Journal of Geography and Cartography 2024, 7(2), 9639.
https://doi.org/10.24294/jgc9639

Article

Impact of extreme rainfall events on soil erosion in downstream Parnaíba River Basin, Brazilian Cerrado

Wellynne Carla de Sousa Barbosa[1,*], **Antonio José Teixeira Guerra**[1], **Iracilde Maria de Moura Fé Lima**[2]

[1] Federal University of Rio de Janeiro, Rio de Janeiro 21941-909, Brazil
[2] Federal University of Piauí, Teresina 64049-550, Brazil
*** Corresponding author:** Wellynne Carla de Sousa Barbosa, wellynnekarla@gmail.com

CITATION

Barbosa WCdS, Guerra AJT, Lima IMdMF. Impact of extreme rainfall events on soil erosion in downstream Parnaíba River Basin, Brazilian Cerrado. Journal of Geography and Cartography. 2024; 7(2): 9639. https://doi.org/10.24294/jgc9639

ARTICLE INFO

Received: 15 October 2024
Accepted: 19 November 2024
Available online: 10 December 2024

Abstract: This study investigates the impact of extreme rainfall events on soil erosion in the downstream Parnaíba River Basin, located in the Brazilian Cerrado. The analysis focused on rainfall erosivity (R factor) and soil erodibility (K factor) as key indicators. The average erosivity in the region was 9051 MJ mm $h^{-1}ha^{-1}year^{-1}$, with a variation between 7943 and 10,081 MJ mm $h^{-1}ha^{-1}year^{-1}$, suggesting a high erosive potential, mainly in the rainiest months, from December to April. The soils of the studied area, mainly Ultisols and Chernosols, present high to very high erodibility, with K factor values ranging from 0.025 to 0.050 t h MJ^{-1} mm^{-1}. Furthermore, fieldwork revealed areas, near highways, with apparently fragile soils, as well as rills and gullies, identified through photographs taken during fieldwork. These locations, due to the combination of high erosivity and susceptible soils, were considered prone to the occurrence of erosion processes, representing an additional risk to local infrastructure. The spatialization of R and K factors, along with field observations, showed that much of the area is at high risk of erosion and landslides, particularly in regions with greater topographic variability and proximity to water bodies. These results provide a basis for the development of mitigation strategies, being important for the effective prevention of landslides.

Keywords: soil erosion; rainfall erosivity; soil erodibility; extreme rainfall events; Brazilian Cerrado

1. Introduction

Soil erosion, intensified by extreme rainfall events, represents one of the greatest environmental challenges in vulnerable regions of Brazil, particularly in the Cerrado. The Parnaíba River Basin, located in this region, is severely affected by erosive processes, which worsen during periods of heavy rainfall, leading to significant soil loss and posing risks to local infrastructure [1–6].

The Universal Soil Loss Equation (USLE) and its revised version (RUSLE) are widely used to estimate soil erosion by combining data on natural factors and human activities. These models, integrated with Geographic Information Systems (GIS) and Remote Sensing technologies, allow for mapping and quantifying soil loss in different regions.

Given the vast extent of the Parnaíba River Basin, the application of the Revised Universal Soil Loss Equation (RUSLE) was particularly suited for this study, as it enables large-scale soil erosion assessments at the watershed level, where direct erosion plot management would be financially unfeasible. This approach is especially valuable in expansive regions like the Cerrado, where varied soil types and challenging terrain impact erosion dynamics [6].

Fieldwork was also conducted to support the model, with strategically collected soil samples across the study area, enhancing the accuracy of the soil erodibility factor (*K*) in the RUSLE model and validating the remote sensing data used. This methodology integrates GIS with empirical data to create a more comprehensive assessment of erosion susceptibility, essential for effective land management and conservation efforts tailored to the Cerrado's unique environmental conditions.

In the study by Dang and Sun [7], USLE was used to evaluate erosion in the Loess Plateau, China. Among the factors analyzed by RUSLE, the *R* Factor, which measures rainfall erosivity, and the *K* Factor, which reflects soil erodibility, stand out. These factors are key to understanding vulnerability to erosive processes and are the central focus of this study.

Studies on rainfall erosivity developed in Brazil highlight some rainfall erosivity indices (EI30) in MJ mm ha^{-1} h^{-1} yr^{-1}: for Lavras (MG), around 6843; for Mococa (SP), 7747; in Paraná State for 32 locations, a range from 5275 to 12,559; for Goiânia, Goiás State, 8355; for Sete Lagoas, Minas Gerais State, 5835; for Lajes, Santa Catarina State, 5790; and for Manaus, Amazonas State, a high value of around 14,129. The author notes that the range for erosivity in Brazil is between 3116 and 20,035 MJ mm ha^{-1} h^{-1} yr^{-1} [8].

Soil erodibility refers to the susceptibility of soil to water erosion. It is an intrinsic attribute of each soil and is fundamental for predicting soil loss and planning land use. Among the soil attributes that, in an integrated manner, affect erodibility are water permeability, water storage capacity, texture (especially silt content), cohesion, structure type and degree, organic carbon, Fe and Al oxide contents, and clay mineral type [9–13].

The relationship between rainfall erosivity and soil erodibility is crucial for understanding the dynamics of erosion. Rainfall erosivity not only varies according to precipitation intensity and duration, but is also related to the spatial and temporal distribution of extreme rainfall, which in turn is influenced by climate change [14–16]. In contexts where improper soil management and deforestation prevail, vulnerability to erosion increases, intensifying the adverse impacts of intense rainfall events [2,11]

Field observations revealed areas near highways with seemingly fragile soils, as well as the formation of rills and gullies, which are indicative of linear erosion and landslide risk. The combination of high erosivity and susceptible soils makes these areas particularly vulnerable [1,11,17]. Additionally, areas with greater topographic variability and proximity to water bodies are more prone to erosive processes, reflecting the importance of physical context and land use in intensifying erosion [3,18–20].

This study aims at analyzing the impact of extreme rainfall events on soil erosion in the Lower Parnaíba River Basin, in the Brazilian Cerrado, using the *K* (soil erodibility) and *R* (rainfall erosivity) factors from RUSLE (Revised Universal Soil Loss Equation). The research integrates Geographic Information Systems (GIS) data and field observations, focusing on these factors. The investigation seeks to identify areas susceptible to erosion, with particular attention to the urban gully in Miguel Alves Municipality, and to provide a foundation for developing mitigation strategies.

2. Materials and methods

2.1. Study area

The area of the downstream Parnaíba River in Piauí State is a strip of land that lies parallel to the Parnaíba River. It begins in Teresina City and stretches to the confluence of the Sub-basin of the Longá River in Buriti dos Lopes Municipality.

This area covers a strip of land that extends from the city of Teresina to the river's mouth in the Atlantic Ocean. However, considering the dynamic differences between the coastal and continental zones, a new spatial delimitation was defined. This delimitation includes only the sub-basins located on the continental perimeter of the region, resulting in an area of approximately 6075.48 km^2. The area lies between the geodetic coordinates 5°1′20.06″ S/42°50′43.95″ W and 3°7′41.42″ S/41°55′32.98″ W, as shown in **Figure 1** [1,21].

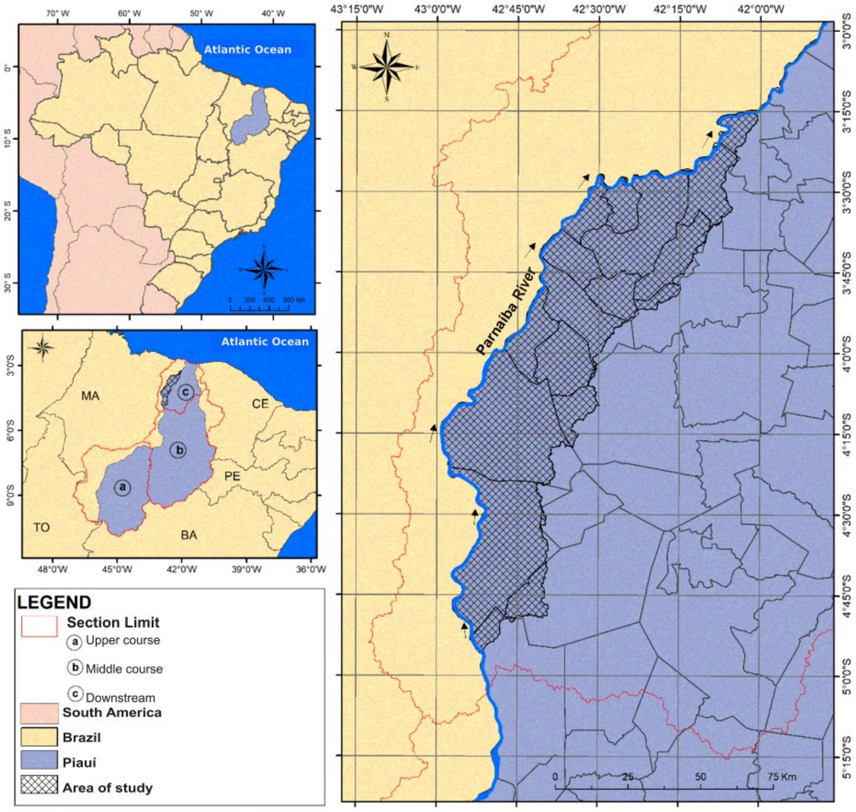

Figure 1. Multiscale view of the Parnaíba River watershed location in the northwest of Piauí State-Brazil.

The dataset for this study was sourced from the United States Geological Survey (USGS). Precipitation data, initially compiled in 2020, were later updated through the HidroWeb platform, which is part of the National Water Resources Information System administered by the National Water Agency (ANA) [22].

The evaluation of soil erosion focused on the *K* factor (soil erodibility) and the R factor (rainfall erosivity) from the Revised Universal Soil Loss Equation (RUSLE), which were critical in determining erosion risk across the study area:

a) Drainage data were obtained from ANA's digital cartographic database [23].

b) The vector cartographic base of soils, in shapefile format, was obtained from the INDE-National Spatial Data Infrastructure website, with the original scale of 1:250,000, and associated with the soil profile information contained in the exploratory soil survey of Piauí State.

c) Erosivity was calculated based on the collection of monthly and annual rainfall data from the Brazilian Rain Atlas (1:5,000,000 scale) between 1977 and 2006 and updated through ANA's HidroWeb tool, corresponding to basin 3–Atlantic, North, and Northeast.

d) Rainfall data from rain gauge stations were obtained from previous studies [22,24], including the Brazilian Rain Atlas. For this study, data from eight stations were used.

2.2. Calculation of RUSLE factors

The *R* (rainfall erosivity) and *K* (soil erodibility) factors were calculated according to the appropriate equations, taking into account the influence of extreme rainfall events on soil erosion in the Baixo Parnaíba basin.

2.3. Soil erodibility (*K* factor)

The *K* factor represents soil erodibility, which is a measure of the soil's susceptibility to erosion under the influence of water. Erodibility is defined by the soil's resistance to dispersive forces, splashing, abrasion, and the transport of soil particles by water, as well as by considering infiltration rate, permeability, and water retention capacity in the soil [2,25,26].

The *K* value can be determined through laboratory methods or empirical estimates, using tables that correlate soil characteristics with *K* values. Despite the limitations in obtaining the *K* factor, various researchers have developed experiments to make this factor applicable to different types of Brazilian soils [4,27–29]. In this research, we opted to adopt the soil erodibility factors available in the literature, considering the soil classes of the Parnaíba River Basin.

The *K* factor data were sourced from the work of Aquino and Oliveira [28], which provided a comprehensive approach to calculating the weighted average soil erodibility for associations in Piauí State. This method involved selecting representative soil profiles by comparing soil descriptions with those outlined in previous studies [30].

Erodibility for each profile was computed based on its specific characteristics and contribution to the soil associations. The *K* values were then averaged arithmetically for each soil type, and a weighted average was calculated, factoring in the proportion of each soil within the association. The erodibility classes were subsequently adapted from the classification system proposed in a previous study [26], as presented in **Table 1**.

Table 1. Soil erodibility (*K*) factor classification [26].

Classification of Soils Based on Erodibility Factor (*K*)	
Propensity to erodibility	(ton.ha.h/ha. MJ.mm)
Very low	< 0.009
Low	0.009–0.015
Medium	0.015–0.30
High	0.30–0.045
Very high	0.045–0.060
Extremely high	> 0.060

2.4. Rainfall erosivity factor (*R* factor)

The *R* factor represents rainfall erosivity, which is a measure of the erosive potential of precipitation in a specific area. Erosivity depends on the characteristics of rainfall, and the *R* factor can be calculated using historical precipitation data, considering the energy and impact of rainfall events. The calculation methodology typically involves the following steps:

a) Collection of precipitation data

Precipitation data were gathered from meteorological stations in the Baixo Parnaíba basin region. These values were estimated based on approximately 30 years of precipitation history, which was used to identify cyclical rainfall patterns [22,31]. According to some authors, around 80% of soil loss is influenced by this factor [32].

b) Calculation of erosivity

To calculate the *R* factor (erosivity), the equation (E2) of Wischmeier and Smith [31] was used, adapted to Brazilian natural conditions [25]

$$R = \sum_{i=1}^{12} \quad 67.355\left(\frac{r_i^2}{P}\right)^{0.85} \tag{1}$$

In the equation, R represents rainfall erosivity (MJ mm h^{-1} ha^{-1} $year^{-1}$), r is the average monthly total precipitation (mm), and P corresponds to the average annual total precipitation (mm). These values were obtained from rainfall data collected from meteorological stations. Rainfall erosivity was then calculated for each station, and the data were interpolated using the Inverse Distance Weighted (IDW) method from the ArcGIS Spatial Analyst Tools.

2.5. Validation

Considering the vast area studied (6075.48 km^2) and the scarcity of erosion plots across the region, a careful approach was adopted in the selection and use of available data. Establishing experimental erosion plots in the lower Parnaíba River basin would be logistically difficult and impractical.

Therefore, alternative validation approaches were used in place of direct experimental data. These included comparisons with field observations and historical data, assessments of internal consistency, cross-referencing with findings from previous studies, and analysis of the sensitivity of results to changes in model parameters.

3. Results and discussion

The results indicated that the impact of extreme rainfall events is greatly intensified by the physical characteristics of the soil in the watershed of the Parnaíba River. The combination of high erosivity and highly erodible soils creates a favorable scenario for the formation of gullies and rills, especially in areas under human interventions.

3.1. Rainfall erosivity (factor *R*) and erosion risk

Erosivity-*R*

The rainfall erosivity analysis for the Parnaíba River watershed revealed an average value of 9051.52 MJ mm h^{-1} ha^{-1} $year^{-1}$, with a standard deviation of 148.33, highlighting the significant erosive potential in the region. These results are consistent with those reported for the Longá River basin, a tributary of the Parnaíba, where critical values ranged from 8865 to 9540 MJ mm h^{-1} ha^{-1} $year^{-1}$ [5]. Specifically, in the downstream area of the Parnaíba River, the R factor ranged from 7943.46 to 10,081.61 MJ mm h^{-1} ha^{-1} $year^{-1}$, with erosivity intensity classified from medium to very strong, as shown in **Table 2**.

Table 2. Interpretation of rainfall erosivity.

Range (MJ mm h^{-1} ha^{-1} $year^{-1}$)	Interpretation of Erosivity
$R < 6000$	Very weak
$6000 > R < 7500$	Weak
$7500 > R < 8500$	Average
$8500 > R < 9000$	Strong
$R > 9000$	Very Strong

Source: Adapted from Morais and Silva [5].

The spatial distribution map of the *R* factor, shown in **Figure 2**, illustrates the significant spatial variability of rainfall. Data linked to individual rainfall measurements monitored by both automatic and conventional stations in Piauí State [22] emphasize that the highest annual rainfall volumes in the state are concentrated in the northern and northwestern regions, where values exceed 1500 mm.

From February to August are the rainiest months, supporting the high *R* values found in this research. In the study area, precipitation values ranged approximately from 1279 to 1710 mm [3].

Similar to studies conducted in other arid and semi-arid regions [16] in northwest Somalia, rainfall erosivity strongly influences soil erosion risk. In Somalia, areas with lower annual rainfall showed low erosivity, while those with moderate rainfall exhibited moderate erosivity. This contrast with the more humid Parnaíba basin emphasizes how local rainfall patterns shape erosion risks, underscoring the need for region-specific monitoring and soil conservation strategies.

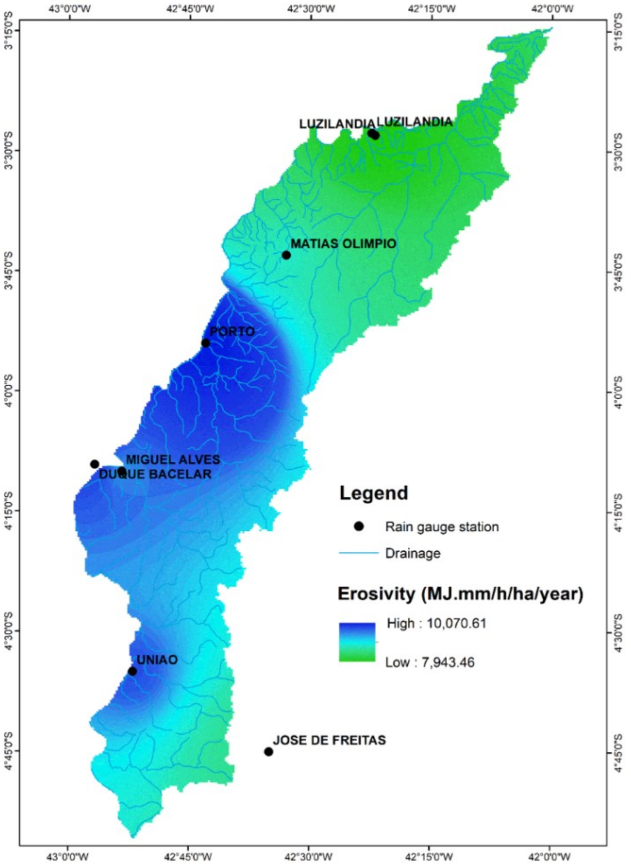

Figure 2. Map illustrating the distribution of rainfall erosivity (*R*).

The analysis of monthly rainfall variations at the rain gauge stations in the study area reveals distinct seasonal trends, as illustrated in **Figure 3**. The dry season, occurring from July to November, is characterized by reduced rainfall, while the wet season, spanning from January to March, experiences significantly higher precipitation levels. This seasonal pattern is vital for identifying periods of increased vulnerability to erosion [2,3,33] During the dry season, the lack of rainfall diminishes the soil's ability to absorb runoff, contributing to soil compaction and degradation. Consequently, when the rains return, the soil becomes more susceptible to erosion.

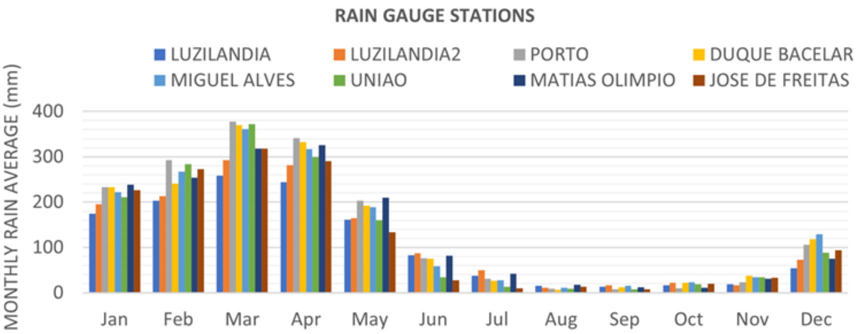

Figure 3. Monthly variation of precipitation from the rain gauge stations in the study area [3].

Figure 4 shows a strong correlation between erosivity (factor *R*) and average annual precipitation, with both parameters closely aligned and relatively stable throughout the year despite monthly fluctuations. This relationship is crucial for assessing erosion risk and developing effective soil erosion prevention strategies.

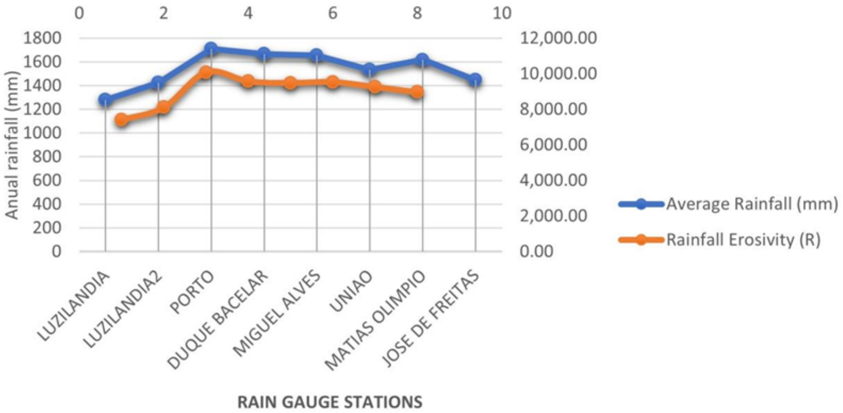

Figure 4. Relationship between erosivity (factor *R*) and average annual precipitation [3].

3.2. Soil erodibility (factor *K*)

The soils in the region, primarily characterized as Argissols and Chernozem, exhibited high erodibility. The most vulnerable areas were identified in regions where the soils are sandier and less cohesive. The combination of these characteristics with the high erosivity of rainfall intensified erosive processes, leading to the formation of features such as ravines and gullies.

The combination of rainfall with high erosivity and fragile, unprotected soils promotes the onset of erosive processes. **Table 3** presents the soil classes found in the area of the Diffuse Basins of Baixo Parnaíba, along with their erodibility values, associated with the extent occupied by each class within the basin.

Table 3. Soil classification based on the soil erodibility factor (*K*) in the study area, northwest Piauí, Brazilian Cerrado.

Soil Unit	Soil Taxonomy	Erodibility Classes	Area (ha)	Area (%)	K Factor ton.ha.h/ha. MJ.mm
A1	ENTISOLS (FLUVENTS)	Medium	38,805.56	5.97%	0.028
A4		High			0.032
BV1	MOLLISOLS	Very high	16,559.63	2.55%	0.05
LA10	OXISOLS	Medium	74,811.94	11.50%	0.025
LA11		Medium			0.028
LA13		Medium			0.028
LA5		High			0.035
LA8		High			0.037
LA9		High			0.035

Table 3. (*Continued*).

Soil Unit	Soil Taxonomy	Erodibility Classes	Area (ha)	Area (%)	K Factor ton.ha.h/ha. MJ.mm
PE10	ALFISOLS	High	49,729.27	7.65%	0.031
PE11		High			0.036
PE9		Very high			0.043
PL3	ULTISOLS	High	25,019.50	3.85%	0.039
PT1	ULTISOLS (PLINTHICS)	Medium	108,837.6	16.73%	0.027
PT12		Very high			0.047
PT3		High			0.038
PT9		High			0.037
PV10	ULTISOLS	High	269,956.7	41.51%	0.031
PV11		High			0.039
PV12		High			0.036
PV13		High			0.037
PV14		Medium			0.03
PV20		Very high			0.042
R1	ENTISOLS (LITHICS)	High	43,476.21	6.68%	0.041
R2					
*	WATER	*	23,011.33	3.54%	*
*	ISLAND	*	2104.23	0.03%	*
Total			650,418.13	100%	*

Source: Organized by the Authors; based on Mannigel et al. [26], Aquino and Oliveira [28], Jacomine and Paulo Klinger Tito Jacomine [30]; (*) no value assigned.

The spatialization of factor *K* can be visualized in **Figure 5**. The soil erodibility values (factor *K*) ranged from 0.025 to 0.050 t h MJ^{-1} mm^{-1}, with a predominance of medium to very high erodibility, according to studies conducted in the region [28].

The Alfisols class comprises 7.65% of the total area, accounting for 49,729.27 hectares. This class shows notable variability in erodibility, with high *K* factor values ranging from 0.031 to 0.036 t h MJ^{-1} mm^{-1} and instances of very high erodibility reaching up to 0.043 t h MJ^{-1} mm^{-1}. These soils are predominantly found in relatively flat to undulating terrains, with slopes between 3% and 20%, which makes them particularly susceptible to erosive processes.

In contrast, the study area does not contain soils classified with low erodibility. The medium erodibility class presents the lowest *K* factor values, with Entisols (Fluvents) showing a *K* factor of 0.028 t h MJ^{-1} mm^{-1} and occupying 5.97% of the area. Other soil classes with very high erodibility include Mollisols, covering 2.55% of the area with a K factor of 0.050.

Another notable soil class is the Oxisols, accounting for 11.50% of the area. These soils exhibit *K* factor values ranging from 0.025 to 0.035 t h MJ^{-1} mm^{-1}. The topography of the area characterized by wide, gentle hills, dissected plateaus, and degraded flat surfaces, directly influences the erosive processes affecting these soils.

Overall, while Alfisols are prominent, they are part of a broader spectrum of soil erodibility in the region, including significant contributions from Ultisols with *K* factor values reaching up to 0.047 t h MJ^{-1} mm^{-1} and occupying 41.51% of the area.

This diverse soil composition underscores the varying susceptibility to erosion throughout the study area.

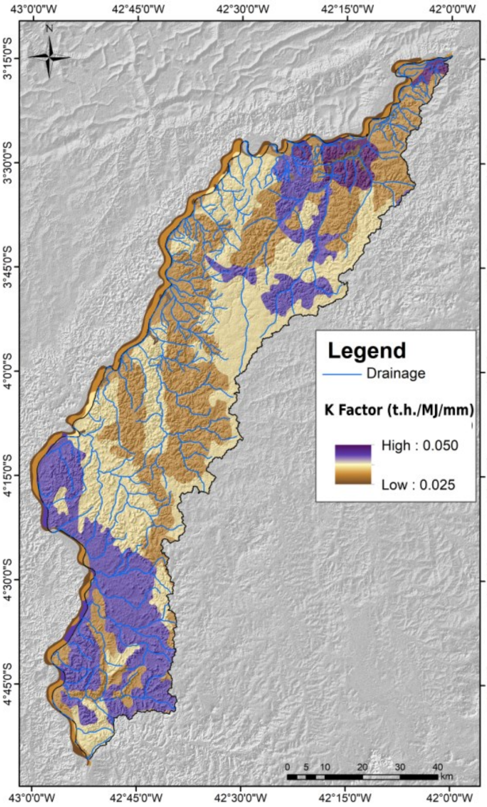

Figure 5. Spatialization of factor *K*.

As shown in **Figure 5** and **Table 3**, there is a predominance of *K* values classified as high and very high erodibility in the study area. This is consistent with previous studies [28] that concluded that about 94.4% of the soils in Piauí State have high or very high erodibility.

Granulometric analyses were carried out to determine the soil textural classes, and although the number of samples analyzed was limited, this analysis is crucial for accurately characterizing the soils in the region. **Figure 6** illustrates the variations in coarse sand, fine sand, silt, and clay fractions across eight strategically selected sites within the study area, offering a detailed insight into the soil textures.

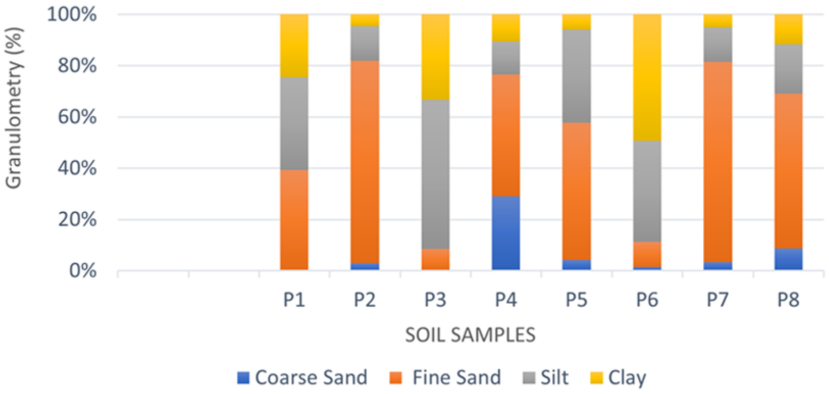

Figure 6. Variation of soil particles in the study area [3].

Erosive features

After analyzing the soil erodibility factors (*K*) and rainfall erosivity (*R*), it is observed that the conditions conducive to erosive processes manifest in various erosive features in the study area. These features, commonly associated with the combined action of rainfall events, vegetation clearing, topographical characteristics, and improper land use, are widely distributed in both urban and rural areas.

Figure 7 illustrates some of these erosive features. In rural areas of the União Municipality, the presence of a gully (**Figure 7A**) reflects the impacts of erosion, reinforcing the need for appropriate conservation practices.

The gully (**Figure 7B**), located in the urban periphery of the municipality of Miguel Alves, was triggered by the natural dynamics of the environment; however, factors such as deforestation, soil compaction, and improper land use may have intensified its development. Additionally, the consequences of improper land use can be observed in features such as rill erosion (**Figure 7C**), generated by the construction of highways in the municipality of União, highlighting soil vulnerability when exposed to human intervention without adequate containment measures.

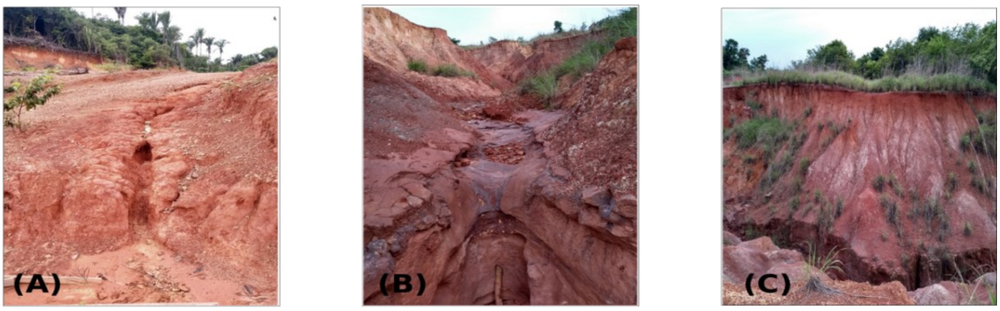

Figure 7. Erosive features found in the study area: **(A)** rills located in the municipality of União; **(B)** gully located in the municipality of Miguel Alves; **(C)** rills located in the municipality of União.

The analysis of the urban gully in Miguel Alves Municipality demonstrated an accelerated growth of 21.85% between 2007 and 2017, a direct result of the combination of erosive rains and erodible soils [34]. The advancement of the gully poses a risk to local infrastructure, especially highways and adjacent urban areas.

The lack of adequate erosion control measures has contributed to this rapid expansion, and the climatic conditions forecasted for the coming years suggest that, without intervention, the gully will continue to expand [35]. In **Figure 8**, it is possible to see the area of growth of the gully.

Figure 8. Area of growth of the gully [34].

4. Conclusion

The study demonstrates that the downstream Parnaíba River Basin presents a high risk of erosion due to the combination of climatic and pedological factors. The erosivity of rainfall, concentrated in the months of highest precipitation, acts as a catalyst for erosive processes, especially in areas with highly erodible soils. The expansion of the gully in Miguel Alves Municipality exemplifies the potential risks that extreme rainfall can bring, particularly when combined with vulnerable soils and the absence of mitigation measures.

The results obtained provide important insights for formulating soil management policies and implementing conservation techniques to mitigate erosion in the Lower Parnaíba Basin. It is essential that erosion control measures, such as revegetation and surface runoff management, be adopted to prevent the worsening of erosion problems and protect both infrastructure and the local environment.

Author contributions: Conceptualization, WCdSB; AJTG and IMdMFL; methodology, WCdSB, AJTG and IMdMFL; validation, WCdSB; formal analysis, WCdSB; investigation, WCdSB, AJTG and IMdMFL; resources, WCdSB, AJTG and IMdMFL; data curation, WCdSB; writing—original draft preparation, WCdSB; writing—review and editing, WCdSB and AJTG; visualization, WCdSB; supervision, AJTG and IMdMFL; funding acquisition, WCdSB. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. Abreu LP, Mutti PR, Lima KC. Spatial and temporal variability of precipitation in the Parnaíba River basin, Northeast Brazil (Portuguese). Revista Brasileira de Meio Ambiente; 2019.
2. Guerra AJT, Fullen MA, Jorg MCO, et al. Slope Processes, Mass Movement and Soil Erosion: A Review. Pedosphere. 2017; 27 (1), 27-41. doi: 10.1016/S1002-0160(17)60294-7

3. Barbosa WCS, Guerra AJT, Valladares GS. Soil Erosion Modeling Using the Revised Universal Soil Loss Equation and a Geographic Information System in a Watershed in the Northeastern Brazilian Cerrado. Geosciences. 2024; 14(3): 78. doi: 10.3390/geosciences14030078
4. Morais RCS, Sales MCL. Estimating the natural soil erosion potential of the Alto Gurguéia watershed, Piauí-Brazil, using a Geographic Information System. (Portuguese). Caderno de Geografia; 2017.
5. Morais RCS, Silva AJO. Estimating the Natural Potential for Soil Erosion in the Longá River Basin, Piauí, Brazil. (Portuguese). Revista Geotemas; 2020.
6. Alves WS, Martins AP, Morais WA, et al. USLE modelling of soil loss in a Brazilian cerrado catchment. Remote Sensing Applications: Society and Environment. 2022; 27: 100788. doi: 10.1016/j.rsase.2022.100788
7. Dang X, Sun Y. Estimation of soil erosion in loess plateau based on geographic information system. Journal of Geography and Cartography. 2021; 5(1): 1. doi: 10.24294/jgc.v5i1.1410
8. Silva AMD, Silva MLN, Curi N, et al. Rainfall erosivity and erodibility of Cambissolo and Latossolo in the Lavras region, southern Minas Gerais. (Portuguese). Revista Brasileira de Ciência do Solo. 2009; 33(6): 1811-1820. doi: 10.1590/s0100-06832009000600029
9. Bonilla CA, Johnson OI. Soil erodibility mapping and its correlation with soil properties in Central Chile. Geoderma. 2012; 189-190: 116-123. doi: 10.1016/j.geoderma.2012.05.005
10. Guerra AJT, Fullen MA, Bezerra JFR, Jorge MCO. Gully Erosion and Land Degradation in Brazil: A Case Study from São Luís Municipality, Maranhão State. Cingapura: Springer Singapore; 2018.
11. Favis-Mortlock D. Erosion by Water: Accelerated. Managing Soils and Terrestrial Systems; 2020.
12. Barbosa WCS, Lima IMMF, Guerra AJT. Study of soil erosion in a gully located in the municipality of Miguel Alves-Piauí/Brazil, based on soil density and porosity parameters. (Portuguese). In: Pereira R, Cachada A, Rodríguez-Seijo A, et al. (editors). Solos e Desenvolvimento Sustentável: Desafios e Soluções, 1st ed. Porto: GreenUPorto-Centro de Investigação em Produção Agroalimentar Sustentável, U.Porto Press; 2021.
13. Delgado D, Sadaoui M, Ludwig W, et al. Depth of the pedological profile as a conditioning factor of soil erodibility (Rusle K-Factor) in Ecuadorian basins. Environmental Earth Sciences. 2023; 82(12). doi: 10.1007/s12665-023-10944-w
14. Freires EV, Silva Neto CÂ, Silva MT, et al. Mapping the erosivity and erodibility of the humid slope of the Uruburetama Massif and its surroundings as a subsidy to environmental planning. (Portuguese). Revista de Geociências do Nordeste. 2023; 9(2): 21-40. doi: 10.21680/2447-3359.2023v9n2id30719
15. Andriyani I, Indarto I, Soekarno S, et al. Analysis of rainfall erosivity factor (R) on prediction of erosion yield using USLE and RUSLE Model's; A case study in Mayang Watershed, Jember Regency, Indonesia. Sains Tanah-Journal of Soil Science and Agroclimatology. 2024; 21(1): 64. doi: 10.20961/stjssa.v21i1.63641
16. Nur AH, Ahmed AH, Mohamed AA,et al. Geospatial Assessment of Aridity and Erosivity Indices in Northwest Somalia Using The CORINE Model. Journal of Environmental and Science Education. 2024.
17. Fullen MA, Catt JA. Soil Management: Problems and Solutions. Edward Arnold, Londres; 2004.
18. Moisa MB, Dejene IN, Merga BB, et al. Soil loss estimation and prioritization using geographic information systems and the RUSLE model: a case study of the Anger River sub-basin, Western Ethiopia. Journal of Water and Climate Change. 2022; 13(3): 1170-1184. doi: 10.2166/wcc.2022.433
19. Amraoui M, Bouabidi L, El Amrani M, et al. Land Use Dynamics And Soil Conservation Strategies In The El Kssiba Region, Atlas Mountains Of Morocco. The Journal "Agriculture and Forestry". 2024; 70(3). doi: 10.17707/agricultforest.70.3.01
20. Ennaji N, Ouakhir H, Abahrour M, et al. Impact of watershed management practices on vegetation, land use changes, and soil erosion in River Basins of the Atlas, Morocco. Notulae Botanicae Horti Agrobotanici Cluj-Napoca. 2024; 52(1): 13567. doi: 10.15835/nbha52113567
21. MMA, Ministério do Meio Ambiente. Parnaíba Hydrographic Region Booklet. (Portuguese). Secretaria de Recursos Hídricos-Brasília: MMA; 2006.
22. Nascimento JRS, Marcuzzo FFN, Pinto EJA. Maps of annual and monthly rainfall distribution and pluviogram of the Parnaíba river basin. (Portuguese). ABRH; 2020.
23. HidroWeb. Historical rainfall series. (Portuguese). Available online: https://www.snirh.gov.br/hidroweb/ (accessed on 12 July 2023).
24. Pinto EJA, Azambuja, AD, Farias JAM, et al. Rainfall atlas of Brazil: monthly isopleths, quarterly isopleths, annual isopleths, driest months, wettest months, driest quarters, wettest quarters. (Portuguese). Brasília: CPRM; 2011.

25. Bertone J, Lombardi Neto F. Soil Conservation (Portuguese). Icone Editora Ltda: São Paulo; 2014.
26. Mannigel AR, E Carvalho MDP, Moreti D, et al. Erodibility factor and soil loss tolerance in the State of São Paulo. (Portuguese). Acta Scientiarum Agronomy. 2008; 24: 1335. doi: 10.4025/actasciagron.v24i0.2374
27. Albuquerque AW, M. Filho G, Santos JR, et al. Determination of universal soil loss equation factors in Sumé, PB. (Portuguese). Revista Brasileira de Engenharia Agrícola e Ambiental. 2005; 9(2): 153-160. doi: 10.1590/s1415-43662005000200001
28. Aquino CMS, Oliveira JGB. Estimating the erodibility factor (k) of soil associations in the state of Piauí described in Jacomine (Portuguese). Revista Geotemas; 2017.
29. Farinasso M, Carvalho Júnior OA, Guimarães RF, et al. Qualitative Evaluation of the Potential for Laminar Erosion in Large Areas by Means of the EUPS Universal Soil Loss Equation Using New GIS Methodologies for Calculating its Factors in the Alto Parnaíba PI-MA Region. (Portuguese). Revista Brasileira de Geomorfologia. 2006; 7(2). doi: 10.20502/rbg.v7i2.80
30. Jacomine PKT, Paulo Klinger Tito Jacomine, C. Exploratory and reconnaissance survey of soils in the state of Piauí. (Portuguese). Embrapa Solos; 1986.
31. Wischmeier WH, Smith DD. Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Department of Agriculture, Science and Education Administration. 1978.
32. Renard KG, Freimund JR. Using monthly precipitation data to estimate the R-factor in the revised USLE. Journal of Hydrology. 1994.
33. Loureiro HAS, Guerra AJT. Landscapes of Geomorphology: Themes and Concepts of the 21st Century. (Portuguese). Rio de Janeiro: Bertrand Brasil; 2022.
34. Barbosa WCS, Lima IMMF, Guerra AJT. Multivariate analysis of the urban gully located in the southern portion of the Lower Parnaíba River basin. (Portuguese). William Morris Davis- Revista de Geomorfologia; 2021.
35. Tesfaye G, Bekele D, Eshetu M, et al. Gully Erosion Risk Assessment Using a GIS-Based Bivariate Statistical Models and Machine Learning in the Dodota Alem Watershed, Ethiopia. American Journal of Environmental Science and Engineering. 2024; 8(3): 49-64. doi: 10.11648/j.ajese.20240803.11