USE OF GEOTECHNOLOGIES AS A TOOL FOR ENVIRONMENTAL CHARACTERIZATION AND PLANNING IN A HYDROGRAPHIC UNIT OF THE CERRADO OF THE DF: IMPLICATIONS FOR PUBLIC POLICIES AND DIFFUSE RIGHTS

USO DE GEOTECNOLOGIAS COMO FERRAMENTA DE CARACTERIZAÇÃO E PLANEJAMENTO AMBIENTAL EM UMA UNIDADE HIDROGRÁFICA DO CERRADO DO DF: IMPLICAÇÕES PARA POLÍTICAS PÚBLICAS E DIREITOS DIFUSOS

USO DE LAS GEOTECNOLOGÍAS COMO HERRAMIENTA DE CARACTERIZACIÓN Y PLANEACIÓN AMBIENTAL EN UNA UNIDAD HIDROGRÁFICA DEL CERRADO DEL DF: IMPLICACIONES PARA LAS POLÍTICAS PÚBLICAS Y LOS DERECHOS DIFUSOS

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Carlos Eduardo Pacheco Lima[1], Mariana Rodrigues Fontenelle[2], Marcos Brandão Braga[3], Ítalo Moraes Rocha Guedes[4], Juscimar da Silva[5]

ABSTRACT

This paper presents an integrated geotechnological approach to assessing the susceptibility to water erosion and the vulnerability to contamination of porous aquifers in a hydrographic unit located in the Cerrado region of the Federal District. Using advanced tools such as GRASS GIS and spatial modeling via RUSLE, thematic maps and indicators were generated. The results demonstrate that, although much of the area presents low susceptibility to erosion, features such as plateau edges can present high and very high susceptibility. Nevertheless, the presence of native or regenerating vegetation as land cover in these features allowed them to be classified primarily as low. The analysis of the vulnerability of porous aquifers, coupled with the very high impairment of the flow rate available for dilution, however, revealed a worrying situation in an area that has been under strong pressure from unplanned urbanization. The findings can support the development, implementation, and execution of public policies and environmental management plans, highlighting the need for compliance with these latter. They are also closely related to diffuse rights, especially the right to a balanced environment, and to the Sustainable Development Goals (SDGs), especially numbers 6, 13, and 15.

Keywords: GIS. Cerrado. Water Erosion. Vulnerability to Aquifer Contamination. GRASS. RUSLE. Global Climate Change.

RESUMO

O presente trabalho apresenta uma abordagem integrada de geotecnologias para a avaliação da susceptibilidade à erosão hídrica e da vulnerabilidade à contaminação de aquíferos porosos em uma unidade hidrográfica localizada no Cerrado do Distrito Federal. Utilizando ferramentas avançadas como GRASS GIS e modelagem espacial via RUSLE,

[1] Dr. in Soils and Plant Nutrition. Embrapa Hortaliças. E-mail: carlos.pacheco-lima@embrapa.br
[2] Dr. in Agricultural Microbiology. Embrapa Hortaliças. E-mail: mariana.fontenelle@embrapa.br
[3] Dr. in Irrigation and Drainage. Embrapa Hortaliças. E-mail: marcos.braga@embrapa.br
[4] Dr. in Soils and Plant Nutrition. Embrapa Hortaliças. E-mail: italo.guedes@embrapa.br
[5] Dr. in Soils and Plant Nutrition. Embrapa Hortaliças. E-mail: juscimar.silva@embrapa.br

foram gerados mapas temáticos e indicadores. Os resultados demonstram que, embora grande parte da área apresente baixa susceptibilidade à erosão, feições como bordas de chapada podem apresentar susceptibilidade alta e muito alta. Ainda assim, a presença de vegetação nativa ou em regeneração como cobertura do solo nessas feições permitiu sua classificação prioritariamente como baixa. A análise da vulnerabilidade aquíferos porosos, associada ao comprometimento muito alto da vazão outorgável para diluição, entretanto, relevou um quadro preocupante em uma área que vem sofrendo forte pressão do processo de urbanização não planejada. Os achados podem subsidiar a elaboração, implementação e execução de políticas públicas e planos de manejo ambiental, ressaltando a necessidade de cumprimento desses últimos. Também se relacionam fortemente com os direitos difusos, especialmente aquele ao meio ambiente equilibrado, e com os Objetivos de Desenvolvimento Sustentável (ODS), em especial os de número 6, 13 e 15.

Palavras-chave: SIG. Cerrado. Erosão Hídrica. Vulnerabilidade à Contaminação de Aquíferos. GRASS. RUSLE. Mudanças Climáticas Globais.

RESUMEN

Este artículo presenta un enfoque geotecnológico integrado para evaluar la susceptibilidad a la erosión hídrica y la vulnerabilidad a la contaminación de acuíferos porosos en una unidad hidrográfica ubicada en la región del Cerrado del Distrito Federal. Utilizando herramientas avanzadas como GRASS GIS y modelado espacial vía RUSLE, se generaron mapas temáticos e indicadores. Los resultados demuestran que, si bien gran parte del área presenta baja susceptibilidad a la erosión, elementos como los bordes de meseta pueden presentar una susceptibilidad alta y muy alta. No obstante, la presencia de vegetación nativa o en regeneración como cobertura del suelo en estos elementos permitió clasificarlos principalmente como bajos. No obstante, el análisis de la vulnerabilidad de los acuíferos porosos, sumado al alto deterioro del caudal disponible para dilución, reveló una situación preocupante en un área que ha estado bajo fuerte presión por la urbanización no planificada. Los hallazgos pueden respaldar el desarrollo, la implementación y la ejecución de políticas públicas y planes de gestión ambiental, destacando la necesidad de su cumplimiento. También están estrechamente relacionados con los derechos difusos, en particular el derecho a un medio ambiente equilibrado, y con los Objetivos de Desarrollo Sostenible (ODS), en particular los números 6, 13 y 15.

Palabras clave: SIG. Cerrado. Erosión Hídrica. Vulnerabilidad a la Contaminación de Acuíferos. GRASS. RUSLE. Cambio Climático Global.

1 INTRODUCTION

There are many environmental threats recently observed, among them, climate change and disorderly urbanization. In particular, watersheds located in urban and peri-urban areas have been greatly impacted, even when they are important repositories of fresh water or for cushioning negative environmental impacts. This fact compromises water security, harming not only the supply for human consumption, but also activities dependent on water resources, such as agriculture (Chelotti & Sano, 2021). This fact has been commonly observed in the Brazilian Cerrado, which is the second largest biome in the country and, given the endemic of its species, one of the world's biodiversity hotspots. It is also one of the main water granaries in South America, where springs and water dividers from some of the main Brazilian hydrographic regions are found (MMA, 2022). In the Federal District (DF), which is the third federation unit with the lowest water availability, and which is undergoing an intense process of population growth and urbanization (CODEPLAN, 2020), this fact gains greater relevance.

Although it is the cradle of a large number of springs and an important watershed in the country, with the presence of the hydrographic regions of Paraná, São Francisco and Tocantins/Araguaia, the DF has hydrography marked by the presence of surface water bodies with small flow and size, very marked by seasonality (Souza et al., 2012). In this context, the watershed of the Tamanduá Stream, located in the southwest of the Federal District, has been under intense pressure due to disorderly urbanization, although it is largely inserted in the Sustainable Use Zone (ZUS) outlined in the Management Plan of the Planalto Central APA. The ZUS, in theory, is intended for sustainable agricultural production, with severe restrictions on the installation of other impactful activities (ICMBIO, 2015). One of the few points preserved or in an advanced regeneration process is a hydrographic unit located at the Tamanduá Farm, headquarters of Embrapa Vegetables, which performs important ecosystem services such as water production.

The present study is a continuation of two others carried out in the same area (Lima et al., 2025a; Lima et al., 2025b). The first aimed at the pedogeomorphological characterization of the area and the second the morphometric characterization of the hydrographic unit, as well as the evaluation of climatic trends and their influence on rainfall erosivity estimates (R factor of the revised universal soil loss equation - RUSLE). The results of the first work pointed to the presence of diversified relief, with the presence of flat to gently undulating areas in the Plateaus and Intermediate Plateaus, in addition to abrupt transitions and with a strong slope in the Edges of Plateaus. Red-Yellow and Red Latosols predominate, followed by Haplic Cambisols. Younger soils such as Litholic Neosols, Fluvic Neosols and Plinthosols can still be observed less frequently. The second work confirmed the presence of embedded valleys, with hydrography marked by the circular shape of the hydrographic unit and elongated water bodies. In addition, a significant change in precipitation patterns was found, with growth and intensification in the recent period (between 2015 and 2024) of annual totals and extreme rainfall and drought events. These climate changes resulted in a great increase in rainfall erosivity, reaching a high potential according to the classification proposed by Lima et al. (2023). The erosivity value found exceeds the average for the DF found by Galdino (2015). The whole scenario exposed tends to make the area very susceptible to erosive processes, especially in the Borda de Chapada, and vulnerable to contamination in the flattened areas, especially in cases of change in land use and occupation, facts that are intended to be confirmed in the study conducted here.

The use of advanced geotechnology tools such as GRASS GIS enables the generation of cartographic products from spatial modeling with high accuracy. They are also capable of achieving a high degree of detail with the production of information on the limits of watersheds, the delineation of sub-basins, hydrography, relief, geomorphology, among others. It also allows the easy, fast and accurate obtaining of parameters necessary for the understanding of hydrology and for the application of RUSLE, such as the LS factor (length and slope of the ramp). The use of this tool is justified by its robustness in hydrological modeling, and it can also be used in open access software such as QGIS.

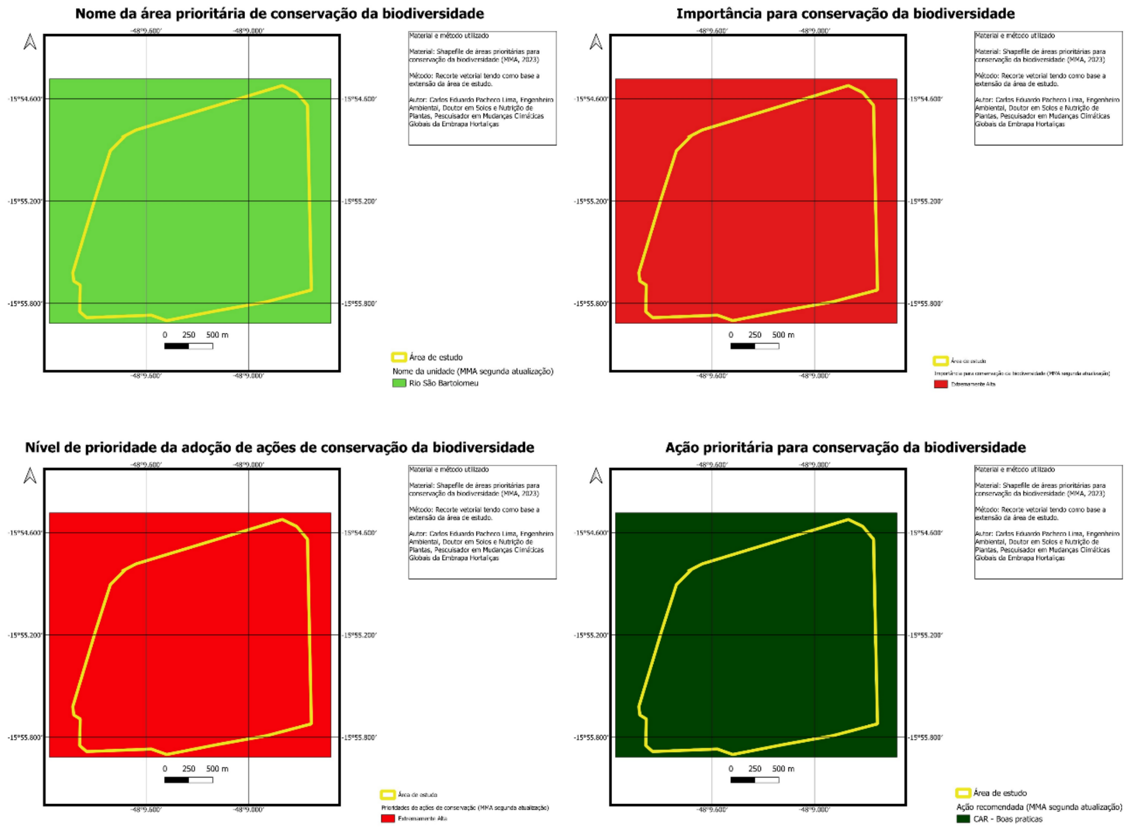
RUSLE (Renard et al., 1997) has been widely used for estimating erosive processes in Brazil (Nachtigall et al., 2020; Silva et al., 2024) and in other parts of the world (Sakhraoui & Hasbaiab, 2023; Barboza et al., 2024; Hamouch et al., 2025). It estimates the average annual soil loss considering the following factors: LS – derived from the combination of the length and slope of the slopes; R – rainfall erosivity factor; K – soil erodibility factor; C – land use and cover factor; P – conservation practices factor. The application of RUSLE is versatile for mapping erosion susceptibility in different areas, and is widely used in countries such as the United States, China, Brazil, Italy and India. Its main advantages are operational simplicity, low application cost, flexibility at different spatial scales, and ease of integration with geotechnologies. However, there are also limitations inherent to the empirical character of the model, which may overestimate or underestimate soil losses depending on the quality of the input data. In addition, RUSLE does not consider processes such as sediment deposition, erosion in deep furrows, or the occurrence of extreme rainfall events (Kumar et al., 2022).

The assessment of the vulnerability of aquifers to contamination, in turn, is important as a strategy for planning and evaluating environmental impacts, defining land use and occupation, as well as establishing monitoring plans for vertical diffusion of contaminants (Souza et al., 2021). It is dependent on multiple factors such as the depth of the aquifer, the permeability and reactivity of the soils, the slope of the terrain, lithostatigraphy, among others (Silva Júnior and Pizani, 2003). In the 1:100,000 scale mapping carried out for the entire Federal District, available in the District Environmental Information System (SISDIA, 2023), the study area is classified as presenting a risk of contamination ranging from very low to high, with a risk of loss of aquifer recharge showing similar behavior. However, the low detail of this information does not allow local actions to be implemented, and it is necessary to generate information on larger scales, which is carried out in the present study (Amaral et al., 2021). The use of models to define the degree of vulnerability of aquifers, associated with the use of geotechnologies, allows the spatialization of this indicator, resulting in greater effectiveness of environmental management plans (Yadav & Gupta, 2022).

In view of this scenario, the importance of state action through environmental public policies aimed at the defense of diffuse rights is highlighted – especially the collective right to an ecologically balanced environment for current and future generations, enshrined in article 225 of the Federal Constitution. Territorial planning instruments such as management plans, ecological-economic zoning and Payment for Environmental Services (PES) strategies must be implemented and, when they exist, complied with. In the case under analysis, the hydrographic unit studied is located in the Sustainable Use Zone (ZUS) of the Environmental Protection Area (APA) of the Central Plateau (ICMBIO, 2015), regularly registered in the Rural Environmental Registry (CAR) of Embrapa Vegetables and is classified as having an extremely high level of priority actions for environmental conservation, as well as its importance for environmental conservation. by the Ministry of Environment and Climate Change (MMA, 2023), which, in itself, denotes its environmental importance. The recommended priority action for this area is respect for the CAR (Figure 1).

Figure 1

Panel showing the name of the priority conservation area (São Bartolomeu River) where the hydrographic unit is located, its importance and the level of priority for the adoption of biodiversity conservation actions (extremely high) and priority action for conservation (Rural Environmental Registry)



Source: MMA (2023).

Thus, the objective of the present work was to evaluate the susceptibility to erosion and the vulnerability to contamination of porous aquifers of a hydrographic unit of the Tamanduá Creek watershed, in the Cerrado of the Federal District, using advanced geotechnology tools, as well as to relate the results obtained with the possible adoption and/or elaboration of public policies and relationship with diffuse rights.

2 MATERIAL AND METHODS

2.1 CHARACTERIZATION OF THE STUDY AREA

The study area (Figure 2) is located in the micro-basin of the Tamanduá Stream, part of the sub-basin of the Corumbá and Descoberto Rivers, in a Cerrado area in the Federal District. Lima et al. (2025a) elaborated their pedogeomorphological characterization. It is inserted in the Brazilian Central Plateau (PCB). In climatic terms, it is tropical savannah (Aw) in the Köppen-Geiger classification, with very well defined dry and rainy periods. The perimeter is 8.71 km, the length is 8.67 km and the area is 4.73 km² (473 ha), being included between the following geographical coordinates: To the North, 15º54'30.24"S; to the West, 48º09'51.84"W; to the South, 15º56'06"S e; to the East, 48º08'34.08"W. The altimetric amplitude was determined by Lima et al. (2025a), being 124 m, with a maximum point of 1,110 m of altitude and a minimum point of 986 m.

Figure 2

3D view in the East-West direction of the study area and its delimitation (yellow polygon)

Source: The authors.

2.2 DATABASE

The following materials were used to prepare the present study:

- SRTM Digital Elevation Model (MDE) with spatial resolution of 30 m x 30 m;
- Contour lines with equidistance of 5 m, obtained from the EAM;
- Google Satellite images with a spatial resolution of 0.5 m x 0.5 m;
- Map of slope classes prepared by Lima et al. (2025a);
- Land use and occupation map on a scale of 1:1,000 prepared by Lima et al. (2025a);
- Semi-detailed soil reconnaissance map at a scale of 1:10,000 prepared by Lima et al. (2025a).
- Average total annual and total monthly precipitation in the historical series between 2014 and 2025 and surveyed by Lima et al. (2025b).
- Rainfall erosivity determined by Lima et al. (2025b) for the period 2014 to 2025.

It was decided to use a more recent historical series so that there would be a representativeness of global climate change (GCM) already in progress, which has increased the occurrence of extreme events and the levels of total annual precipitation, with a consequent increase in erosivity, as demonstrated by Lima et al. (2025b) for the study area.

2.3 SOFTWARE USED

To perform the geospatial analyses, Google Earth Pro and QGIS software were used. GRASS GIS was operated as a complement in a GRASS/QGIS environment.

2.4 SPATIAL PROCESSING AND ANALYSIS

Initially, the MDE originating from the SRTM image with 30 m x 30 m of spatial resolution had its spurious depressions corrected, using the r.fillnulls algorithm, of the GRASS/QGIS complement. Subsequently, using the r.watershed with the corrected MDE as the input layer and minimum size of outer cells of 10, the drainage direction map and the topographic indices LS, slope, Stream Power Index (SPI) and flow accumulation (number of cells draining) were generated. Maps of hydrological units and flow segments were also generated. Although the maps are presented in the WGS84 projection system, for RUSLE calculation they were redesigned for metric coordinates (SIRGAS2000/UTM).

2.5 DETERMINATION OF SOIL LOSS BY EROSION AND MODELING OF SUSCEPTIBILITY TO THIS PROCESS

The estimate of annual soil loss due to erosion was based on the Revised Universal Soil Loss Equation (RUSLE). Its formula is as follows:

$$A = R \times K \times LS \times C \times PA$$

Where:

A is the loss of soil (t.ha-1.year-1)

R is the rainfall erosivity factor (MJ.mm.ha-1.h-1ano-1).

K is the erodibility factor of the soil ($t.ha.h.ha^{-1}.MJ^{-1}.mm^{-1}$).

LS is the length-slope factor

C is the land use and land cover factor.

P is the factor of conservation practices.

The R factor was determined by Lima et al. (2025b) based on a recent historical series of precipitation, between 2015 and 2024, with a value equal to 9239 MJ.mm.ha-1.h-1year-1, a value that represents an increase of 1,921 MJ.mm.ha-1.h-1year-1 in relation to the last period for which this value had been calculated (2002 to 2012). Because it represents such a significant difference and because we are already experiencing GCMs, this representative value of the recent decade was chosen.

Factors K and C, in turn, were defined based on a literature review and expert opinion. Table 1 shows the K values assumed in the present study, according to the soil classes existing in the area and mapped at a scale of 1:10,000 by Lima et al. (2025a). Table 2 shows the values of the reclassification of factor C for each class of land use and occupation mapped by these same authors at a scale of 1:1,000, based on satellite images with a resolution of 0.5 m x 0.5 m.

Table 1

Soil erodibility factors (K) of the Revised Universal Soil Loss Equation (RUSLE) used in the present work

Soil Class	K (t·ha·h/ha· MJ·mm)
Red Latosol	0,025
Haplic Cambisol	0,030
Litholic Neosol / Plinthosol	0,030
Red-Yellow Latosol	0,020
Hydromorphic Soils / Fluvic Neosols	0,035

Source: The authors.

Table 2

Values of factor C used in the present study

Land use and occupation	Factor C
Forest formations and Cerrado sensu stricto	0,01
Grassland formations and Cerrado Field	0,03
Agriculture (with adoption of no-tillage)	0,12
Exposed Soil	0,40
Urban areas	1,00

Source: The authors.

The LS factor was determined using the corrected MDE of the area as a basis, using the r.watershed algorithm in a GRASS/QGIS environment. The P factor, in turn, followed the values shown in Table 3. By means of spatial algebra, using the QGIS raster calculator, the soil loss was then calculated.

Table 3

Values of the P factor used in the present study

Practices adopted	P Factor
Adoption of conservation practices such as no-till farming	0,50
No adoption of conservation practices	1,00

After calculating the estimate of the annual soil loss due to water erosion, the values were reclassified according to the ranges shown in Table 4, using the QGIS raster calculator, with a view to generating the erosion susceptibility map.

Table 4

Reclassification of Factor A values for erosion susceptibility mapping of the study area

Class	Interval (kg.ha-1.year-1)	Assigned value
Very Low	0 – 200	1
Low	200 – 500	2
Moderate	500 – 1.000	3
Discharge	1.000 – 2.000	4
Very High	>2,000	5

Source: The authors.

2.6 DETERMINATION OF THE VULNERABILITY OF POROUS AQUIFERS TO CONTAMINATION

To determine the vulnerability of porous aquifers to contamination, the following equation was used, proposed in the present work for the reality of the study area.

$$IV = (S \times 0,25) + (T \times 0,15) + (L \times 0,10) + (D \times 0,25) + (R \times 0,25)$$

Where:

S = water infiltration capacity into the soil

T = slope

L = superficial lithology

D = depth + hydraulic conductivity of the porous aquifer

R = geochemical reactivity of the soil

Variables S (Table 5) and R (Table 6) were assigned scores from 0 to 10, based on the soil map of the study area on a scale of 1:10,000 (Lima et al., 2025a). The definition of the scores attributed to the S factor was based on the work of Lima et al. (2020), Murta et al. (2022) and Ottoni et al. (2025). The definition of the R factor was based on the work of Lima (2007).

Table 5

Reclassification of the S factor for the main soil classes present in the 1:10,000 mapping of the study area

Soil Class	Note(s)
Red Latosol (LV)	9 (High infiltration capacity)
Red-Yellow Latosol (LVA)	7 (intermediate infiltration capacity)
Haplic Cambisol	6 (intermediate infiltration capacity)

Source: The authors.

Table 6

Reclassification of the R factor for the reactivity of the soils present in the study area

Class	Note (R)
Red Latosol	**3** (High Reactivity)
Haplic Cambisol	**9** (Low Reactivity)
Red-Yellow Latosol	**4** (reactivity still high but slightly lower than LV)

Source: The authors.

The T factor followed the logic of the definition of the slope classes, according to SIBICS (2025) and its values were assigned according to what is shown in Table 7. The L factor, in turn, followed the values assigned in Table 8, according to the lithostatigraphy map of the area available in the RIGEO repository. Factor D (Table 9), in turn, was assigned according to the porous hydrogeology map of the study area, also available in the RIGEO repository and the description of the porous hydrogeological units available in the Environmental Atlas of the Federal District, prepared by IPEDF (IPEDF, 2020).

Table 7

Reclassification of the T factor extracted from the slope map of the study area

Slope	Embossing class	T
0-3	Plan	10
3-8	Smooth-wavy	8
8-20	Wavy	6
20-45	Strong-wavy	4
45-75	Mountainous	2
>75	Steep or strong-mountainous	1

Source: The authors.

Table 8

Reclassification of the L factor for the lithostatigraphy of the study area

Associated superficial lithology	Note (L)
Detrito-lateritic cover	**9**
Fine/medium quartzites, metasediments and schists	**4**

Source: The authors.

Table 9

Reclassification of factor D for the depth of porous aquifers in the study area

Associated porous hydrogeological unit	Sheet depth	Hydraulic conductivity	Note (D)
P1	Deep (> 5 m)	Discharge	4
P4	Very shallow (<1 m)	Low	7

Source: The authors.

After calculating index IV, the values were then classified as shown in Table 10.

Table 10

Final reclassification of the vulnerability index IV and its classification

Final index	Class
8 - 10	Very high vulnerability
6 - 8	High vulnerability
4 - 6	Moderate vulnerability
2 - 4	Low vulnerability
<2	Very low vulnerability

Source: The authors.

2.7 STATISTICAL ANALYSIS AND INTERPRETATION OF LARGE VOLUMES OF DATA

The statistical analyses, generation of graphs, as well as the interpretation of the large volume of data generated in the present work were carried out with the aid of Generative Artificial Intelligence (AI) Data Analyst. It is necessary to emphasize, however, that all processes were supervised and critically analyzed by humans and that the data used were obtained according to the processes previously described.

3 RESULTS AND DISCUSSION

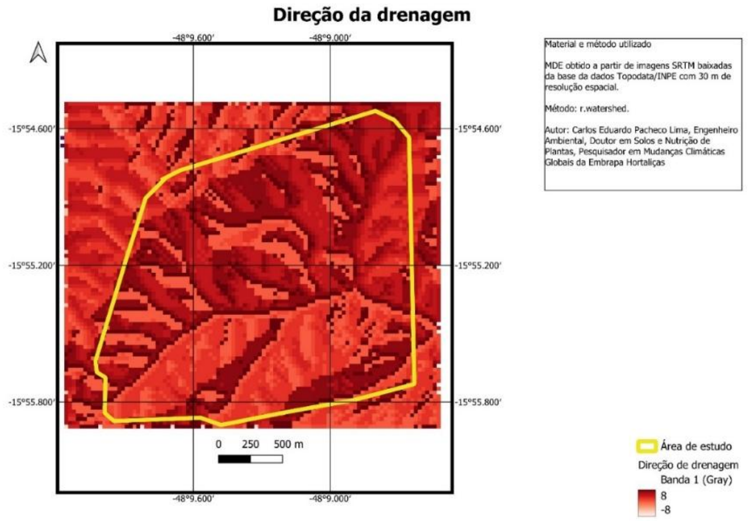
Figure 3 shows the direction of drainage of the hydrographic unit that is the object of study in this article. This Figure, as well as most of the others that will make up the set of results of this article, are derived from the corrected MDE of the area. The use of MDE from

SRTM images was shown as a valid technique for morphometric analysis of watersheds in the Brazilian territory by Oliveira et al. (2010). The map represented by Figure 3 is the result of the flow determinism method based on the cell with the highest slope among eight neighbors, calculated by the r.watershed (Grass Development Team, 2024). Each value represents one of the eight possible flow directions (N, NE, E, SE, S, SW, W, NW).

The map legend shows that lighter colors indicate more negative values, while darker colors indicate positive values. From the analysis of the image, it is possible to verify a clear pattern of dendritic drainage, confirming the previous findings of Lima et al. (2025a) and Lima et al. (2025b). The main channels converge to an axis, which is exultant from the Tamanduá Stream on the Ponte Alta River, in a Southeast-East direction and the secondary channels in an East-Southeast, Northeast-East and North-East direction. The Northeast and North parts, already outside the limits of the study area, function as recharge areas for the hydrographic unit. It is clearly perceived that the study area concentrates drainage, which is why it is clear that there are large springs in the area. This fact corroborates the need to conserve the area for regional supply purposes, as well as to cushion possible negative impacts, as pointed out by Moreira et al. (2019) and Ferreira et al. (2020). The flow pattern in embedded valleys, as discussed in the two previous works, is also clear from the image analysis. The drainage density also seems to be compatible with those characteristics classified as moderate to high, typical of areas with higher relief energy, as shown by Lima et al. (2025a). These findings are in line with other studies conducted for the Cerrado, such as those prepared by Capoane & Silva (2020) and Costa & Leite (2023).

Figure 3

Map of the drainage direction found in the study area

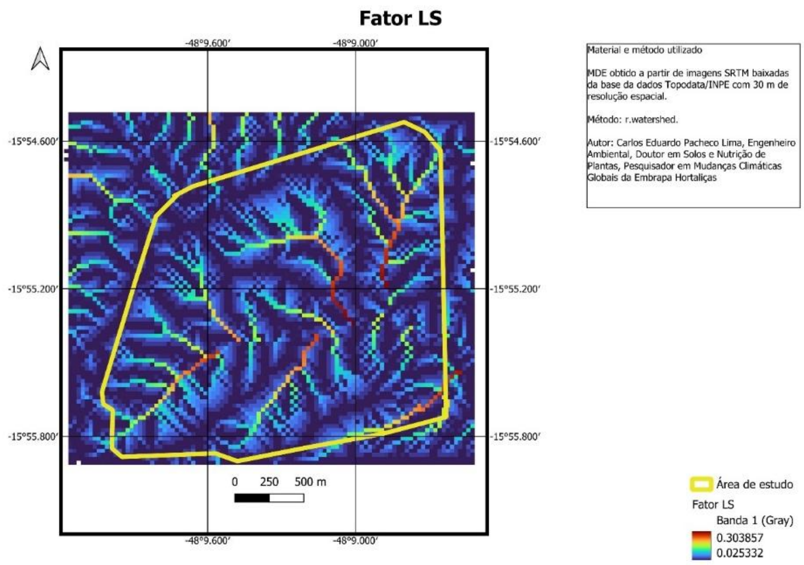


Source: The authors.

Figure 4, in turn, refers to the determination of the LS factor (length-slope), a component of the RUSLE, which was also determined by the r.watershed. The determination of the LS factor in GRASS is performed from the derivation of flux accumulation, which is obtained by the D8 method. The modulus then returns combined values of slope and length using the modified equation of Moore & Burch (1986) for the calculation. The approach considers the spatial discretization of the basin and the raster topology of the MDE (GRASS DEVELOPMENT TEAM, 2024).

Figure 4

Map of the LS factor values found in the study area



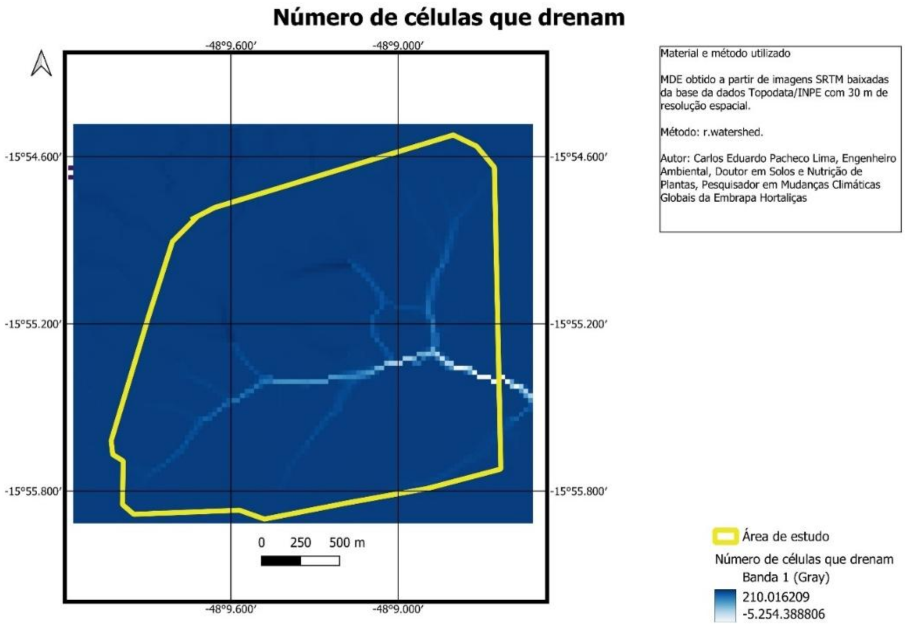
Source: The authors.

The LS factor is one of the main indicators of susceptibility to water erosion, being obtained from the corrected DEM data. The map legend points to lower values in blue and higher values in red, with intermediate values growing between green and yellow. It also points to values ranging between 0.025 and 0.303, demonstrating the variation in local relief. Planed areas receive lower values, while busier areas receive higher values. The analysis of Figure 4 shows that the areas with higher values of the LS factor are compatible with those representative of the Borda de Chapada and Vales Dissecados, while the areas with lower values are associated with the Plateaus and Plateaus This pattern is in accordance with that observed by Lima et al. (2025a) when pedogeomorphological compartmentalization of the study area and constitutes a pattern commonly found in the Brazilian Central Plateau (PCB) and was also found for the DF (Martins et al., 2024). Areas with higher LS factor values are more susceptible to erosion.

Figure 5 shows the map relative to the number of draining cells. It represents the accumulation of flow per cell based on the corrected EDM, that is, the number of upstream cells that contribute to each cell evaluated. It allows the delimitation of drainages and evaluation of potential channels of concentrated flow.

Figure 5

Map containing the amount of draining cells in the study area



Source: The authors.

The evaluation of Figure 5 shows that the lighter values indicate cells with a greater flow contribution, while the darker ones contribute with greater drainage for the former. The drainage lines represented by the lighter cells coincide with the hydrography, which reinforces the coherence of the model. The interpretation of the model also reinforces the fit of the water bodies and the drainage pattern, which, once again, is well defined dendritic, and these features are typical of areas under homogeneous lithological control and dissected, consistent with the pedogeomorphological findings. It also shows, complementing previous information, that the study area concentrates a significant part of the runoff, suggesting that the springs and main channels are contained in it. It is, therefore, an area of relevant water contribution.

These facts reinforce the need for conservation and maintenance of the CAR as originally registered by Embrapa Vegetables, in which this area is classified as a remnant of native vegetation and APPs, in line with the recommendation of the MMA (2023). In this document, the Ministry of Environment and Climate Change classified the area as of extremely high importance for the conservation of biodiversity, the same classification attributed to the urgency of adopting good practices which, according to the ministry itself, must be compliance with the CAR. Silva et al. (2024) demonstrate that spring conservation strategies such as restoration favoring the natural regeneration of native species are essential for maintaining the hydrological potential of springs.

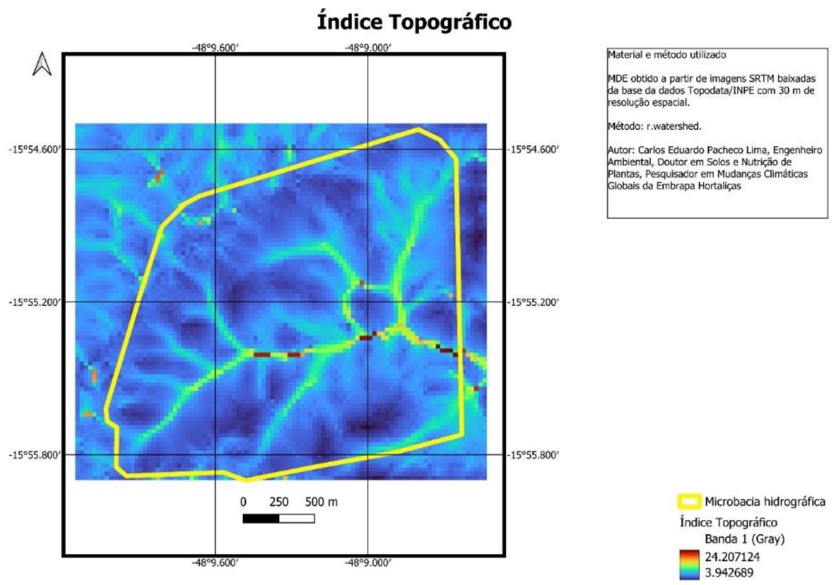
By capturing most of the local hydrological dynamics, an eventual compromise of the area could generate direct impacts on the quality and quantity of water, causing losses at the regional level, since the surface water resources present there still have good quality in a regional context where the Ponte Alta River, exultant of the Tamanduá Stream, is already Class 3 and with advanced silting and sedimentation processes, according to information available in the District Environmental Information System (SISDIA – DF) and in Rodrigues et al. (2024).

Figure 6 shows the Topographic Index. This index, also known as the Topographic Wetness Index (TWI), is widely used in hydrology and geomporphology to represent the potential for water accumulation due to topographic position. In this figure, blue tones have less potential for water accumulation, while red tones have greater potential, with intermediate bands growing between green and yellow.

It can be observed that the highest TWI values are observed within the study area (hydrographic unit evaluated), concentrated along the channels and the main and secondary drainage. This indicates zones of greater convergence of surface flow, with a high tendency to soil water saturation, making them critical for water regulation, spring formation and maintenance of soil moisture.

Figure 6

Topographic Index Map (TWI) of the study area



Source: The authors.

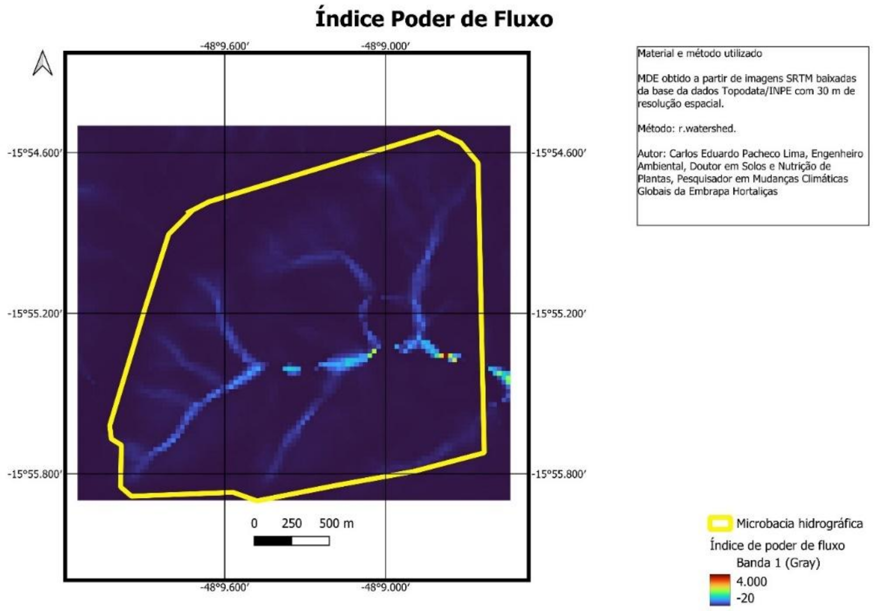
The areas farther from the channels, in turn, indicate places of higher altitude and lower flow accumulation, which confirms their role as a water recharge zone previously discussed. The spatial organization is compatible with the dissected morphology previously discussed in this study and in the other two studies conducted in the same area (Lima et al., a and b). The importance of recharge areas for the cerrado is discussed by Rodrigues & Cambraia Neto (2021).

The observed pattern reinforces the strategic role of the area for maintaining regional water availability, whether qualitative or quantitative, as it acts as a zone of water catchment, retention and regulation, a fact that is especially relevant given the context of pressure for urbanization that the area has been suffering and its role as a tributary of the Ponte Alta River. It should be noted that the TWI has been used for environmental planning and land use and occupation actions, as can be seen in the works of Santos & Coide (2016) and Hung et al. (2016).

Figure 7 shows the map of the Stream Power Index (SPI). This index reflects the potential for water erosion along the surface. It combines the slope of the terrain with the flow contribution area, being useful for identifying areas with higher energy available for sediment transport.

Figure 7

Map of the Flow Power Index (SPI) of the study area



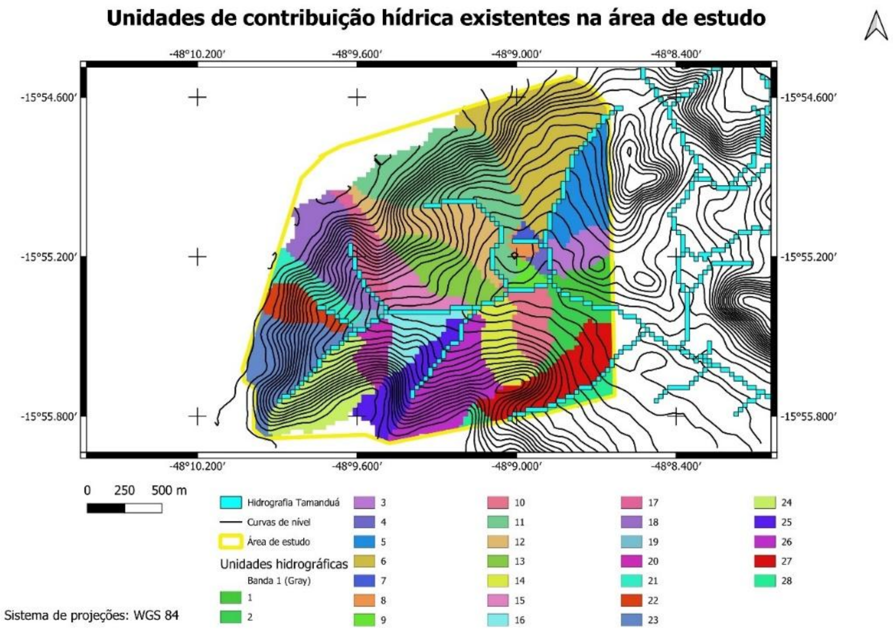
Source: The authors.

The map shown in Figure 7 indicates that the highest values are concentrated in the main channels and drainage convergence points, which are characterized by having higher slopes and surface runoff. At these points are the critical zones with the highest flow energy, with the potential for more intense erosive processes. Therefore, they demand greater attention in environmental planning and land use and occupation. There is coherence between the SPI and the topographic and hydrological patterns previously found, reinforcing the reliability of the model. The increase in the worsening of erosive processes in areas with high relief energy in geomorphological compartmentalization of the Cerrado due to changes in land use and occupation was clearly demonstrated by Rodrigues (2002).

The compartmentalization of the study area into hydrological units is shown in Figure 8. They represent small internal units responsible for directing surface runoff to the main drainage, which is the Tamanduá Stream.

Figure 8

Existing water contribution units in the study area with overlapping contour lines

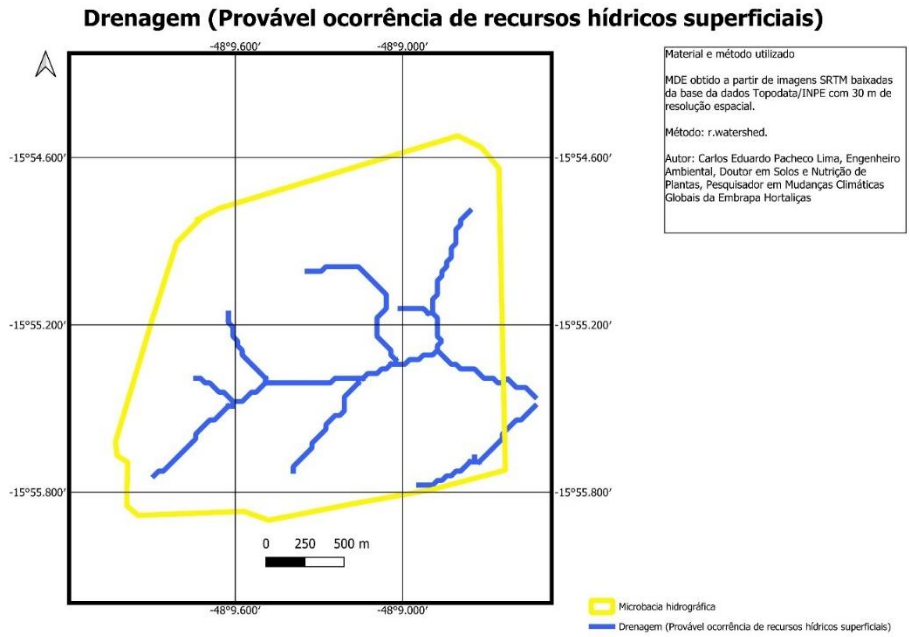


Source: The authors.

The division of the area into 28 other smaller hydrological units shows a high compartmentalization. It is also possible to visualize the convex profile of the dissection of the relief, fundamentally found in the Borda de Chapada. This is a pattern typically found in areas with dissected relief and well-defined drainage (Lazlo, 2016; Manoel & Rocha, 2017), supporting the previous results. The organization in several other hydrological units is an indication of the effectiveness of the area in acting as a water catchment zone. The overlap with the contour lines allows us to support the assertion that the flow is organized from the high and flattened tops towards the embedded valleys, reinforcing, once again, the role of the area in maintaining the ecosystem service of water production. Leite & Brito (2012), evaluating the relationships between geomorphology and hydrology of a Cerrado area in the north of Minas Gerais, verified the fundamental role that river plains play in maintaining water flow in the region. It is possible to perceive that, especially to the north and northeast, there is an area that does not contribute to the drainage of the hydrological unit under study, which is linked to the division between the sub-basins of the Corumbá River, to which the unit belongs, and the Descoberto, a fact that was verified when the map of sub-basins of the Federal District was superimposed with the study area. The findings shown so far are consistent with those of the studies by Lima et al. (2025a and b) and with the drainage network traced using the watershed, which points to dendritic drainage running in river plains and embedded bed, as can be seen in Figure 9.

Figure 9

Probable occurrence of surface water resources in the study area, determined by the r.watershed algorithm in a GRASS/QGIS environment

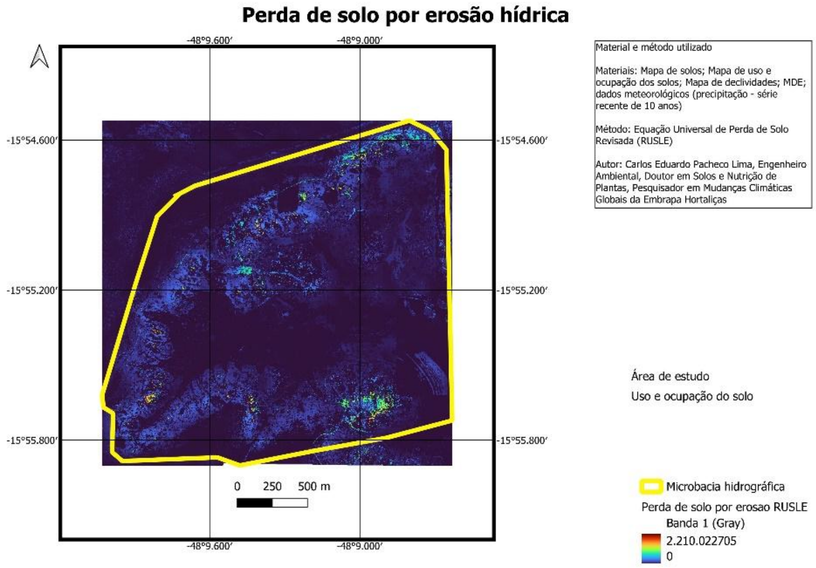


Source: The authors.

Soil losses due to erosion, as well as susceptibility mapping, are shown in Figures 10 and 11, respectively. It is observed that the areas with greater soil loss and greater susceptibility to erosion are indicated by warmer colors in both maps, coinciding with those areas with busier relief and where Haplic Cambisols predominate, according to the pedogeomorphological assessment prepared by Lima et al. (2025a). The coherence between the maps reinforces the reliability of the adopted model (RUSLE). In addition, the patterns observed were possibly greatly influenced by land use and occupation, especially by the high degree of conservation of the area, which is in the process of regeneration of the Cerrado (Map of Land Use and Occupation – Lima et al., 2025a). In this sense, even most of the areas considered fragile, as previously mentioned, had a predominance of low to moderate soil loss and susceptibility to erosion, a fact derived mainly from the low values observed for factor C. The distribution of the susceptibility classes as a percentage of the occupied area is shown in Table 11.

Figure 10

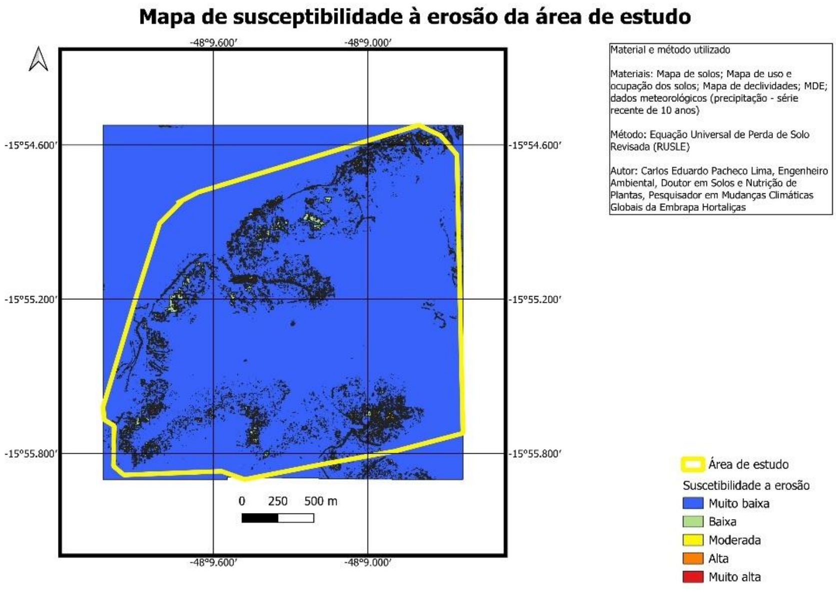
Soil losses due to erosion (A of the RUSLE equation) estimated for the study area



Source: The authors.

Figure 11

Distribution in the landscape of the classes of susceptibility to water erosion



Source: The authors.

Table 11

Distribution, as a percentage of the area, of the classes of susceptibility to water erosion

Soil loss range (t/ha/year)	Area (ha)	Approximate proportion (%)
0.0 – 200.0	160.49 ha	33,9%
200.0 – 500.0	236.74 ha	50,0%
500.0 – 1000.0	53.87 ha	11,4%

1000.0 – 2000.0	20.79 ha	4,4%
>2000.0	1.71 ha	0,4%

Source: The authors.

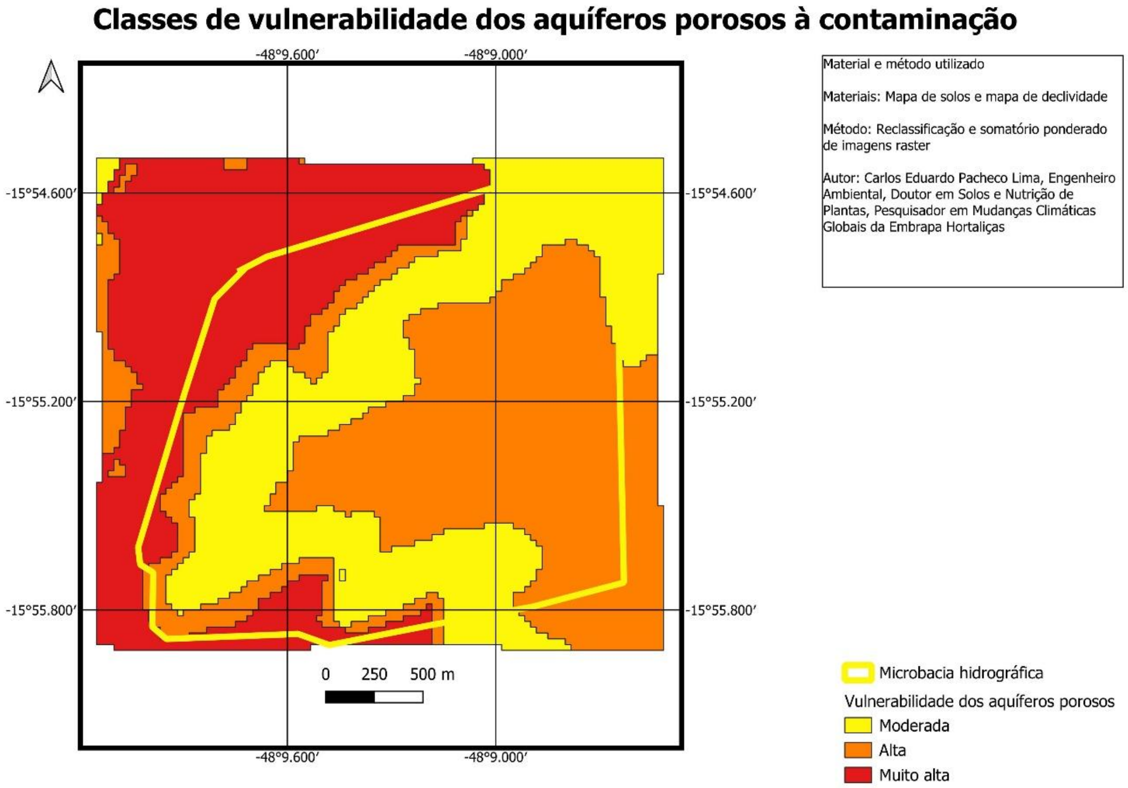
The average value of soil loss in the area was 232.42 t.ha-1.year-1, classified as low. The minimum value was 0 t.ha-1.year-1 and the maximum value was 5849.44 $^{t.ha-1.year-1,}$ which was observed in a small patch of mountainous relief to the southwest of the area. The standard deviation was 372.67 and the 95% confidence interval was from 228.75 $^{t.ha-1.year-1}$ to 236.10 t.ha-1.year-1, values determined by spatial algebra using QGIS. Therefore, the average soil loss in the area can be classified as low, but with a maximum value classified as very high and occasional occurrences of patches classified as high susceptibility to erosion. This scenario, however, can change if the vegetation is suppressed and there is the installation of structures or uses that cause waterproofing or soil compaction, exposing the fragile soils and the high slope of the Borda de Chapada.

Barbosa et al. (2024), when assessing soil losses in the Cerrado of Piauí, found higher rates in sloping areas with fragile soils, in addition to evidencing the protective role of natural vegetation or vegetation in restoration on the reduction of erosive processes. Schwamback et al. (2024), in turn, identified that soils commonly found in busy areas such as Cambisols are more susceptible to erosion, a process that can be mitigated by the presence of natural vegetation in conserved or regenerating areas. These authors also highlight that the use of RUSLE generated a mapping pattern consistent with the regional pedogeomorphological characteristics. The protective role of natural vegetation on erosive processes was also found by Rios et al. (2024).

Figure 12 shows the contamination vulnerability map generated for the study area.

Figure 12

Map of vulnerability of porous aquifers to contamination in a hydrographic unit in the Cerrado of the Federal District



Source: The authors.

The flow rate granted for dilution is present in the entire hydrographic unit studied, classified as very high compromise, that is, greater than 70% of the available flow is already allocated for this, according to information available spatially in SISDIA-DF. This implies a limited capacity for effluent assimilation, with a high risk of loss of water quality, especially in periods of drought or in case of intensive use (Monfared et al., 2017; Patil et al., 2022). This critical condition imposes restrictions on the issuance of new grants for dilution purposes and reinforces the need for strict control over the discharge of effluents (Speed et al., 2013).

The results of this study highlight the importance of integrating territorial planning and environmental management through public policies aimed at soil and water conservation. The association with the results found by Lima et al. (2025 a and b) still indicate concrete risks to the diffuse right of all to an ecologically balanced environment, as provided for in Article 225 of the Federal Constitution. In addition, the findings dialogue with the Sustainable Development Goals (SDGs), especially SDG 6 (Clean water and sanitation), SDG 13 (Action against global climate change) and SDG 15 (Life on land). Such evidence justifies the need for more restrictive land use policies, protection of recharge areas, maintenance of APPs and establishment and respect for existing management plans.

4 CONCLUSIONS

The present work closes a trilogy of studies conducted in the same area, complementing the work of Lima et al. (2025 a and b). Although the susceptibility to erosion of most of the area is low, there are features such as the Borda de Chapadas that have a high and very high classification. Most of these features, however, showed low susceptibility mainly due to the maintenance of native or regenerating vegetation. The vulnerability to contamination of porous aquifers, however, was a concern, especially in the current context of very high compromise of the flow rate granted for dilution.

These findings reinforce the urgent need to implement public policies and comply with existing management plans. Therefore, the strong connection of the findings with respect for diffuse rights and compliance with the SDGs is highlighted.

REFERENCES

Amaral, B. P., Valle Junior, R. F., Machado, E. R., & Siqueira, H. E. (2021). Vulnerability analysis of underground aquifers to contamination using the DRASTIC method and risk determination. Caminhos de Geografia, 22(84), 227–245. https://doi.org/10.14393/RCG228457049

Barbosa, W. C. S., & Guerra, A. J. T. (2024). Soil erosion modeling using the Revised Universal Soil Loss Equation and a Geographic Information System in a watershed in the northeastern Brazilian Cerrado. Geosciences, 14(3), Article 78, 1–28. https://doi.org/10.3390/geosciences14030078

Barboza, E., Raymundo, A. A., Valqui, L., & Salas Lopez, R. (2024). Estimation of soil loss using RUSLE model and GIS tools: Case study in the Jucusbamba Micro-Watershed (Amazonas, NW Peru). Revista Ambiente & Água, 19, e2998. https://doi.org/10.4136/ambi-agua.2998

Capoane, V., & Silva, D. A. (2020). Avaliação de parâmetros geomorfométricos derivados de modelos altimétricos de diferentes fontes e resoluções: Estudo de caso da bacia hidrográfica do córrego Lajeado, Campo Grande, MS. Revista Brasileira de Geografia Física, 13(2), 674–690. https://periodicos.ufpe.br/revistas/rbgfe

Costa, E. S., & Leite, E. F. (2024). Análise morfométrica na bacia hidrográfica do Ribeirão Vermelho-MS. Revista Eletrônica da Associação dos Geógrafos Brasileiros – Seção Três Lagoas, 1(38), 124–147. https://revista.agbtrslagoas.org

Ferreira, F. L. V., Vieira, F. C. C., Sousa, I. P., Figueiredo, F. P., & Frazão, L. A. (2020). Diagnóstico ambiental de nascentes em uma bacia hidrográfica do Cerrado brasileiro. Caderno de Ciências Agrárias, 12, 1–11. https://doi.org/10.35699/2447-6218.2020.20739

GRASS Development Team. (2024). r.watershed – GRASS GIS manual. https://grass.osgeo.org/grass-stable/manuals/r.watershed.html

Hamouch, C., Chaaouan, J., & Bouiss, C. E. (2025). Spatial-temporal assessment of soil erosion using the RUSLE model in the upstream Inaouène watershed, Northern Morocco. Natural Hazards Research, 5, 148–156. https://doi.org/10.1016/j.nhres.2024.08.002

Hashemi Monfared, S. A., Dehghani Darmian, M., Snyder, S. A., Azizyan, G., Pirzadeh, B., & Azhdary Moghaddam, M. (2017). Water quality planning in rivers: Assimilative capacity and dilution flow. Bulletin of Environmental Contamination and Toxicology, 99(5), 531–541. https://doi.org/10.1007/s00128-017-2182-7

Instituto de Pesquisa e Estatística do Distrito Federal (IPEDF). (2020). Hidrogeologia. In Atlas do Distrito Federal. IPEDF. https://atlas.ipe.df.gov.br/?p=1699

Kumar, M., Sahu, A. P., Sahoo, N., Dash, S. S., Raul, S. K., & Panigrahi, B. (2022). Global-scale application of the RUSLE model: A comprehensive review. Hydrological Sciences Journal, 67(5), 806–830. https://doi.org/10.1080/02626667.2021.2020277

Laszlo, J. (2016). Padrões de dissecação do relevo e morfologias dominantes nas Bacias Hidrográficas dos Rios Aguapeí e Peixe. In Simpósio Nacional de Geomorfologia, 11., Maringá. Anais... União da Geomorfologia Brasileira. https://www.sinageo.org.br/2016/trabalhos/6/6-345-1099.html

Leite, M. R., & Brito, J. L. S. (2012). Mapeamento morfoestrutural e morfoescultural na região de cerrado no Norte de Minas Gerais. Sociedade & Natureza, 24(1), 115–126.

Lima, C. E. P. (2007). Produção de mapas de vulnerabilidade de solos e aquíferos à contaminação por metais pesados para o estado de Minas Gerais [Dissertação de Mestrado, Universidade Federal de Viçosa]. Viçosa, MG.

Lima, C. E. P., Fontenelle, M. R., Braga, M. B., Florindo, B. S., Ferreira, J. G., Figueiredo, J. M. R., Freire, V. P., Silva, J., & Guedes, Í. M. R. (2025a). Fragilidade e relevância ambiental de uma área do Cerrado no DF: Subsídios pedogeomorfológicos para a proteção dos direitos difusos. Revista Aracê, 7(7), 38028–38054. https://doi.org/10.56238/arev7n7-168

Lima, C. E. P., Fontenelle, M. R., Braga, M. B., Silva, K. M. N. B., Rodrigues, G. S. S., & Silva, K. C. R. (2025b). Clima, morfometria e erosividade em unidade hidrográfica do Cerrado do DF: Implicações socioambientais e direitos difusos. Revista Aracê, 7(7), 39480–39503. https://doi.org/10.56238/arev7n7-250

Lima, F. P., Almeida, F. P. S., Mendonça Filho, S. F., Murta, J. R. M., Brito, G. Q., & Salemi, L. F. (2020). Water infiltration in the Brazilian tropical savanna: The case of Cerrado típico.

Journal of Biotechnology and Biodiversity, 8(3), 165–171. https://doi.org/10.20873/jbb.uft.cemaf.v8n3.lima

Manoel, J. L., & Rocha, P. C. (2017). Levantamento e análise comparativa dos padrões de drenagem das bacias hidrográficas dos rios Aguapeí e Peixe. In Simpósio Brasileiro de Geografia Física Aplicada, 17.; Congresso Nacional de Geografia Física, 1., Campinas. Anais... Instituto de Geociências – Unicamp. https://doi.org/10.20396/sbgfa.v1i2017.1778

Martins, E. S., & et al. (2004). Unidades de paisagem do Distrito Federal, escala 1:100.000. Embrapa Cerrados.

Ministério do Meio Ambiente e Mudança do Clima (MMA). (2023). Áreas prioritárias para conservação da biodiversidade: Segunda atualização. MMA. https://www.gov.br/mma/pt-br/assuntos/biodiversidade/areas-prioritarias

Moore, I. D., & Burch, G. J. (1986). Physical basis of the length-slope factor in the universal soil loss equation. Soil Science Society of America Journal, 50, 1294–1298.

Moreira, E. A., Souza, T. S., Domingo, S. S., & Siqueira, A. P. (2019). Protocolo de recuperação de nascentes no bioma do Cerrado. Informe Goiano – Circular de Pesquisa Aplicada, 7(4), 1–4.

Murta, J. R. M., Brito, G. Q., Mendonça Filho, S. F., & Salemi, L. F. (2022). Topsoil physical properties under a riparian forest in Central Brazil: Infiltration and penetration resistance. Hoehnea, 49, e332021. http://dx.doi.org/10.1590/2236-8906-33/2021

Nachtigall, S. D., Nunes, M. C. M., Moura-Bueno, J. M., Lima, C. L. R., Miguel, P., & Beskow, S. (2020). Modelagem espacial da erosão hídrica do solo associada à sazonalidade agroclimática na região sul do Rio Grande do Sul, Brasil. Engenharia Sanitária e Ambiental, 25(6), 933–946. https://doi.org/10.1590/S1413-4152202020190136

Oliveira, P. T. S., Sobrinho, T. A., Steffen, J. L., & Rodrigues, D. B. B. (2010). Caracterização morfométrica de bacias hidrográficas através de dados SRTM. Revista Brasileira de Engenharia Agrícola e Ambiental, 14(8), 819–825. http://www.agriambi.com.br

Ottoni, M. V., & et al. (2025). Saturated hydraulic conductivity and steady-state infiltration rate database for Brazilian soils. Revista Brasileira de Ciência do Solo, 49, e0240003. https://doi.org/10.36783/18069657rbcs20240003

Patil, R., Wei, Y., Pullar, D., & Shulmeister, J. (2022). Effects of change in streamflow patterns on water quality. Journal of Environmental Management, 302(Pt. A), 113991. https://doi.org/10.1016/j.jenvman.2021.113991

Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., & Yoder, D. C. (Coords.). (1997). Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE) (Agriculture Handbook, n. 703). United States Department of Agriculture.

Rios, G. S., Santana, D. B., Lense, G. H. E., Rubira, F. G., Ayer, J. E. B., & Mincato, R. L. (2024). Serra da Canastra National Park: Influence of forest fires on the RUSLE C factor and its impact on water erosion. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 52(1), Article 13577. https://doi.org/10.15835/nbha52113577

Rodrigues, L. N., & Cambraia Neto, A. J. (2021, April 5). Recarga e sua importância para as águas subterrâneas e para a sustentabilidade da agricultura na região do Cerrado. Portal Embrapa. https://www.embrapa.br/busca-de-noticias/-/noticia/60455159/artigo---recarga-e-sua-importancia-para-as-aguas-subterraneas-e-para-a-sustentabilidade-da-agricultura-na-regiao-do-cerrado

Rodrigues, R. C. S., Minoti, R. T., & Alves, C. M. A. (2024). Avaliação da qualidade das águas superficiais em cursos d'água na bacia hidrográfica do rio Paranaíba a partir da análise do IQA e do ICE. Geo Ambiente On-line, 48, 157–179. https://revistas.ufj.edu.br/geoambiente

Rodrigues, S. C. (2002). Mudanças ambientais na região do Cerrado: Análise das causas e efeitos da ocupação e uso do solo sobre o relevo. O caso da bacia hidrográfica do Rio Araguari, MG. GEOUSP – Espaço e Tempo, 12, 105–124.

Sakhraoui, F., & Hasbaia, M. (2023). Evaluation of the sensitivity of the RUSLE erosion model to rainfall erosivity: A case study of the Ksob watershed in central Algeria. Water Supply, 23(8), 3262–3284. https://doi.org/10.2166/ws.2023.182

Santos, R. M., & Koide, S. (2016). Avaliação da recarga de águas subterrâneas em ambiente de Cerrado com base em modelagem numérica do fluxo em meio poroso saturado. Revista Brasileira de Recursos Hídricos, 21(2), 451–465. http://dx.doi.org/10.21168/rbrh.v21n2.p451-465

Schwamback, D., Brandão, A. R. A., Bertotto, L. E., Berndtsson, R., Zhang, L., Wendland, E., & Persson, M. (2024). Quantifying soil loss in the Brazilian savanna ecosystem: Current rates and anticipated impact of climate changes. Land Degradation & Development, 35(18), 5786–5803. https://doi.org/10.1002/ldr.5331

Silva Júnior, G. C., & Pizani, T. C. (2003). Vulnerability assessment in coastal aquifers of Rio de Janeiro State, Brazil. Revista Latino-Americana de Hidrogeologia, 3, 93–98.

Silva, M. A. P., Evangelista, L. P., Silva, W. H. O., & Santo, F. S. E. (2024). Diagnóstico e estratégias para a conservação ou restauração de nascentes em ambientes com ações antrópicas. Ciência Florestal, 34(3), e71553, 1–24. https://doi.org/10.5902/1980509871553

Silva, R. G., Nascimento, J. G. C., Oliveira, C. M. E., & Listo, D. G. S. (2024). Equação universal de perda de solos revisada (RUSLE) para quantificação de perda de solos na bacia hidrográfica do Rio Goitá, Zona da Mata do Estado de Pernambuco. In Simpósio Brasileiro de Geografia Física Aplicada, 20.; Encontro Lusoafroamericano de Geografia Física e Ambiente, 4., Anais... [S.l.: s.n.].

Souza, M. E. R., Vargas, T., & Belladonna, R. (2021). Vulnerabilidade à contaminação de aquíferos fraturados com base no método DRASTIC: A influência da densidade de lineamentos. Revista Águas Subterrâneas, 35(3), e30086. https://doi.org/10.14295/ras.v35i3.30086

Speed, R., Yuanyuan, L., Le Quesne, T., Pegram, G., & Zhiwei, Z. (2013). Basin water allocation planning: Principles, procedures and approaches for basin allocation planning. UNESCO.

Yadav, S. K., & Gupta, A. (2022). Assessment of groundwater vulnerability to contamination using GIS-based DRASTIC model in Lucknow, India. International Journal for Research in Applied Science & Engineering Technology, 10(10), 1229–1236. https://doi.org/10.22214/ijraset.2022.47166