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Research Article

Mapping, typological characterization, and geomorphometric analysis of the gullies of the Tupanciretã Formation

Mapeamento, caracterização tipológica e geomorfométrica das voçorocas da Formação Tupanciretã

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Abstract: The Tupanciretã Formation, of sedimentary origin, has a high incidence of gullies caused by water erosion. This study sought to carry out a regional characterization of the geological and geomorphological processes that act on the formation's gullies using satellite images and a global digital elevation model. Specific methodologies were used to map and record 351 gullies in a 1,147,750 ha area. The delineated gullies were entered in a GIS database, so the data could be manipulated using geoprocessing to assign a unitary typology to each erosion as well as to define its shape, its relationship with the drainage network, and area. The spatial distribution of the gullies in the study area was considered, and their behavior in relation to geomorphometric variables such as slope, hypsometry, terrain shape, and slope direction analyzed. The most commonly found gully form is branched, predominantly connected to the drainage network, small to medium in area, and in concave-convergent relief. Ultimately, it was possible to understand the spatial variability of occurrence as well as the Tupanciretã Fm.'s gully patterns and the conditioning factors within the area.

Keywords: Erosive processes; Water erosion; Remote mapping; Geoprocessing.

Resumo: A Formação Tupanciretã, de origem sedimentar, apresenta elevada incidência de voçorocas resultantes do processo de erosão hídrica. Neste sentido, o objetivo deste estudo é realizar uma caracterização regional dos processos de natureza geológica e geomorfológica que atuam nas voçorocas da Fm. Tupanciretã, por meio de imagens de satélites e modelo digital de elevação global. Foram empregadas metodologias específicas para mapeamento e cadastro de 351 voçorocas em um recorte de 1.147.750 ha. As voçorocas delineadas compuseram um banco de dados em ambiente SIG, o que permitiu a manipulação dos dados por geoprocessamento, atribuindo unitariamente a tipologia de cada erosão, definindo suas formas, sua relação com a rede de drenagem e área da feição. Além disso, foram feitas ponderações a respeito da distribuição espacial das voçorocas na área de estudo, bem como analisado seus comportamentos perante as variáveis geomorfométricas, como declividade, hipsometria, formas de terreno e orientação das vertentes. Dentre o conjunto de voçorocas, a forma mais comumente encontrada é a ramificada, estando predominantemente conectada à rede de drenagem, com dimensões pequenas e médias, em relevo côncavo-convergente. Ao final foi possível compreender a variabilidade espacial de ocorrência, bem como padrões e fatores condicionantes das voçorocas da Fm. Tupanciretã no recorte proposto.

Palavras-chave: Processos erosivos; Erosão hídrica; Mapeamento remoto; Geoprocessamento.

1. Introduction

Water erosion, the process of detachment, transportation, and deposition of soil particles triggered by rainfall, occurs when the transport potential of the water exceeds the particles' ability to aggregate (FAO, 2019). This phenomenon represents a serious environmental and agronomic problem and is responsible for the accelerated degradation of arable land and the siltation of water bodies. Among its most severe manifestations are gullies — linear incisions that characterize advanced surface water erosion — which can reach a depth of several meters by collapsing slopes and exposing the water table. In southern Brazil, particularly in the states of Paraná (PR) and Rio Grande do Sul (RS), the combination of intense rainfall and friable sedimentary substrates favors the development of these large features (Cabral; Nummer; Bateira, 2020; Petsch et al., 2022; Dummer; Verdum, 2023; Nóbrega et al., 2023).

In this context, the Tupanciretã Formation, a post-Gondwana sedimentary geological unit in north-central Rio Grande do Sul, is a critical area. Originally described as a fluvial-lacustrine sequence (Menegotto; Sartori; Maciel Filho, 1968) and regionally mapped as fine quartz sandstones, paraconglomerates, and conglomeratic sandstones overlying the volcanics of the Serra Geral Formation (CPRM, 2008), its poorly consolidated lithology results in predominantly sandy and friable soils (Menegotto, 1980). This geomorphological condition engenders a high susceptibility to erosive dissection, making it a natural laboratory for soil degradation studies. Recent changes in land use have amplified this vulnerability. The transition from extensive livestock farming to intensive soybean cultivation (Moreira, 2013) on the formation's outcrops has accelerated the genesis of gullies, causing the loss of productive land.

Accelerated erosion of the Tupanciretã Fm. sandstones has been observed predominantly along the region's natural fields and cultivated areas. These features tend to develop at the headwaters of drains, contributing to the redirection of surface flows toward the various local drainage networks' thalwegs. This process favors the evolution of huge, elongated gullies — still poorly documented — which are potential study targets for better understanding the geological unit's erosion dynamics as well as developing strategies for predicting and mitigating their most critical outbreaks.

Both the mechanisms instigating these large linear features and the geological history of the Tupanciretã Fm. lack technical and scientific studies. Existing works address fragmentary aspects: geomorphometric analyses on a municipal scale (Pinheiro, 2023), morphostructural and tectonic influences (Marin, 2022), and sedimentary contexts on different time scales (Reis, 2020; Mexias, 2024; Ruppel; Dani; Lisboa, 2023).

Geographic Information Systems (GIS) offer methodological potential to overcome these limitations. They allow quantitative description of the relief, erosion process modeling (Otto et al., 2017), and geomorphometric signature analysis that elucidate the evolution of the landscape (Andrades Filho et al., 2017). Its application to studying gullies using morphometric variables (Viero, 2004; Cabral; Nummer; Bateira, 2020) enables the construction of spatialized databases to investigate territorial patterns.

With this situation in mind, this study aims to holistically map and characterize the Tupanciretã Formation's gullies in north-central Rio Grande do Sul. Specifically, it seeks to identify and classify existing gullies types, describing their shapes and dimensions as well as analyzing their spatial distribution relative to the geological and geomorphological factors in the area. Through this, the hope is to improve the regional geological-geomorphological mapping of areas susceptible to erosion as well as to provide technical support for strategies to mitigate and control the gullying process. Ultimately, the desired results could aid soil conservation and prevent environmental impacts associated with erosion in similar sedimentary environments.

2. Materials and Method

2.1 Study area

The study area is located in southern Brazil, in the state of Rio Grande do Sul, in the southern portion of the Paraná Intracratonic Basin. In this north-central region of the state, there are discontinuous and isolated exposures of Tupanciretã Formation sedimentary deposits in contact with the volcanic rocks of the Serra Geral Formation. Menegotto, Sartori, and Maciel Filho (1968) focused their research on the municipality of Tupanciretã, which time they named the geological unit the Tupanciretã Formation.

Gamermann et al. (1970) apud Coulon, Gamermann, and Formoso (1973) later extended the unit’s borders to include other municipalities. The current geological mapping of these deposits is part of the Geological Map of Rio Grande do Sul (CPRM, 2008), drawn on a 1:750,000 scale by a team from the Companhia de Pesquisa de Recursos Minerais (Mineral Resource Research Company, CPRM).

As such, it was necessary to expand the remote mapping area of the unit's gullies, defining a 10 km buffer around the isolated patches (the study area) covering 37 municipalities falling partially or wholly within the buffer, for a total area of 11,477 km². Of these, 22 municipalities mostly cover the already-mapped areas of the Tupanciretã Fm., i.e., the current area of the units on the state geological map (CPRM, 2008), approximately 2,309 km², while the others only partially overlap the defined buffer, as shown in Figure 1.

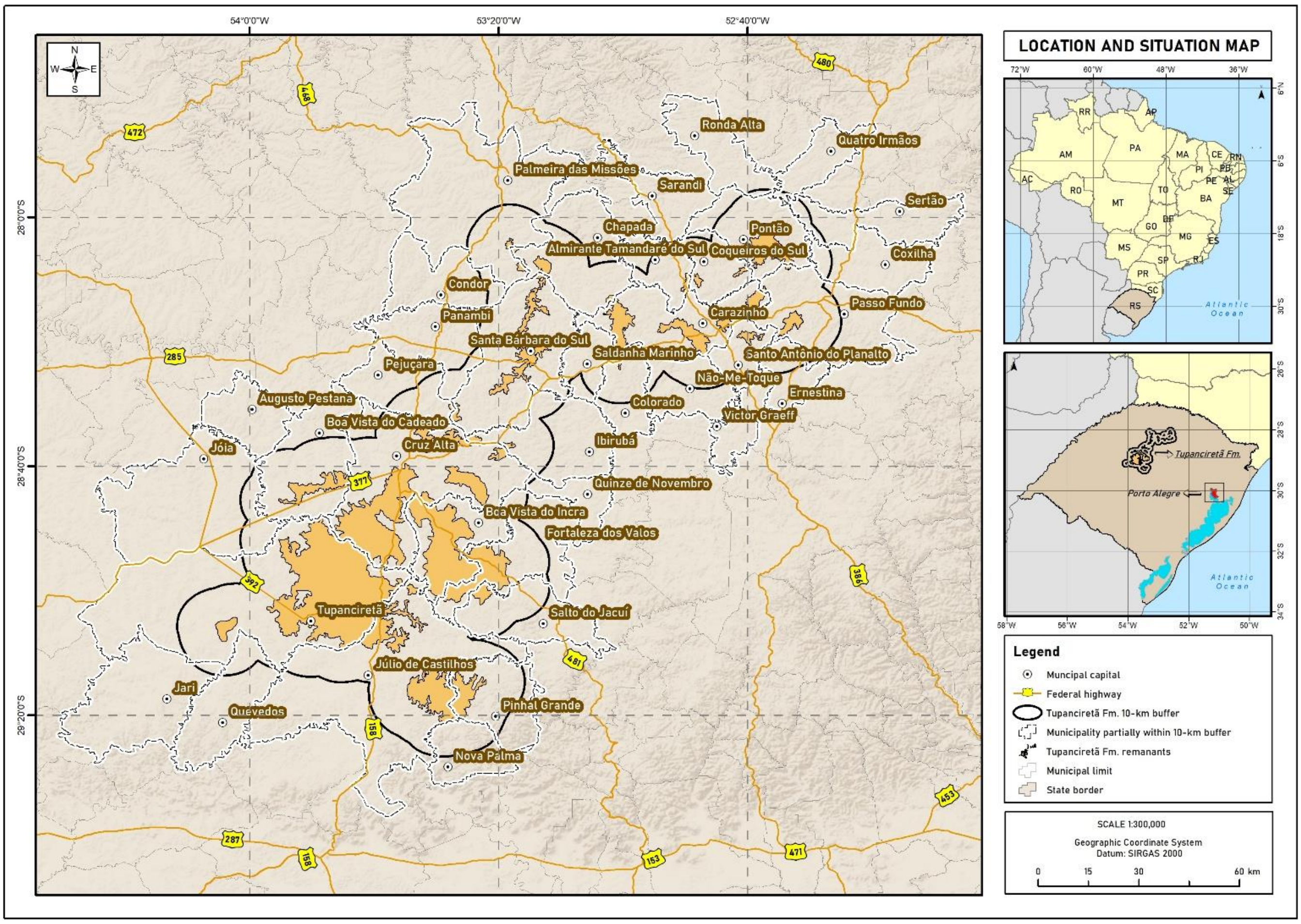


Figure 1. Study area location and disposition.

The Tupanciretã Formation’s sedimentary rocks are located in the southern portion of the Paraná Basin, in north-central Rio Grande do Sul. These rocks are superimposed on the Gondwana III Supersequence (Neojurassic-Eocretaceous) (Milani, 1997), specifically on the volcano-sedimentary package of the basin (Figure 2a), the top of which is represented by the Serra Geral Formation. In this volcanic unit, lavas overflowed the Botucatu Formation eolian sand desert, resulting in a volcanic stack with six distinct facies (Wildner et al., 2004), predominantly basalts.

Ruppel, Dani and Lisboa (2023), upon analyzing the post-Gondwana morphotectonic elements of the Santa Tecla and Tupanciretã Formations in Rio Grande do Sul, attributed the deposition of the second formation to the basin generated by the forced subsidence of Serra Geral Formation basalts, which created space for sediments resulting from the uplift of the crystalline basement in the south of the state, a process related to the breakup of the Gondwana supercontinent. During the Paleogene and Neogene periods, tectonic movements and diagenetic processes helped invert the relief and intensified erosion, evidenced today by gullies in the interfluves.

Riccomini, Sant'Anna and Fambrini (2016) describe the Tupanciretã Formation’s deposits as mainly composed of sandstones, medium-grained to conglomeratic at the base of the surveyed section; fine-grained with plane-parallel stratification and cross-layering in the middle portion; and fine-grained and massive at the top. In addition, in a continental survey, the CPRM (2008) mapped the Tupanciretã Formation (ENtp) in isolated patches atop the Serra Geral Formation's flood basalts, which occupy 2,309 km² or 0.82 % of the state's territory, as shown in Figure 1b.

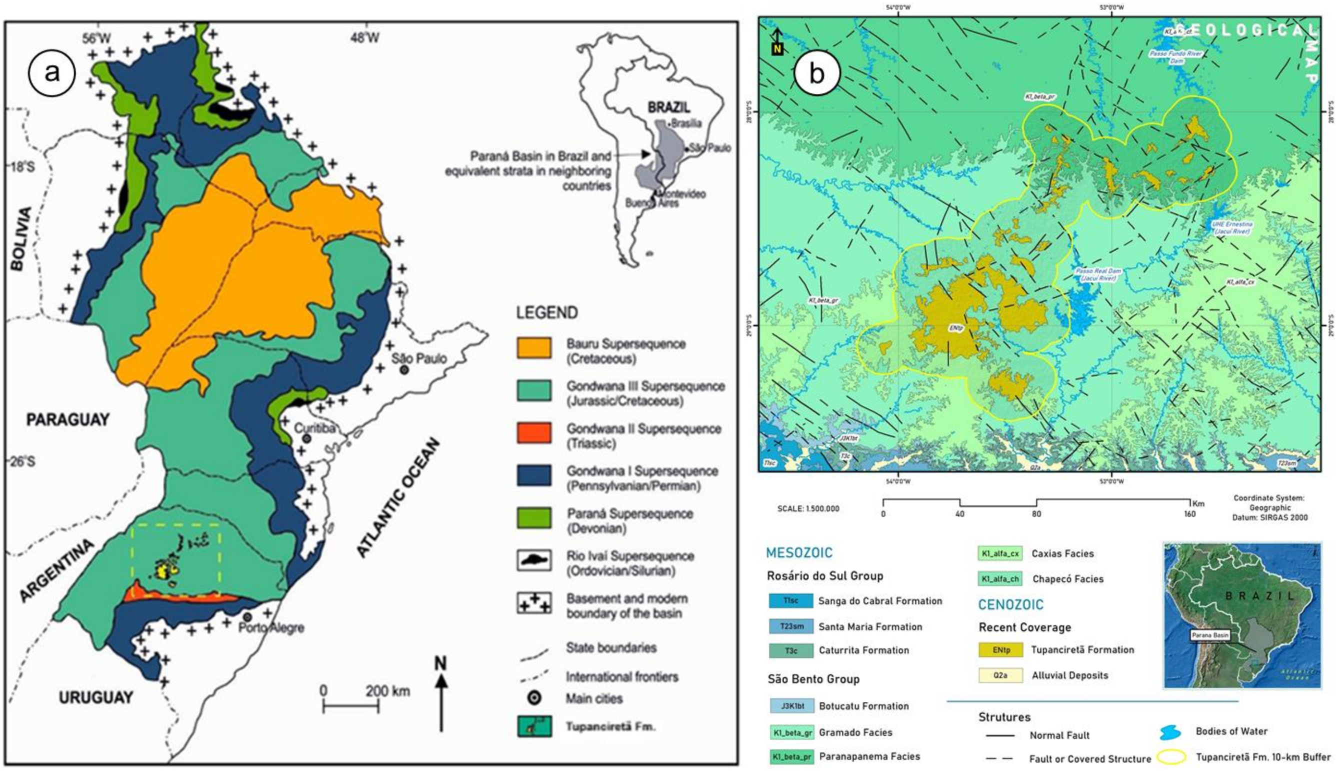


Figure 2. (a) Location of the Paraná Basin within South America and distribution of the Supersequences within Brazil, with areas of overlap with the Tupanciretã Fm. Adapted from Souza et al., (2021); (b) Geological map of the study area. Adapted from CPRM (2008).

The volcanic flows over the Tupanciretã Formation sedimentary package include mafic facies (Paranapanema and Gramado) and acid facies (Caxias), composed of fine- to medium-grain basalts and of rhyodacites to rhyolites, respectively (CPRM, 2008). These flows give rise to soils with a more clayey texture when derived from extrusive igneous rocks and sandier soils when formed from sandstones and similar materials, generally at an advanced stage of laterization, as shown in Figure 3.

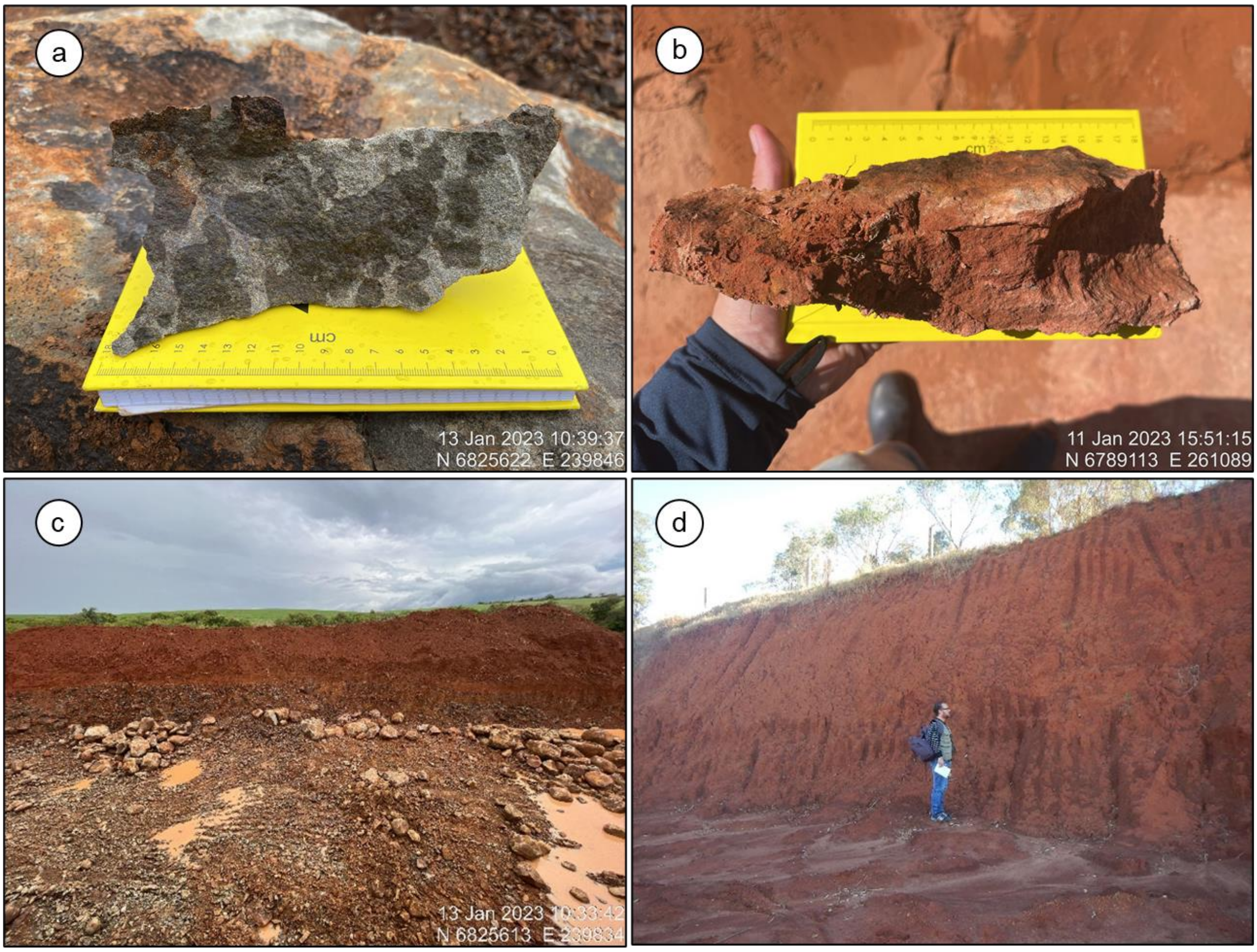


Figure 3. (a) Mesocratic basalt sample; (b) altered sandstone sample with a massive structure; (c) profile of red latosol evolved from transformations of volcanic material, less thick and more clayey; (d) very deep, highly weathered red latosol from the Tupanciretã Fm. sedimentary lithotype.

Red latosols cover most of the study area (IBGE, 2021a) and appear mainly in road cuts, integrating the internal profile of different erosions, and during the preparation of soybean fields, the predominant crop in the region. In the landscape, the tableland that houses the Tupanciretã Formation sedimentary package is located on the Missões Plateau. This relief is homogeneous, consisting of gentle, rounded hills (Figure 4), carved mainly from volcanic rocks of the Serra Geral Formation and, to a lesser extent, from sedimentary rocks of the Tupanciretã Formation.

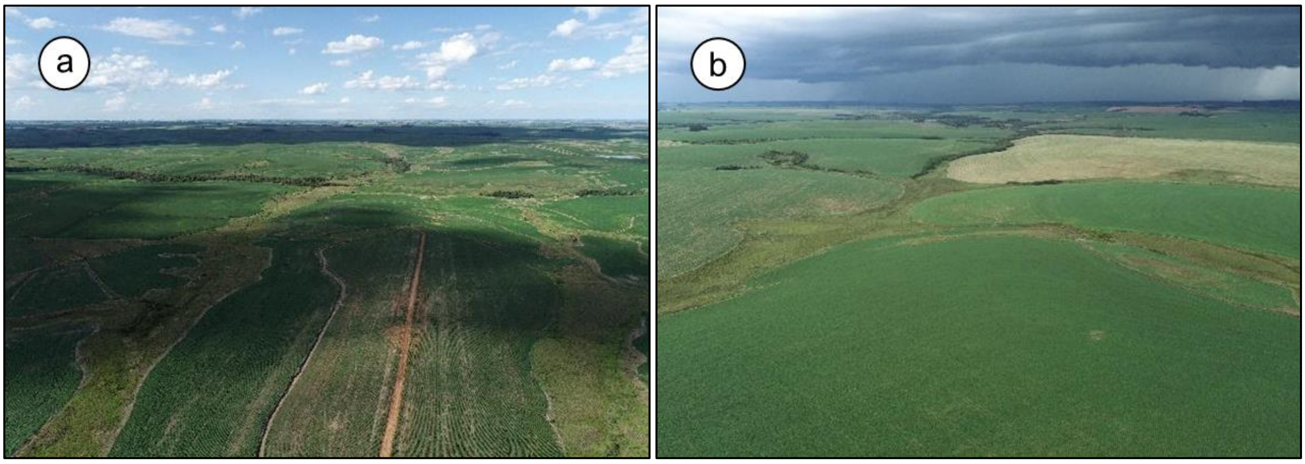


Figure 4. (a) Homogeneous and gentle relief with slightly convex heights; (b) View of the relief featuring gentle hills with well-rounded heights.

2.2 Cartographic database selection

To create the cartographic graphics, state-level digital databases obtained from the library of the Henrique Luís Roessler State Environmental Protection Foundation (FEPAM, 2005) and the Brazilian Continuous Cartographic Database (BCIM) (IBGE, 2021b), both at a scale of 1:250,000, were used. The official geological map, containing the Tupanciretã Formation patches was derived from the latest state-level mapping carried out by the Mineral Resources Research Company (CPRM, 2008) at a scale of 1:750,000. To extract morphometric indices, altimetric data from the Copernicus DEM, with a pixel size of 30 m, available free of charge on the OpenTopography platform, was used. ArcGIS 10.8 was used to generate thematic cartographic products and perform geoprocessing analyses.

2.3 Gully mapping and cataloging

To search the entire study area for erosions whose features are large enough to appear on high-resolution satellite images, a specific methodology was developed to map and catalog the gullies using photo-interpretation of remote sensing images. Two areas were defined for surface mapping. The first covers the Tupanciretã Formation units (CPRM, 2008), including a 10-km buffer around each, since the current mapping was carried out on a smaller scale than that adopted in this study. The second corresponds to the extensions of the units themselves, where most erosion is concentrated, precisely because they have sandy and fragile soils.

To avoid mapping errors, given the territorial extent analyzed and the diversity of information in the aerial images, the area of interest was subdivided into quadrants using the ArcGIS Fishnet tool. This grid facilitates control of previously mapped quadrants and organizes the scanning process (e.g., Carvalho and Castro, 2023; Nunes and Castro, 2023).

The study area was divided into 905 quadrants. Of these, 695 are located in regions adjacent to the Tupanciretã Formation and were 4.33 km × 4.20 km, for a total area of 11,477 km²; the remaining 210 quadrants are located within the units and were 1.28 km × 1.24 km — as these parcels required extra attention in manual mapping to identify erosion points and facilitate the interpretation of orbital images — comprising an area totaling 2,309 km² (Figure 5).

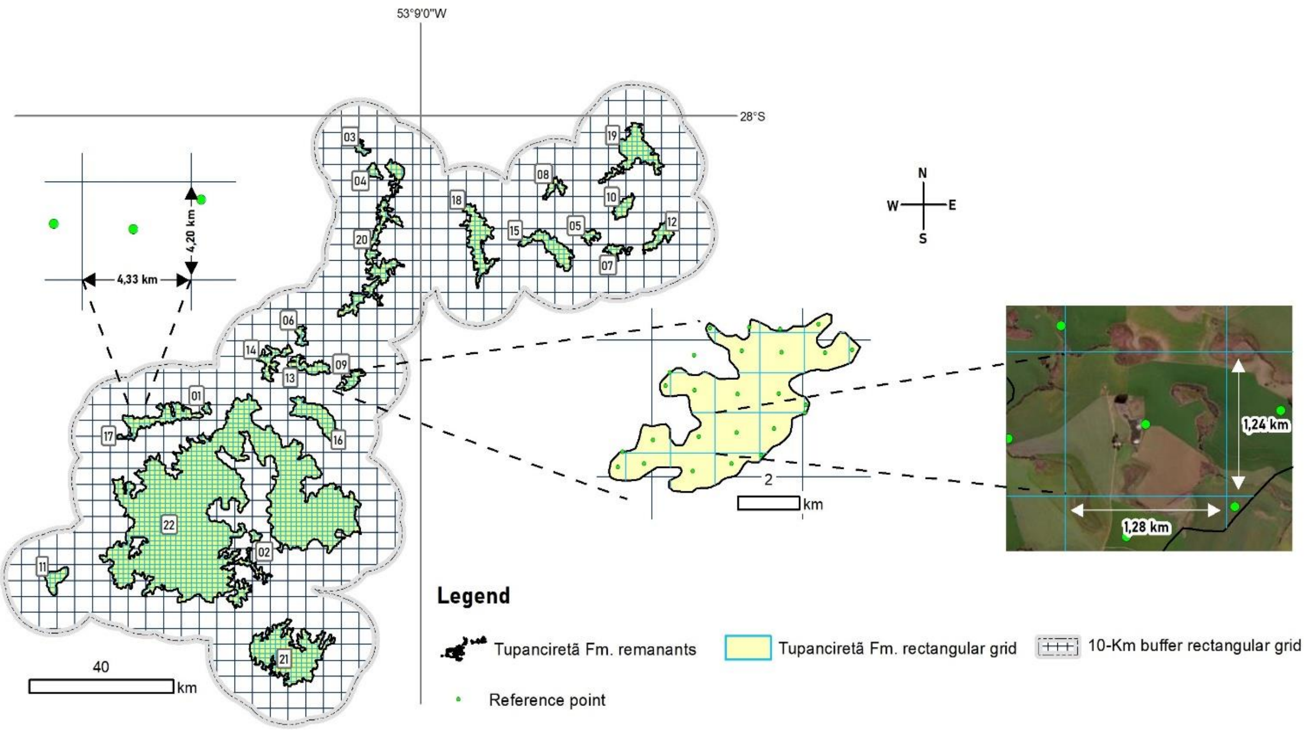


Figure 5. Distribution of quadrants according the mapping detail level.

The rectangular grid and the central points of each polygon were imported into Google Earth Pro, and each cell was assigned a sequential number to manage the mapped quadrants. Remote mapping was carried out manually by visually interpreting the high-resolution images available on Google Earth Pro, which provides a mosaic of orbital photos, mainly from the GeoEye satellite, orthorectified and in composed RGB (red, green, and blue bands).

Earlier studies (e.g., Quevedo; Etchelar; Guasselli, 2017; Castro et al., 2010; Garritano et al., 2018; Marchioro and Oliveira, 2014; Petsch et al., 2022; Carvalho; Castro, 2023) successfully utilized Google Earth to map erosion and other features of interest. Google Earth Pro's historical image feature made it possible to evaluate locations as far back as 2002.

The quadrants were visually scanned from west to east and from south to north, both individually and when covering all of them from south to north within the study area, as shown in Figure 6.

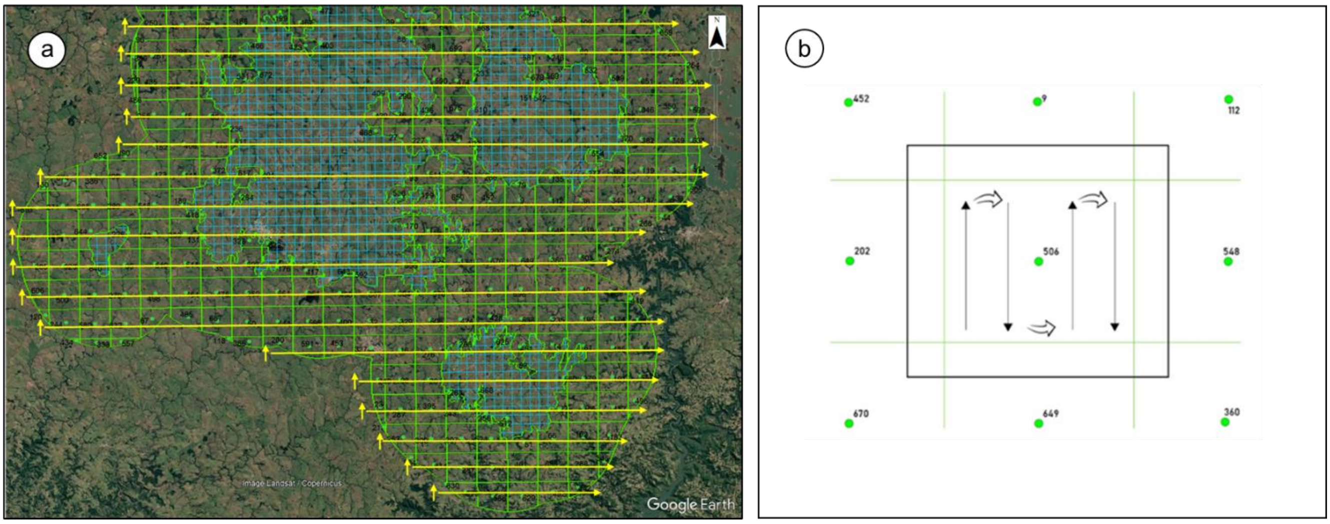


Figure 6. Gully mapping and cataloging. (a) Quadrant subdivision and overall vertical and horizontal mapping direction of mapping; (b) Intra-quadrant mapping direction.

In the mapping phase, all erosion or soil exposure types visible in the satellite images were first identified according to Gianni (2023). In the next stage, after the first field visit and on-site reconnaissance of some of the gullies in the unit, the features classified as gullies were cataloged and delineated. At this point, the thousands of erosion points previously identified were analyzed with the same level of detail.

To differentiate ravines, furrows, anthropogenic excavations, drainage channels, and other erosive features identified as erosion points, the shape, size, and depth (shadow) of the features were used as interpretive criteria. The gullies were delineated manually by visual interpretation, in the form of polygons in Google Earth Pro, and then imported into ArcGIS, and finally converted into vector data for the analysis phase.

2.4 GIS database creation and gully classification

At this stage, the mapped gullies polygons were incorporated into a georeferenced database in ArcGIS (ArcMap). Since the study area covers two UTM zones, the data was reprojected using the Albers Equivalent Projection to extract metrics, and the SIRGAS 2000 geodetic reference system used to present the products and visualizations.

Next, the Feature to Point tool converted each erosion feature into a point, allowing the data to be interpolated using the kernel density estimation (KDE) statistical method. This procedure generated a thematic cartographic product showing the gullies' intensities, assigning warm colors to the highest densities and cool colors to the lowest. The influence radius was calculated automatically by ArcGIS based on Silverman's rule of thumb, a statistical formula that estimates the ideal bandwidth for smoothing density estimates.

The polygons' areas (m^2) and perimeters (m), representing the spatial extent and contour measure of each gully, were obtained directly from the attribute table using the Calculate Geometry tool. The erosion shapes were compared to the eleven typologies proposed by Ireland et al. (1939), Vieira (2008), and Cabral (2018), as shown in Figure 7, in order to understand the origins and morphological changes of the gullies.

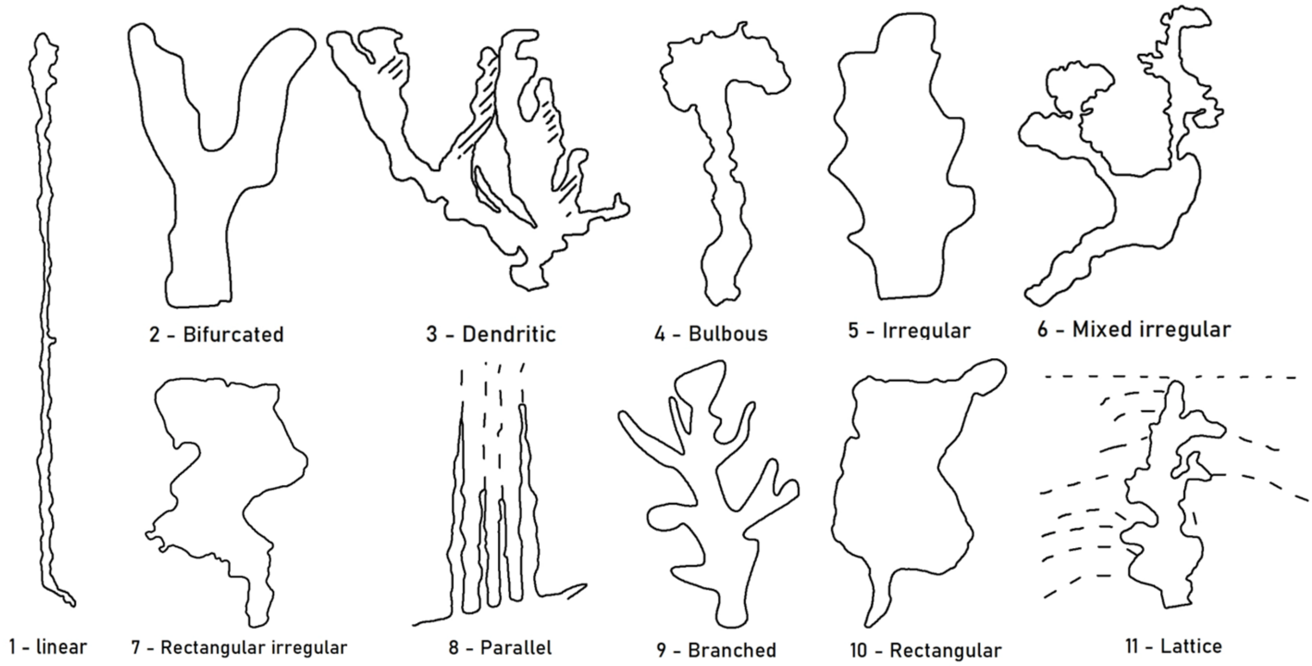


Figure 7. Compilation of the main forms of gullies proposed in some national and international works. Adapted from Ireland et al. (1939), Viera (2008) and Cabral (2018).

When classifying the erosion type, Oliveira's (1989) evolutionary model of linear erosion was used to classify the gullies as being connected to, disconnected from, or integrated with the drainage network. These features were characterized using photo-interpretation of historical images and 3D visualization available on Google Earth Pro. In addition, the incisions were classified according to size and depth (small, medium, or large), according to Fendrich (1997).

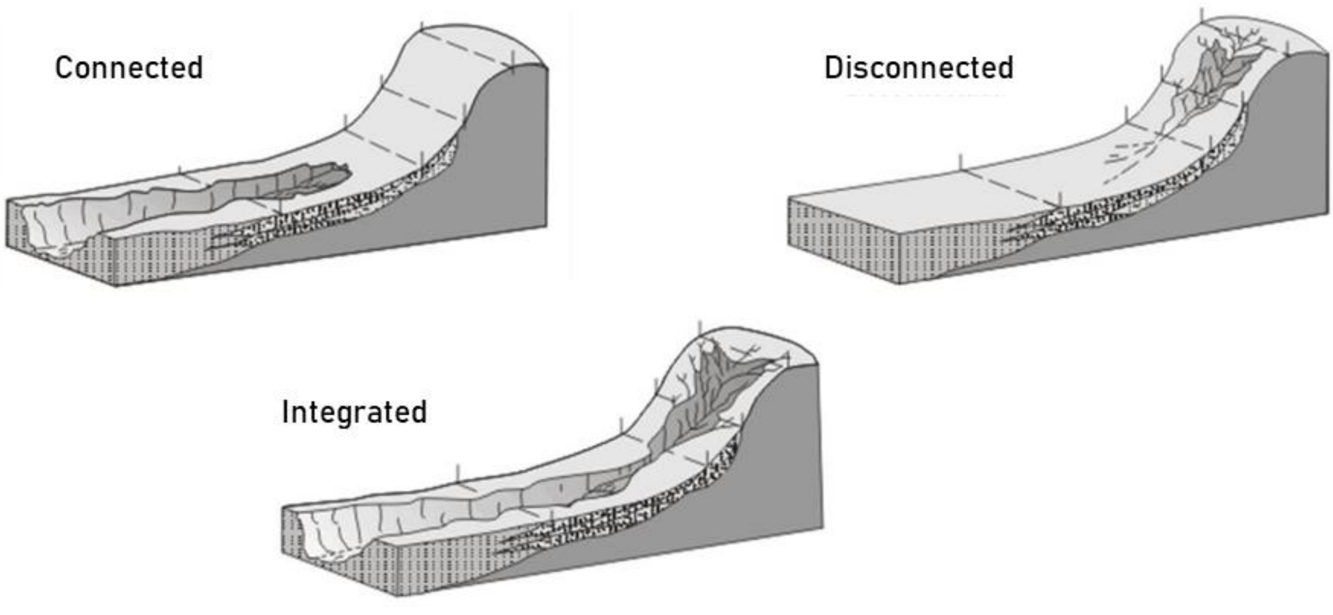


Figure 8. Gully evolution typology. Adapted by Cabral (2018) from Oliveira (1989).

2.5 Geomorphometric and lineament analyses

The geomorphometric analyses utilized the Copernicus Digital Elevation Model (DEM). The variables investigated, related to the landscape's natural aspects, were extracted automatically and semi-automatically, enabling a quantitative approach. These include hypsometry, slope, terrain curvature (horizontal, vertical and combined), slope orientation, and lineament analysis.

To optimize the computational procedures and avoid information loss at the gully edges, the following procedure was carried out: i) convert the matrix and vector data from the SIRGAS 2000 geodetic reference system to the Albers Equivalent Projection to conserve the erosion areas; ii) apply conservative clipping with a 60 m buffer around the gullies to reduce the volume of data; iii) process the clipped matrix data using equations available in ArcMap; iv) reclassify the matrix data into pixel classes; v) convert the matrix data into vector format; vi) clip the vector data to cover only the polygonal features of the gullies; and vii) extract areas and occurrence percentages.

To assess the individual altitude of each erosion — considering upstream and downstream points and the altimetric range — the Zonal Statistics as Table tool was used to determine the maximum and minimum values for each gully. The slopes (%) were obtained using the Slope tool and classified according to Embrapa (1997) into six taxa: flat (0-3 %), gently undulating (3-8 %), undulating (8-20 %), strongly undulating (20-45 %), mountainous (45-75 %), and steep (> 75 %).

As for terrain shape, vertical and horizontal curvature parameters were generated using the Curvature tool from the DEM. For vertical curvature, three types were assigned: convex slopes (values ≤ –0.010), rectilinear curvatures (–0.010 to 0.010), and concave slopes (≥ 0.010), following Valeriano (2008). An analogous procedure was adopted for horizontal curvature, defining convergent slopes (≤ -0.010), planar curvatures (–0.010 to 0.010) and divergent slopes (≥ 0.010). It should be noted that exact values of 0.00 were not taken into account, as they rarely occur in nature and are generally restricted to large bodies of water.

After processing the curvature data, the two matrix files were combined with the Combine tool, integrating them into nine slope curvature classes: convex-convergent, convex-planar, convex-divergent, concave-convergent, concave-planar, concave-divergent, rectilinear-convergent, rectilinear-divergent, and rectilinear-planar.

The slope orientation was determined using the Aspect tool, which assigned exposure classes ranging from 0° to 360° in ten intervals. To assess the lineaments' influence, the features were first manually inspected, and the preferred direction of erosion (upstream–downstream) was assigned using abbreviations for the cardinal points. This data enabled comparison of the predominant orientations with structural behavior studies of the Tupanciretã and Serra Geral formations.

3. Results and Discussion

3.1 Gully cataloging, analysis, and characterization

3.1.1. Gully cataloging and analysis

Within the defined mapping quadrants — within each formation and up to 10 km from its current contours— 303 gullies were identified inside the Tupanciretã Formation and 48 outside it. These 351 gullies comprised 413 ha of degraded area, corresponding to 0.19 % of the sedimentary unit's area.

The study area's erosion mapping allowed creation of Figure 9's products. In addition to plotting the points of each gully, KDE was used within the external and internal areas of the Tupanciretã Formation patches. From this, five classes of gully occurrence density were defined (very low, low, medium, high, and very high) in each section, highlighting the areas with the greatest concentration of this type of erosion.

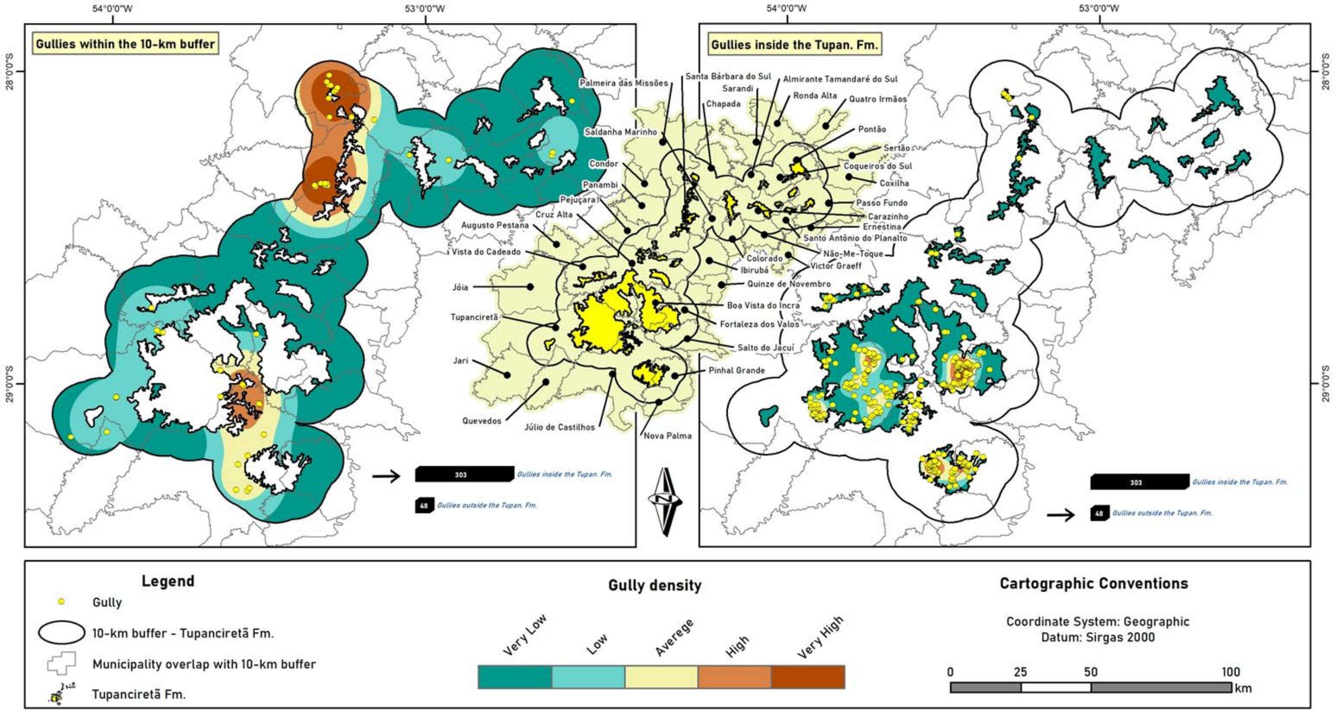


Figure 9. Spatialization of gullies over municipalities and density classes of occurrence. Source: authors.

The above figure shows that the gullies mapped within the 10-km buffer, and hence outside the lithological contours of the sedimentary formation, include points both near and far from the units. Gullies more than seven kilometers from the contours are noteworthy, as they indicate discrepancies in the current CPRM (2008) mapping.

The gullies recorded in the inner portion of the Tupanciretã Formation's contours had linear erosion epicenters concentrated in the south-central patches, with a large number occurring in the municipality of Tupanciretã, which has 114 large erosion foci. A total of 73 gullies were cataloged in Júlio de Castilhos, followed by smaller numbers (in no particular order) in the municipalities of Pinhal Grande, Fortaleza dos Valos, Boa Vista do Incra, and Boa Vista do Cadeado, among others.

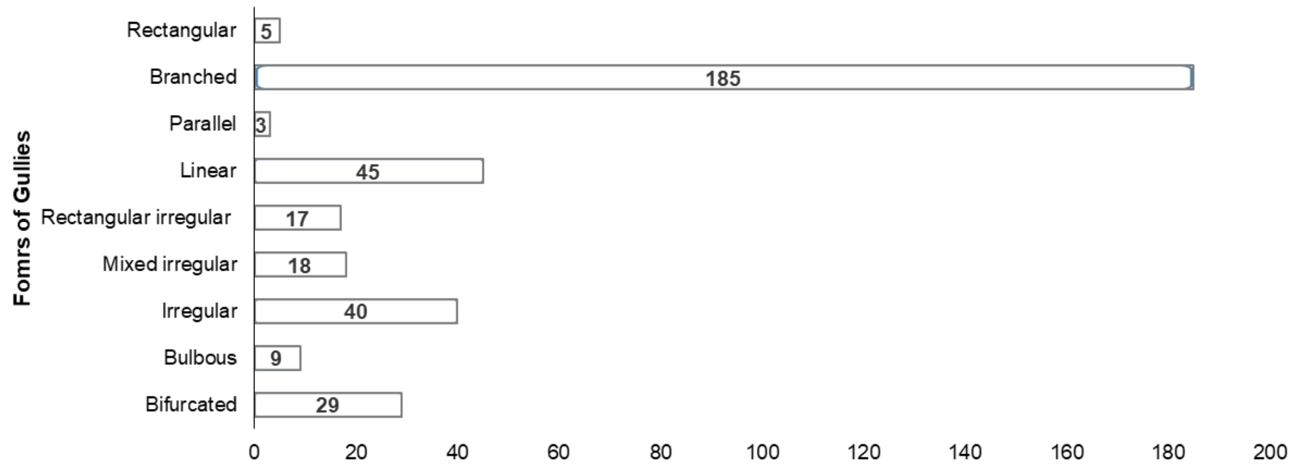
Overall, the mapping showed gullies occur predominantly in rural areas used for agricultural production, where the vegetation cover has been removed and converted. A significant portion of these erosion incisions are close to roads, situated on or near water dividers, in accordance with the position of the Tupanciretã Formation sedimentary package at the top of the relief. In this region, surface runoff is heightened due to the relationship between the altimetry and the length of the slopes.

3.1.2 Characterizing gully type and form

3.1.2.1 Erosive forms

The mapping and cataloging of gullies revealed a multiplicity of incisions having distinct shapes influenced by the relief, the dynamics of surface and groundwater, and possible structural controls. These shapes reflect the evolution of erosion processes over time, changing as the processes become more recurrent or intense.

Based on Ireland et al. (1939), Vieira (2008), and Cabral (2018), the gullies were classified into nine types: bifurcated (n = 29), bulbiform (n = 9), irregular (n = 40), mixed irregular (n = 18), rectangular irregular (n = 17), linear (n = 45), parallel (n = 3), branched (n = 185), and rectangular (n = 5), as illustrated in Figure 10.



	Bifurcated	Bulbous	Irregular	Mixed irregular	Rectangular irregular	Linear	Parallel	Branched	Rectangular
No. Of Gullies	29	9	40	18	17	45	3	185	5

No. of Gullies

Figure 10. Gullies and their form classification.

In the Tupanciretã Formation, the most common gully form is branched, with 185 occurrences, corresponding to more than 50 % of the total. This type is associated with retrogression, in which erosion advances opposite the water flow direction — that is, from downstream (lower part) toward upstream (upper part) — hence, toward the convergence of concentrated flows that feed the main channel from multiple directions. This gives rise to irregular secondary branches, with spacing that varies from close to far. Their depth tends to vary, although many branches occur in low-amplitude hilly relief and can develop near the headwaters or on the sides of the incision.

Elongated and narrow, linear gullies account for 13 % of the total. They result from a single concentrated surface flow and typically have a small area, a low volume of removed soil, and lack depth and width. This form generally corresponds to the initial gullying phase, occurs carved into the interfluves' thalwegs, and can evolve into other types.

The irregular, mixed irregular, and rectangular irregular patterns account for 11 %, 5 %, and 4 % of the 351 gullies, respectively. Irregular gullies have a more open center and variable surface flows at the edges, with relatively short and sparsely spaced arms. In the mixed irregular ones, there are open areas along some stretches and different shapes in others, for a varied layout. The rectangular irregular shape shows a basically rectangular plan with sinuous edges. These patterns indicate a more advanced evolutionary stage, with a wide bottom that favors the establishment of vegetation within.

Five gullies (1.40%) were classified as rectangular. These typically older erosions have deep profiles, flat bottoms and homogeneous walls. Being somewhat rectilinear, they are more symmetric than the purely irregular shape.

In the bulbiform pattern (n = 9), the headwaters widen into a bulb or oval shape, while the channel downstream narrows, resulting in an onion-like shape. This widening of the upper portion may be due to the confluence of several branches that continue to erode until they consolidate into this shape.

The bifurcated form occurred in 29 gullies and is characterized by two concentrated flows in the upstream region that converge to form more intense erosion in the main channel. This configuration is associated with concentrated surface flows from roads or hill contour lines, which widen the channels in both directions in the upstream sections.

Parallel gullies, the least frequent (n = 3), exhibit branches or channels running very close to each other and sharing the same erosion flank, which suggests structural control or anthropogenic interference — such as artificial channels built following contour lines flowing into transverse collector channels.

Classifying erosion forms influenced by natural and man-made factors involves knowledge and common sense, as some can fall into multiple categories. In this study, we adopted the patterns shown in Figure 11, which illustrates each shape identified.

Figure 11. Examples of each gully form in the present study.

3.1.2.2 Gullies and drainage networks

The clusters of gullies mapped tend to be located near water dividers, where the relief is generally homogeneous, ranging from flat to undulating. In this sort of position, a drainage network is born, which increases the speed of surface runoff and abets water erosion, especially in the absence of adequate vegetation cover.

In terms of its position on the slopes, the typology of each gully classifies it as a first-order channel according to Oliveira (1989), who groups gullies into connected to, disconnected from, or integrated with the drainage network. For a connected gully, erosion has a subsurface contribution and forms a first-order channel, usually in the valley or at the base of the slope. If erosion occurs at the top of the slope and depends only on surface runoff, it is characterized as an unconnected gully, with no direct link to the drainage network. When these two types come together at an intermediate point on the slope, it is considered an integrated gully, usually indicating an advanced stage of evolution (Oliveira, 1989).

Based on this classification and the analysis of all the mapped gullies, 274 units (78 %) were recorded as connected to, 39 units (11 %) as disconnected from, and 38 units (10 %) as integrated into the drainage network (Figure 12). These figures show that most gullies contribute directly to water body siltation and accelerate the large-scale removal of the Tupanciretã Formation's sediments.

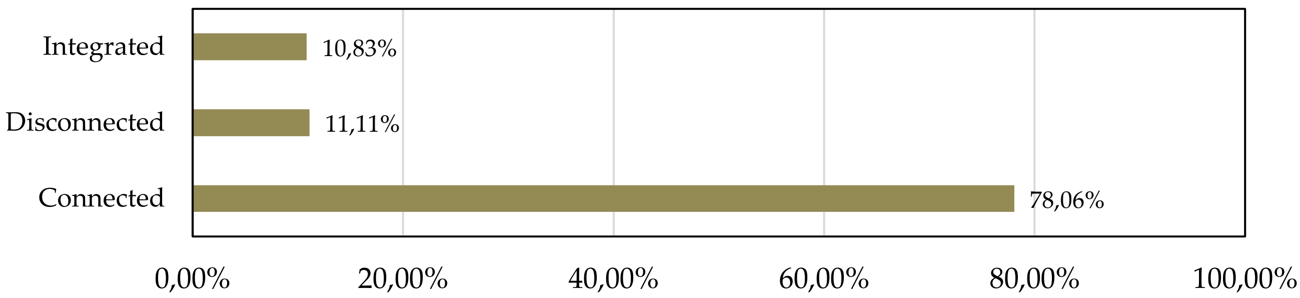


Figure 12. Distribution of gullies by typology.

After classifying the gullies by shape in the previous section, this information was cross-referenced with the typology (Table 1) and patterns were identified directly reflecting the evolutionary stage of the features. These patterns allow predicting the upstream progression of erosion.

Table 1. Number of gullies by type and shape.

Shapes \ Types	Connected	Disconnected	Integrated
Bifurcated	25	3	1
Bulbiform	2	2	5
Irregular	33	5	2
Mixed irregular	13	0	5
Rectangular irregular	9	6	2
Linear	31	12	2
Parallel	1	2	0
Branched	160	4	21
Rectangular	0	5	0

When erosion incisions go deeper into the sedimentary substrate, they can reach the water table and become first-order drainage channels, with no tributaries and integrated into the main network. In the region, the erosion forms exemplifying this behavior are branched (*n* = 160), bifurcated (*n* = 25), irregular (*n* = 33), and linear (*n* = 31). In the case of branched gullies, most of which are connected to the drainage network, depth and width have greater influence: intermittent and ephemeral channels deepen and widen erosion, and their branches promote erosion in depressed areas flanked by hills, without significantly advancing over the slopes, as illustrated in Figure 13.

Figure 13. Examples of branched gullies connected to the drainage network. Adapted from Google Earth Pro (2024).

Gullies disconnected from the drainage network are generally in the initial stage of the erosion process, when surface runoff or mass movements have started the incision, resulting in temporary channels. Except for the mixed irregular form, all the typologies included some disconnected gullies, particularly the linear (n = 12). Linearity is the usual initial gully configuration where it deepens and widens, coming to be preferentially fed by surface flow.

In addition to lacking a connection to the drainage network, these gullies are situated midway up or at the top of the slope. In some cases, eroded sediment beds formed by intense rainfall can be seen at the base of the slope (downstream), as illustrated in Figure 14.

Figure 14. Examples of gullies disconnected from the drainage network, with a circle indicating a fan of sediment transported by runoff action. Adapted from Google Earth Pro (2024).

The integrated type occurs when an erosion incision connected to the drainage network advances upstream and meets, at an intermediate point on the slope, another, previously unconnected incision to form a single feature from slope top to base. The small number in this category (n = 38) may reflect the need for relief with higher altitudes and steep slopes, as well as indicating older erosional features in the final stages of evolution. Figure 15 shows that the main channel is located in a depressed area of the terrain, while the upstream branches reach the middle third of the hill slope, near the side roads, which are often located on the water dividers.

Figure 15. Examples of gullied integrated with the drainage network. Adapted from Google Earth Pro (2024).

3.1.2.3 Erosion size

Another way of classifying gullies is by size, adopting parameters such as channel depth, erosion incision area, and eroded volume. Except for the area, determining depth and volume requires greater precision and accuracy than that available in remote sensing databases.

When measuring the dimensions of the polygons, a significant variation was observed: the areas of the gullies range from 322.02 m² (0.032 ha) to 94,901.31 m² (9.49 ha). According to Frendrich et al. (1991), this corresponds to small (< 2 ha) to medium (2 to 20 ha) area gullies. As can be seen, the number of gullies decreases as the size increases, as illustrated in Figure 16.

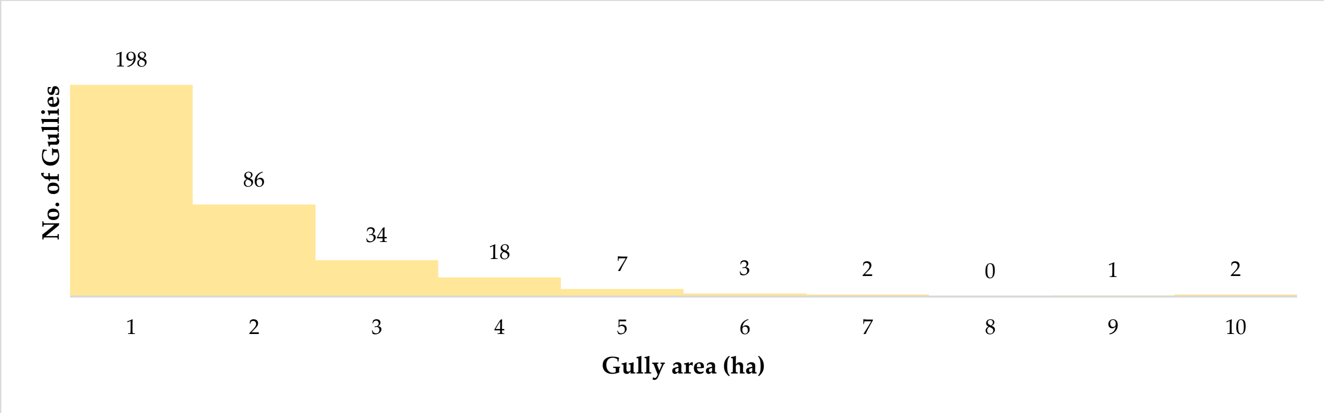


Figure 16. Gully frequency versus area.

3.2 Gully geomorphometric characterization and analysis

3.2.1 Hypsometry

The hypsometry cartographic product was created using the altimetry data from the DEM (Figure 17). It uses a color scheme ranging from cool (low altitude) to warm (high altitude) to represent the study area's pixel altimetry classes, with the mapped gullies overlapping. In the area analyzed, the elevations vary from 103 to 712 m. The topography is higher in the north, northeast, and southwest regions, while lower altitudes prevail in the west, east, and south, with the central area comprising most of the intermediate altitudes.

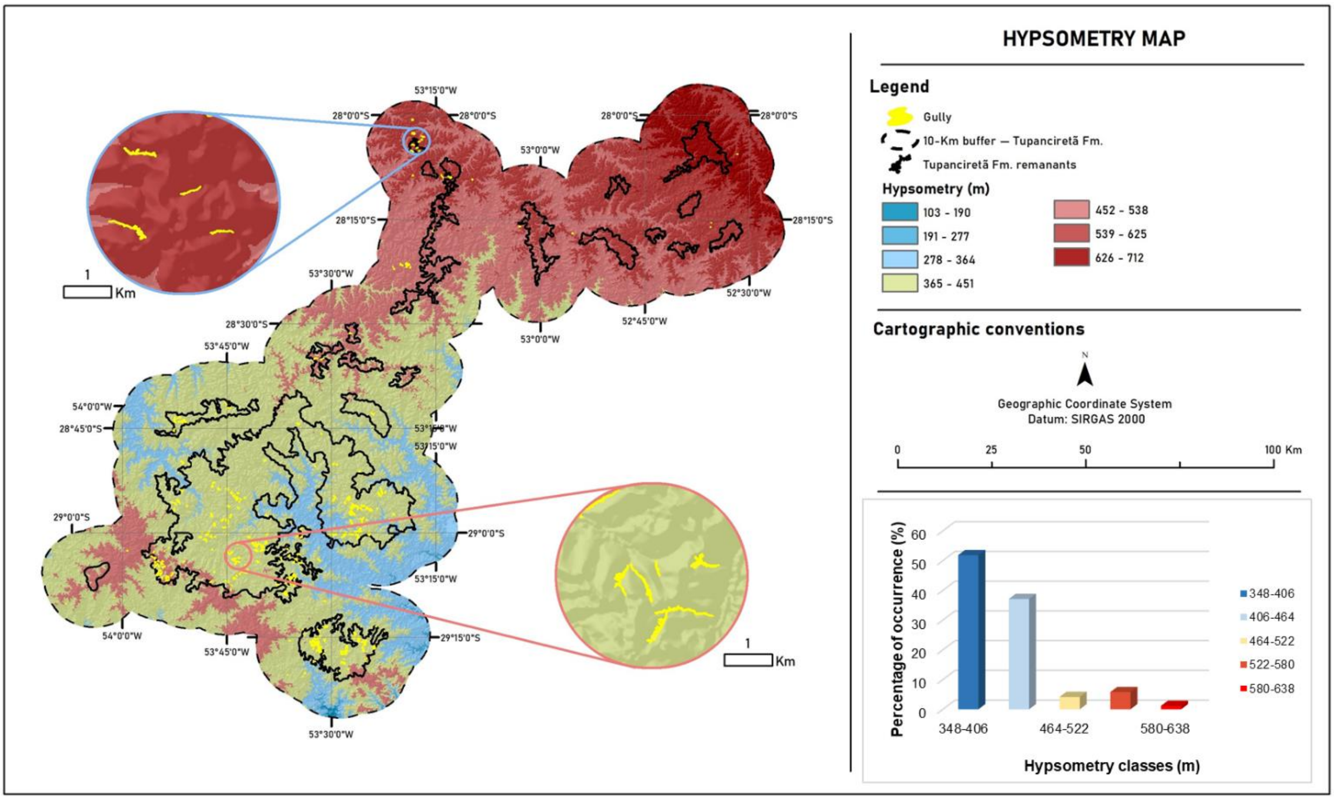


Figure 17. Study area hypsometry with overlapping erosion areas.

Altitudes of 348 to 406 m are home to 51.81 % of the mapped gullies, followed by the 406 to 464 m range, with 37 %. Erosion was less frequent between 464 and 533 m (4.14 %) and between 522 and 580 m (5.77 %). At the highest altitudes, 580 to 638 m, the incidence of gullies is lowest, at only 1.14 %.

An analysis of the erosion incisions specifically shows that the highest headwaters point is 638 m, while the lowest mouth is at 348 m. Thus, the Tupanciretã Formation gullies occur between 348 and 638 m, resulting in an overall altimetric range of 290 m and an average of 18 m in the units analyzed.

3.2.2 Slope

Each DEM cell in the study area's geospatial analysis had its slope analyzed and expressed as a percentage (EMBRAPA, 1997). The slope classes present within each gully were investigated, allowing identification of the slope patterns most associated with these features' development. Although the results only refer to the internal portion — and not the upstream segments — they reflect the general disposition of the surface, as the edges often fell withing a pixel, resulting in a tendency to underestimate the real slopes within the erosion.

Large-scale erosion is predominantly concentrated in gently undulating terrain, 59 % of which lies in areas of this terrain type, but it is also found on flat (17.45 %) and undulating (20 %) terrain. To a lesser extent, there were erosion branches on strongly undulating terrain (2.85 %) but almost none on mountainous terrain (0.06 %) (Figure 18).

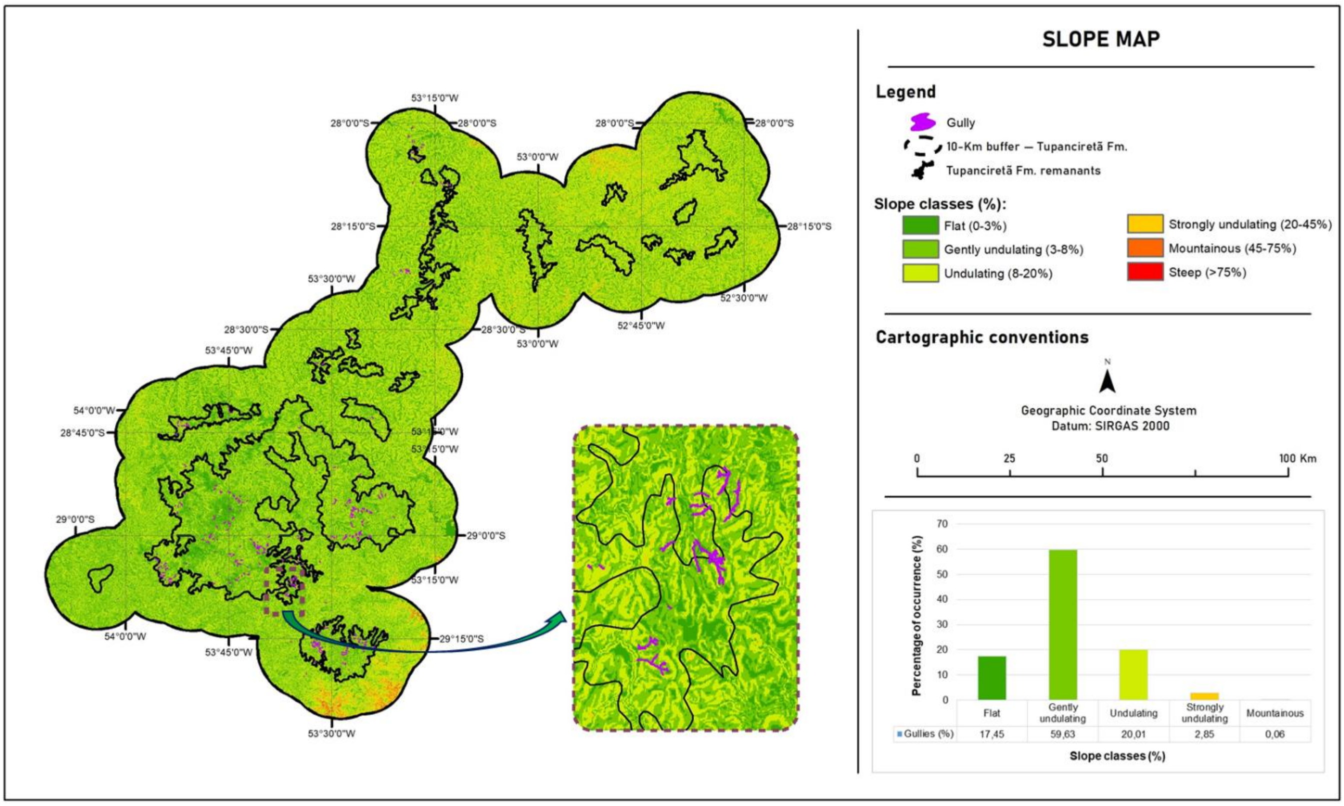


Figure 18. Slope with the overlapping Tupanciretã Fm. units and their respective gullies.

There are countless gullies with similar patterns of development across the land. Most of them are flat near the mouth (valley bottom) and woven into gently undulating areas upstream. In some cases, especially when the feature is integrated with or disconnected from the drainage network, there are steeper slopes near the headwaters, in undulating or strongly undulating relief.

Note that although 78 % of the gullies are connected to the drainage network and smooth surfaces predominate, the slope does not have to be high for erosion to begin and evolve. This is because, in addition to the length of the slope and the nature of the material (poorly cohesive, friable, and sandy), intense agricultural activity and improper land use amplify erosion features. Thus, the magnitude of erosion is not directly related to the intensity of surface runoff, but primarily to the nature of the substrate.

3.2.3 Terrain Forms (Profile and Slope Curvature Plan)

Slopes establish the connection between the water dividers (tops) and the river channels and/or valleys (bottoms). They are closely linked to the rainwater runoff regime and the behavior of the slope imposed on the surface. Depending on the terrain curvature, the flow may converge or diverge, favoring or disfavoring, respectively, water erosion processes.

The slope morphology, in particular the gradient, can accelerate or decelerate the surface flow coming from upstream. The curvatures imposed on the profile defines the runoff direction and shape (laminar or concentrated), which directly influences the occurrence of erosion.

3.2.3.1 Vertical Curvatures

Profile or vertical curvature represents flow that always runs parallel to the direction of maximum slope, which primarily affects flow velocity, either slowing or speeding it. To evaluate these geometric surfaces, slopes were classified into three categories: convex (increasing slope downstream), rectilinear (constant slope), and concave (greater slope upstream). Based on Figure 19, it can be seen that convex surfaces (red colors), located mainly high on the slope, dominate the regional relief; mid-slope, they often migrate to a rectilinear pattern (green colors); and, finally, they transition to concave curvatures (cream colors).

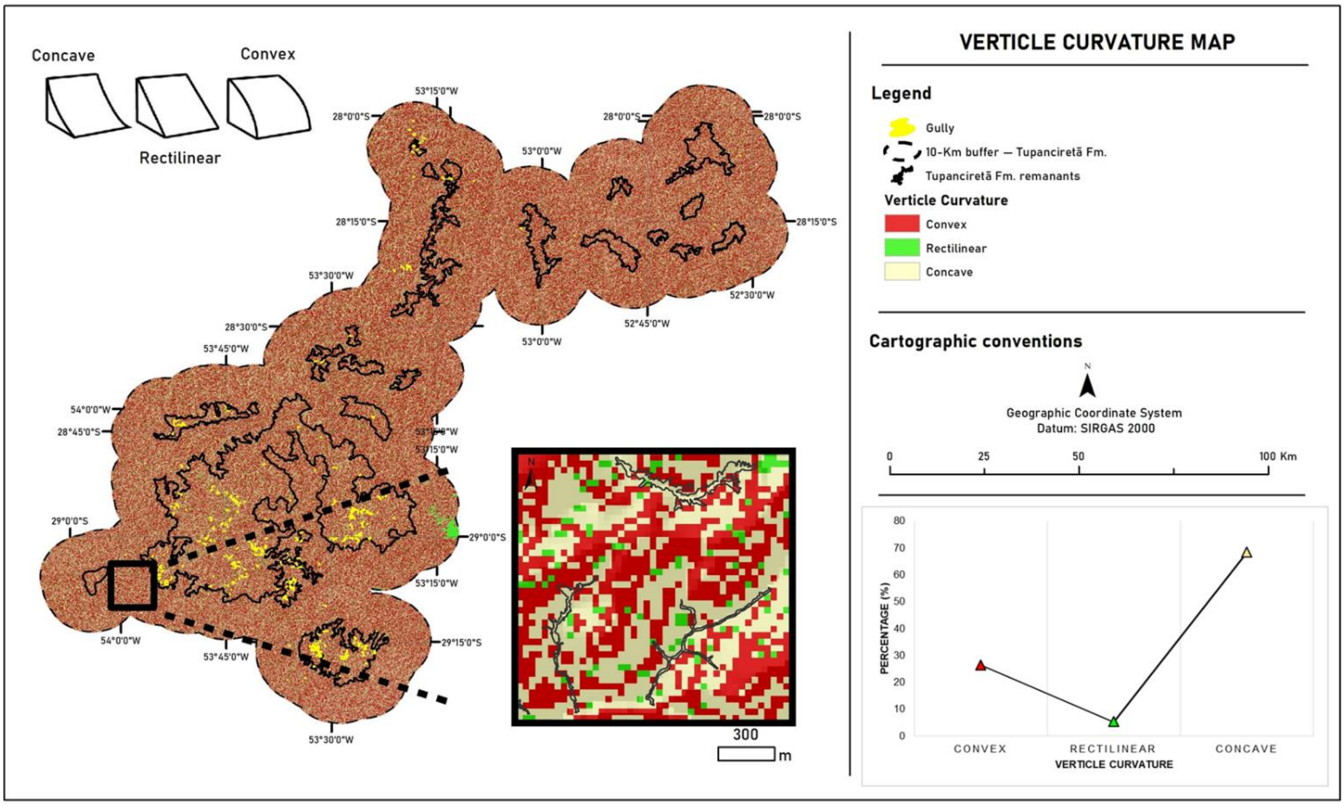


Figure 19. Study area vertical curvature with a graphical slope representation and table showing the number of gullies.

Most of the gullies are in concave vertical curves (68 %), a shape that lends itself to interior water accumulation, concentrated flow with greater erosive force, and gravitational discharge. This is followed by gullies in convex curvatures (26 %), where rainwater flow dissipates (diffuse flow), and, lastly, rectilinear curvatures (5 %), which hinder infiltration and accelerate runoff.

3.2.3.2 Horizontal Curvatures

Another way of identifying slope flow patterns is through horizontal curvatures, also known as planes, which are based on the horizontal plane of the slope, which corresponds to the divergent or convergent dynamics of the slope surface's flow lines. Three taxa encompassed the roles convergent, planar, and divergent curvatures play in both the relief and the gullies.

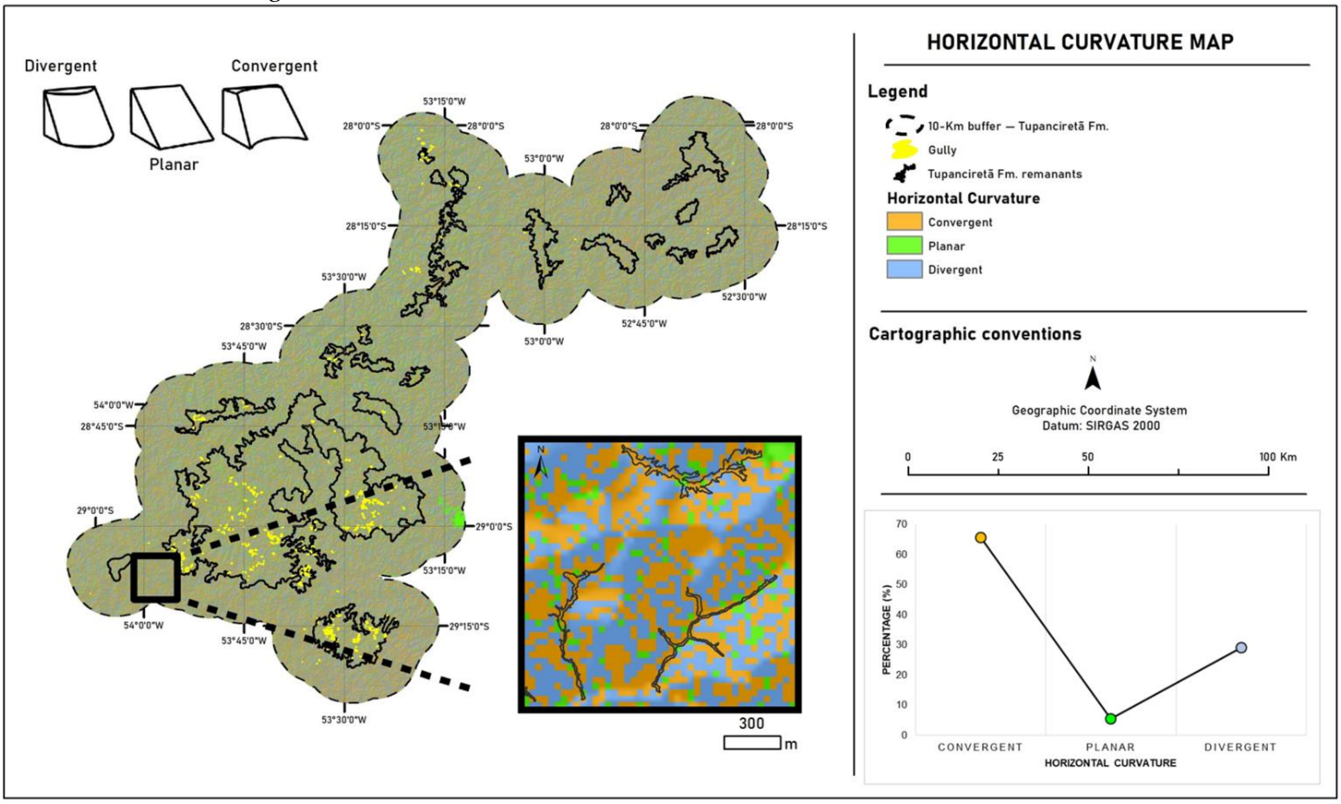


Figure 20. Horizontal curvature in the study area with a graphic representation of the slopes and table showing the number of gullies.

Upon analyzing gullying processes vis-á-vis horizontal curvatures, it was notes that 65 % are situated in the convergent areas, followed by divergent (29 %) and planar (5 %). The predominance of gullies in convergent curvatures occurs because the flow on the face of the slope follows directions of greater gradient towards the center, concentrating flows and increasing susceptibility to linear erosion. In contrast, the flow in divergent curvatures moves towards the edges of the profile, dissipating and reducing the erosive potential. The planar shape represents an intermediate condition, in which the surface shows neither lateral convergence nor divergence, maintaining the flow along the entire slope.

3.2.3.3 Joint terrain forms

On slopes, different segments and curvatures determine different surface shapes. These shapes influence the dynamics and functioning of morphogenetic processes on the slope, including mass movements and water erosion. Another approach to representing slope curvatures consists of combining vertical and horizontal flow classes, resulting in nine categories of slope curvatures (Figure 21).

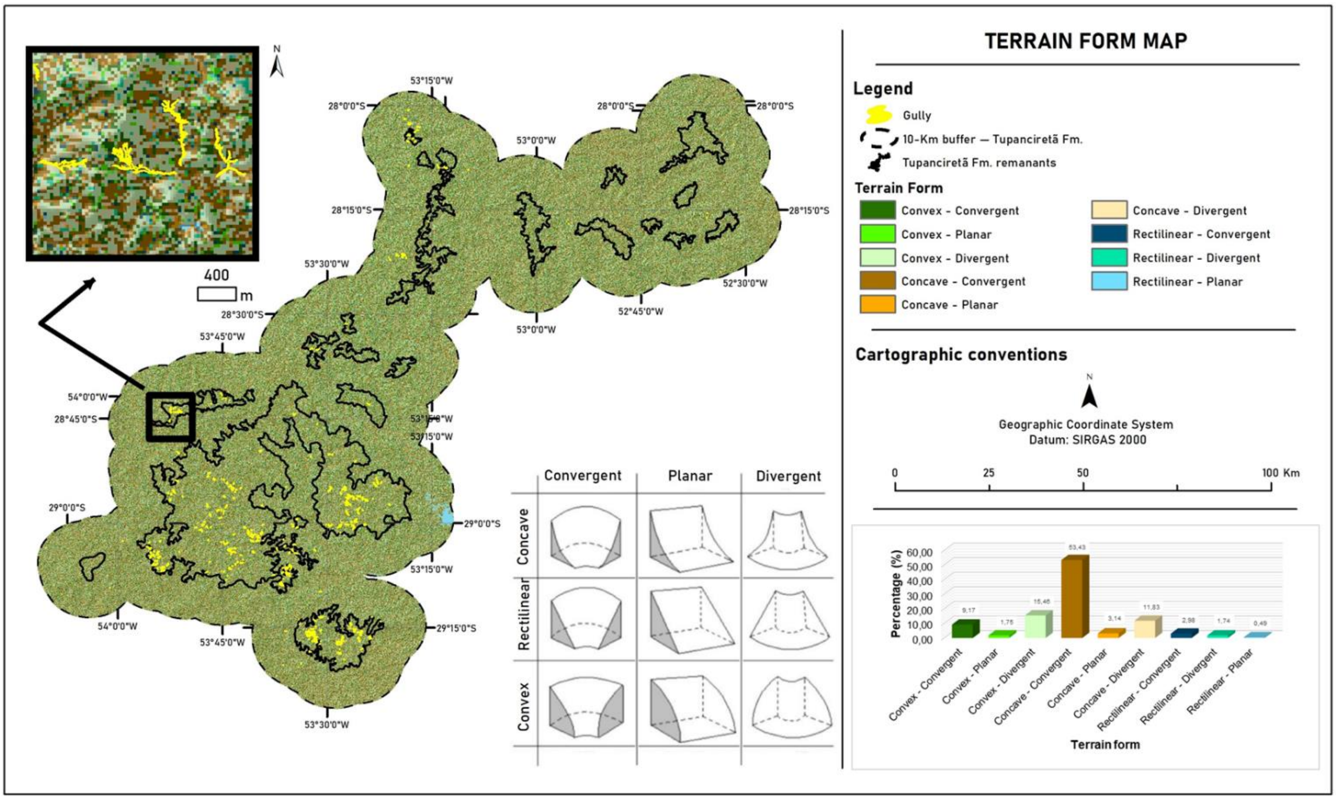


Figure 21. Terrain forms illustrating vertical and horizontal slope curvatures. Representation of forms by Valeriano (2008), adapted from Dikau (1990).

Curvature class integration foregrounds hydrological scenarios that intensify water erosion, while at the same time revealing opposing combinations of flow on the slopes, making it easier to interpret the slope morphology in terms of the appearance or continuity of erosive incisions. The relationship between gullies and terrain form — the result of the combined vertical and horizontal curvatures of the slope profile — is represented in the graph above, which shows the percentages of gully areas in the nine classes resulting from the combination.

The concave-convergent class stands out as the most common among the Tupanciretã Formation's gullies, comprising 53 % of its area. In this configuration, the flow tends to be channeled into a single vector, favoring concentrated runoff and accelerating the erosion process. At the same time, divergent-convex slopes (15%) are important in the process, as they promote flow dispersion, albeit on a smaller scale.

The concave-divergent class, with 11 % of gullies, represents flow that is concentrated towards the center, laterally dispersed at the same time, which can generate multiple channels (branches) on the slope. In 9 % of the gully area, the convex-convergent class slows the flow; however, due to lateral convergence, it can intensify gullying, albeit with less vigorous processes.

The remaining classes — which account for around 10% of the area — reflect planar and rectilinear curvatures combined with the other configurations. Although their participation is smaller, these classes contribute to the evolution of erosive features as well, because they have all been intercepted by large gullies throughout the study area.

In general, the area's slopes have different segments: concave curvatures in the lower third (with lower slope towards the base), rectilinear patterns in the middle portion, and convex curvatures at the top (with an increase in slope downstream). This configuration, combined with the presence of convergent and flat plans, increases the chances of laminar erosion and, more quickly, of erosion by concentrated surface flows, thereby developing furrows, ravines, and gullies.

3.3.3 Lineament analysis

To analyze the possible influence of geology (lithology and structures) on the genesis and evolution of gullies in the Tupanciretã Formation, the main gully erosion (ephemeral, intermittent, or perennial) directions were characterized and this data was compared with morphostructural lineament analyses carried out by other researchers in the same geological formation and study region. In a post-Serra Geral Formation context, the Tupanciretã Formation's sedimentary origin implies a predominance of quartz sediments with low cementation, resulting in sandstones that are by and large poorly consolidated and friable, and hence easily erodible and moldable.

Surface runoff in this type of soil is aggressive, contributing to the formation of numerous linear erosions resulting from poor rainwater management in agricultural areas. Thus, it is characterized as an anthropogenic phenomenon. However, whether naturally or as a result of human interference in land use and cover, the onset of gullies in the region may also be associated with tectonic influence.

Each unit was manually assigned the main direction of the gully on the central axis, from upstream to downstream. As such, it is assumed that there is some geomorphological control acting on the landscape's relief, favoring the surface runoff contribution as well as the action of subsurface flow conditioned by faults and fractures, which facilitates the sediment mobility.

When analyzing the predominant orientations, there was a higher frequency of NW-SE (n = 59), followed in descending order by E-W (n = 53), SE-NW (n = 47), N-S (n = 46), NE-SW (n = 42), SW-NE (n = 38), W-E (n = 36), and S-N (n = 30). Figure 22 shows this distribution and highlights the predominant directions in a radial histogram of relative percentages.

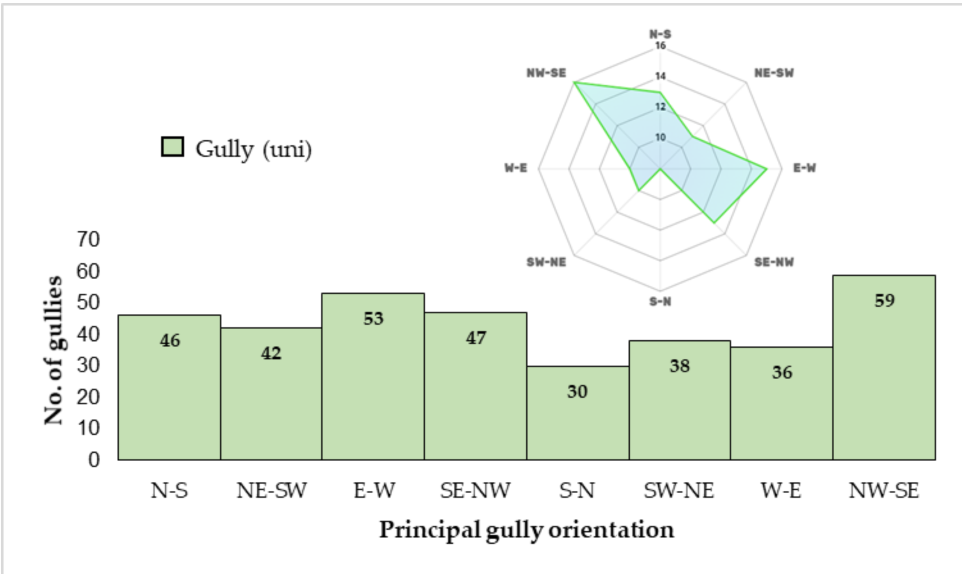


Figure 22. Distribution of the number of gullies by predominant orientation of main axis.

As can be seen in the above figure, large erosions occur in all directions, with no strong preference, which indicates that structural control is not paramount in these features' genesis. However, the disparity observed in gullies with a preferential NW-SE orientation, followed by NE-SW and, to a lesser extent, E-W, may be associated with regional arcs and lineaments in the Paraná Basin tectonic framework, corresponding to reactivated Proterozoic structures (Zalán et al., 1990).

Reis (2020), when conducting a morphostructural analysis in an area similar to this study, including regions dominated by volcanic rocks of the Serra Geral Formation and sandstones of the Tupanciretã Formation, identified the main lineament orientations as being E-W, followed by NE-SW and, to a lower degree, N-S, the last being most expressive in the sedimentary unit. These three directions account for 40% of the gullies mapped. When comparing with other studies, the author points out that these directions, in particular E-W, coincide with the regional patterns of Paraná Basin structures, which are prevalent in the two formations analyzed and associated with upper Cenozoic tectonic activities in the basin (Peyerl et al., 2018). Thus, the inference is that the Tupanciretã Formation was tectonically affected.

In line with Reis (2020), Mexias (2024) undertook a similar study in the municipality of Santiago, RS, where, outside the study area as well as unmapped by the state's official geological chart, there are additional Tupanciretã

Formation Cenozoic deposits and significant numbers of gullies. As in this study, Mexias found a dominant NW-SE gully orientation, indicating a correlation with the morphostructural and tectonic character of reactivations of pre-existing lines.

In view of the above, it can be concluded that some of the gullies have directions that coincide with pre-existing structures, as noted by morphostructure studies in the Tupanciretã Formation outcrop over the Serra Geral Formation (Reis, 2020; Mexias, 2024; Marin, 2022), reinforcing the hypothesis that the orientation of some gullies follows ancient tectonic lines. In addition, around 90% of the features are interconnected with the drainage network, whose pattern usually reflects these geological conduits. However, this does not necessarily imply structural control predominates in most of the gullies, as such control is difficult to ascertain.

3.3.4 Aspect orientation

The orientation of the slope faces of the mapped erosions is largely related to the gullies' principle axis orientation. However, when using a 30-meter spatial resolution DEM, the pixels do not capture the preferential runoff directions in detail. In other words, the exposure face corresponds to the maximum downward slope.

To correlate the lineament orientation and the gullies themselves with the slope directions, analysis was carried out in four quadrants (N-E, E-S, S-W, W-N), since the same orientation class can correspond to multiple preferential erosion directions.

Next, the chart in Figure 23 was created It uses nine orientations for the study area's slopes, expressed in degrees from 0° to 360°, or -1° when the face is considered flat. The geoprocessing data show that 22.48 % of the gullies are located on west-facing slopes. This was followed by northwest (17.33 %), southwest (15.91 %), and north (11.01 %), positions perpendicular to the main orientations of the gullies (NW-SE/SE-NW, E-W, NE-SW/SW-NE, and N-S). On the south-, east-, northeast-, and southeast-facing slopes, the presence of gullies is lower, comprising 9.96 %, 7.07 %, 7.78 %, and 8.45 %, respectively, which correspond to the least frequent gully directions (S-N and W-E).

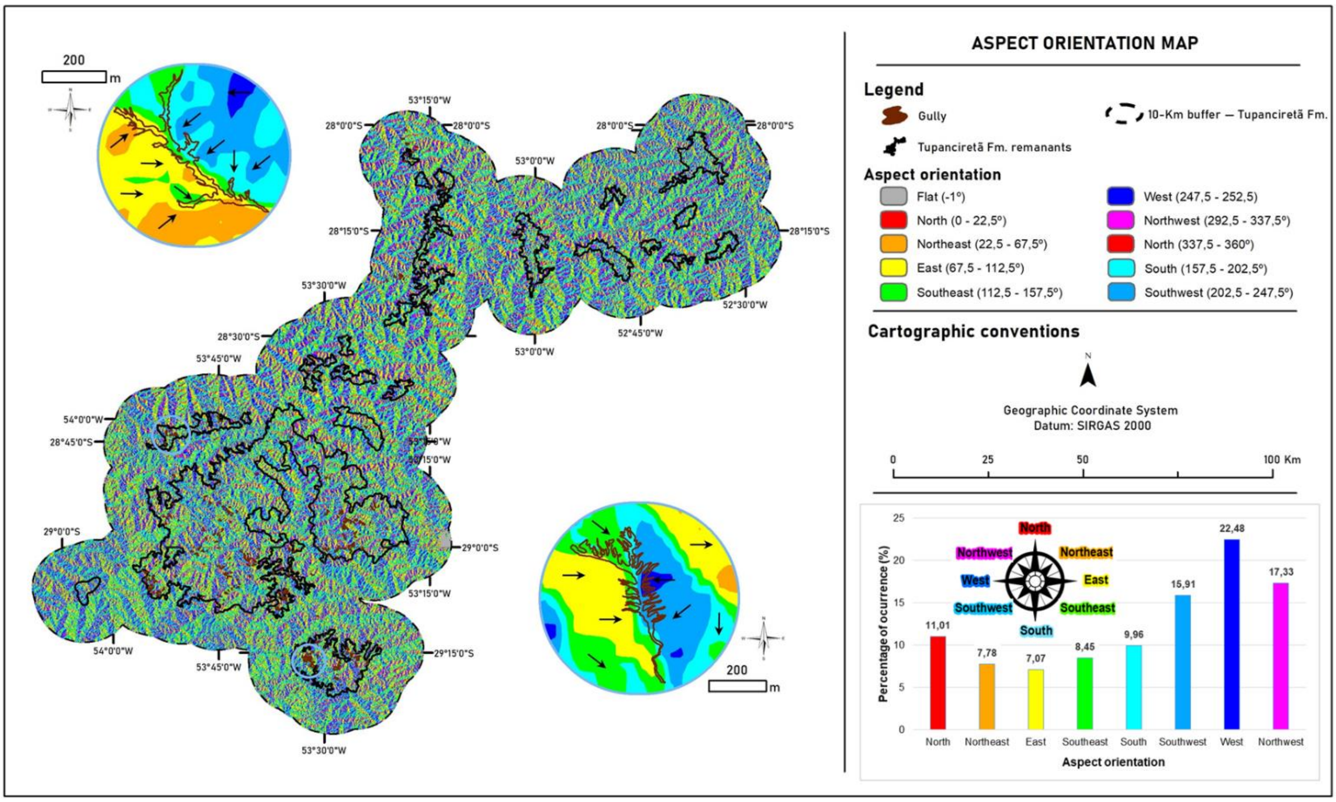


Figure 23. Aspect orientation map of the study area, with representative details.

In addition to the possible structural control on the dissipation of the Tupanciretã Formation gullies, which shapes the relief surfaces, the proximity of many gullies to water dividers explains the diversity of aspect orientations identified in the analyses. Geomorphology strongly encourages drainage direction towards the center of the watershed.

5. Conclusions

This study gathered and generated new data on gullies resulting from the fragile weathering mantle of the Tupanciretã Formation that affect large areas in the center-north of the state. The geotechnological procedures and techniques used to obtain the data demonstrated the applicability of different tools in assessing erosion processes, making it possible to quantify and qualify each gully in the area studied.

The most common form of gully is branched, accounting for more than 50 % of the total. This configuration reflects multiple concentrated flows that converge on the main channel, giving rise to irregular and secondary branches, with variable spacing, which can occur both near the headwaters and on the sides of the incision.

As for connection to the drainage network, 65 % of the gullies are located close to water dividers, especially those that feed the Alto Jacuí watershed. Of all the gullies mapped, 274 (78 %) are connected to the network, 39 (11 %) remain disconnected, and 38 (10 %) show partial integration. These figures indicate that most contribute directly to the silting of water bodies and intensify sediment removal from the Tupanciretã Formation.

The gullies occur preferentially at altitudes between 348 and 406 m. The highest headwater point recorded is 638 m, while the lowest mouth is at 348 m, for an altitude range of 290 m.

Regarding the slope of the gullies' internal reliefs, 59 % are on gently undulating relief, 17.45 % on flat, 20 % on undulating, 2.85 % on strongly undulating, and 0.06 %, mountainous. This data indicates that steep slopes are not a prerequisite for the emergence and development of gullies, for other factors — such as the slope length, poor cohesive nature, and improper agricultural use — also have a significant influence on erosion processes.

Upon assessing the slope morphology, it was observed that 68 % of the gullies are in concave vertical curvatures, which tend to retain water inside and generate concentrated flow. For horizontal curvatures, 65 % occur on converging slopes, which direct the flow toward the center of the slope. When combined, concave-convergent curvatures predominate in 53 % of the gullies, indicating that a concentrated flow channel favors erosive evolution.

The analysis of possible structural controls revealed that the gullies occur in all orientations, showing that tectonic influence is not a primary consideration for their formation. Nonetheless, some preferential orientations (NW-SE, NE-SW, and E-W) do coincide with pre-existing tectonic structures, suggesting that some of the gullies follow old structural lines. In addition, around 90% are connected to the drainage network, whose pattern generally reflects geological guidelines, without implying primary structural control in all features.

Finally, the exposure face of the slopes where gullies occur reveals that 22.48 % are on west-facing slopes, 17.33 % northwest-facing, 15.91 % southwest, and 11.01 % north, orientations perpendicular to the most frequent directions of gullies. The south (9.96 %), east (7.07 %), northeast (7.78 %), and southeast (8.45 %) orientations have fewer gullies. This distribution reflects the strong influence of geomorphology, as many gullies occur close to water dividers, which explains the diversity of patterns in slope orientations observed in the results.

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