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Mapping potential erosive zones in a Brazilian watershed: towards sustainable territorial planning

Mapeamento de zonas de potencial erosivo em uma bacia hidrográfica Brasileira: rumo a um planejamento territorial sustentável

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Resumo: A erosão do solo é um dos maiores problemas ambientais do século XXI, principalmente devido aos danos econômicos, sociais e ambientais causados mundialmente. O Brasil está inserido nesse contexto, onde a implementação de estratégias de apoio ao planejamento territorial voltadas para a conservação do solo é urgente. Assim, este trabalho teve como objetivo utilizar técnicas de cartografia geoambiental para mapear as zonas erosivas potenciais na bacia do córrego Gouveia (Brotas, Brasil) com base em dados geográficos sistematizados por geoprocessamento. Parâmetros de geologia, pedologia, forma do terreno, declividade do terreno, uso e cobertura do solo foram sistematizados em ambiente SIG por meio de operações matemáticas e inferência fuzzy para mapear as potenciais zonas erosivas. Os resultados obtidos indicam que 63% da bacia é constituída por áreas de potencial "Alto" e "Muito Alto" para o processo erosivo, o que requer uma necessidade urgente de implementação de estratégias de gestão e ordenamento territorial sustentável. Esta abordagem pode potencialmente contribuir para o processo de tomada de decisão na área de estudo e ser aplicada em outras bacias hidrográficas em todo o mundo.

Palavras-chave: Erosão dos Solos; SIG; Planejamento da Paisagem; Bacias Hidrográficas, Brasil

Abstract: *Soil erosion is one of the greatest environmental problems in the 21st Century, mainly due to the economic, social, and environmental damages caused worldwide. Brazil is inserted within this context, where the implementation of strategies to support territorial planning aimed at soil conservation is urgently required. Thus, this work aimed to use geoenvironmental cartography techniques to map the potential erosive zones at the Gouveia stream watershed (Brotas, Brazil) based on geographic data systematized by geoprocessing. Parameters of geology, pedology, terrain shape, terrain slope, land use, and land cover were used and systematized in a GIS environment through mathematical operations and fuzzy inference to map the potential erosive zones. The results indicate that 63% of the basin consists of "High" and "Very High" potential areas for the erosion process, which requires an urgent need to implement management strategies and sustainable territorial planning. This approach can potentially contribute to the decision-making process in the study area and be applied in other watersheds worldwide.*

Keywords: *Soil Erosion; GIS; Landscape Planning; Watersheds; Brazil.*

1. Introduction

Despite decades of scientific research and socio-environmental concerns, soil erosion is still a major threat worldwide. The most frequent threats related to soil erosion are the loss of arable areas, the decrease in biodiversity, the imbalance of soil nutrients, and the intensification of the desertification process (FAO, 2015). Therefore, the development of methods to prevent soil erosion is urgently required.

Natural or anthropogenic-related soil erosion is common in the Brazilian landscapes, especially in the regions of intense human occupation such as the Southeastern portion of the country. Poor distribution of incomes, the industrialization process since the 1950s, which increases the demand for natural resources, the lack of adequate urban planning, the disorderly occupation of territories, the inefficiency of governments in dealing with *favelas*, and the lack of legal guidelines to tackle soil erosion are the most important causes of this environmental problem in Brazil (FIGUEIREDO, 1994).

In this scenario, the State of São Paulo, Southeastern Brazil, stands out for housing 22% of the Brazilian population and 22.8% of the national industrial production (IBGE, 2018) in an environment dominated by human-modified landscapes. Considering the extensive territorial dimension of São Paulo (248,219 km^2) and the need for accurate identification of the erosion processes occurring there, often resulting from isolated activities on agricultural properties, the research, planning, and action strategies must be taken at a local scale to better understand environmental impacts and the adverse effects of this environmental problem (GUERRERO *et al.*, 2016; SILVA, 2003).

Within São Paulo, the central region stands out since it has several landscapes showing high rates of erosion susceptibility, mainly due to the predominant sandy geological features (São Bento and Bauru groups, for example) promoted under the relief of sandstone-basaltic cuesta (IPT, 1981, 2012).

Due to its location on the back of the sandstone-basaltic cuesta, the municipality of Brotas is of special interest in terms of soil erosion, as the municipality has several areas with essentially sandy soils, high slopes, intensive land use, and a history of linear erosions. These characteristics directly contribute to the degradation of both soil and surface water resources and have been causing several socio-environmental problems such as the loss of agricultural areas and silting of water bodies. The elements mentioned above justify the immediate need for studies that promote geo-environmental diagnoses of areas most susceptible to erosion in order to guide territorial planning and organize land use actions in the region, which would effectively contribute to more sustainable municipal development.

In order to establish technical and scientific parameters that help in the decision-making process in landscapes susceptible to the occurrence of erosive processes, methodological procedures from geoenvironmental cartography are highlighted for the possibility of spatially representing the geological/geotechnical information that is necessary for identifying the soil erosion process (VALLEJO *et al.*, 2002). Thus, geoenvironmental cartography has techniques for producing maps showing the potential erosion zones, an essential planning tool that, based on basic cartographic documents such as maps of geology, pedology, slopes, and land use and land cover (LULC), allows detecting the most sensitive areas to the occurrence of these processes in landscapes (ZUQUETTE and GANDOLFI, 2004).

In the literature, several methods are found in geoenvironmental cartography aimed at analyzing susceptibility to erosion, such as Boolean analysis models, hierarchical analyses, and machine learning techniques, among others. For this study, due to promoting analyses at the planning scale and aiming at an integrated analysis of several geoenvironmental parameters considered of interest to the process, we used a geoenvironmental model based on mathematical operationalization in fuzzy logic, presented as efficient in delimiting geoenvironmental zones in several studies, such as Zuquette and Gandolfi (2004).

According to Botelho (2012), watersheds are the ideal scale of analysis for mapping the erosive processes, given that their spatial delimitation is based on geomorphological criteria. Therefore, the watershed scale allows an integrated perspective of the elements that contribute to soil erosion locally. Thus, this analysis parameter was taken into account when choosing the study area, in order to contemplate strategic territorial planning in the context of the municipality of Brotas, Brazil.

Following these considerations, the objective of this study was to map the potential erosion zones at the Gouveia stream watershed, entirely located in the municipality of Brotas, based on geoenvironmental cartography techniques. This initiative contributes to the implementation of more effective actions to tackle soil erosion in the study area, where there are natural conditions for the occurrence of erosive processes and increasing anthropogenic pressure on the preserved natural environment. It can also be applied in other watersheds worldwide.

2. Study area

The Gouveia stream watershed is located in the municipality of Brotas, in the central portion of São Paulo (**Figure 1**), with an area of approximately 79 km². According to the classification proposed by Strahler the Gouveia stream is a second-order watershed. On the national scale, the study area is fully inserted within the Paraná basin, while at the state scale it is inserted within the Water Resources Management Unit 13 – Tietê-Jacaré (UGRH – 13), one of the largest basins of São Paulo.

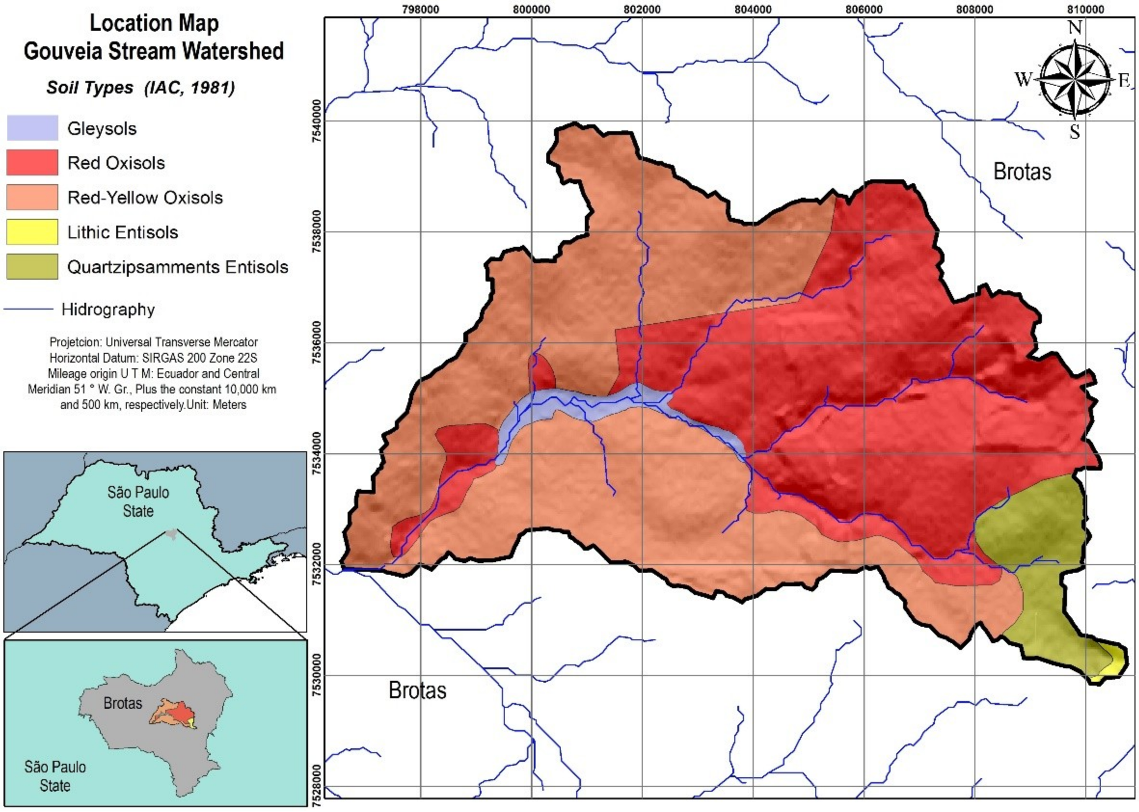


Figure 1: Gouveia Stream Watershed location map.

The surface geology of the Gouveia stream watershed is mostly composed of sandstones from the Botucatu formation (95.8%), dating from the Jura-Cretaceous period, which are pink in color with thickness not exceeding 150 meters and fine to coarse granulation (MEZZALIRA, 1981). The second largest geological unit in the region is formed by Quaternary Alluvial Deposits (2.8%), which correspond to layers composed of sediments transported and deposited by the influence of river movements with a predominantly sandy characteristic. Moreover, some areas of Triassic sandstones of the Pirambóia formation (1.4%) are also found, which are sediments of aeolian and fluvio-eolian origin deposited in a desert environment (MEZZALIRA, 1981; REGRA, 2013). A small area (0.012 km²) composed by basalts from the Serra Geral Formation, a group of rocks from basaltic flows with aphanitic texture dating from the Jura-Cretaceous (LORANDI *et al.*, 2014), is also found. The average annual rainfall varies between 1300 mm and 1600 mm, concentrated during the rainy season from October to March (CEMADEN, 2019). These characteristics contributed to the fact that the study area was severely modified by anthropogenic actions. Only 9% of the basin was covered by natural vegetation in 2019, while 89% was used for agropastoral production (sugarcane, coffee, oranges, forestry, and pastures). The remaining area was divided among urban areas, rivers, and bare soil (MAPBIOMAS, 2019).

3. Materials and method

Figure 2 summarizes the methodological flow proposed for the development of this study, divided into 6 main structures, explained later:

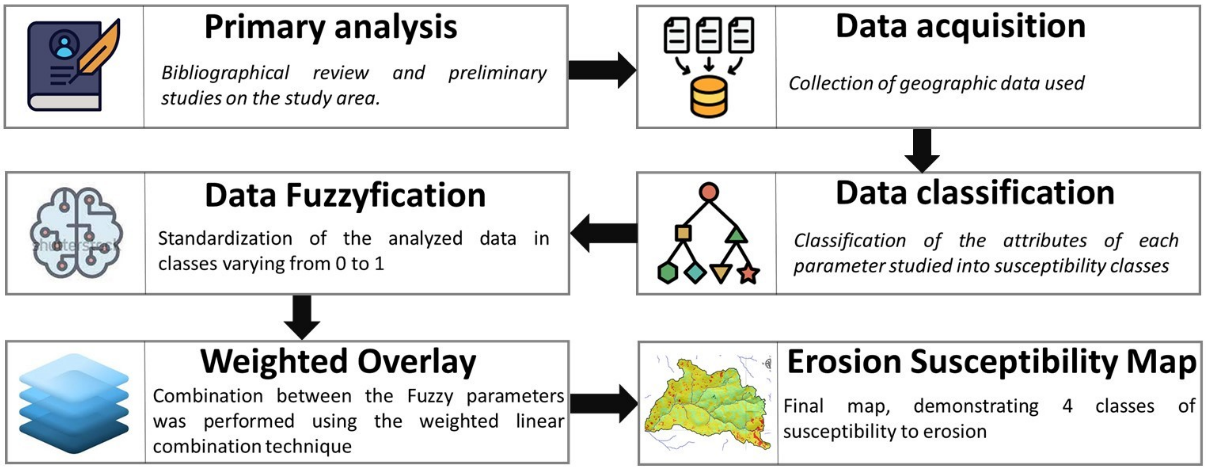


Figure 2: Methods flowchart.

3.1. Materials

The procedures required to apply the geoenvironmental cartography techniques for mapping the potential erosive zones are the overlaying between the layers of geology, soil types, terrain forms, slopes, and land use (ZUQUETTE and GANDOLFI, 2004) (**Figure 2**).

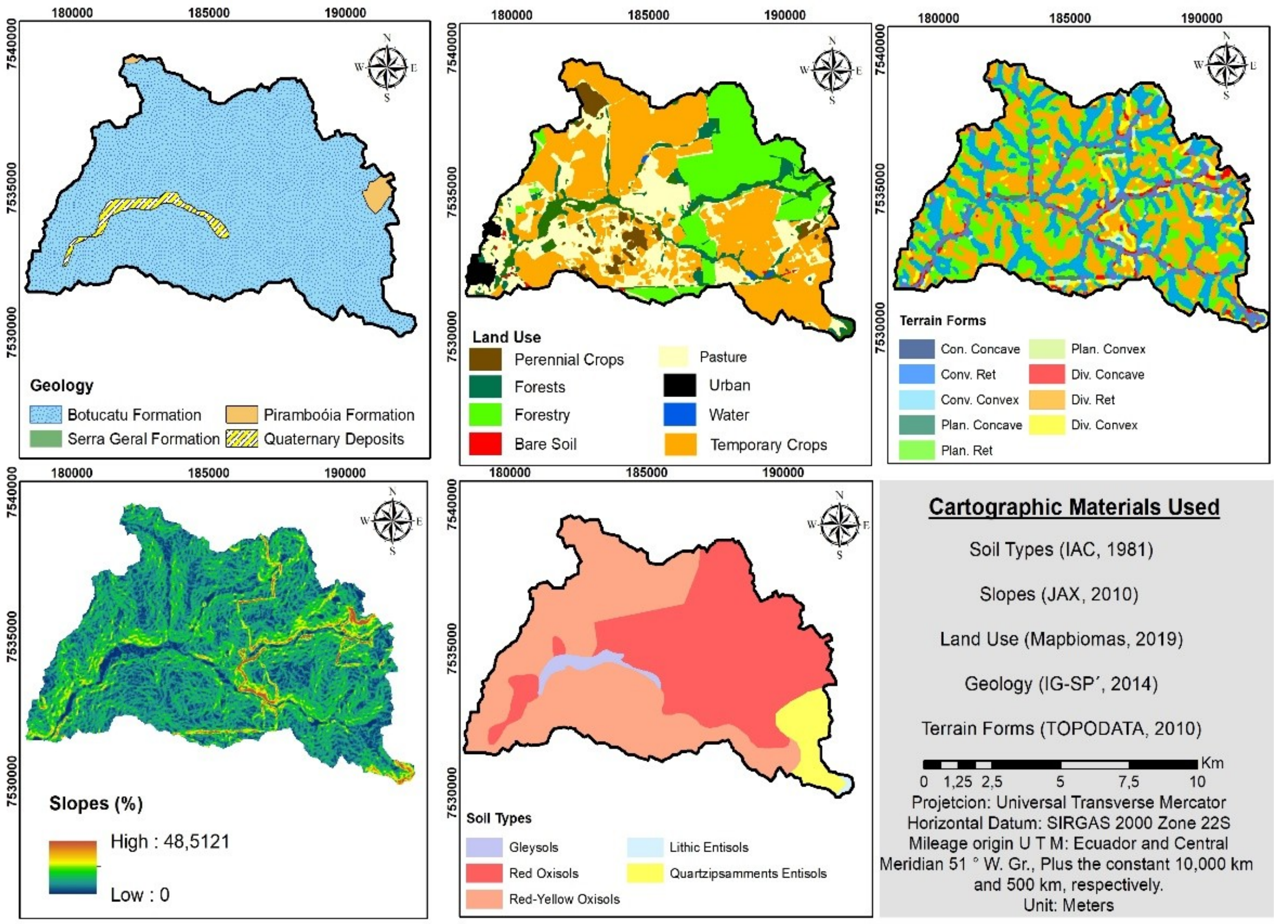


Figure 3: Geoenvironmental parameters.

The layer about geological formations, important to understand the structural context of the landscape, was made available by the Geological Institute of São Paulo at a scale of 1:75,000 (IG/SMA, 2014). For its use, we used selection and extraction functions per layer in ArcGis 10.8, using the limit of the Gouveia watershed as a basis.

The pedological layer was acquired from the *Campinas Agronomic Institute* (IAC, 1981) at a scale of 1:50,000. The original data was obtained in image format. Thus, we carried out the georeferencing and polygonization procedures in the image, which allowed its inclusion in the geographic database of this study.

The terrain layer, information that characterizes the morphology of the vertical and horizontal curvatures of the slopes, was obtained from the Topodata project (TOPODATA, 2010). for the entire municipality of Brotas. Later, we cut out the area of interest with the "extract by mask" function in ArcGis 10.8.

For the identification of terrain slope, a slope map in percentage was generated using the “slope” tool in ArcGis 10.8, based on the ALOS Elevation Digital Model with 12.5 meters of spatial resolution.

Finally, the LULC layer for the year 2019 was acquired from the freely available MapBiomas collection 6.0 dataset (MAPBIOMAS, 2019), where we downloaded the scene that covers the entire municipality of Brotas and extracted the area of interest.

3.2. Method

The mapping of the potential erosive zones aims to support the decision-making process following the spatial identification of the most susceptible areas to the occurrence of erosive processes. In this work, we adapted the method proposed by Lollo and Sena (2013), which considers aspects of the physical environment and the dynamics of anthropogenic occupation to identify, through geographic information systems (GIS), the areas where the probability of erosive events occurring is higher.

The methodological operationalization applied consisted of allocating values to the attributes of each layer described in the previous section, according to their characteristic to facilitate or hinder the occurrence of linear erosive processes and then systematize the layers using a Fuzzy logic approach. The adopted erosion susceptibility values are described in **Table 1**.

Table 1: Erosion susceptibility values assigned to the attributes of each input parameter of the geoenvironmental model to map the potential erosive zones.

Attributes	**Erosion susceptibility**			
	Low	**Moderate**	**High**	**Very High**
Erosion susceptibility values	**0 – 0.25**	**0.25 – 0.5**	**0.5 – 0.75**	**0.75 – 1**
Geology	Serra Geral	-	Pirambóia	Botucatu; Alluvial Deposits
Pedology	Red Oxisols	-	Red-Yellow Oxisols	Quartzipsamments Entisols; Gleysols; Lithic Entisols
Terrain Shape	Convex-Divergent; Rectilinear-Divergent; Concave-Divergent	Rectilinear Planar; Convex Planar	Convex-Convergent; concave-planar	Convex-Convergent; Concave-planar
Terrain Slope	0.0% – 6.0%	6.1% – 12.0%	12.1% – 30.0%	> 30.1%
LULC	Forest Formation; Cerrado	Perennial Agriculture	Pasture; Forestry	Urban; Temporary Crops; Bare Soil

The assigned values described in **Table 1** were adapted from the method proposed by Lollo and Sena (2013) following the criteria described in sequence. The weights assigned to Geological formations in the model are based on the understanding of the geological evolution of the territory and the geological formations such as texture, compaction, particle size, and grain density *(CREPANI et al., 2001; LOLLO et al.*, 2019; LORANDI *et al.*, 2014).

Thus, the larger, more disaggregated, and sandy the material, the greater its chance of erosion, while the greater the aggregation of the material (in the case of clayey textures) the occurrence of mechanical disaggregation is lower. Thus, the surface geological formation present in the Botucatu Formation was considered to have a very high susceptibility to erosion, and the Serra Geral Formation had low susceptibility.

Regarding pedology, soils are fundamental agents in the erosion process. Thus, the attribution of values to soil attributes was based on the characteristics related to the structure, permeability, depth, and material that compose the soil (CREPANI *et al.*, 2001). For example, Neosols are considered to have very high susceptibility, and Red Latosols are considered to have low susceptibility.

Terrain shape is a geotechnical parameter that expresses the independent variation of geomorphological variables related to the horizontal curvature and the vertical curvature of the slopes. This parameter must be assessed since it can potentially intensify the morphogenetic processes and/or the flow intensity of surface runoff (CASSETI, 2005; VALERIANO, 2008). For example, terrains with concave-convergent or rectilinear-convergent shapes are highly susceptible to erosive processes, while terrains with convex-divergent shapes have low susceptibility. For the terrain slope, it is assumed that the greater the slope the greater the process of surface runoff and the drag of soil particles.

Therefore, areas with a slope greater than 30% are considered to have a very high susceptibility to erosive processes, and areas with a slope between 0% and 6% are considered to have low susceptibility. Finally, regarding LULC, the susceptibility to erosion was attributed to the influence of each LULC type on attenuating or accentuating the occurrence of erosive processes. For example, forests are considered of low susceptibility to the erosive processes, while exposed soil areas have a very high susceptibility.

One of the problems in cartographically representing the real world is that the spatial characteristics of landscapes do not have well-defined limits, especially in transition zones, which limits, for example, the use of Boolean models for such operations.

For this reason, the combination of the geospatial data in this study was performed using the Fuzzy logic approach, originally proposed by Zadeh (1965) and reported by several authors, such as Cereda Junior (2011) and Kainz (2007) as a mathematical tool for cartographic normalization, capable of solving this problem caused by traditional Boolean analysis. In this context, Burrough abd McDonnel (1998) stated that whenever there is ambiguity, ambivalence, or abstraction in mathematical models, scientists should implement fuzzy sets.

The Fuzzy logic consists of a geographic inference technique that, based on an algebraic analysis to generate integrated maps, expresses the relationship between the analyzed elements where the limits between the classes are less abrupt than the Boolean logic (SILVA, 2003) and, therefore, presents a greater variation between the classes of susceptibility. The application of the Fuzzy logic (treated here as Fuzzyfication) requires the standardization of the analyzed data in classes varying from 0 to 1, according to the intensity of susceptibility to erosion (as also shown in **Table 1**).

The combination between the Fuzzy parameters was performed using the weighted linear combination technique in ArcGis 10.8. Considering the local scale of this study, added to the small size of the basin studied and the physiographic analyses performed, the multidisciplinary team carrying out this work concluded that assigning different weights to the parameters could bias the analysis based on a specific parameter. For this reason, we concluded that the weighted sum should attribute the same relative importance to all elements studied, as presented by Equation 1.

$$PEZ = (G*0.2) + (P*0.2) + (TS*0.2) + (TSl*0.2) + (L*0.2) \quad (1)$$

where ZEP is the Potential Erosive Zone, G is the Geology parameter, S is the pedology parameter, TS is the terrain shape parameter, TSl is the terrain slope parameter, and L is the LULC parameter. All parameters were converted to fuzzy values before applying the equation.

At the end of the procedure, four classes of potential erosion were defined in the study area: (i) Zone 1 - low susceptibility (0.0 - 0.25), (ii) Zone 2 - moderate susceptibility (0.25 - 0.5), (iii) Zone 3 - high susceptibility (0.5 - 0, 75), and (iv) Zone 4 - very high susceptibility (0.75 – 1).

4. Results and discussion

The five parameters used to identify the potential erosive zones at the Gouveia stream watershed are shown in **Figure 3**. All parameters were converted to fuzzy values.

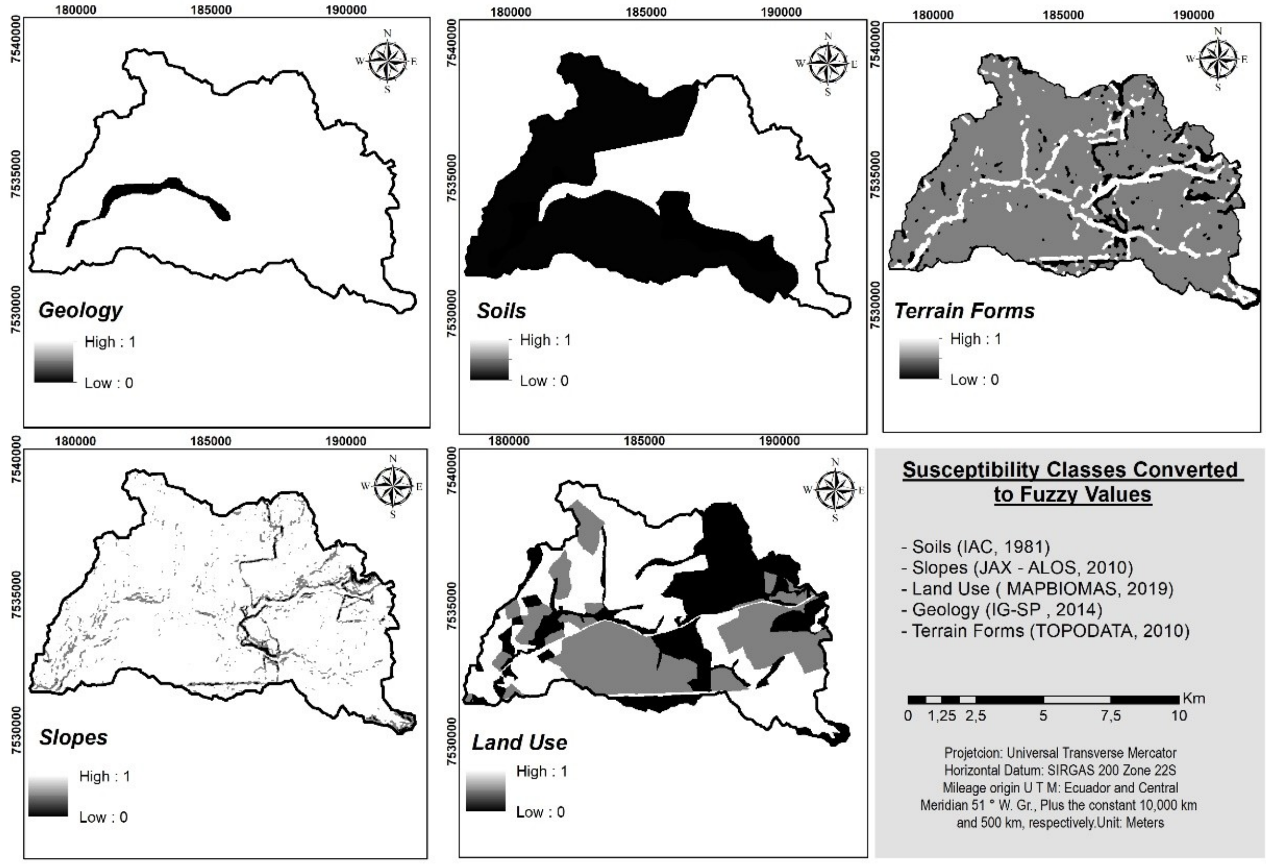
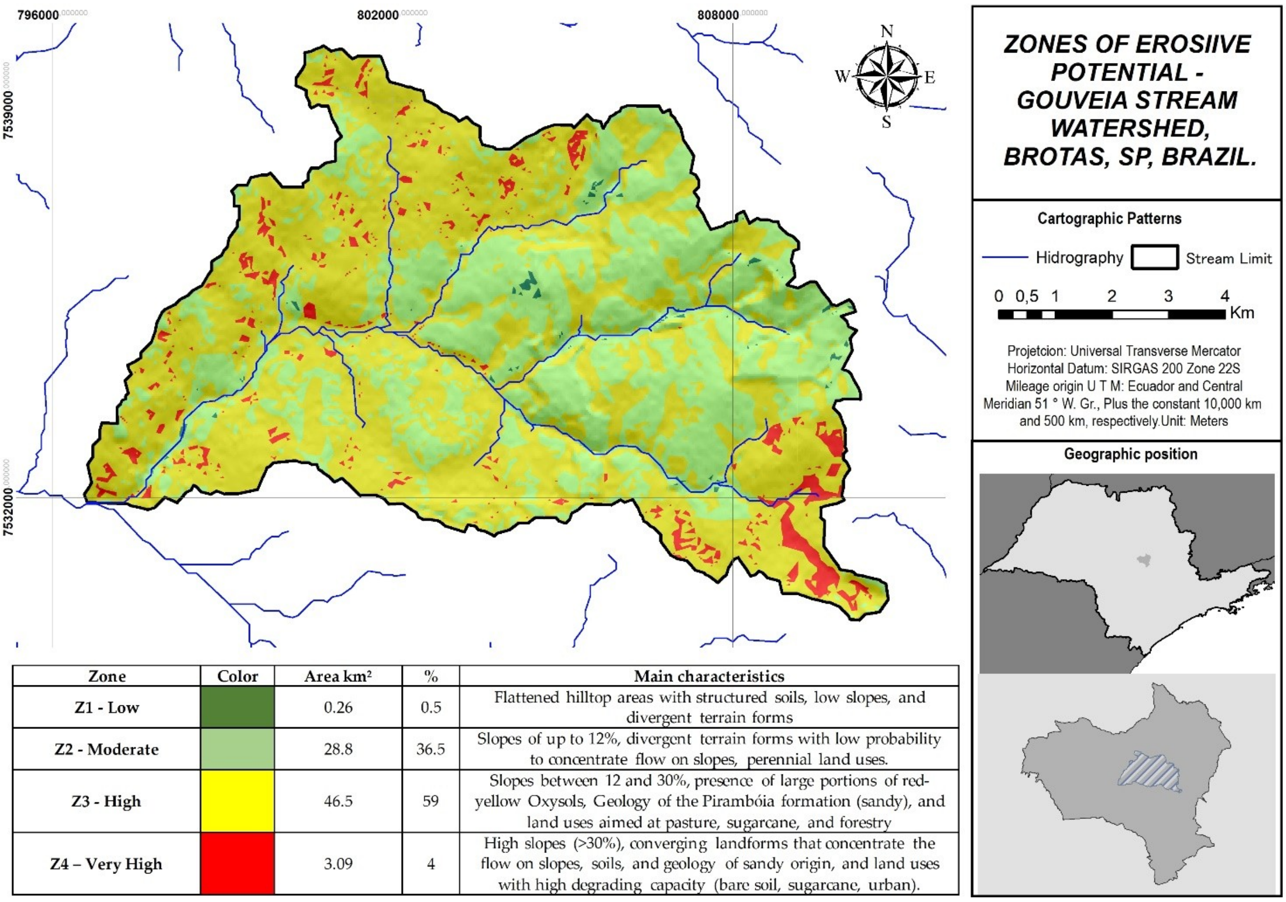


Figure 2. Geoenvironmental parameters converted in Fuzzy values.

The geology parameter indicates that a large portion of the Gouveia basin is composed by sandy characteristic formations (Botucatu, Pirambóia, and Quaternary Deposits), which contributes to a higher susceptibility to erosive processes. For pedology, we can identify (due to the black and gray colors) that the basin presents sandy characteristics that contribute to a greater susceptibility to erosive processes due to the lower level of particle aggregation and, consequently, greater flow and material loss through gravitational and/or runoff. For terrain shape, despite the heterogeneity of the values resulting from the diversity of horizontal and vertical curvatures of slopes, the shapes that greater contribute to the erosive potential are located mainly in the valleys and drainage headwaters, precisely where there is greater erosive action (historical and current) from the hydrogeomorphological dynamics of the watershed. Moreover, for terrain slope, the Gouveia basin has, predominantly, values lower than 12%, tending towards Fuzzy values closer to zero, that is, with lower susceptibility to erosion. The highest values of terrain slope can be found in drainage headwaters with a high level of dissection and in valleys embedded along the basin. Finally, the analysis of the LULC parameter allows inferring that the high degree of anthropogenic areas within the Gouveia stream basin, mainly for agricultural purposes, increases the potential for the occurrence of erosive processes. The combination of the parameters shown in **Figure 3** through the Fuzzy inference approach resulted in the map showing the potential erosive zones of the Gouveia basin (**Figure 4**).

The "Low" class occurred in 0.5% of the study area (0.26 km²), being concentrated over more flattened reliefs such as on top of elongated hills and in regions where the terrain shape favors infiltration. In areas with these characteristics, even when the predominant LULC class is not related to vegetation cover such as bare soil, the potential of erosive processes is very low, since they are areas of aggradation where surface runoff is inexpressive (SALOMÃO, 2012). These "Low" susceptibility areas are geotechnically stable and, therefore, the most recommended for the implementation of anthropogenic activities (excluding areas with legal restrictions and those with forest cover). The "Moderate" class corresponds to 36.5% of the study area (28.8 km²). In these areas, despite the predominance of geological and pedological formations of sandy structure, there is an attenuation of the potential erosive processes shaped by (i) elongated hills and slopes below 12%, (ii) convex and rectilinear planar terrain shapes, and (iii) LULC related to perennial and less intensive agriculture (such as coffee and oranges). The areas of this susceptibility class can be designated to anthropogenic activities as long as adequate management is carried out to ensure soil stability.



Zone	Color	Area km²	%	Main characteristics
Z1 - Low		0.26	0.5	Flattened hilltop areas with structured soils, low slopes, and divergent terrain forms
Z2 - Moderate		28.8	36.5	Slopes of up to 12%, divergent terrain forms with low probability to concentrate flow on slopes, perennial land uses.
Z3 - High		46.5	59	Slopes between 12 and 30%, presence of large portions of red-yellow Oxysols, Geology of the Pirambóia formation (sandy), and land uses aimed at pasture, sugarcane, and forestry
Z4 – Very High		3.09	4	High slopes (>30%), converging landforms that concentrate the flow on slopes, soils, and geology of sandy origin, and land uses with high degrading capacity (bare soil, sugarcane, urban).

Figure 3. Zones of Erosive Potential.

The concern with the potential erosive processes at the Gouveia stream watershed raises from the result that 63% of the study area is composed of the “High” and “Very High” susceptibility classes (**Figure 4**). These are concentrated in areas presenting sandy textured soils (such as Neosols), sandstones from the Botucatu or Pirambóia formations, slopes above 12%, and terrain shapes that concentrate the flow and facilitate surface runoff (such as convex-convergent). In addition, the analysis of the relationship between the geoenvironmental parameters and the final potential erosive map indicates that these classes are distributed over areas of drainage headwaters with a high degree of carving in the slope, embedded valleys of high dissection, and valley bottoms with soils and geology essentially composed by sand. The regions with the greatest risks related to hydrogeomorphological dynamics (springs, valleys, and floodplains) must have special attention because they concentrate most of the “High” and “Very High” areas, mainly due to the action of the Gouveia stream and its contributors to the formation of the local landscape and, consequently, to the potential of the erosive processes.

Previous studies carried out in São Paulo agree with the results obtained in this study (IAC, 2014; STEFANUTO and LUPINACCI, 2021). These have also established a direct correlation between Litholic and Quartzarenic Neosols with a high potential for erosion. Moreover, the work of Guerrero *et al.* (GUERRERO *et al*., 2016) also highlights the lack of stability in areas of the Botucatu formation, dominant in the study area. Other previous studies have also stated that in general areas of “Very High” susceptibility occur in springs, valley bottoms, and drainage headwaters (NUNES *et al.*, 2020; SALOMÃO, 2012). In these areas, the underground hydraulic gradients are high and composed of materials that are less abrasive. Therefore, they are easily removed by water action. Finally, the identification and classification of potential erosive zones demonstrate that any LULC class not related to natural vegetation jeopardizes soil stability. Therefore, territorial planning regulations must be established to limit anthropogenic land uses in improper areas and encourage adequate management and reforestation, preferably with native species (ZOLIN *et al.*, 2011).

The great challenge for local managers is to overcome the unfavorable natural characteristics of the basin with the proposition of public policies following sustainable goals, such as land use planning and reforestation programs. This could potentially raise the number of areas unfavorable to erosive processes in the near future. The relationship between land management and the soil erosion process is clearer when it affects agricultural productivity and, consequently, the local economy. In this sense, the government of the

State of São Paulo has been encouraging the control of the erosion processes by promoting projects such as "Integra SP" (SSG, 2014), which aims to provide financial support for rural producers that adopt conservationist practices.

Specifically for the Gouveia stream, the concern with the increasing erosive processes is greater because the watershed supplies the municipality of Brotas (BROTAS, 2018). Counteract measures have been taken to contain the erosive processes, such as the installation of urban equipment to reduce surface runoff from the urbanized areas and the direct control of the erosion processes such as re-sloping slopes and the use of gabion and retaining walls to prevent runoff (BROTAS, 2018). However, these actions only seek to mitigate the existing processes and not prevent future ones. On the other hand, we can highlight the implementation of the Forest Restoration Plan of the Gouveia stream watershed as an action to prevent the emergence of new erosive processes through territorial planning techniques (SSG, 2014). This plan aims to conduct an environmental diagnosis of the Gouveia basin in order to guide forest restoration actions that help to improve the local environmental quality. Additionally, the government can consider other sustainable territorial development measures, such as payment for environmental services, which have shown effective results (MATAVELI *et al*., 2018; PARRON *et al*., 2015). Encouraging ecotourism as a development strategy (GUERRERO *et al*., 2020; KENT, 2003) and the recovery and sustainable management of pastures (FRANCO *et al*., 2012; MELADO, 2016) are also potential actions.

5. Conclusion

In this study, our methodological application produced a mapping that diagnosed four classes of susceptibility to erosion in the Gouveia stream basin, in Brotas, state of São Paulo, Brazil. By converting these potential areas into geoenvironmental zones, the work is highlighted by combining geoenvironmental cartography techniques with territorial planning, directly contributing to the decision-making process in the Gouveia stream watershed.

The geoenvironmental conditions observed at the Gouveia stream watershed directly contribute to the fact that 62.8% of its area is constituted by areas of "High" or "Very High" susceptibility to erosion. This raises more concern when it is emphasized that the watershed is the main water source for the municipality of Brotas, which houses a population of 24,636 inhabitants (IBGE, 2018). It is also important to point out that the identification of such a low relative percentage of areas showing "Low" erosion potential (0.5%) occurs due to two connected factors: (i) the natural characteristics of the basin that do not favor the ecodynamic stability and (ii) the intensive land use and changes without technical guidelines that have a high potential for degradation.

The identification of potential erosion zones is an important tool for territorial planning. Considering that it can show spatially critical areas where the pressure is greater and where control, mitigation, and prevention actions must be taken. This makes the decision-making process more efficient and cheaper. Due to the more limited territorial extension of watersheds, such as the Gouveia stream, it is easier to direct territorial planning strategies and actions in order to avoid or mitigate erosive processes. Therefore, watersheds are efficient management units.

We can reaffirm that geoenvironmental cartography and geoprocessing techniques, as long as they are properly applied, constitute an excellent instrument for territorial planning, presenting results consistent with reality and relatively low cost of implementation.

Finally, as gaps in the work, we can indicate that the data and methods used limit the results to the planning scale, making it impossible to outline strategies on action scales, such as recovery of already eroded areas. It is worth noting that when we indicate this gap, we also aim to promote the production and availability of data on larger scales (1:10.000, for example) in Brazil, a practice that is still in its infancy across the entire national territory.

We hope that the methodological application and the results obtained can encourage new studies that consider territorial planning aimed at preventing soil erosion in small river basins, aiming to directly contribute to water security in Brazil.

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