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Arbi Chafai[1], Khaled Taghouti[2]

GIS-BASED ASSESSMENT OF THE PHYSICAL EROSION SUSCEPTIBILITY USING RAINFALL EROSIVITY (R) AND TOPOGRAPHIC FACTOR (LS): CASE OF THE SILIANA RIVER WATERSHED, NORTH-WESTERN TUNISIA

Abstract: This study analyzes the spatial variability of rainfall erosivity (R factor), the topographic factor (LS), and their interaction in the Siliana river watershed, located in northwestern Tunisia, using a GIS-based integrated approach. The R factor was estimated from multi-year rainfall data covering the period 1990–2022, applying Arnoldus' index and spatial interpolation via kriging. The LS factor was derived from a 30 m resolution SRTM digital elevation model, incorporating slope and slope length. The spatial combination of R and LS factors allowed for the assessment of water erosion potential at the watershed scale. Results show that annual precipitation ranges from 417 to 523 mm, with higher values in the mountainous areas of Bargou and Makthar. Rainfall erosivity exhibits moderate spatial variability, dominated by low to medium classes over most of the watershed. In contrast, the LS factor displays strong spatial heterogeneity, controlled by the relief morphology, with high values concentrated in the mountainous sectors of Kesra, Bargou and Makthar. The LS × R map reveals a highly contrasted erosion potential, with values ranging from 0 to 2069. High to very high risks dominate the upstream areas, whereas agricultural plains show generally low risk. These results highlight the amplifying role of topography and provide a valuable basis for soil conservation planning and sustainable watershed management.

Keywords: water erosion, R factor, LS factor, RUSLE, GIS, Siliana river watershed

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[1] University of Tunis El Manar, Faculty of Sciences of Tunis, Department of Geology, Tunisia, ORCID ID: https://orcid.org/0000-0003-4838-4886, email: geologue.arbi@hotmail.com
[2] Higher Institute of Technological Studies of Siliana, Department of Civil Engineering, Tunisia, ORCID ID: https://orcid.org/0000-0002-4618-4186, email: Khaltag@hotmail.fr

Introduction

Soil constitutes the fundamental support of agricultural systems and terrestrial ecosystems, performing essential functions such as food production, water regulation, carbon storage, and biodiversity maintenance. It is a dynamic medium whose evolution results from a complex balance between pedogenetic formation processes, which tend to thicken and improve its structure, and degradation processes, among which water erosion plays a predominant role (FAO, 2023). When this balance is disrupted, erosion leads to the gradual loss of fertile surface horizons, reducing land productivity and compromising the sustainability of agricultural systems, particularly in regions subjected to pronounced climatic constraints.

At the global scale, water erosion is now recognized as one of the main threats to soil resources. It affects not only soil fertility and structural stability but also water quality through increased sediment loads, reservoir siltation, and the degradation of aquatic ecosystems (Borrelli et al., 2021; Panagos et al., 2022). The associated socio-economic impacts are significant, especially in agricultural regions dependent on fragile soils, where erosion contributes to declining yields, food insecurity, and increased vulnerability of rural populations (Alewell et al., 2019; Montanarella et al., 2023).

Semi-arid Mediterranean environments are among the zones most exposed to water erosion. They are characterized by strong spatial and temporal variability in precipitation, alternating long dry periods with short but intense rainfall events, often concentrated in a few extreme episodes (López-Vicente et al., 2020; Cerdà et al., 2023). These climatic conditions, combined with often discontinuous vegetation cover and sometimes inappropriate agricultural practices, promote surface runoff and enhance soil particle detachment and transport. Recent climate projections also indicate a likely increase in the frequency and intensity of extreme rainfall events in the Mediterranean basin, which could amplify erosive processes in the coming decades (IPCC, 2023; Panagos et al., 2024).

Among the factors controlling water erosion, rainfall erosivity, expressed by the R factor in empirical models such as RUSLE, is a key indicator of the erosive potential of precipitation. This factor integrates the intensity, duration, and intra-annual distribution of rainfall, reflecting its capacity to generate runoff and detach soil particles (Renard et al., 1997; Panagos et al., 2022). Numerous recent studies have shown that short-duration, high-intensity rainfall events can cause significant soil losses, even in regions where annual totals remain relatively moderate (Liu et al., 2023; Wang et al., 2024). This highlights the importance of a detailed analysis of the spatial and temporal variability of rainfall erosivity, particularly in semi-arid contexts.

Topography is another determining factor in the dynamics of water erosion. The LS factor, which combines slope length and steepness, governs the velocity, energy, and concentration of surface flows, directly influencing sediment transport magnitude (Cerdà, 2021). Long and steep slopes favor accelerated runoff and the development of concentrated erosion forms such as rills and gullies. Recent advances in topographic modeling, especially through high-resolution digital elevation models derived from LiDAR or radar data, have significantly improved LS factor estimation and the identification of highly erosion-prone areas (Nguyen et al., 2025; Kumar et al., 2025).

Although the individual influence of R and LS factors is well documented, their spatial interaction remains insufficiently explored in many Mediterranean catchments, particularly in North Africa. Several recent studies highlight that the combination of high rainfall erosivity and unfavorable topographic conditions can produce non-linear effects, significantly amplifying soil losses (Borrelli et al., 2021; Panagos et al., 2024). Therefore, a joint analysis of these factors is essential for a comprehensive understanding of water erosion dynamics.

In this context, Geographic Information Systems (GIS) are particularly suitable tools for the spatial integration of erosion factors and their analysis at different scales. Coupling GIS with empirical models such as RUSLE enables the production of detailed susceptibility maps, identification of sediment source areas, and prioritization of sectors for soil conservation measures (Alewell et al., 2019; Borrelli et al., 2021). Recent advances in geospatial data, including access to increasingly precise DEMs and continuous rainfall series, further enhance the reliability of these approaches and open new perspectives for sustainable soil management in vulnerable Mediterranean environments (Zhao et al., 2022; Smith & Jones, 2024).

In the Siliana river watershed (North-west of Tunisia), water erosion represents a major environmental challenge due to climatic variability, the predominance of rugged terrain, and increasing anthropogenic pressures. However, studies specifically integrating the joint analysis of R and LS factors through a GIS-based approach remain limited. This study aims to fill this gap by providing a GIS analysis of the interaction between rainfall erosivity (R) and the topographic factor (LS), to better understand their combined contribution to water erosion dynamics and identify the most vulnerable areas. The results will provide a basis for planning appropriate soil conservation measures adapted to the semi-arid Mediterranean context of Tunisia.

Materials and methods

Study area. The Siliana river watershed, located in northwestern Tunisia, covers an area of approximately 1039 km^2 and is primarily drained by the Siliana River, as shown in Fig. 1. The region exhibits a semi-arid climate, characterized by two dominant bioclimatic zones: upper semi-arid (73 %) and middle semi-arid (23.7 %). During the 1990–2022 period, the Siliana region recorded an average annual temperature of approximately 19.1°C, which is characteristic of the semi-arid Mediterranean climate prevailing in inland Tunisia. Mean monthly temperatures generally ranged from about 10°C in winter to nearly 30°C in summer, with maximum values typically observed during July and August.

Average annual precipitation ranged between 410 and 420 mm/year, with marked interannual variability. Rainfall was mainly concentrated between October and April, whereas the summer season remained particularly dry. December, January, and March were generally the wettest months, with monthly totals frequently exceeding 50 mm.

Intense rainfall events exceeding 60 mm/day were also recorded in some years, temporarily contributing to soil moisture recovery and groundwater recharge. The climatic analysis of this period further indicates a gradual warming trend accompanied by a relative decline in precipitation, reflecting the increasing impacts of climate variability in Tunisian semi-arid environments.

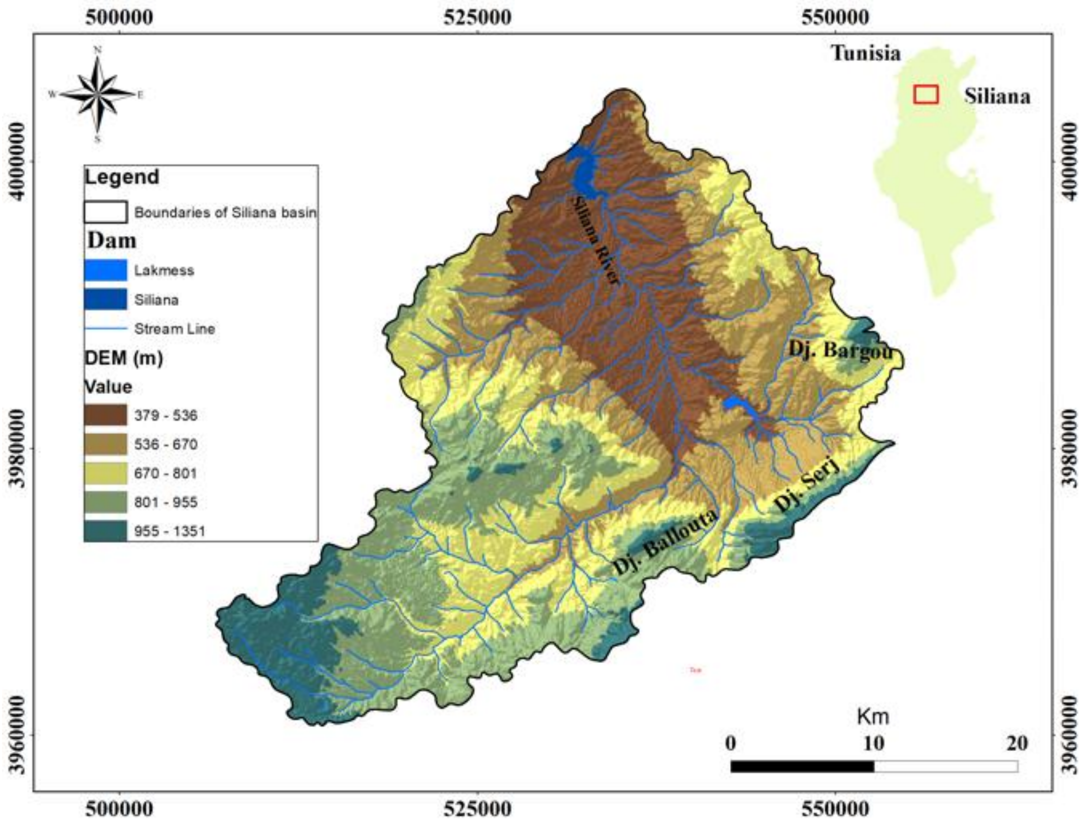

Fig. 1. Location map and DEM of the Siliana river watershed
Source: Author's own elaboration using ARC-GIS software

From a geological perspective, the watershed is primarily composed of sedimentary formations ranging from the Paleozoic to the Tertiary, including limestones, dolomites, marls, and clays. In areas of moderate relief, sandstones and conglomerates are also present. The topography is structured by northwest–southeast-oriented faults and fractures, a legacy of Alpine tectonic activity, which influences both the distribution of geological formations and the basin's morphology.

The dominant soils are clay-loam and sandy types, while land use is largely devoted to cereal and tree crop cultivation. The combination of climate, precipitation, temperature, geology, and soil characteristics strongly governs the hydrological dynamics and soil erosion within the Siliana river watershed, making this region particularly sensitive to erosive processes.

Topographically, the basin exhibits rugged terrain with the presence of mountainous massifs and significant elevation variation, as illustrated in Fig. 1, with elevations ranging from 379 m at the outlet to 1351 m at the summit of Djebel Serj.

Data collection and preparation. For modeling water erosion in the Siliana river watershed, several types of spatial and climatic data were collected:

1. **Topographic data:** A Shuttle Radar Topography Mission (SRTM) image with a 30 m resolution, available from http://opentopo.sdsc.edu/datasets, was used. This dataset allowed the creation of several thematic maps, including the watershed boundary map, the hydrographic network map, the elevation map (DEM), the slope map, and the LS factor map.
2. **Climatic Ddata:** Monthly and annual precipitation data were obtained from the Siliana Regional Commissariat for Agricultural Development (CRDA Siliana) for the period 1990–2022. These data were used to determine the rainfall erosivity factor (R).

All datasets were imported into a GIS environment (ArcGIS 10.8) and projected into a common coordinate system (Carthage UTM, Zone 32N) to ensure spatial compatibility.

Calculation of Rainfall Erosivity (R). Rainfall erosivity represents the potential of rainfall to cause soil erosion. It was calculated using the formula proposed by Arnoldus (1987), which considers the ratio between the squared sum of the mean monthly precipitation of each month and the mean annual precipitation. This calculation was applied to six rain gauges located within and around the study area. It is expressed as follows: In the GIS, precipitation station data were interpolated using the Kriging method to generate a raster surface of R covering the entire Siliana river watershed.

Calculation of the Topographic Factor (LS). The LS factor combines the effects of slope length (L) and slope steepness (S) on erosion. It was calculated using the equation developed by Wischmeier and Smith (1978), adapted for semi-arid regions (1):

$$LS = \left(\text{Flow accumulation} \times \frac{\text{résolution}}{22.13}\right)^{m} \times \left(0.065 + 0.045 \times S + 0.0065 \times S^{2}\right) \quad (1)$$

Where:

S is the slope (%) and m is a parameter that varies according to the slope percentage, as presented in Table 1

Table 1. Slope exponent (m) Values for Each Slope Class

Slope (%)	S > 5%	3.5 < S < 5%	1 < S < 3.5%	S < 1%.
m	0.5	0.4	0.3	0.2

Source: Wischmeier & Smith, 1978; McCool et al., 1989

Analysis of the R × LS interaction. To investigate the relationship between rainfall erosivity and topography, the two raster layers (R and LS) were multiplied using ArcGIS to generate the combined R × LS factor, which represents the potential for water erosion. Statistical analyses were carried out to assess:

- The spatial distribution of R, LS, and R × LS values across the study area.
- Areas with high erosion potential, which were classified into different risk levels (low, moderate, high, and very high) using the Reclassify tool.

Results and discussion

Precipitation and rainfall erosivity in the Siliana river watershed. Figure 2 highlights the spatial variability of mean annual precipitation across the studied watershed, with values ranging from 417 mm to 523 mm. The dominant class, ranging from 417 to 452 mm, covers 574 km^2, representing 55.25 % of the total area, and is mainly located in the central part of the basin along a north-south axis. The highest precipitation class, ranging from 474 to 523 mm, occupies only 15.69 % of the area and is primarily found at the basin margins, in the southwest (Makthar) and northeast (Bargou). This distribution reveals a pronounced spatial variability in precipitation, with a tendency for higher rainfall at stations situated at elevated altitudes.

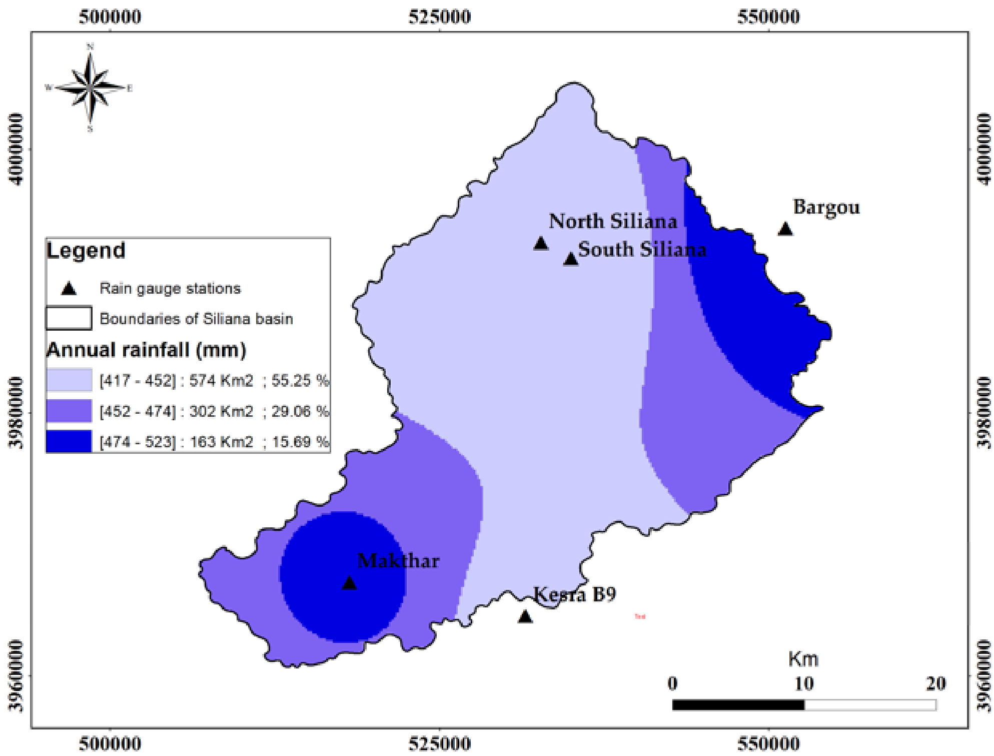

Fig. 2. Spatial variability of annual precipitation in the Siliana river watershed
Source: Author's own elaboration using ARC-GIS software

Figure 3 shows the spatial distribution of the Arnoldus index, highlighting three classes of rainfall erosivity. The central part of the basin is characterized by low erosivity ([39–43]), covering 635 km^2, or 61.12 % of the total area. The southwest and northeast areas exhibit moderate erosivity ([43–46]), distributed over 331 km^2 (31.86 %). Finally, the Bargou station stands out with relatively high erosivity ([46–52]), covering 73 km^2, representing 7.02 % of the watershed. The highest values are observed in the mountainous areas, particularly Djebel Serj and Djebel Bargou, whereas the lowlands in the central part of the basin display lower erosivity indices.

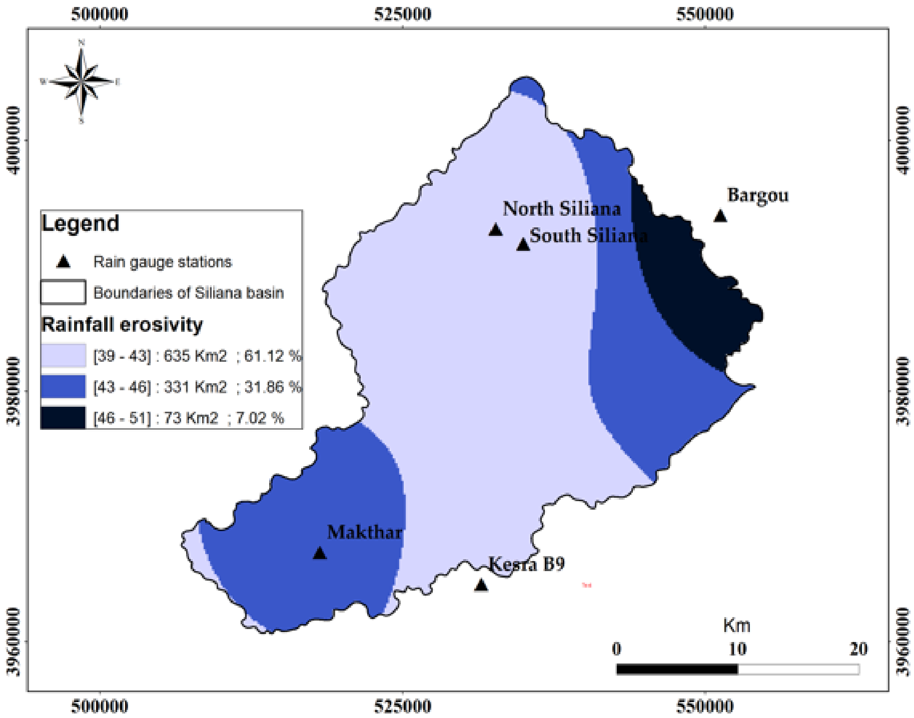

Fig. 3. Spatial distribution map of rainfall erosivity in the study area
Source: Author's own elaboration using ARC-GIS software

Table 2. Spatial distribution of rainfall and erosivity classes in the Siliana river watershed

Class	Rainfall (mm/year)	Rainfall Area (km^2)	Rainfall (%)	Erosivity (Arnoldus)	Erosivity Area (km^2)	Erosivity (%)	Main Location
Low	417 – 452	574	55.25 %	39 – 43	635	61.12 %	Central basin
Medium	453 – 473	299	28.81 %	43 – 46	331	31.86 %	Southwest (Makthar) and Northeast (Bargou)
High	474 – 523	163	15.69 %	46 – 52	73	7.02 %	Bargou & Mountainous areas (Djebel Serj, Djebel Bargou)

Source: Author's own elaboration

The joint analysis of precipitation and rainfall erosivity reveals a clear spatial correspondence: the central areas, characterized by moderate precipitation (417–452 mm), exhibit low erosivity, whereas stations located at the basin margins, where precipitation is higher, correspond to zones of moderate to high erosivity. The Bargou station particularly illustrates this relationship, combining high rainfall with strong erosivity, especially in areas of steep terrain. These observations confirm that rainfall erosivity increases with altitude and that the spatial distribution of erosion is strongly influenced by both precipitation patterns and topography, as summarized in Table 2.

Slope map analysis. Figure 4 illustrates the distribution of slope classes in the Siliana River watershed, revealing a predominance of gentle to moderate slopes across the study area. Slopes below 10% cover an area of 556 km^2, representing 53.5% of the total watershed area. Moderate slopes, ranging from 10% to 15%, occupy 197 km^2 (19%). Relatively steep slopes, between 15% and 25%, account for 192 km^2, corresponding to 18.5% of the territory. Finally, steep slopes exceeding 25% extend over 94 km^2, approximately 9% of the total area, as summarized in Table 3. These steep areas are primarily located in the high-relief zones at the eastern end of the basin, notably around Djebel Serj and Djebel Bargou.

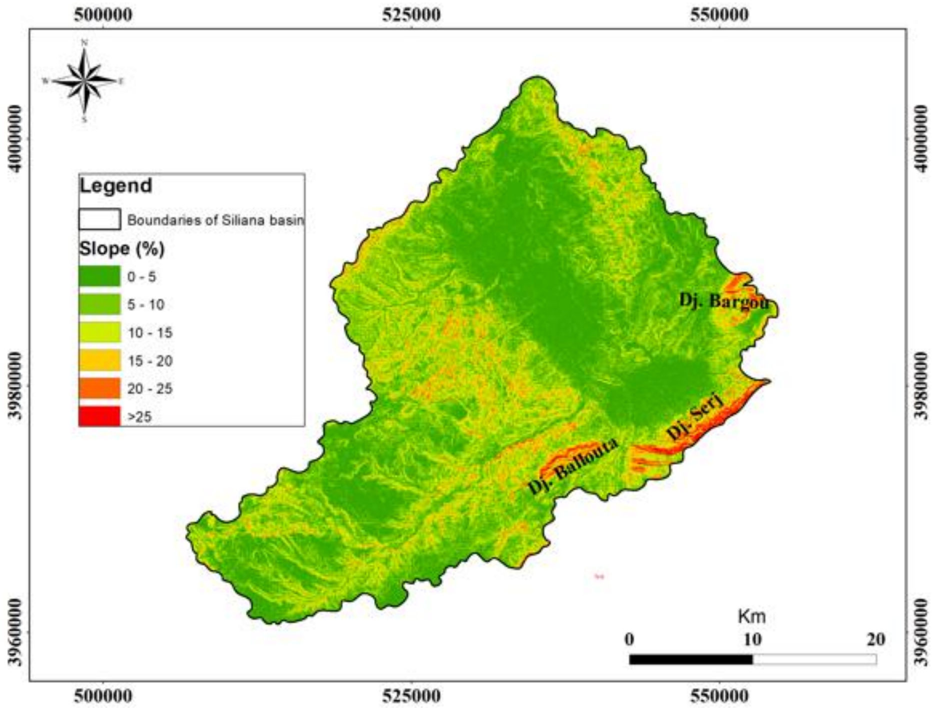

Fig. 4. Slope map of the study area
Source: Author's own elaboration using ARC-GIS software

Table 3. Spatial distribution of slope classes in the study area

Class number	Slope (%)	Solpe class	Area (%)
1	0 – 5	Very slight slope	24.86
2	5 – 10	Slight slope	28.61
3	10 – 15	Medium slope	18.98
4	15 – 20	Fairly steep slope	11.85
5	20 – 25	Steep slope	6.65
6	>25	Very steep slope	9.05

Source: Author's own elaboration

Spatial distribution of the topographic LS factor. Figure 5 illustrates the spatial distribution of the topographic LS factor within the Siliana river watershed, highlighting pronounced heterogeneity associated with the basin's morphological variability.

By combining slope length and steepness, the LS factor represents a key indicator of terrain susceptibility to runoff concentration and soil erosion dynamics.

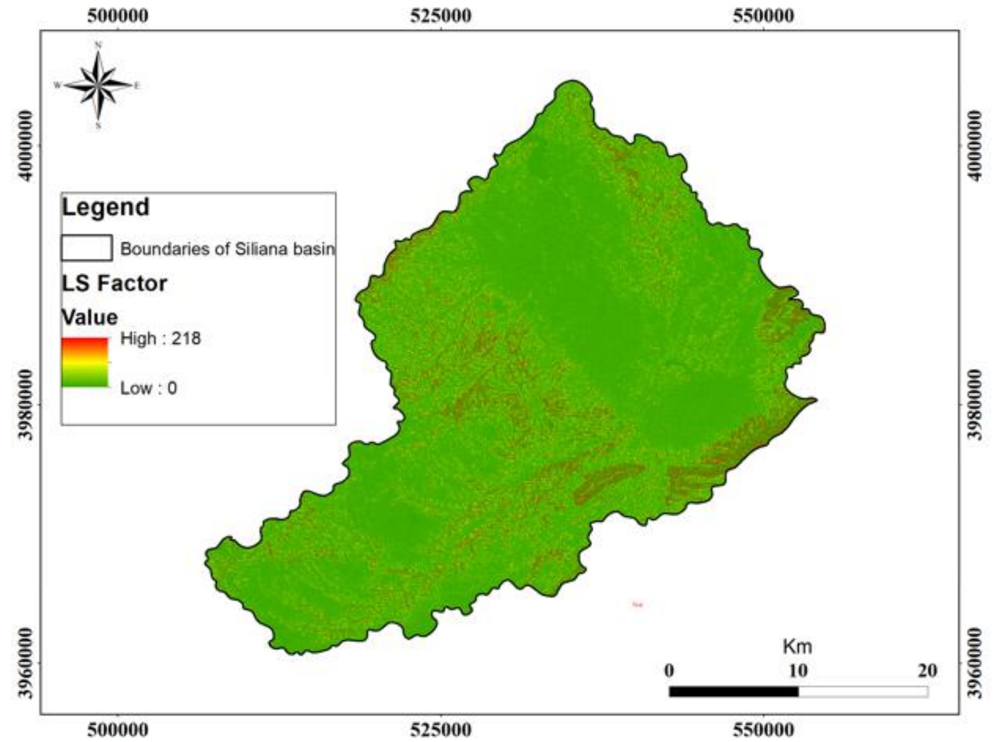

Fig. 5. Spatial distribution of the topographic factor LS
Source: Author's own elaboration using ARC-GIS software

High LS factor values are primarily concentrated in the upstream and mountainous areas of the watershed, notably in the Kesra, Bargou, and Makthar sectors, where slopes are steep to very steep and the slope lengths are relatively long. These areas correspond to the ridges of the Tunisian ridge, characterized by rugged topography that promotes the acceleration of surface flows and increases their erosive power. Under these conditions, concentrated runoff enhances the detachment and transport of soil particles, making these sectors particularly vulnerable to rill and gully erosion.

In contrast, low LS factor values dominate the downstream areas and agricultural plains, particularly around Siliana Nord, Siliana Sud, Gaâfour, and Bou Arada, where slopes are gentle and slope lengths are short. In these sectors, the relatively flat morphology limits runoff energy, thereby reducing the intensity of erosive processes.

The spatial distribution of the LS factor thus highlights the critical role of topography in controlling water erosion within the Siliana river watershed. This map provides a fundamental basis for integration with other RUSLE model factors, enabling the identification of highly erosion-prone areas and the prioritization of sectors for the implementation of soil conservation measures and sustainable watershed management.

Spatial analysis of the LS × R factor. The map of the combined LS × R factor for the Siliana River watershed, illustrated in Figure 6, reveals pronounced spatial variability in water erosion potential, with values ranging from 0 to 2069.

This wide range reflects the combined influence of rainfall erosivity and topographic parameters, notably slope steepness and slope length. The lowest values are associated with low-relief plain areas, whereas the highest values are concentrated in regions with pronounced terrain. For a clearer spatial interpretation, the LS × R values were classified into four main classes, as presented in Table 3.

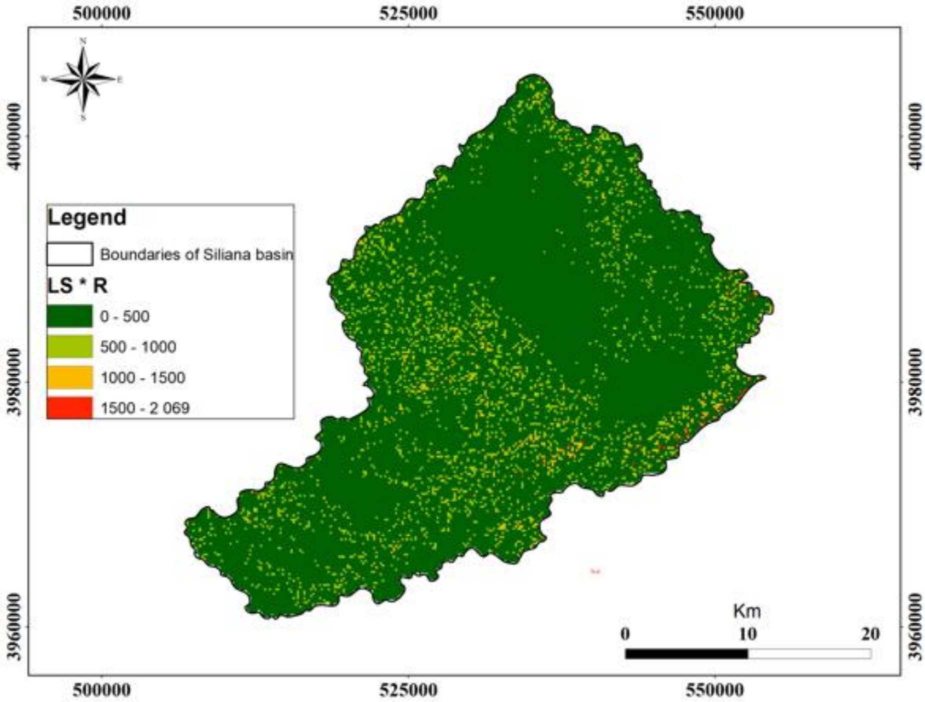

Fig. 6. Map of the combined LS × R factor in the Siliana river watershed
Source: Author's own elaboration using ARC-GIS software

Table 3. Erosivity risk classification based on LS × R values the Siliana River Watershed

Class	LS × R Interval	Erosive Risk Level
1	0 – 500	Low
2	500 – 1000	Moderate
3	1000 – 1500	High
4	> 1500 (up to 2069)	Very high

Source: Author's own elaboration

High LS × R factor values are mainly concentrated in the northern and northeastern parts of the watershed, particularly within the mountainous areas of Kesra and Jebel Bargou, where values frequently exceed 1000 and locally surpass 1500. These zones are characterized by steep to very steep slopes, extended slope lengths, and a dense hydrographic network, all of which favor intense surface runoff. The combined effect of these topographic conditions and high rainfall erosivity results in a very high potential for water erosion, identifying Kesra and Bargou as the principal sediment source areas within the watershed.

These results are consistent with the findings of Nearing et al. (1997), who demonstrated in Mediterranean environments that steep slopes associated with intense rainfall considerably enhance the topographic factor, leading to an exponential increase in soil loss estimated by RUSLE-based models. Similarly, Hachicha and Bargaoui (2014) reported very high LS values (>1000) associated with severe water erosion in the Tunisian Atlas Mountains, emphasizing the dominant role of topography in controlling erosion processes in mountainous environments.

The central part of the watershed, including the regions of Gaâfour and El Aroussa, is characterized by intermediate LS × R values, generally ranging from 500 to 1500. This area is dominated by moderately undulating topography, which reduces the influence of the LS factor compared with the surrounding mountainous regions. Nevertheless, the presence of cultivated slopes and the proximity to the main drainage network contribute to the occurrence of localized areas exposed to moderate to high erosion risk, particularly along valleys and tributaries of the Siliana River. These findings are consistent with those reported by Ben Salem et al. (2018) in the El Korfa river watershed (northern Tunisia), where intermediate LS × R values were associated with moderate slopes affected by intensive agricultural activities, thereby increasing the susceptibility to localized water erosion.

The Makthar region, located on a relatively flat plateau, is mainly characterized by intermediate LS × R values ranging between 500 and 1500. Slopes are generally gentle to moderate, while slope lengths remain relatively limited, thereby reducing the influence of the topographic factor on erosion processes. However, locally higher values may occur along plateau margins and near secondary wadis, indicating areas with moderate to locally high water erosion potential. Comparable findings were reported by Boussetta and Omrani (2026) in the semi-arid plateaus of central-western Tunisia, where transitional zones between plateaus and valleys displayed higher LS × R values than the plateau interiors due to subtle variations in slope gradient and slope length.

In contrast, the southern and southwestern parts of the watershed, particularly around Bourouis and the surrounding agricultural plains, are dominated by low LS × R values, generally below 500. These sectors are characterized by gentle slopes and short slope lengths, which considerably reduce the influence of the topographic factor despite rainfall erosivity levels that may locally be comparable to those observed elsewhere in the basin. Consequently, the water erosion potential remains generally low and predominantly diffuse. Similar trends were identified by El Jany and Chabbi (2011) in the eastern Tunisian plains, where low LS × R values were associated with low-relief landscapes and erosion processes dominated by diffuse rather than concentrated runoff.

Overall, the spatial distribution of the LS × R factor reveals a pronounced north–south erosion gradient primarily controlled by topography. The mountainous regions of Kesra and Bargou represent the most vulnerable zones to water erosion, followed by intermediate-risk sectors such as Gaâfour, El Aroussa, and Makthar, whereas the Bourouis plains exhibit substantially lower susceptibility. These findings emphasize the importance of implementing differentiated soil and water conservation strategies, with priority given to mountainous areas and plateau margins characterized by high combined LS × R values. Comparisons with other Mediterranean watersheds further support the robustness of these results and confirm the dominant role of topography in controlling water erosion processes at the regional scale.

Conclusions

The integrated analysis of water erosion in the Siliana River watershed, based on the spatial assessment of rainfall erosivity (R factor), the topographic factor (LS), and their interaction, reveals pronounced spatial heterogeneity in erosion susceptibility, closely associated with the climatic and geomorphological contrasts of the basin.

The results show that annual precipitation ranges from 417 to 523 mm, with the highest totals mainly recorded in the mountainous regions of Bargou and Makthar. This distribution corresponds to R factor values varying between 39 and 52, where low to moderate erosivity classes dominate 61.12 % of the watershed, whereas high values (46–52) occupy only 7.02 % of the total area, mainly in elevated sectors. These findings indicate that rainfall erosivity remains generally moderate across the watershed, although some localized areas display significant erosive potential.

The topographic analysis highlights the predominance of gentle to moderate slopes (<10 %), covering 53.5 % of the watershed area, while steep to very steep slopes (>25 %) account for nearly 9 % of the basin. These steep terrains, mainly concentrated in the Kesra, Bargou, and Makthar regions, generate high LS factor values, reflecting strong runoff concentration and sediment transport potential.

The combined spatial analysis of the R and LS factors reveals LS × R values ranging from 0 to 2069. High to very high susceptibility classes (LS × R >1000) are mainly concentrated in the mountainous northern and northeastern sectors of the watershed, where steep slopes coincide with highly erosive rainfall conditions. In contrast, the agricultural plains, characterized by gentle slopes and LS × R values generally below 500, exhibit relatively low erosion susceptibility.

Overall, these results demonstrate that topography constitutes the dominant factor controlling the spatial distribution of potential water erosion within the Siliana River watershed, while rainfall erosivity acts as an amplifying factor. The GIS-based approach adopted in this study provides an effective framework for identifying priority areas requiring soil and water conservation measures, particularly in mountainous regions characterized by high combined LS × R values. Consequently, the study contributes to a more targeted and sustainable watershed management strategy.

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets analyzed during the current study are not publicly available but can be obtained from the corresponding author upon reasonable request.

Use of generative AI and AI-assisted technologies

Generative AI tools were employed only for linguistic editing and grammar enhancement. The authors critically reviewed, validated, and approved the final manuscript, assuming full responsibility for its content.

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