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Article

Rain Erosivity Factor (R) and Topographic Factor (LS) of the Universal Soil Loss Equation (USLE) in Semi-Desert Areas

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Highlights

What are the main findings?

- The rainfall erosivity factor (R) was estimated for the Cañitas Sub-basin using long-term precipitation data and geospatial analysis.
- The Modified Fournier Index proved to be a reliable alternative for estimating rainfall erosivity in semi-arid regions with limited pluviographic data.
- The spatial analysis identified areas with higher erosive potential associated with topography and intense rainfall events.
- The results provide useful information for soil conservation planning and sustainable watershed management in northern Mexico.

What are the implications of the main findings?

- Advancement in the understanding of rainfall erosivity in semi-arid environments Identification of priority conservation areas.
- Methodological contribution for estimating rainfall erosivity under limited data conditions.
- Identification of spatial patterns of erosion risk through geospatial analysis.
- Contribution to sustainable watershed management and soil conservation strategies

Abstract

Water erosion is a critical degradation process that reduces fertility and agricultural sustainability, especially in semi-arid regions. The Universal Soil Loss Equation (USLE) allows for the quantification of this phenomenon using factors such as rainfall erosivity (R) and topography (length-slope, LS). In this study, both factors were estimated and analyzed in the Cañitas sub-basin, located in the semi-desert area of the state of Zacatecas, Mexico, characterized by irregular precipitation and limited data availability. The objective of this study is to estimate and analyze the R factor and LS factor to evaluate their influence on soil water erosion processes. Records from five meteorological stations (1986–2022) were used, along with the Modified Fournier Index (MFI) and Geographic Information Systems (GIS) tools, generating spatial maps of rainfall erosivity and topography. An average R factor of 240.608 MJ·mm/ha·h·year was estimated, consistent with the values obtained using the MFI. The LS factor shows that the northwestern area of the study zone has the most extensive and steepest slopes (up to 20.78). This study provides useful information for understanding soil erosion processes, which can serve as a reference for planning conservation actions and managing watersheds in semi-arid areas with high climatic variability.

Keywords: water erosion; USLE; R factor; Modified Fournier Index; LS factor

1. Introduction

One of the main environmental problems globally is soil erosion [1], due to its economic and social impact [2]. Loss of biodiversity, soil degradation, nutrient loss, and water and soil pollution are negative impacts of erosion. In 2018, the International Resolution on Soil and Water Conservation established that “global average soil erosion is estimated at between 12 and 15 t/ha/year” (FAO, 2018), meaning that, globally, the Earth’s land surface loses between 0.90 and 0.95 mm of soil annually.

The economic, social, and ecological impacts, which affect fertility, biodiversity, and water quality, have made soil erosion one of the main environmental problems, given its impact on fertility, biodiversity, and water quality. Precipitation, topography, and land use are fundamental factors in water erosion, which also exhibits high spatial and temporal variability. In this context, the integration of models such as USLE/RUSLE with geospatial tools has allowed progress in identifying critical areas; however, limitations persist in the detailed representation of these factors, especially in semi-arid regions with limited data. In particular, understanding the spatial distribution of the R factor and the heterogeneity of the LS factor remains a significant challenge for adequately interpreting erosive processes under conditions of climatic variability.

Aiello et al. in 2015 used a 20m digital elevation model (DEM) and the Desmet & Govers model, in southern Italy found that slopes greater than 15–20% increase erosion up to 10 times, with topographical factor being the main geomorphological control [3]. Using the RUSLE method and GIS, Tahiri, M., et al. in 2015 identified LS as one of the fundamental factors in the erosion process [4]. In the next year Panagos et al. using high-precision precipitation data, the R-value in Europe was analyzed using the RUSLE method, revealing high variability and elevated values associated with extreme events in the Mediterranean region. [5]. Panagos et al. using the GAM statistical model and the RUSLE method, found that erosivity is concentrated in autumn and winter, with a clear relationship between rainfall intensity and the spatial distribution of the erosivity factor [5]. In Rwanda in 2016, Karamage et al. used the USLE method, GIS, and remote sensing, finding that water erosion is very severe in Rwanda, concentrated in agricultural areas with steep slopes [6]. That same year, Gelagay, H. S. and Minale, A. S. used RUSLE, GIS and remote sensing, finding severe erosion in the Koga basin, related to topography, rainfall and intensive agricultural use [7]. In 2017 Panos Panagos, in collaboration with dozens of researchers, collaborated on a R factor global study using high-density climate databases, concluding that rainfall erosivity is highly variable in space and time, concentrating in the tropics and at specific seasons [8]. In the same year, Ahmed Benchettouh et al. assessed erosion risk using the integration of RUSLE and GIS, concluding that it is a powerful tool for diagnosing erosion and prioritizing areas for ecological restoration [9]. W.M. Navarro et al. analyzed in 2021 erosivity and its trend in Juliaca, calculating R using USLE and the Mann-Kendall method. They concluded that rainfall erosivity in Juliaca is high and variable, directly linked to annual precipitation, with no clear trend during the evaluated period, but with a potentially significant impact on soil erosion [10]. Next year Castro Villarreal et al. they used USLE and GIS methods to estimate soil loss in the Estibaná River sub-basin, comparing different types of vegetation cover and their effects, as well as agricultural management practices. Concluding that erosion in the Estibaná River sub-basin is a serious problem caused mainly by intense rainfall and rugged topography [12]. Ares and Entrantes, in that same year, conducted a study using the USLE equation, demonstrating the spatial and temporal interactions between different factors (precipitation, slope, soil, crops, management) [13]. At the same time Ricardo-Calzadilla et al. using local precipitation data (20 years), soil and topographic factors were estimated using the RUSLE method, validating indices such as rainfall erosivity, and employing the Modified Fournier Index to estimate erosion risk in the Los Palacios River sub-basin (Cuba). This reflected the spatial and temporal interactions between natural factors (rainfall, slope, soil) and anthropogenic factors (crops, management), where rainfall exhibits very high erosive aggressiveness [14]. In 2023 Bouayad et al. analyzed a basin in

northwestern Morocco using GIS, DEM, and RUSLE, identifying risk areas and highlighting the LS and R factors importance of the RUSLE equation as the most relevant factors in the spatial variability of erosion [15]. In China, in 2024 the authors Li et al. applied the improved USLE equation methodology with global climatic, soil, topographic, and satellite data from 1992–2015, analyzing temporal trends and regional variations. They also validated the results by comparing them with previous global studies, concluding that global potential water erosion is highly sensitive to precipitation and changes in land cover [16]. The study by Gvozdenovich et al. provides a robust application of the USLE integrated with GIS to assess soil loss and its economic impact in an agricultural watershed, highlighting the effectiveness of conservation practices. Critical areas associated with slope and position in the landscape are identified [17]. The USLE/RUSLE methods, along with GIS and remote sensing, have enabled various studies worldwide (see Table 1) to demonstrate that heavy rainfall, topography, and land use are important factors in the erosion process. Water erosion has been shown to increase significantly with heavy rainfall and steep slopes, exhibiting marked spatial and temporal variability. This allows for the identification of risk zones and facilitates soil management and watershed planning. Previous studies demonstrate that topography and climate change significantly affect water erosion. This study contributes to the spatial accuracy of the R factor and demonstrates that the topographic LS factor exhibits a marked spatial heterogeneity associated with the influence of relief on water erosion. These results provide information for planning soil conservation strategies and integrated watershed management in semi-arid zones.

Table 1 shows some of the studies carried out in the period 2015–2025 [4–12,15,17–22].

Table 1. Some of the studies carried out in the period 2015–2025.

Author/ Year	Country/ Region	Methodology	Main focus	Main findings	Limitations	Comparison with the present article
Tahiri et al. (2015)	Morocco	RUSLE+GIS	Spatial analysis.	LS as a fundamental factor.	Without temporal analysis of R factor.	A temporal analysis of the R factor is included.
Panagos et al. (2016)	Greece	RUSLE+DEM high resolution + GAM	Spatiotemporal erosivity (R factor).	High spatial and temporal variability.	Dependence on high-resolution pluviographic data. Approach with Mediterranean conditions.	Analysis with limited rainfall data. Semi-arid zone.
Karamage et al. (2016)	Rwanda	RUSLE+GIS	Erosion assessment.	High erosion in sloping agricultural areas.	Tropical context.	Semi-arid zone.
Gelagay et al. (2016)	Ethiopia	RUSLE+DEM (30 m)	Critical erosion zones.	Identification of vulnerable areas.	Without methodological validation.	Validate alternative methods.
Panagos et al. (2017)	Global	RUSLE+ climatological data	Global R factor.	High spatial and temporal variability.	Global scale without local detail.	Detailed local analysis.

Benchetto et al. (2017)	Algeria	RUSLE+GIS	Risk of erosion.	A useful tool for planning.	Without validation of the R factor or long time series.	Validation of the R factor, using series 1986-2022.
Navarro et al. (2021)	Perú	USLE + Mann-Kendall	R Factor	High erosivity and decreasing erosivity trend	Short series (2013-2017); not calculated LS	Cañitas uses a long series, including LS and methodological validation
Calero et al. (2021)	Colombia	Empirical models of R	Erosivity assessment	Significant differences between methods	Data dependency; does not include LS.	Cañitas validates R (IMF vs GIS) and includes LS in semi-arid zone
Aguirre-Salado et al. (2017)	Mexico	RUSLE+SWAT+ HIT	Agricultural basins.	Integration of hydrological models.	Not validated in semi-arid zones.	Focused on semi-arid zones.
Gaubi et al. (2017)	Tunisia	RUSLE	R and LS factors.	Interaction between factors in the Mediterranean Basin.	Without methodological comparison.	MFI vs GIS is compared.
Yue et al. (2020)	China	Rainfall Temporal Resolution Analysis + USLE (R factor)	R factor accuracy.	Erosivity decreases when using low temporal resolution data; errors increase >15 min.	Dependence on high-resolution data; methodological approach.	Cañitas uses limited data but validates R with alternative methods.
Fiener et al. (2020)	Europe (Czech Republic, Germany, Austria)	USLE/RUSLE comparative + SIG	Comparison of model implementations.	Differences of up to 75% in erosion estimates depending on implementation. Even greater variability at the plot scale.	Lack of standardization between countries.	Cañitas provides methodological validation of the R and analysis under semi-arid conditions, reducing local uncertainty.
Castro Villarreal et al. (2022)	Panama	USLE+ plots +GIS	Soil use	Influence of soil cover and management.	No methodological validation of the R factor.	Validation of R factor, analyzes R and LS factors.

Ares et al. (2022)	Argentina	USLE (monthly scale)	Spatio-temporal analysis.	Interaction of natural and anthropogenic factors.	Monthly scale.	Annual Scale.
Marcillo & Triana (2024)	Ecuador	MCDA + GIS	Risk zoning.	Identification of critical areas by slope and cover.	Subjectivity in weightings; no physical model or validation.	Cañitas uses USLE, a quantitative approach in R and LS.
Li et al. (2024)	China	USLE+DEM+GIS	Global trends.	High sensitivity to climate and land use.	Global scale.	Regional scale.
Santos et al. (2025)	Brazil	RUSLE + GIS + MLR	Identification of priority areas and geomorphometric control.	Predominantly low risk, with localized critical areas. Topographic factors explain much of the variability. Identification of key geomorphological variables (curvature, humidity index, etc.).	The model partially explains the variability. Dependence on spatial data. Tropical regional focus.	Cañitas delves into specific R and LS, including methodological validation (IMF vs GIS) and temporal analysis in a semi-arid zone.

2. Materials and Methods

2.1. Study Area

The study area is located in the Cañitas Sub-basin, situated between the geographic coordinates $-102^{\circ}4'49.888564''$ longitude and $23^{\circ}27'47.102213''$ latitude, within the Fresnillo-Yesca Basin, in the State of Zacatecas, Mexico. This region is located in a semi-desert zone, characterized by high-intensity rainfall over short periods, high hydroclimatic variability, and erosivity associated with high-intensity rainfall events [19].

The Cañitas sub-basin shares with several international studies the predominant influence of the R and LS factors on the dynamics of water erosion; however, it is distinguished by its semi-arid condition, limited data availability, and high climatic variability, which modifies the erosion generation mechanisms. Unlike tropical or temperate regions, where erosion is more constant, in Cañitas it is associated with intense but sporadic rainfall events. Furthermore, the use of different techniques for validating the R factor represents a significant contribution compared to studies lacking methodological rigor. The Cañitas Sub-basin (Figure 1) has an area of 4949.22 km² and a perimeter of 428.12 km (SIATL, 2025). Within the sub-basin, different land uses are observed (agricultural, land-use change, limited vegetation) associated with soil degradation processes. The Cañitas sub-basin contributes to surface runoff and the recharge of local aquifers, which is fundamental for the sustainable management of water resources in the northern part of the state of Zacatecas [24]. The analysis of the R (rainfall erosivity) and LS (topography) factors in the Cañitas sub-basin is fundamental to understanding the mechanisms that control water erosion in semi-arid environments characterized by high climatic variability, with rainfall concentrated between June and September. This favors short-duration, high-kinetic-energy erosion events. The R factor quantifies the energy and intensity of precipitation, while the LS factor shows the influence of topography on

the erosion process. Evaluating both factors allow for identifying the spatial distribution of erosion risk and distinguishing areas where climatic or topographic effects predominate. Furthermore, this approach helps reduce uncertainty in erosion estimation using the USLE (United States of Local Erosion), particularly in contexts with limited information, thus strengthening the analysis of the erosion process at a local scale.

The aforementioned conditions and the physical properties of the soil make the Cañitas sub-basin a site of interest for evaluating water erosion and the potential impacts of climate change on soil loss [25].

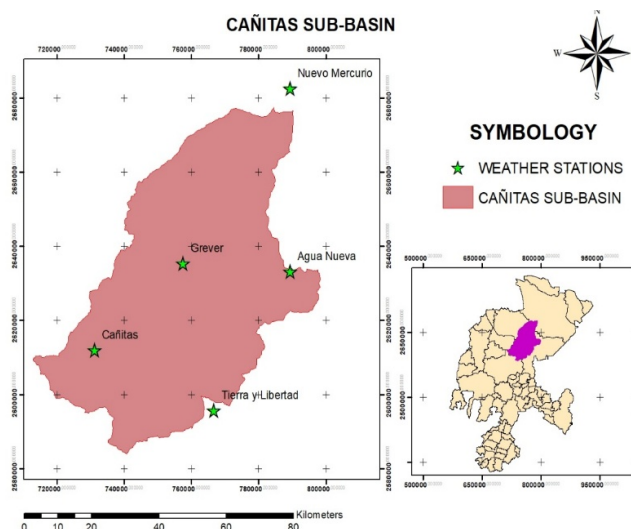


Figure 1. Location of the Cañitas sub-basin and the five meteorological stations analyzed.

Table 2 shows the general characteristics of the five weather stations analyzed over a period of more than 30 years.

Table 2. General characteristics of climatological stations (National Meteorological Service).

Weather Station	Name	Basin	Municipality	Latitude	Longitude	Msnm	Years of Service
32001	Agua Nueva	Fresnillo-Yesca	Villa de Cos, Zac.	23°46'58"	-102°09'37"	1932	1964-2022
32005	Cañitas de Felipe Pescador	Fresnillo-Yesca	Cañitas de Felipe Pescador	23°36'08"	-102°44'02"	2046	1941-2022
32040	Nuevo Mercurio	Camacho-Gruñidora	Mazapil, Zac.	24°13'38"	-102°09'09"	1706	1969-2022
32076	Col. Grever Colorada	La Fresnillo-Yesca	Villa de Cos, Zac.	23°48'34"	-102°28'19"	1950	1971-2023
32142	Tierra y Libertad	Fresnillo-Yesca	Villa de Cos, Zac.	23°27'00"	-102°23'32"	2030	1982-2023

This research aims to determine and evaluate the R factor and LS factor in the Cañitas Sub-basin, located in the Fresnillo-Yesca Basin within the semi-arid region of the State of Zacatecas, Mexico. GIS tools based on the Modified Fournier Index (MFI) were applied, enabling a spatial assessment of rainfall erosivity and topography in the study area.

This study provides new evidence on the spatial distribution of rainfall erosivity and the topographic influence on soil erosion in a semi-arid watershed in northern Zacatecas State, Mexico.

It demonstrates the applicability of the Modified Fournier Index combined with GIS techniques in data-scarce environments.

2.2. Universal Soil Loss Equation

The Universal Soil Loss Equation (USLE) is a mathematical model that calculates water erosion of soil [26], based on factors given by Equation (1) [27].

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P, \quad (1)$$

where: A is the annual average soil erosion $Mg/(ha \cdot year)$, R is rainfall erosivity ($MJ \cdot mm/ha \cdot h \cdot year$), K is soil erodibility $(Mg \cdot h)/(MJ \cdot mm)$, L is slope length (dimensionless), S is slope grade (dimensionless), C is crop and crop management (dimensionless), and P is soil management practices (dimensionless) [28].

2.3. Modified Fournier Index (MFI)

The index of maximum intensity in 30 minutes (EI₃₀) represents the result of the kinetic energy from the impact of raindrops on the soil multiplied by the maximum continuous intensity of precipitation over a 30-minute rainfall period. Fournier, in 1960, calculated the precipitation coefficient (R_c) to estimate erosivity [29]. Lombardi Neto and Moldenhauer (1992) established an equation between precipitation and erosivity using the Fournier Index (FI), where EI₃₀ and the precipitation coefficient R_c are represented. This allows for the calculation of erosivity [30].

The R factor, called rainfall erosivity or soil erosivity, is a function of the kinetic energy and intensity of precipitation. The calculation is based on the climatic aggressiveness index or FI (Equation (2)), which is calculated using data from weather stations. The formula for the FI is obtained from Equation (2) [31].

$$FI = \frac{p_{max}^2}{P}, \quad (2)$$

where: FI is the Fournier Index, p_{max} is the average precipitation of the rainiest month (mm), and P is the average annual precipitation (mm).

The MFI (Equation (3)) is obtained from the ratio of the sum of the squares of the monthly precipitation for a year to the total average annual precipitation [31].

$$MFI = \frac{\sum_{i=1}^{12} p_i^2}{P_t}, \quad (3)$$

where: MFI is the Modified Fournier Index, p_i is the mean monthly precipitation (mm), and P_t is the mean annual precipitation (mm).

In 2018 Benavidez et al. applied a correlation between the R factor and the MFI to readjust the model [32]. In 2016 Crettaz et al. stated that "The Modified Fournier Index by Arnoulds shows a high degree of fit with the R factor." [31]. According to Jaya-Santillán in 2023, the equation for calculating the R factor is given by Equation (4) [33].

$$R = 2.56 \cdot MFI^{1.065}. \quad (4)$$

The calculation of the R-value is supported by ArcGIS software as a geospatial platform [34]. Weather stations are strategically located for the study, easing visualization, analysis of their distribution, and the generation of continuous surfaces across the study area. To calculate the R-value, data from five weather stations located near and within the study area were incorporated.

The inverse distance weighting (IDW) method was used for spatial interpolation of precipitation. This study includes five weather stations heterogeneously distributed across the study area, requiring an interpolation method that gives greater weight to values observed at points closer to the estimation location. In this regard, the IDW method is suitable, since it considers that the influence of data points decreases with distance, allowing the generation of a continuous surface that represents the spatial variability of precipitation. The result of the interpolation was a raster for each month of the year representing the precipitation across the entire sub-basin. The erosivity factor could then be calculated using the generated monthly rasters.

2.4. Topographic Factor LS

Slope length (L) and slope (S) are two fundamental elements in the USLE equation for calculating the LS factor in watershed studies, which includes the influence of topography on soil loss. [35].

Foster (1977) proposed Equations (5)-7 for L factor estimation.

$$L = \left(\frac{\lambda}{22.13} \right)^m, \quad (5)$$

$$\text{with } m = \frac{F}{1+F'} \quad (6)$$

$$\text{and } F = \frac{\sin\beta/0.086}{3(\sin\beta)^{1.8}+0.56}, \quad (7)$$

where: L is the slope length (m), λ is the surface flow area (m²), F is the slope factor that defines m, m is the exponent influenced by the slope length and angle, and β is the slope angle.

In 2015, Panagos and Meusburger, building on the work of Desmet Gover (1996) and the emergence of GIS, proposed Equation (8) [5].

$$L_{(i,j)} = \frac{[A_{(i,j)}+D^2]^{(m+1)} - A_{(i,j)}^{(m+1)}}{x^m D^{(m+2)} (22.13)^m}, \quad (8)$$

where: β Slope, A Flow accumulation, D Grid cell size (m), x Shape coefficient (x=1).

According to Renard et al. (1997), soil loss increases with slope length, hence the importance of the S factor [36].

The formula for obtaining the slope is derived from Equations (9) and (10) based on McCool et al. (1987) [36].

$$\tan\beta_{(i,j)} < 0.09 \rightarrow S_{(i,j)} = 10.8\sin\beta_{(i,j)} + 0.03, \quad (9)$$

$$\tan\beta_{(i,j)} \geq 0.09 \rightarrow S_{(i,j)} = 16.8\sin\beta_{(i,j)} - 0.5. \quad (10)$$

3. Results and Discussion

3.1. R Factor

Figure 2 shows the average results of the R factor at the five meteorological stations analyzed between 2000 and 2022, showing significant changes in precipitation.

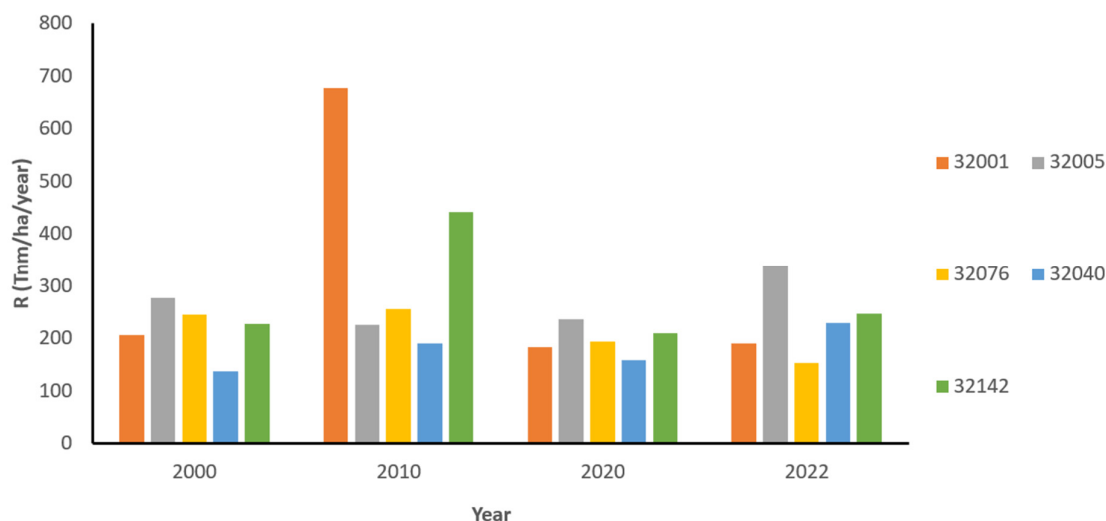


Figure 2. Average of the R factor where significant changes in precipitation are shown.

The R-factor was calculated based on data from weather stations over the period 1986–2022 (National Meteorological Service).

Figure 2 shows that the stations exhibiting the highest R factor in 2020 and 2022 are located in the southwest of the sub-basin (32005) and in the southeast (32142). In 2010, the highest factor was

found in the west (32001) and in the southeast (32142). In 2000, the highest R factor was found in the southwest (32005) and in the center of the sub-basin (32076).

The results indicate that the highest R factor recorded in 2022 reached 339.71 MJ-mm/ha-h-year, concentrated in the southwest sector of the Cañitas sub-basin. This area shows greater susceptibility to water erosion due to the combination of high-intensity rainfall events that favor runoff generation. The spatial distribution of this maximum value suggests the influence of intense, short duration storms during the analyzed period, a typical behavior of semi-desert regions where storms occur in localized areas and with high kinetic energy (Figure 3).

The highest erosivity index in 2022 in the Cañitas sub-basin was obtained in the southwest (Figure 3).

EROSIVITY FACTOR MAP OF THE CAÑITAS SUB-BASIN (2022)

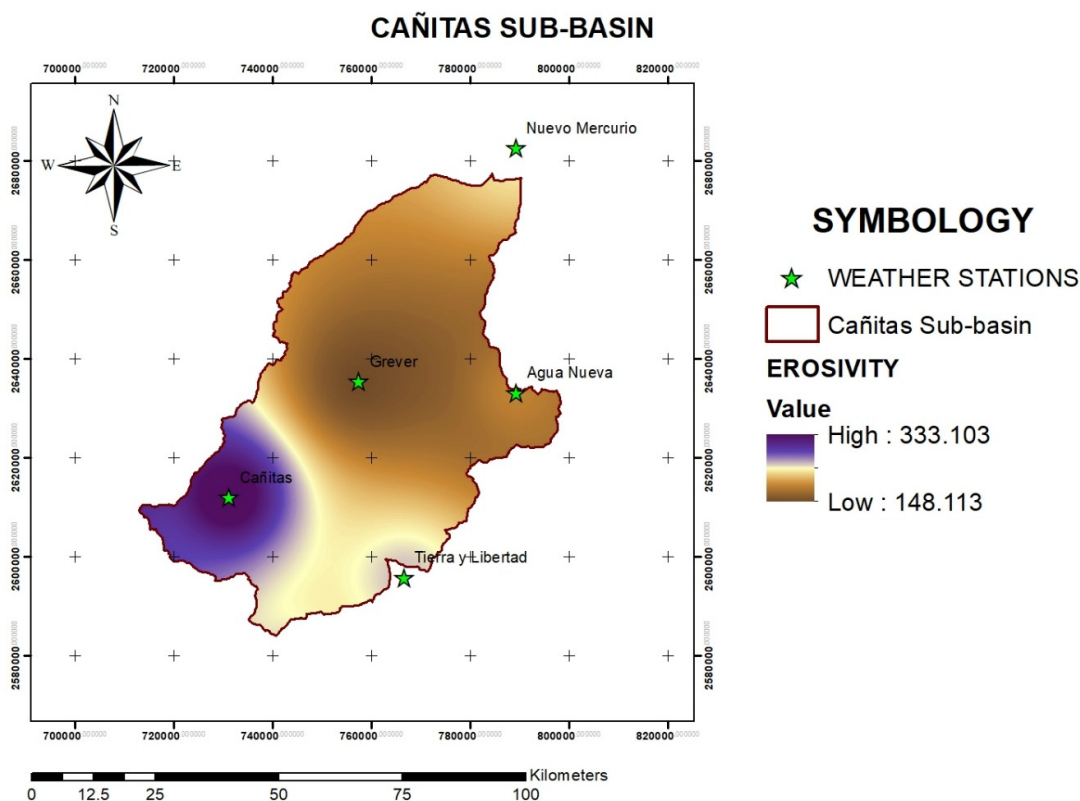


Figure 3. Erosivity factor map of the Cañitas sub-basin (2022) shows the southwestern zone with the highest erosivity index.

The western part of the study area has the highest erosivity values, while the southern part has the lowest. Similarly, low erosivity values predominate in the central and eastern parts of the sub-basin, while average values are recorded in the north and center.

During the period 1986–2022, the rainfall erosivity values ranged from 219.088 MJ-mm/ha-h-year in 1986 to 232.21 MJ-mm/ha-h-year in 2022. The difference between the two years (13.12 MJ-mm/ha-h-year) is relatively insignificant; however, some years show more marked variations, such as 1991, when erosivity reached considerably higher values than the historical average for the period studied (Figure 4).

The comparative analysis between the two methods applied shows that the R factor values obtained for 2022 are considerably similar. The method based on the MFI yielded an average value of 232.21 MJ-mm/ha-h-year, while the geospatial processing method developed in ArcGIS yielded a value of 240.608 MJ-mm/ha-h-year. The difference between the two results has a relative error of

3.49%, which demonstrates methodologically consistency and reinforces the reliability of the obtained values.

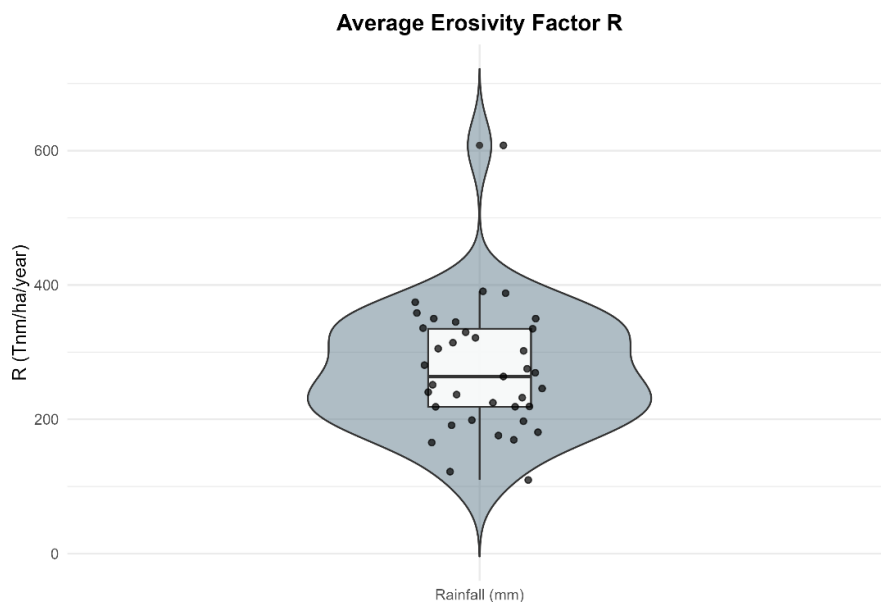


Figure 4. Average R factor for the period 1986-2022, where the variability of precipitation can be observed.

The closeness of the obtained values indicates that, even though both methods are based on different principles, they converge on a consistent representation of the erosive potential of precipitation, demonstrating that the estimation of the R factor is not affected by the different methodologies, thus strengthening the validity of the results (Table 3) [37]

Table 3. Classification of R Factor values.

R Factor	R factor classification
0-50	Light
50-500	Moderate
500-1000	High
>1000	Very high

In 1990 and 2010, the eastern part of the sub-basin had an R index of 941.89 and 678.04 MJ·mm/ha·h·year, respectively. In 2018, the southern part had an R index of 608.92 MJ·mm/ha·h·year; in all cases, the index was classified as high. The R index decreased throughout the basin due to the decline in precipitation.

3.2. LS Factor

The results of the LS factor (Figure 5) indicate that the northwest part has a topography with extensive lengths and steeper slopes, making it more prone to erosion.

Figures 5 and 6 show significant spatial differences in the influence of topography within the Cañitas sub-basin. The LS values range from 0.03 to 20.78, indicating wide variability in lengths and slopes.

The northwest zone is characterized primarily by steep slopes and long hillsides, where surface runoff acquires greater energy and transport capacity, creating critical areas with erosion potential, especially during heavy rainfall. The eastern part of the sub-basin exhibits a low to moderate

topographic intensity factor (0.94–3.77). Conversely, most of the sub-basin presents very low LS values (≤ 1), corresponding to gentle terrain with short slopes and relatively flat areas.

TOPOGRAPHIC FACTOR MAP OF THE CAÑITAS SUB-BASIN (2022)

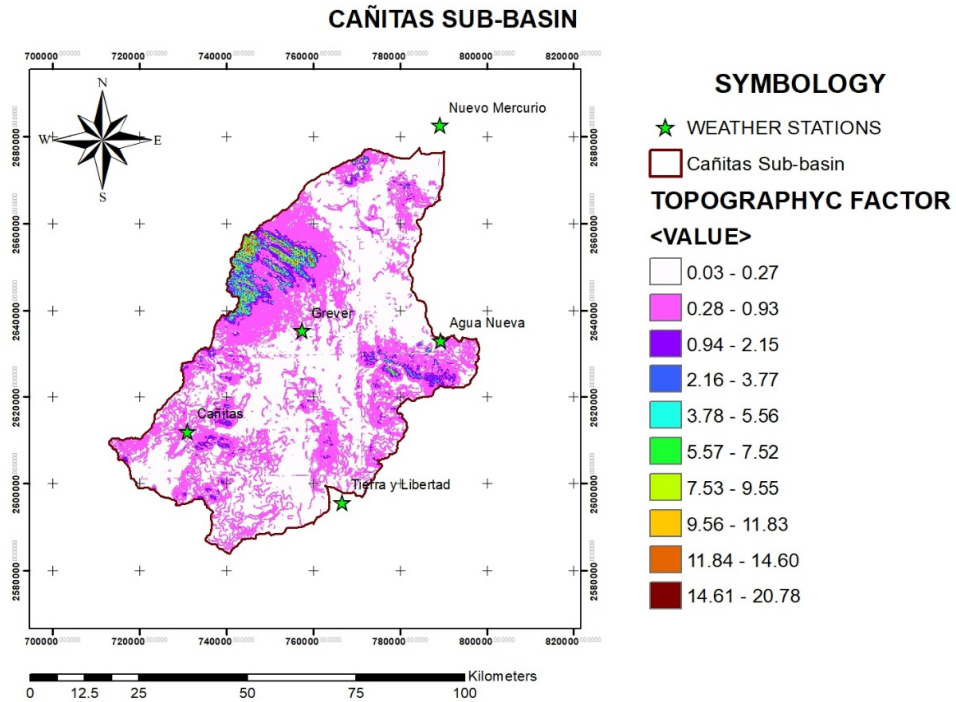


Figure 5. The LS factor shows the northwest part with a topography with extensive lengths and steeper slopes.

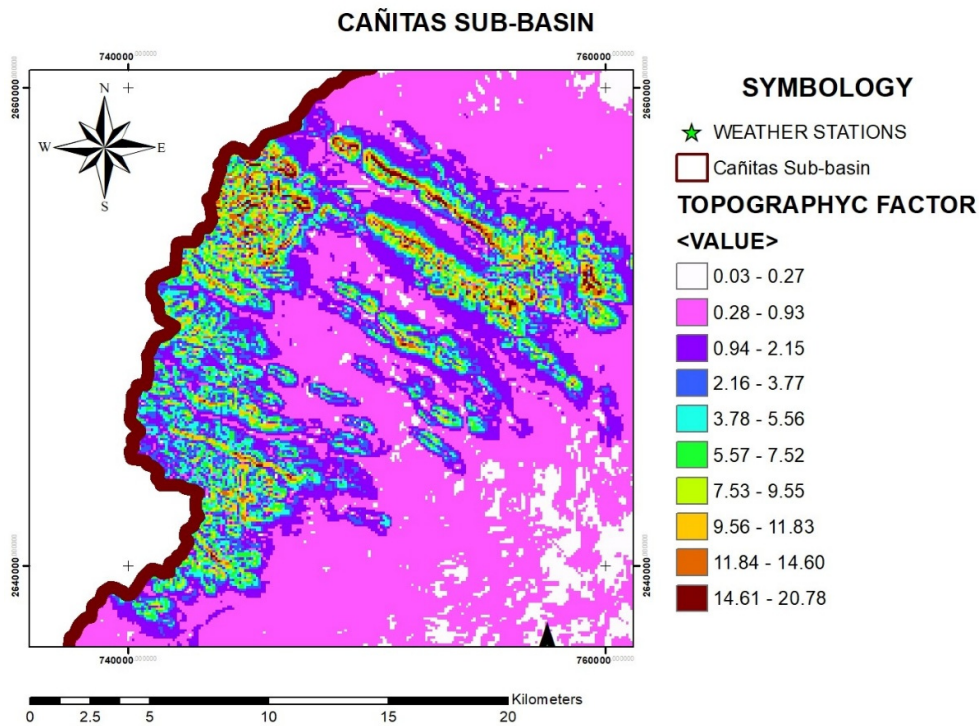


Figure 6 Approach to the northwest zone of the LS factor with extensive lengths and steeper slopes.

Table 4 shows the classification of the LS factor values [37].

Table 4. Classification of LS Factor.

CLASS	LS factor classification	VALUE
1	< 1.5	Very low
2	1.6-3	Low
3	3-5	Moderate
4	5.1-7	High
5	> 7	Very high

The results show that potential erosion is conditioned by the R and LS factors, with the R factor remaining stable throughout the year, except during periods of intense rainfall. This analysis provides valuable information for the delimitation of priority conservation areas, decision-making, and the calibration of erosion models at a regional scale.

4. Discussion

The study revealed a decrease in the R factor related to reduced precipitation in the study area, with greater susceptibility in the southwest sector during intense rainfall events, while the rest of the Cañitas Sub-basin maintains a moderate level of erosivity. The LS factor showed marked spatial heterogeneity, identifying the northwest as the area with the greatest erosive potential due to its steep slopes and extensive hillsides. The rest of the Cañitas Sub-basin presents low LS values associated with gentle topography. These results allowed for the identification of two critical erosion areas controlled by distinct factors: rainfall erosivity and topography. Furthermore, the MFI was tested as a reliable alternative for calculating rainfall erosivity in semi-arid regions with limited data. This provides important information for planning soil conservation strategies and integrated watershed management in northern Zacatecas State, Mexico, such as agricultural terraces, living barriers, storage dams, and small dams, among others.

5. Conclusions

The analysis shows a decreasing trend in the R factor over the last few decades, from 607.91 MJ·mm/ha·h·year in 1991 to 165.32 MJ·mm/ha·h·year in 2019, which coincides with a reduction in regional precipitation. However, the southwest of the Cañitas sub-basin remains at moderate risk of water erosion during periods of heavy rainfall. Therefore, the R index is classified as moderate.

On the other hand, the LS factor results show marked spatial heterogeneity within the sub-basin. The northwest region has the most extensive slopes and the steepest gradients (LS up to 20.78), where surface runoff generates greater energy and transport capacity, creating critical areas of erosive potential. Conversely, most of the sub-basin area has low values ($LS \leq 1$), associated with gentle relief and small slopes, where the topography has a minimal impact on erosion.

The analysis of the R and LS factors shows that the R factor in the southwest area indicates a greater tendency toward erosion, while the LS factor indicates a higher probability of erosion by transport in the northwest area due to the local topography. This identifies two critical areas susceptible to erosion from different causes. This provides empirical validation of the MFI as an alternative method for estimating rainfall erosivity in semi-arid environments with limited pluviographic data, strengthening the regional calibration of the USLE/RUSLE model. This contribution helps improve the spatial accuracy of the R factor. The LS factor shows marked spatial heterogeneity within the sub-basin, associated with the influence of topography on water erosion.

The results suggest that the critical areas identified are more likely to experience accelerated erosion.

These findings support the planning of soil conservation strategies and integrated watershed management in semi-arid regions of northern Mexico, which can serve as a basis for formulating recommendations on land management and use aimed at soil conservation.

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Abbreviations

The following abbreviations are used in this manuscript:

R	Rainfall erosivity factor
GIS	Geographic Information System
MFI	Modified Fournier Index
LS	Topographic Factor
USLE	Universal Soil Loss Equation
t/ha/year	Tons of soil per hectare
FAO	Food and Agriculture Organization of the United Nations
DEM	Digital Elevation Model
RUSLE	Revised Universal Soil Loss Equation
GAM	Generalized Additive Model
MCDCA	Multiple Criteria Decision Analysis
Rm	Rainfall magnitude
SWAT	Soil and Water Assessment Tool
C	Crop and crop management
ArcGIS	Software as a geospatial platform
L	Slope length
S	Slope grade
SIATL	Environmental and Territorial Information System (Sistema de Información Ambiental y Territorial)
EI_{30}	Maximum intensity in 30 minutes
R_c	Precipitation coefficient
FI	Fournier Index
IDW	Inverse Distance Weighting
MJ-mm/ha-h-year	Megajoules per millimeter per hectare per hour per year

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