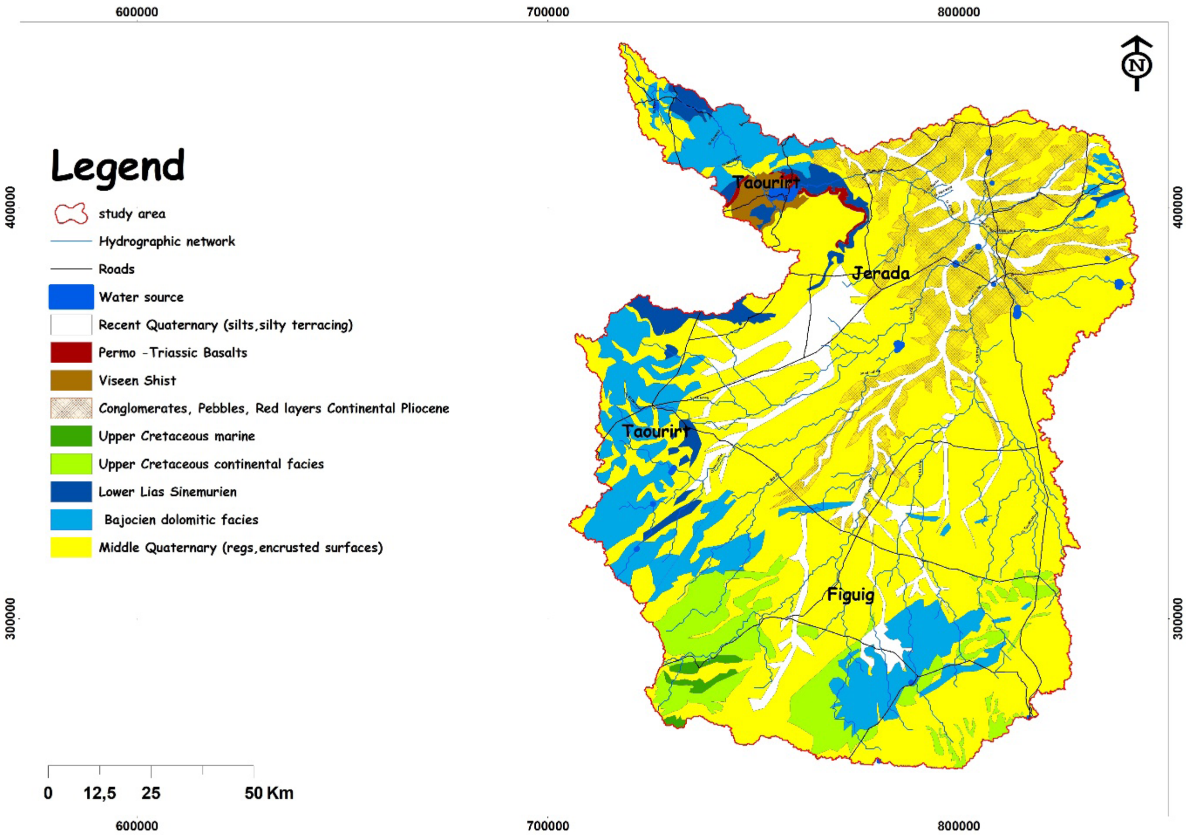

Figure 5. Map of the lithological formations of the Za watershed (from the geological map of Oujda at 1/500000, Choubert 1954).

Table 3. Coordinates of the meteorological stations of the Oued Za watershed and their R indices.

Name	X (m)	Y (m)	Annual average P (mm)	Observation period	R MJmm/ha, hr,yr (metric system)
AIN BNI MATHAR	809200	391300	241.8	2000-2017	91.99
GUENFOUDA	806750	439600	251.8	2000-2017	95.30
GUEFAIT	775100	408275	216.7	2000-2017	85.23
Dam OUED ZA	808800	388700	224.4	2000-2017	87.38
LAAYOUNE	765 422	446 578	269.6	1980-2014	100.46
TAOURIRT	731 447	427 010	193.0	1980-2013	77.92
MELGA EL OUIDANE	716 937	442 370	182.1	1981-2014	92.34
MELLOULOU GUERCIF	689000	404400	182.2	1998-2017	74.64
TENDRARA	821248	299450	138.9	2005-2016	62.39

The values of the R factor vary between 62.39 (Tendrara) as the minimums and 100.46 MJ.mm/ha.h. yr., (Laayoune) as the maximums, with a mean of 85.30, a variance of 140.19 and a standard deviation of 11.84 (Fig. 6).

The classification adopted for the mapping of this factor is presented with the areas highlighted in the following Table 3 and Figure 7.

The most dominant R-factor class is 19.27 to 57.29 covering nearly 30% of the total area, while classes 150.02-201.02 and 201.02 - 255.73 have minimum values totaling 21%. Roughly speaking, the watershed experiences average rainfall aggressiveness (Fig. 8).

Soil erodibility (K) depends on several soil factors, mainly organic matter, soil texture, permeability and soil profile structure. K-factor is related to combined impact of rainfall, runoff soil loss drainage accounting for soil erosion factor at upland stream events (Benzougagh *et al.* 2020).

The K factor is determined by using the nomograph of Wischmeier & Smith (1978) consisting of five soil and soil profile parameters, as follows:

$$100K = 2,1.M^{1,14}.10^{-4}(12\text{-}A) + 3,25\ (B\text{-}2) + 2,5\ (C\text{-}3)$$

Where:

- M : particle size diameter = ((% Silt + % very fine Sand × (100 − % Clay)),
- A : organic matter percentage,
- B : soil structure code,
- C: profile permeability class.

For this study it varies from 0.039 for the most fragile soils to 0.081 for the most stable soils (Fig. 9).

About 70% of the study area has soils with K-factor values between 0.052 and 0.062, followed by the 0.039 class which represents 13%, while the other classes cover only 17% of the total area (Fig.10).

Topographic LS-factor

The LS factor consists of (L), the length of slopes that conditions the runoff velocity and the transport of the torn particles, and (S) the angle (inclination) of slopes that significantly influences soil water erosion (Roose 1994). Their calculations are based on the digital terrain model (DTM) using "the terrain analysis," extension of software, and GIS. It is classified according to values ranging from 0.03 to 16. 03 (Fig. 11).

Several methods allow the calculation of this factor from the digital terrain model (30 m resolution), such as Wischmeier & Smith (1978) and Zhang *et al*. (2013).

The minimum values of LS-factor (0.03-0.84) cover most (58.75%) of the total area of the watershed and generally occur in the south of the watershed. Values between 0.84% and 6.49% are distributed throughout the rest of the basin covering (41.01%). The remaining area of the basin (0.22%) corresponds to values between 6.49% and 16.03% scattered in the north-western part of the basin generally coinciding with areas of high slopes associated with large lengths, especially the downstream areas on both sides of the Oued Za watershed (Fig. 12).

C- Factor

The vegetation C-factor is by far the most important factors that controls soil erosion risk (Knijff *et al*. 2000). Whatever the values of climatic aggressiveness, erodibility of the soil, the inclination of the degree of the slope, their effects are insignificant, if the ground is preserved by a good vegetation cover which slows down the runoff to facilitate infiltration and prevent the onset of erosion (Sadiki *et al*. 2009). However, when the soil is completely bare, erosion phenomena become catastrophic. A Landsat 8 satellite image from 25/Nov, 2019 (Path: 199, Row: 37) was used for supervised classification to produce the land use map of the study area. The values of the C-factor vary between 0 and 1 depending on the land use (Fig. 13). Since NDVI values correlate with C-factor, many researchers use regression analysis to estimate C-factor values for land use/land cover classes in erosion assessment (Durigon *et al*. 2014).

The obtained map (Fig. 13) shows the distribution of C-factor values ranging from 0.21 up to 0.64 with 86.19% of the watershed area having an average vegetation cover rate with $0.44 \leq C \leq 0.48$ and only 13.79% in area seems to be well protected with $0.21 \leq C \leq 0.44$ (Fig. 14).

P-factor

The factor (P) is the anthropogenic factor that translates soil erosion practices into the effect of water and soil conservation measures in estimating erosion. For the factor of anti-erosion practices only a few fruit banks (Dada Ali, Sidi Lahcen areas), dry stone cordons (Guafait commune), a few crops in the direction of the contour lines (scattered everywhere), are encountered. However, the areas occupied remain very limited, which leads us to grant the factor of cultivation practices a single value P = 1 (Payet *et al.* 2011, Benzougagh *et al*. 2020, 2022) for the entire watershed. Thus, it will be taken equally everywhere, and its impact in predicting soil losses will be neglected.

Estimation of soil losses in the Za watershed according to USLE Model.

The map obtained by multiplying the above factors expresses an approximate result of sheet erosion in the erosion in the Za watershed. It provides an average annual estimate of soil losses according to the predefined conditions of topography, soils, climate and vegetation cover. The superposition of the five factors evaluated under GIS software gives a synthetic map of the distribution of erosion rates in the Oued Za watershed. Soil losses for the entire study area show a large variability ranging from 0.01 to 13.64 t/ha/year, with an average loss of 2.91 t/ha/year. Total losses for the entire watershed are estimated at 4 620 393.911 t/yr (Fig. 15).

The class of low erosion rate dominates the study area, totaling nearly 51.85% of the total area. On the other hand, the class of very high erosion does not exceed 0.58 %, scattered in a few points in the extreme North East and North West. The erosion is medium on 42.64 % and high on the 4.90 % of the total surface of the watershed. The analysis of the factors of erosion led us to note that the erosion, in the Za watershed is of weak extent. The most sensitive areas (Fig. 16) are highly concentrated at the level of river banks in the central, eastern and western parts, while it is scattered on rugged reliefs with high friability in the rest of the watershed. The erosive processes are therefore affected more by the morphology of the relief, followed by the rate of soil cover, then the erodibility of the soils and finally the rainfall aggressiveness (Fig. 16).

The application of the USLE model remains universal. Nevertheless, its application in Morocco has been tested and has given satisfactory results in similar studies of watersheds such as: Moulay Bouchta (Zouagui *et al.* 2018), Boussouab (Sadiki *et al*. 2004).

The erosion rate estimated in the Oued Za watershed by the USLE method remains less important compared to other watersheds in Morocco. Several studies in the Rif have shown that erosion has caused significant soil losses and causes siltation of dams and degradation of water resources (Heusch 1970, Laouina *et al.* 2000, Benzougagh *et al.* 2020, 2022). In the Oued Arbaa Ayacha watershed (western Rif, northern Morocco) for example, annual soil losses have been estimated to range from 0.11 t/ha/yr to 468 t/ha/yr (Oullali *et al*. 2016).

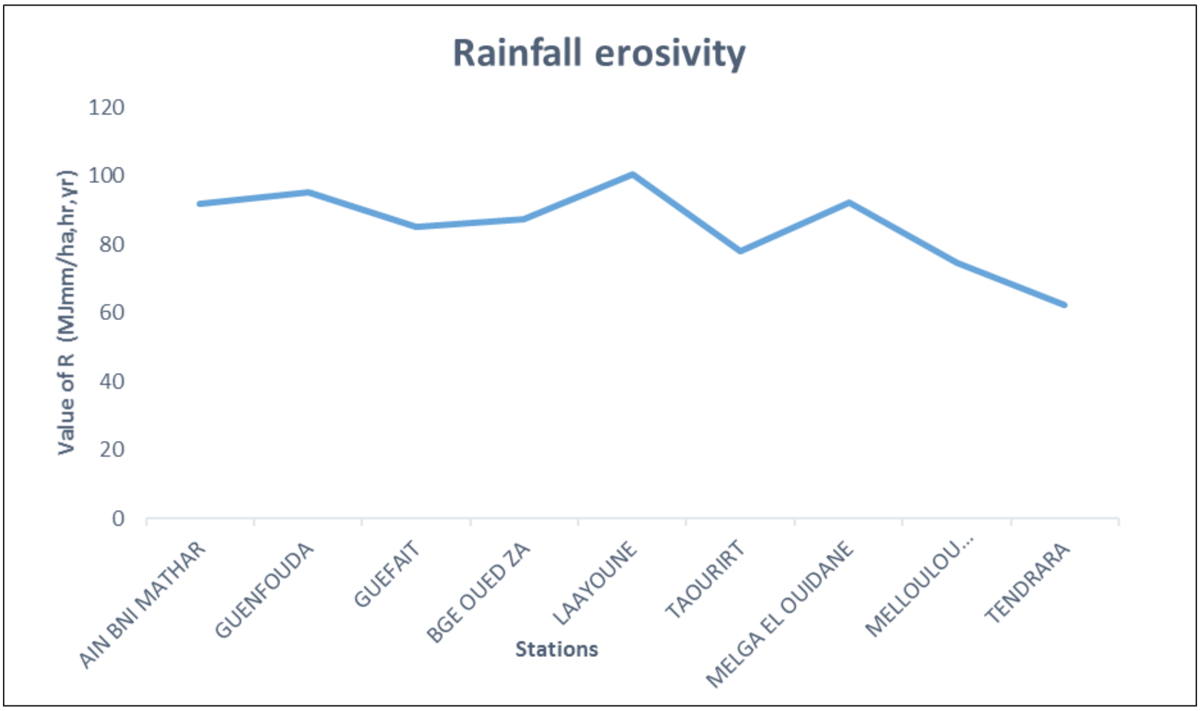

Figure 6. R-factor values in the rainfall stations of the Za watershed.

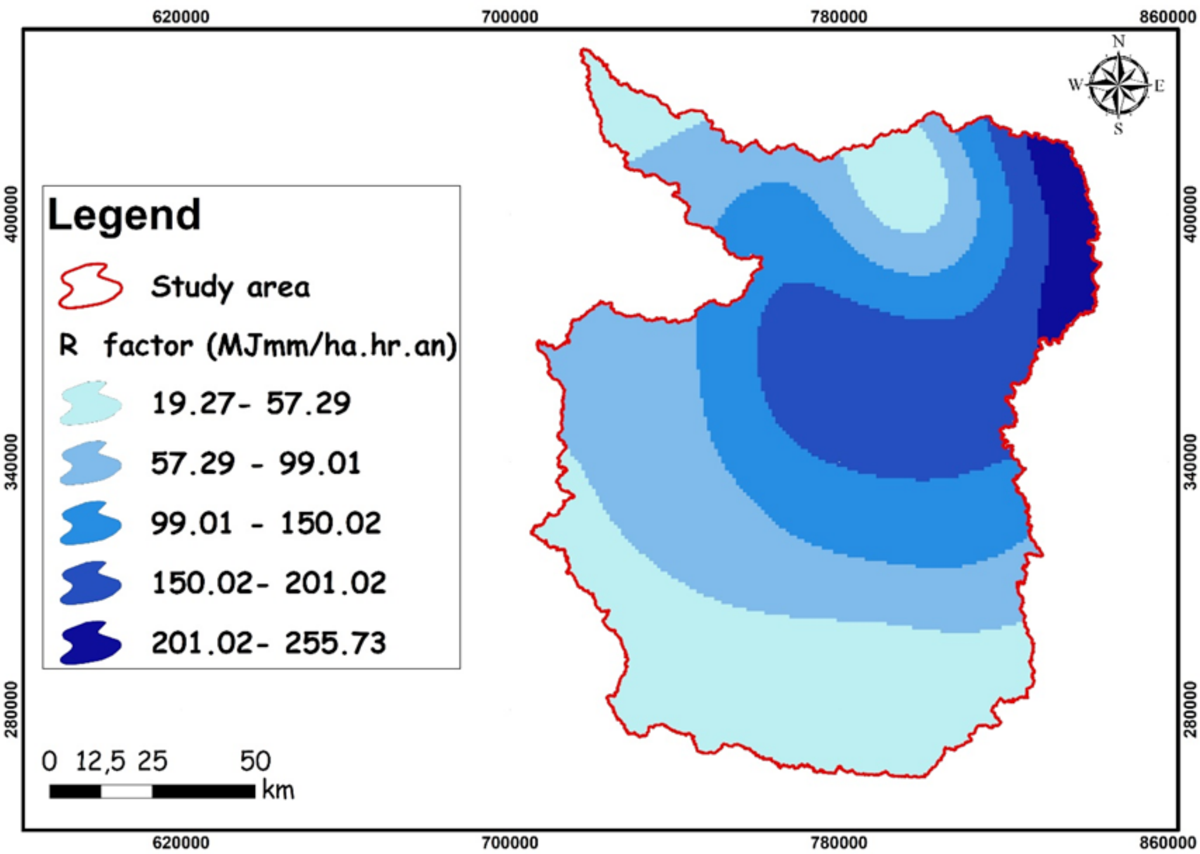

Figure 7. Class distribution of R-factor values in the Oued Za watershed (MJ. Mm/ha.hr.an).

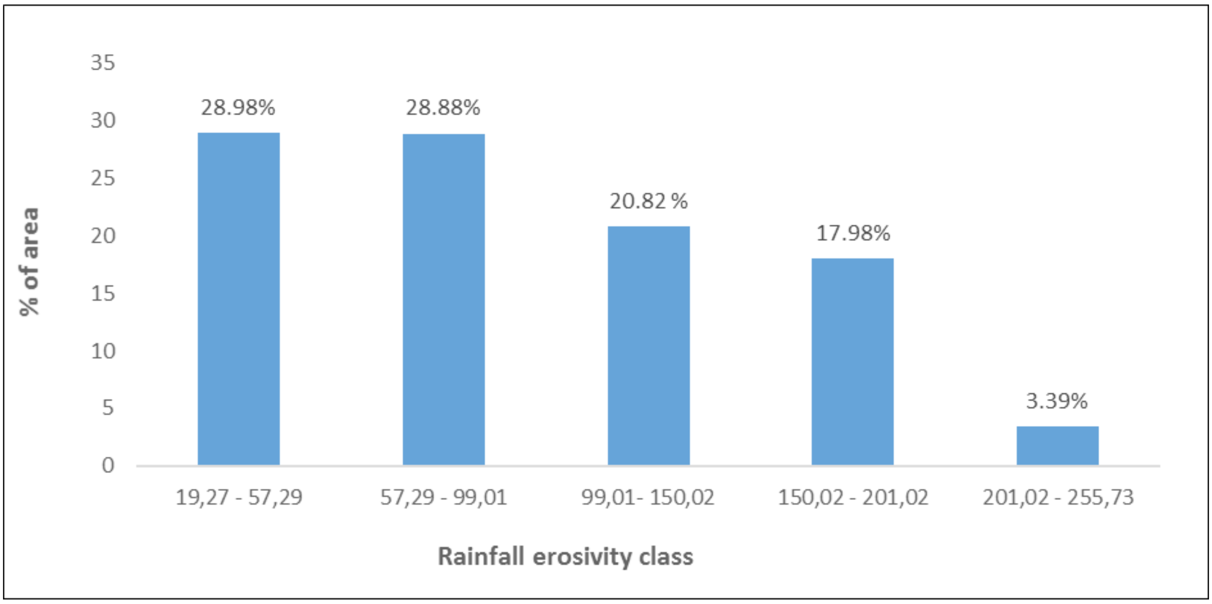

Figure 8. Percentage of rainfall aggressiveness classes.

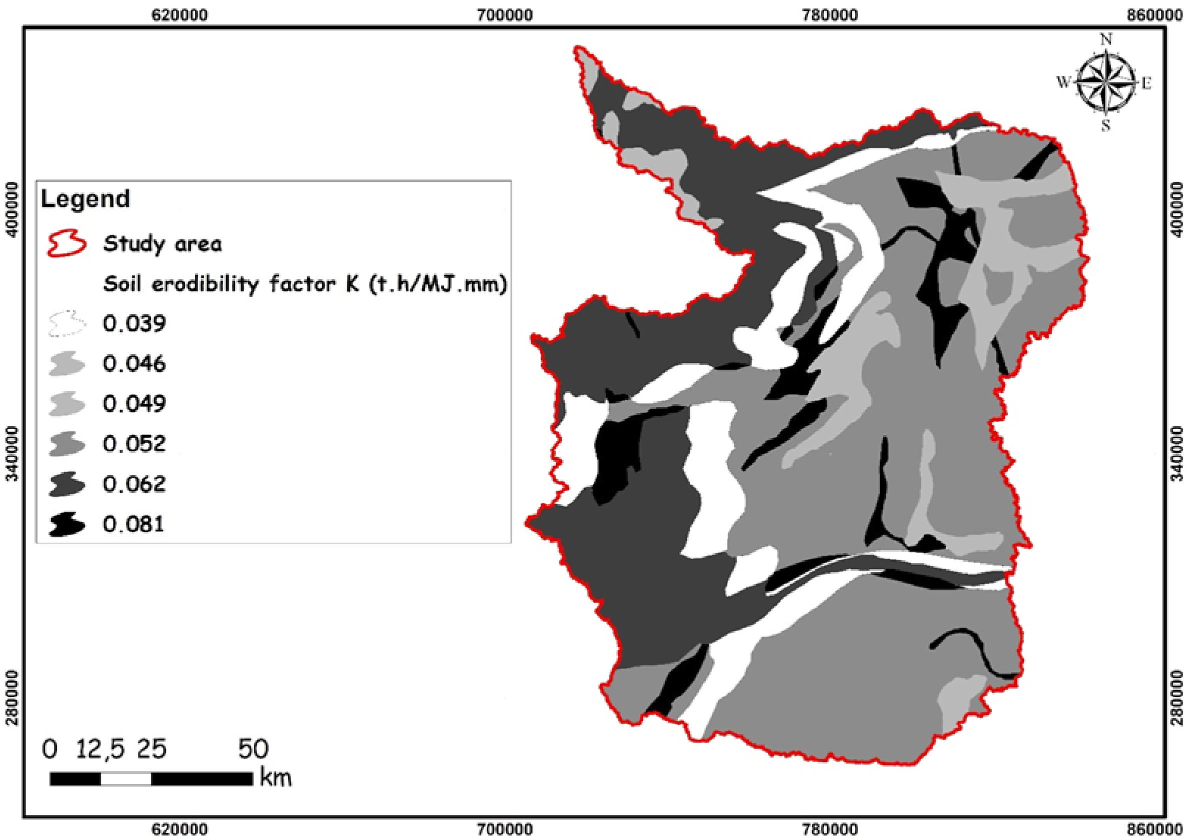

Figure 9. Distribution of the K-factor values in the Za watershed.

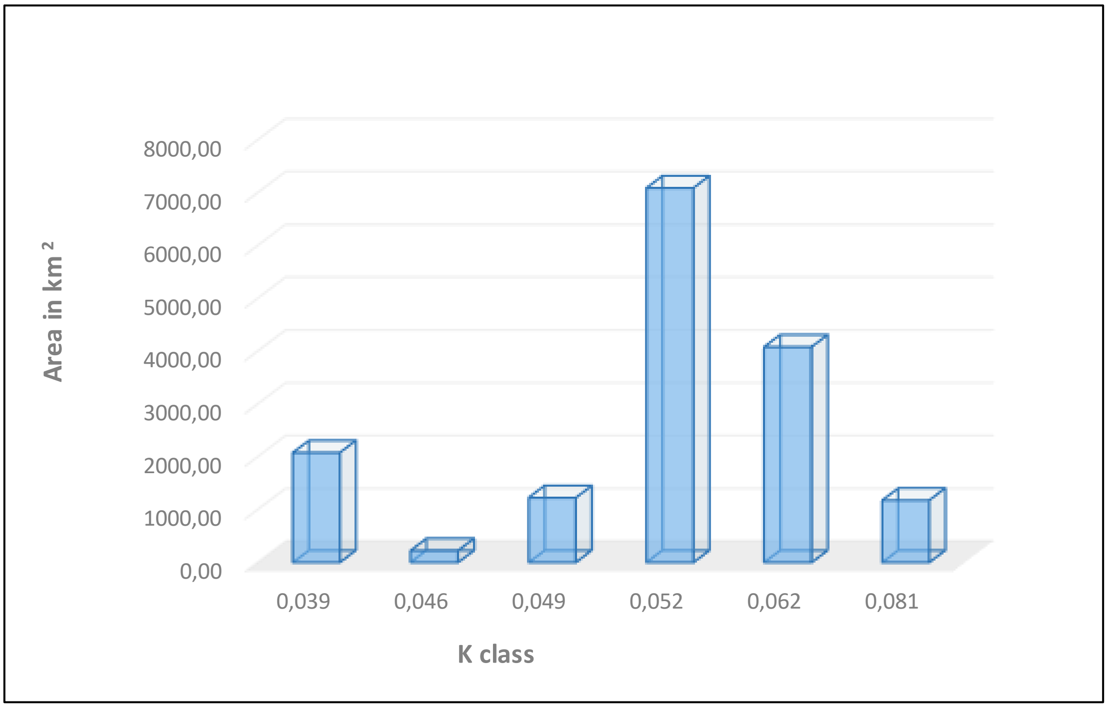

Figure 10. Percentage of soil erodibility classes in the Za watershed.

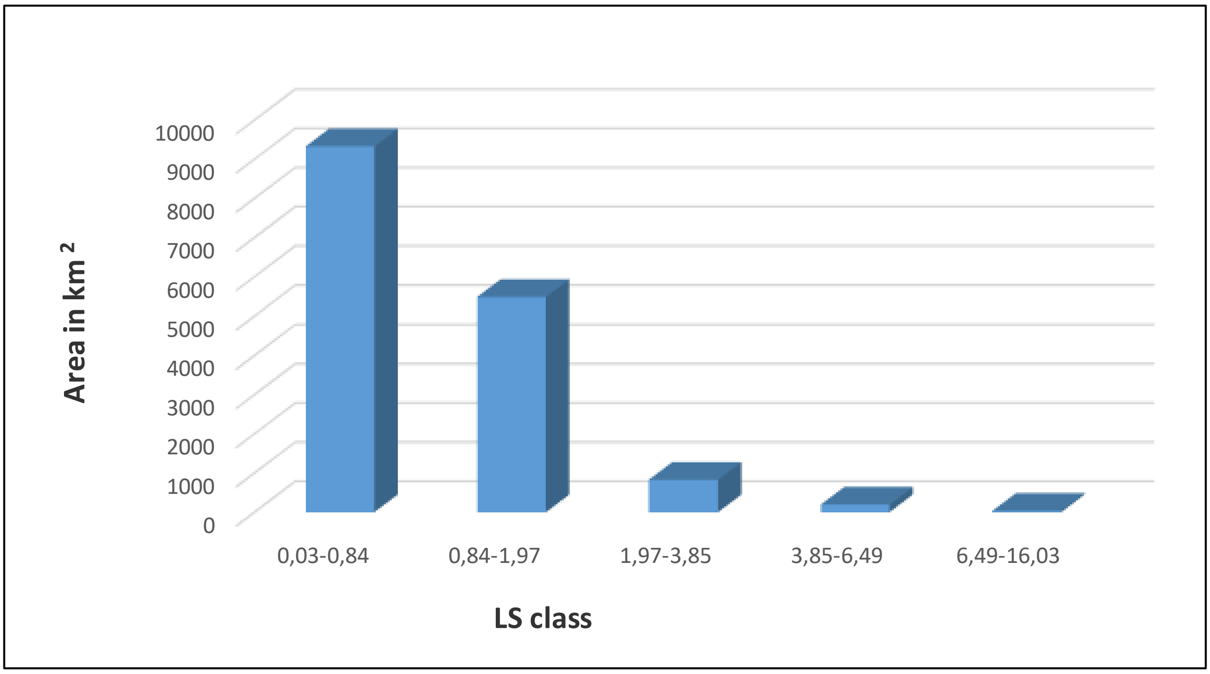

Figure 11. Area of the LS factor classes (km²) in the Za watershed.

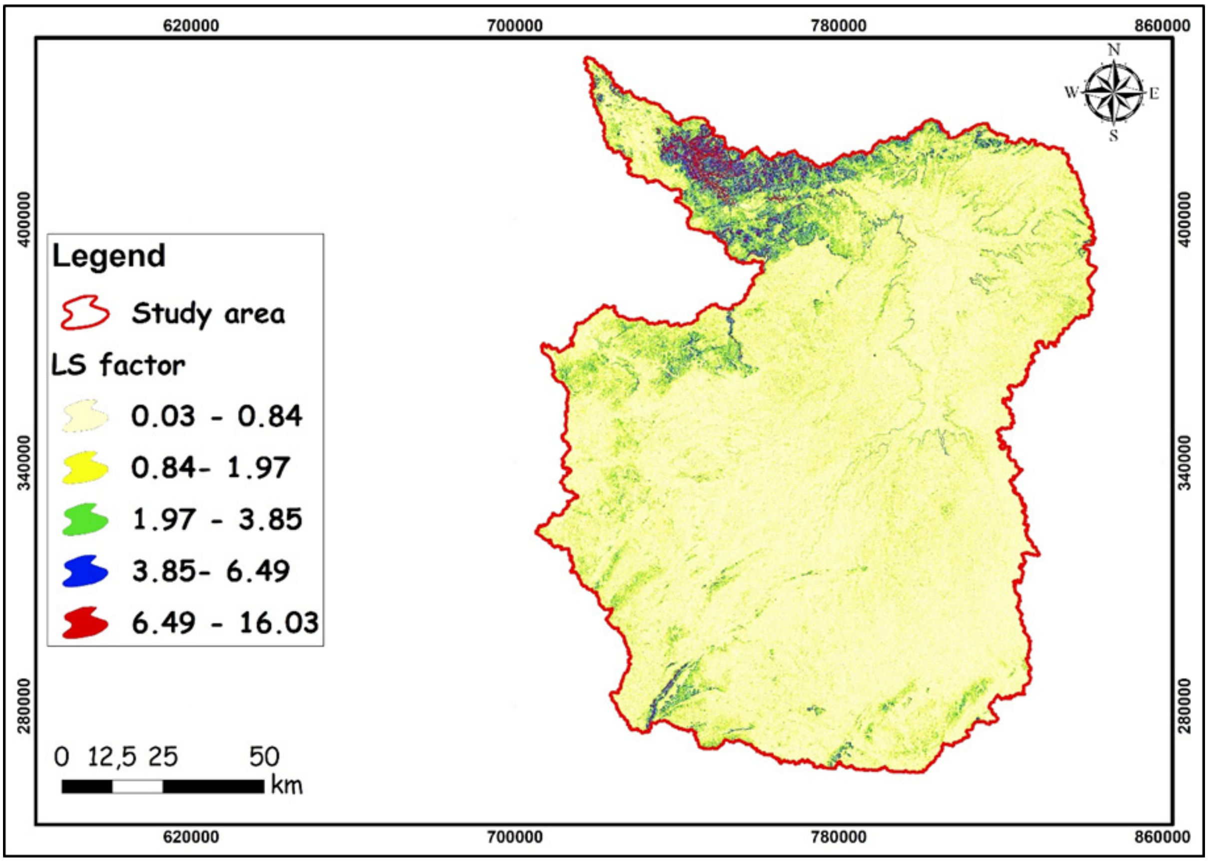

Figure 12. Class distribution of LS factor values in the Oued Za watershed.

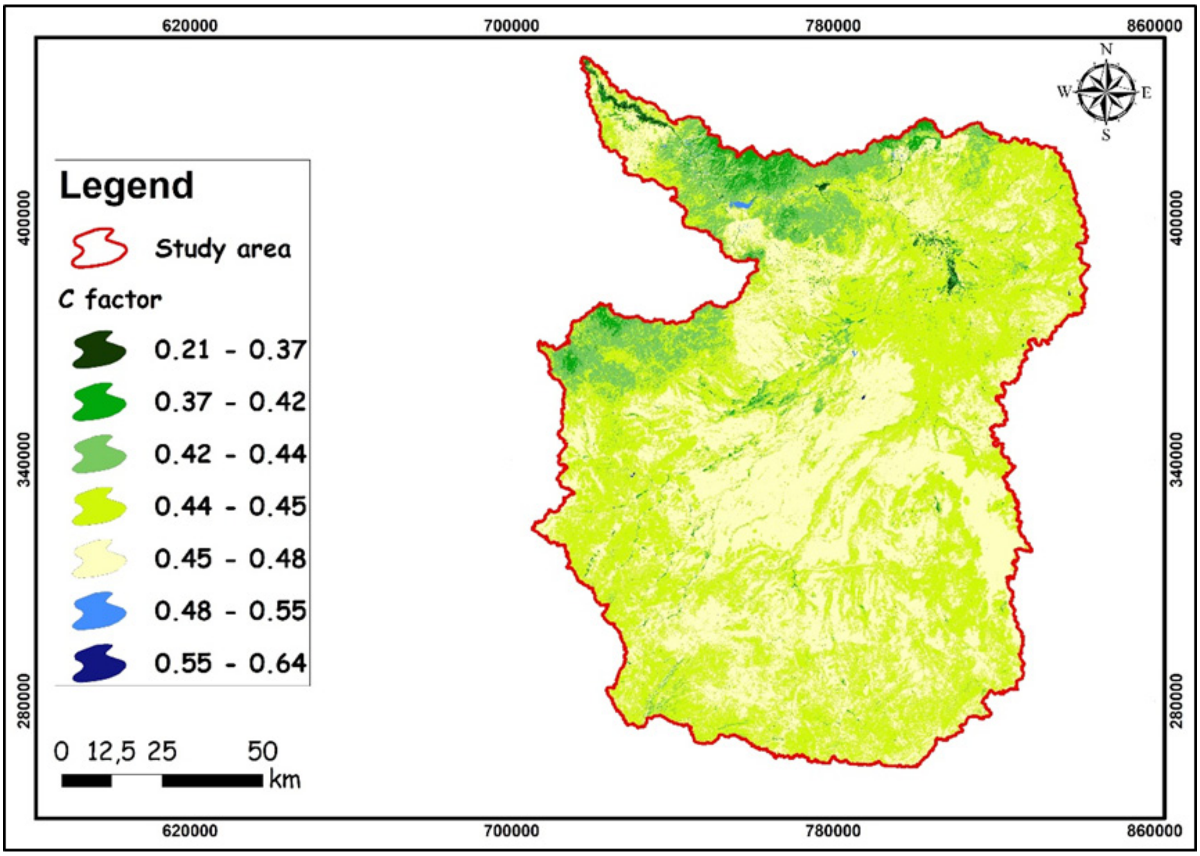

Figure 13. Class distribution of C-factor values in the Oued Za watershed.

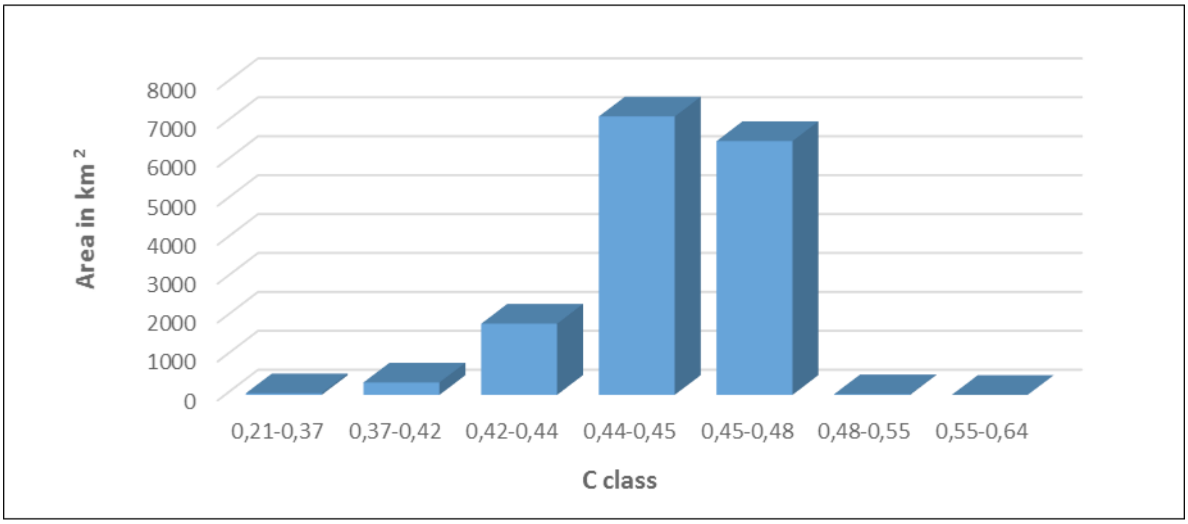

Figure 14. Percentage of C-factor classes, in the Za watershed.

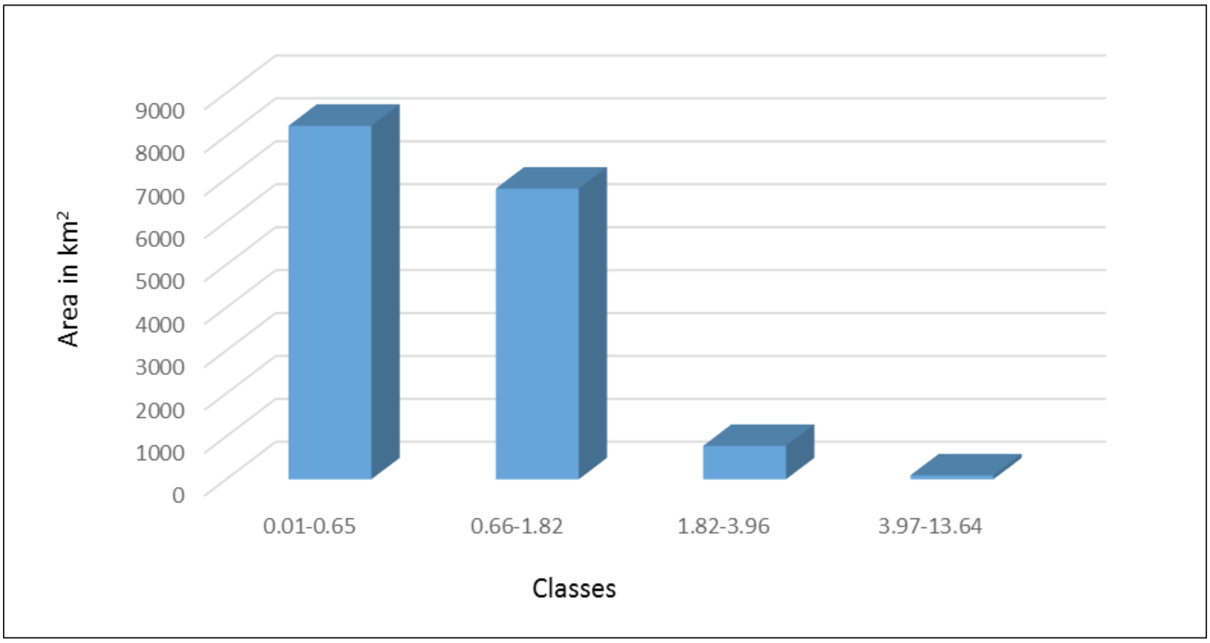

Figure 15. Distribution of soil loss classes (t/ha/year), in the Za watershed.

CONCLUSION

This study presents the results of the application of the Universal Soil Loss Equation using a Geographic Information System in the Za watershed. The study showed that the watershed loses an average of 2.90 t/ha/year. This led us to note that erosion in the Za watershed is low (97% of the watershed has a low to medium erosion rate). The erosive processes are affected more by the morphology of the relief, followed by the rate of soil cover, then the erodibility of the soil and finally the rainfall aggressiveness. The most sensitive areas are highly concentrated at the level of watershed banks in the central, eastern and southern parts, while it is scattered on rugged reliefs with high friability in the rest of the watershed.

Although the validity of the USLE soil losses is debatable, the method is still very positive in that it provides valuable information on the risk of erosion and fine sediment production and is an important aid to decision makers and planners in simulating scenarios of regional change and planning erosion control interventions. It also allows monitoring the impact of land use and development. These results can be compared with those obtained by other methods of assessing water erosion for more precision, such as radioisotopic methods, the SWAT (Soils Water Assessment Tools) model, the SAM (spectral angel mapper) model.

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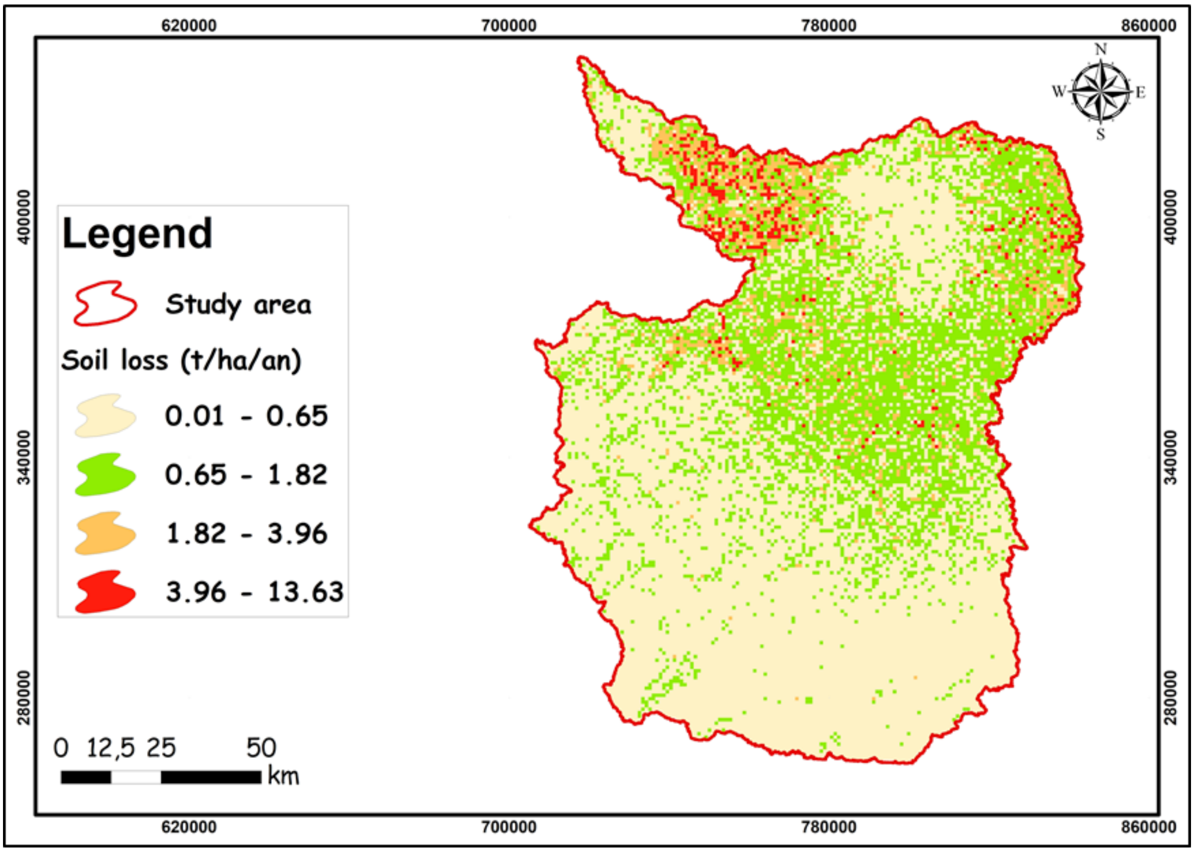

Figure 16. Map of class of soil loss in the Za watershed.

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