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Research Article

The development of erosion features in cuesta relief regions

O desenvolvimento de feições erosivas lineares em região de relevo de cuestas

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Abstract: The cuesta relief is characterized by high slopes, colluvial deposits and intense evolutionary dynamics, making the region especially prone to soil degradation. This study intends to identify how the relief, lithology, and soils influence the occurrence of linear erosion processes of rill erosion, ravines and gullies in the cuestas environments. For that, the density of linear erosion features of 1972 and 2010/2011 were mapped and then analyzed in comparison with the mapped morphological features of the Cuesta in Botucatu, also prepared in this study, and lithological and soil maps from secondary sources. Quantitative and qualitative analysis identified concentrations of gullies in the cuesta reverse, at drainage headwaters, close to lithological contacts and over latosols. On the cuesta front, concentrations of rills, ravines and small gullies were identified, driven by the steep slope, colluvial covers, and transitions of heterogeneous lithologies and soils. The data demonstrated that lithological and pedological transitions, typical of cuesta regions due to high geodiversity, in addition to other conditions, are factors that enhance erosive dynamics and must be considered in territorial planning in order to preserve soils and other natural resources of these regions.

Keywords: Erosive dynamics; cuesta relief; lithological contacts; cartographic relationships

Resumo: o relevo de *cuestas* se caracteriza pelas altas declividades, presença de depósitos coluvionares e intensa dinâmica evolutiva, tornando a região especialmente propensa a degradação dos solos. Este estudo buscou identificar como o relevo, litologia e solos influenciam na ocorrência de processos erosivos lineares, que dão origem aos sulcos, ravinas e voçorocas, em ambiente de *cuesta*. Para isso, mapeou-se a densidade de feições erosivas lineares dos anos de 1972 e 2010/2011, o qual foi cruzado com o mapeamento das feições morfológicas da Cuesta em Botucatu, também elaborado nesse estudo, e mapas litológicos e de solos de fontes secundárias. As análises quantitativas e qualitativas identificaram concentrações de voçorocas no reverso cuestiforme, nas cabeceiras de drenagem, próximas a contatos litológicos e sobre Latossolos Vermelhos e Vermelho Amarelo. No *front*, foram identificadas concentrações de sulcos, ravinas e pequenas voçorocas, dinamizadas pelo declive mais acentuado, coberturas coluvionares, e transições entre litologias e solos heterogêneos. Os dados demonstraram que os contatos e transições litológicas e pedológicas, típicas das regiões de *cuestas* em razão da alta geodiversidade, são fatores que potencializam a dinâmica erosiva e devem ser consideradas no ordenamento territorial a fim de preservar os solos e demais recursos naturais dessas regiões.

Palavras-chave: Dinâmica erosiva; relevo cuestiforme; contatos litológicos; cruzamentos cartográficos.

1. Introduction

Cuestas are characterized as a dissymmetrical relief, sculpted by denudation processes, identified in several regions of Brazil and around the world in sedimentary basins with heterogeneous sub-horizontal layers (PENTEADO, 1983; SCHIMIDT, 1989). The evolutionary process of these structures occurs due to the lower resistance of the inferior layer, which leads to more accelerated erosion of the base, resulting in the undermining of the more resistant upper formation. In this way, the cuesta-shaped relief evolves through differential erosion processes, retreating laterally without a generalized lowering of the reverse. Morphologically, the cuesta is divided into the Peripheral Depression, which corresponds to the portion lowered by erosion; the reverse, which corresponds to the highest portion of the relief, supported by the more resistant upper formation; and the front, which corresponds to the erosion front and is marked by high slopes, making the transition between the low-lying terrain of the depression and the high terrain of the reverse (PENTEADO, 1983).

Due to their morphodynamic characteristics, several international and national studies point to a high susceptibility of cuestiform relief regions to varied geomorphological processes, depending on the lithostructural and climatic characteristics of each region. Schimidt; Bayer, (2002); Den Eeckhaut; Marre; Posen, (2010) Sheehan; Ward, (2018) report the occurrence of landslides and rockfalls in cuestas located in Germany, France and the United States, respectively. Gobin et al (1999), Silva and Lupinacci, (2021) and Stefanuto et al (2022) associate cuestiform relief regions with accelerated linear erosion processes in cuestas in Nigeria and Brazil, respectively.

Thus, it is understood that lithological variations, high slopes and the presence of colluvial deposits, typical of regions with cuesta relief, can make these areas especially sensitive to geomorphological processes and environmental degradation. It is worth adding that, although the processes mentioned are associated with the natural evolutionary dynamics of these structures, the bibliography points to an intensification of these processes associated with human activities, especially land use. In addition, geomorphological processes, such as accelerated soil erosion, for example, are serious socio-environmental problems, compromising agricultural production and urban infrastructure and also contributing to the silting of water bodies and carbon emissions into the atmosphere (MONTGOMERY, 2007; GOUDIE, 2013; LABRIÈRE et al., 2015). For this reason, it is understood that knowledge about the geomorphological dynamics of the cuestiform relief and the identification of the sectors most sensitive to degradation by geomorphological processes, with emphasis on those of accelerated linear erosion, is fundamental to support land-use planning in these regions.

Facing this problem, the objective of this article is to discuss how physical characteristics, such as lithology, soils, and morphology of the cuesta relief, enhance accelerated erosion processes, specifically the occurrence of linear erosive features. In order to obtain data that allowed this objective to be achieved, it was selected as study area the hydrographic basins that drain the cuesta of the municipality of Botucatu (SP). This area is considered to constitute a representative sector of the regional context of this relief system, and can contribute significantly to the understanding of the Basalt Cuestas of the state of São Paulo. It is understood that the analysis of linear erosion features, which consist of forms that register accelerated soil erosive processes, allows advances in the understanding of erosion dynamics in regions of the cuesta relief.

To perform this analysis, the density of linear erosion features was mapped in two scenarios (1972 and 2010), which made it possible to identify the terrains most severely affected by this dynamic. These data were then cross-referenced with maps of the geology, soils, and morphological features of the cuestiform relief, in order to identify how these elements influence the linear erosion dynamics in the study area.

2. Study Area

The study area is a fragment of the municipality of Botucatu, in the interior of the state of São Paulo, which contains an area of cuesta relief (Figure 1a and b). The spatial section analyzed is located between latitudes 22°42′30″S and 23°0′33″S and longitudes 48°17′22″W and 48°32′48″W and corresponds to sections of four anaclinal hydrographic basins, which flow from the reverse of the cuesta towards the Peripheral Depression. The basins analyzed correspond to sections of the drainage area of the Araquá, Lavapés, Capivara and Alambari rivers. The selected area contains all compartments of the cuestiform relief, from the reverse to the Peripheral Depression (Figure 1c).

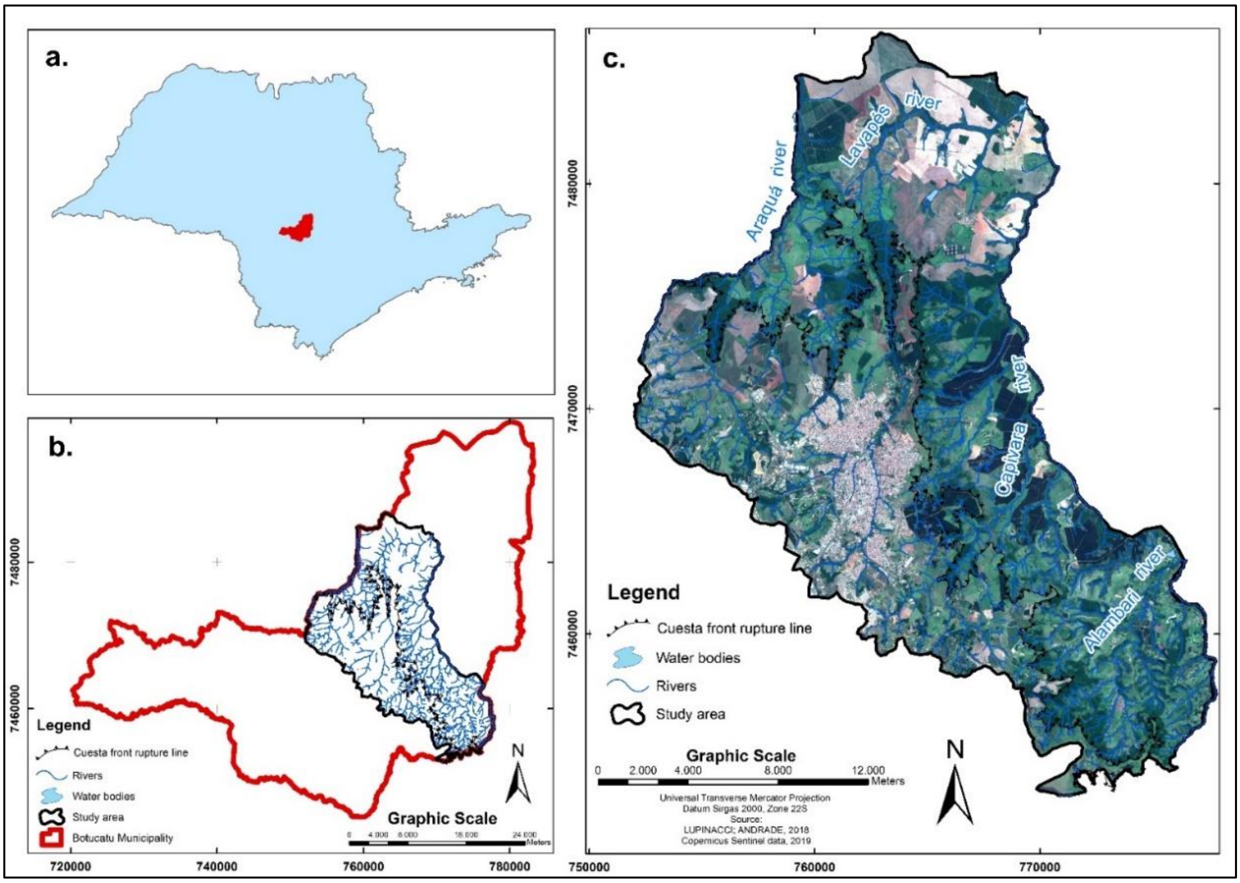


Figure 1. Location of the study area. In a, the state of São Paulo is shown; in b, the boundary of the municipality of Botucatu; and in c, the study area.

This area is part of the Paraná Sedimentary Basin and represents a fragment of the São Paulo landscape. The so-called Cuestas Paulistas, object of this research, cross the entire state of São Paulo in the NNE-SSW direction, separating the terrains of the Peripheral Depression of São Paulo, sculpted by circumdenudational processes (AB'SABER, 1949), from the Western Plateau (AB'SABER, 1956; ALMEIDA, 1974; ROSS; MOROZ, 1997). The stratigraphic decay of the formations of the Paraná Sedimentary Basin in the NW direction guides the superimposed drainage system, called the large consequent rivers: Grande, Tietê and Paranapanema. The drainage system establishes the base level for the generalized lowering of the region, carried out especially by its tributaries. The Cuestas Paulistas mark the landscape of the interior of the state as residual features that stand out due to the greater altimetric differences, and were sculpted by the more accelerated erosion of the sandstones of the Botucatu Formation, in comparison to the superimposed basaltic flows and silicified sandstones of the Serra Geral Formation (AB'SABER, 1956; ALMEIDA, 1974).

Regarding the geology, São Paulo (1984) identified in the study area (Figure 2) the Pirambóia Formation, made of medium to fine-grained fluvial and aeolian sandstones, whitish, orange or reddish in color (Figure 3a), from the Neotriassic period (PERROTA et al, 2005), located in the Peripheral Depression; the Botucatu Formation, which is characterized by medium to fine-grained Aeolian sandstones, pinkish in color (Figure 3b), from the Jura-Cretaceous period (MILANI et al, 2007), located mainly close to the cuestiform front (Figure 2); the Serra Geral Formation, composed of basaltic flows (Figure 3c) and intertrapped sandstones also from the Jura-Cretaceous period (MILANI, et al, 2007), located close to the front and on the cuesta reverse; and the Marília Formation, consisting of coarse sandstones, cream and red in color (Figure 3d) from the Cretaceous period. In addition, São Paulo (1984) also identified colluvial deposits from the Pliocene-Pleistocene, composed of "sands with an argillaceous matrix; limonite and quartz gravels at the base" and alluvial deposits from the Holocene, composed of sands, clays and gravels at the base, both occurring in areas of the Peripheral Depression and the cuesta reverse (SÃO PAULO, 1984).

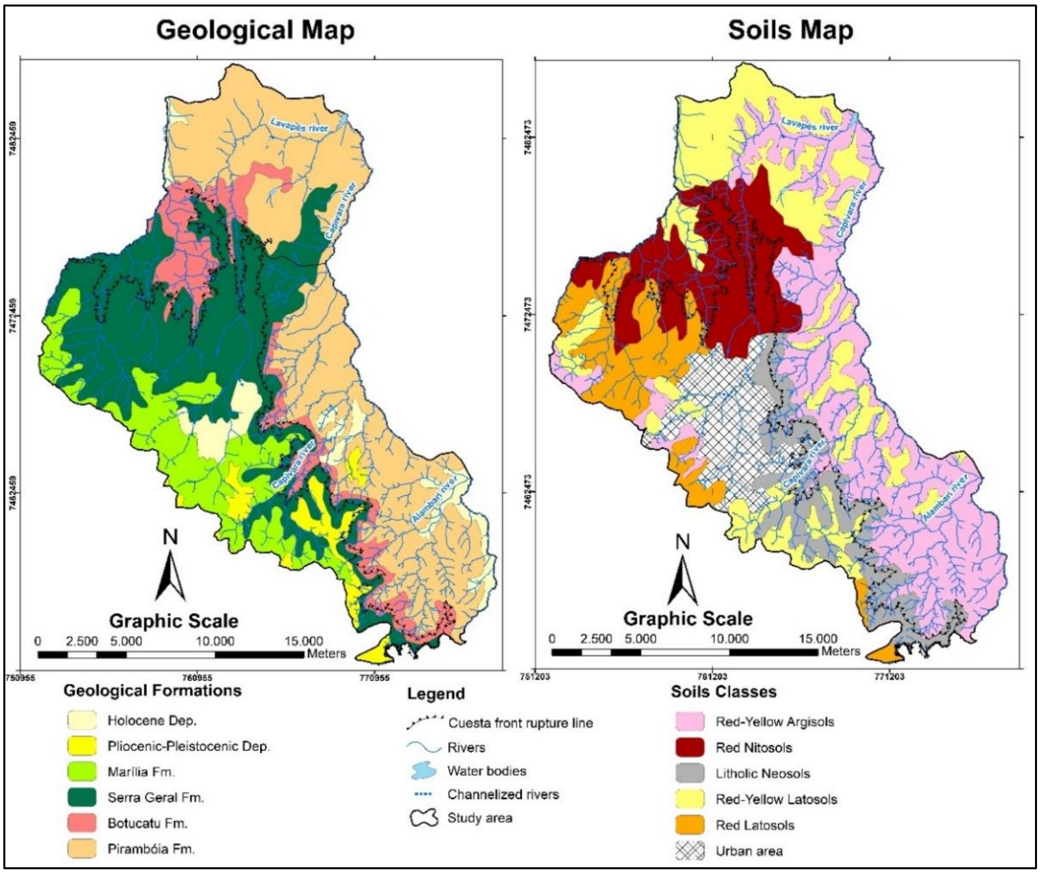


Figure 2. Geological Map and Soil Classes of the Study Area. Source: Adapted from São Paulo, 1984; Rossi, 2017

Figure 3. Pirambóia Formation (a); Botucatu Formation (b); Serra Geral Formation (c); Marília Formation (d). Source: The Authors

Lithological diversity generates distinct classes of soils identified in the study area by Rossi (2017) and presented in Figure 2. The author points out the occurrence of Red-Yellow Argisols in the Peripheral Depression and the reverse, coinciding with the basement of the Pirambóia and Marília sandstones, which are characterized by a moderate or weak A horizon and sandy/medium texture. Red-Yellow Latosols are identified both in the Peripheral Depression and in the reverse and have a moderate or weak A horizon and medium texture (ROSSI, 2017). Red Latosols are identified mainly in the cuestiform reverse on the basement of the Serra Geral and Marília formations and have a medium texture. Near the cuestiform front, on basement areas of the Serra Geral Formation, Red Nitosols are identified, characterized by their moderate A horizon and clayey to very clayey texture (ROSSI, 2017). Finally, Litholic Neosols are mostly identified along the front and have clayey characteristics when of basaltic origin, or sandy characteristics when of sandstone origin (ROSSI, 2017).

3. Materials and Methods

In order to identify the relationship between relief, lithology, and soils and the susceptibility of the terrain to the development of linear erosion features, cartographic documents were prepared and subsequently cross-referenced with each other and with secondary sources maps in order to identify the overlaps between these variables in a quantitative and qualitative manner. In the case of this research, the morphological features of the cuesta relief and the density of linear erosion features were mapped at a scale of 1:10,000 using aerial photographs from 1972, scale 1:25,000, and digital orthophotos from EMPLASA, from 2010/2011, scale 1:10,000. In addition, lithology (SÃO PAULO, 1984) and soil (ROSSI, 2017) maps were used in order to identify the spatial relationship of these elements with linear erosion features.

3.1 Map of Cuesta Morphology Features

The mapping of the Cuesta Morphology Features in Botucatu sought to identify the compartments of the cuestiform relief and evaluate how these structures influence the occurrence of linear erosion features. For this, principles and techniques of geomorphological cartography (TRICART, 1965; VERSTAPPEN; ZUIDAN, 1975) were used, adapted to the objective of this research.

In this study, aerial photographs from 1972, at a scale of 1:25,000, were used to create anaglyphs in the EstereoPhotoMaker application, according to the procedures described by Souza and Oliveira (2012). These techniques allowed the analysis of the relief in three dimensions and the subsequent mapping of the cuestiform compartments over this material. In addition to the anaglyphs, the vector files referring to the contour lines and rivers at a scale of 1:10,000 (IGC, 1970) and the slope map of Botucatu (ANDRADE; LUPINACCI, 2021) were also used, and field surveys were carried out. The mapped cuestiform features, the criteria used to define them, the symbology adopted and the bibliographic reference used in their preparation are described in Table 1.

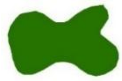
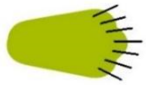
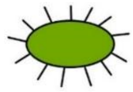
Cuestiform feature	**Characterization**	**Symbology**
Peripheral Depression	Lowered terrain, already eroded by circumdenudation, limited by the cuesta front.	ROSS; MOROZ (1997)
Reverse	Elevated terrain southwest of the front, not yet affected by erosion processes.	 ROSS; MOROZ (1997)
Talus	Land covered by colluvial ramps deposited at the foot of the front. It was mapped as a polygon that starts at the rupture line of the cuesta front and continues to its base.	 The authors
Front with cornice	Line and rupture of the front of the cuesta where it occurs abruptly.	 (VERSTAPPEN; ZUIDAN 1975)
Dismantled Front	Line and rupture of the cuesta front where this occurs gradually, without an abrupt transition.	 VERSTAPPEN AND ZUIDAN (1975)
Residual Hills	Residual features that were separated from the front by erosive processes (cut off) but still maintain a height similar to the front.	 TRICART (1965)
Residual Features	Surfaces of structural ridges identified on the front that are not covered by colluvial deposits.	 The authors
Structural ridges	Well-marked topographic ruptures, denoting structural influence in the support of these features. These ruptures are distinguished from the front due to their smaller altimetric difference and their discontinuity.	 TRICART (1965)

Table 1. Criteria and symbols used to represent the cuesta morphology features in Botucatu

3.2 Linear Erosion Features Density Map

The *Linear Erosion Features Density Map* were prepared according to the principles and techniques described by Andrade and Lupinacci (2023). This procedure is based on the identification and mapping of the linear erosion features rills, ravines and gullies present in the analyzed area. These were then quantified to identify the terrains where such features are concentrated. The maps, which were prepared for two scenarios, were performed based on the careful analysis of aerial photographs from 1972 and the mosaic of digital orthophotos from 2010, seeking to identify mappable linear erosion features at a scale of 1:10,000. The rills and ravines were differentiated in the photo-interpretation process by the greater depth and presence of sidewalls in the case of ravines and, due to their morphodynamic characteristics, were mapped as lines over the incisions (Table 2). In the case of gullies, their widening and branching upstream due to subsurface flow processes (FENDRICH et al, 1997; SALOMÃO, 1999; OLIVEIRA, 1999) led to them being mapped as lines on the sidewalls (Table 2).

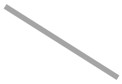
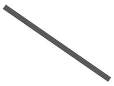
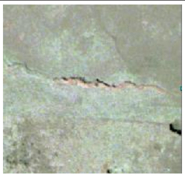
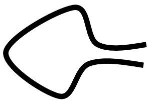
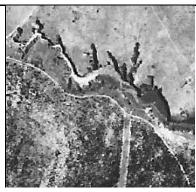
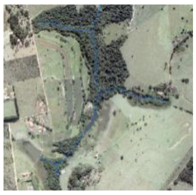
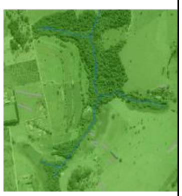
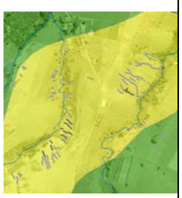
Erosion feature	Symbology	Aerial Photographs (TERRAFOTO, 1972)	Orthophotos (EMPLASA 2010)
Rills			
Ravines			
Gullies			

Table 2. Criteria for identifying linear erosion features in aerial images and digital orthophotos

After mapping the linear erosion features, their density was calculated in order to identify the locations of greatest concentration. To this end, a grid with 500m squares was created over the analysis area. Then, the sum of the length of the linear erosion features (rills, ravines, and gullies) within each square was calculated. It is worth mentioning that the length values of the rills, as they correspond to the initial and less intense process of linear erosion, had their length values multiplied by 0.5 in order to reduce the weight of these features in the calculation of the density values, as justified by Andrade and Lupinacci, (2023). Then, the value of the sum of the length of the linear erosion features within each square was divided by the area of the square in order to identify the density. Finally, this density value was assigned to the central point of each square and interpolated to the study area using the natural neighbors parameter. To prepare the final map, the density values of linear erosion features were divided into five classes (Table 3), with exponential intervals between them, doubling for each class.

Density Classes of Linear Erosive Features	**Aerial Photographs**	**Density of Erosive Features**
Class I (0 -l 10 m/ha): land little affected by erosion features, with exceptional presence of rills or ravines.		
Class II (10 -l 20 m/ha): land affected by erosion features, mainly rills and ravines and exceptionally small and isolated gullies, indicating land affected by poorly developed erosion processes, but with potential for evolution.		

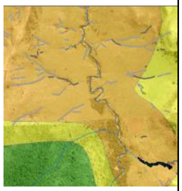
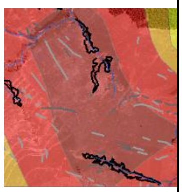
Class III (20 -l 40 m/ha): land heavily affected by rills and ravines, and occasionally gullies, indicating a more developed stage than the second class, where erosion processes already compromise land use activities on site.		
Class IV (40 -l 80 m/ha): land with the presence of developed gullies associated with rills and ravines. In these places, erosion already represents a problem for land use and it is necessary to apply containment measures		
Class V (80 -l160 m/ha): land marked by large gullies, often associated with rills and ravines, with significant soil damage and the need for containment techniques. In some places, these methods havealready been applied in attempt to stabilize the gullies.		

Table 3. Criteria for adopted to quantify the linear erosion features density classes.

3.3 Cross-referencing and analysis of geospatial data

To identify the spatial relationship between the density of linear erosion features and the properties of the cuesta relief, lithology, and soils in the analysis area, the map of the linear erosion features density (1972 and 2010) were superimposed on the maps of the cuesta morphology features, soils and lithology. From this procedure, the overlap areas between the density classes of linear erosion features were calculated with the elements of the other maps in order to understand which relief compartments, soil type and lithological formation are associated with the higher density classes. The analysis of the spatial relationships was performed quantitatively by evaluating the areas of overlap between the density classes and the relief, soils and lithology, and also qualitatively, based on analyses of the context and characteristics of the locations where the density classes are concentrated.

4. Results and Discussion

The Cuesta Mophology Features map (Figure 4) indicates the presence of a cuesta front with heterogeneous morphological characteristics. In addition to the festooning typical of this structure, a well-marked cornice is observed in certain places (Figure 5a), while in others, a dismantled cornice is observed, often associated with structural ridges (Figure 5b). It is understood that the layers and internal discontinuities of the Serra Geral Formation or its contact with the Botucatu Formation (IPT, 1981b; HARTMANN, et al, 2014) lead to the development of intermediate steps, resulting in a staggering of the front and, consequently, breaking the energy of the dissection processes, giving rise to smoother forms.

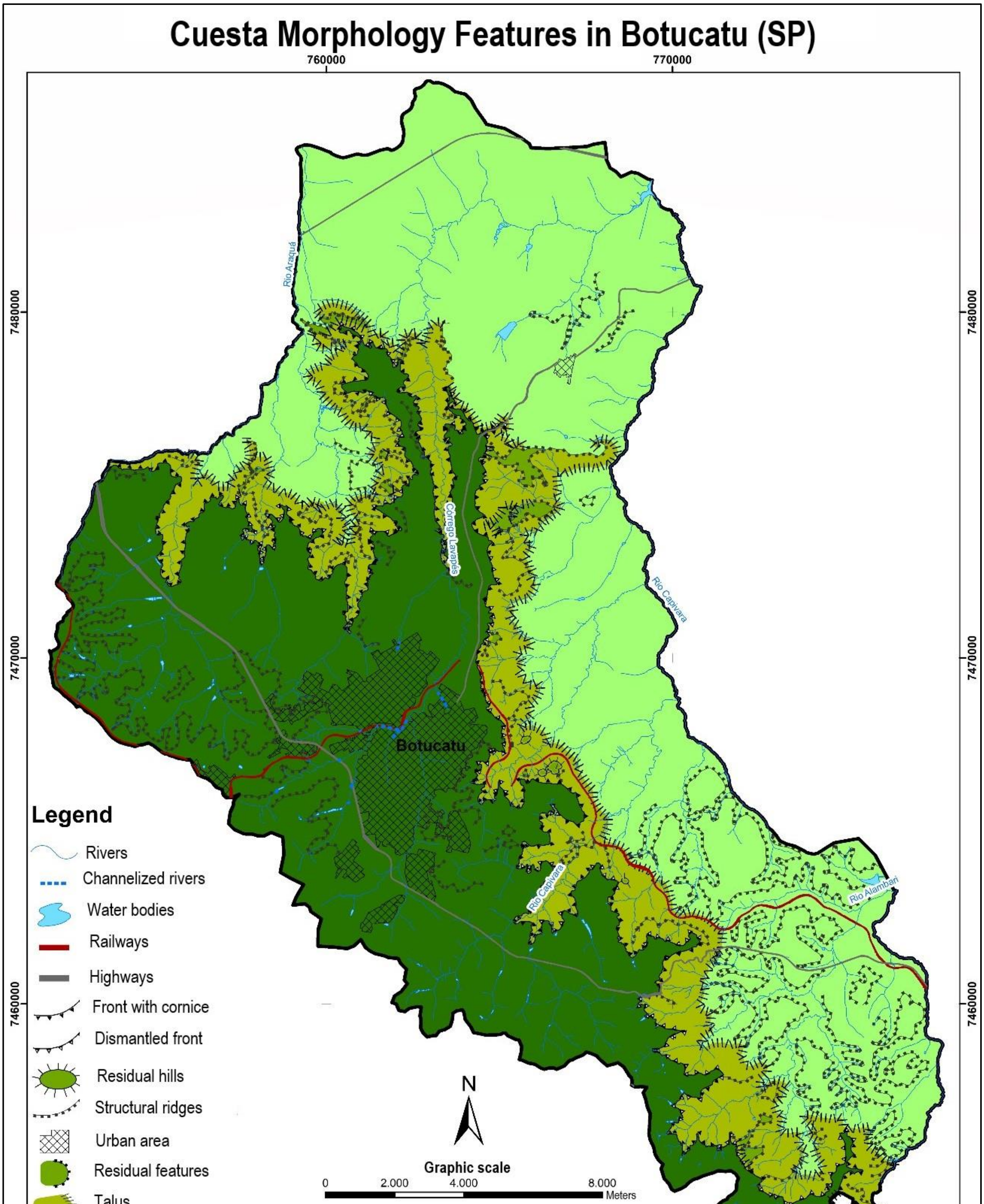


Figure 4. Cuesta Mophology Features in Botucatu Map.

The scaling of the relief associated with the occurrence of structural ridges is not restricted to the front, but is also noted in the reverse and the Peripheral Depression. This finding demonstrates that the cuestiform relief in Botucatu is not configured only by a well-marked topographic step, but a succession of ridges associated with the region's geodiversity. In the Peripheral Depression, especially in the Alambari River basin, several structural ridges were identified in the Pirambóia Formation, probably associated with differences in resistance of the facies of the Formation itself (CORTÊS; PERINOTTO, 2015). On the reverse, the structural ridges were identified especially in the drainage headwaters of the Araquá River and Lavapés stream basins, close to the contact between the Marília and Serra Geral formations. It is worth noting, however, that the structural ridges are not identified in all contact zones between these two formations, suggesting that, similarly to what was seen in the case of the Pirambóia Formation, this fact is due to the heterogeneous facies or internal variations of the Marília Formation itself.

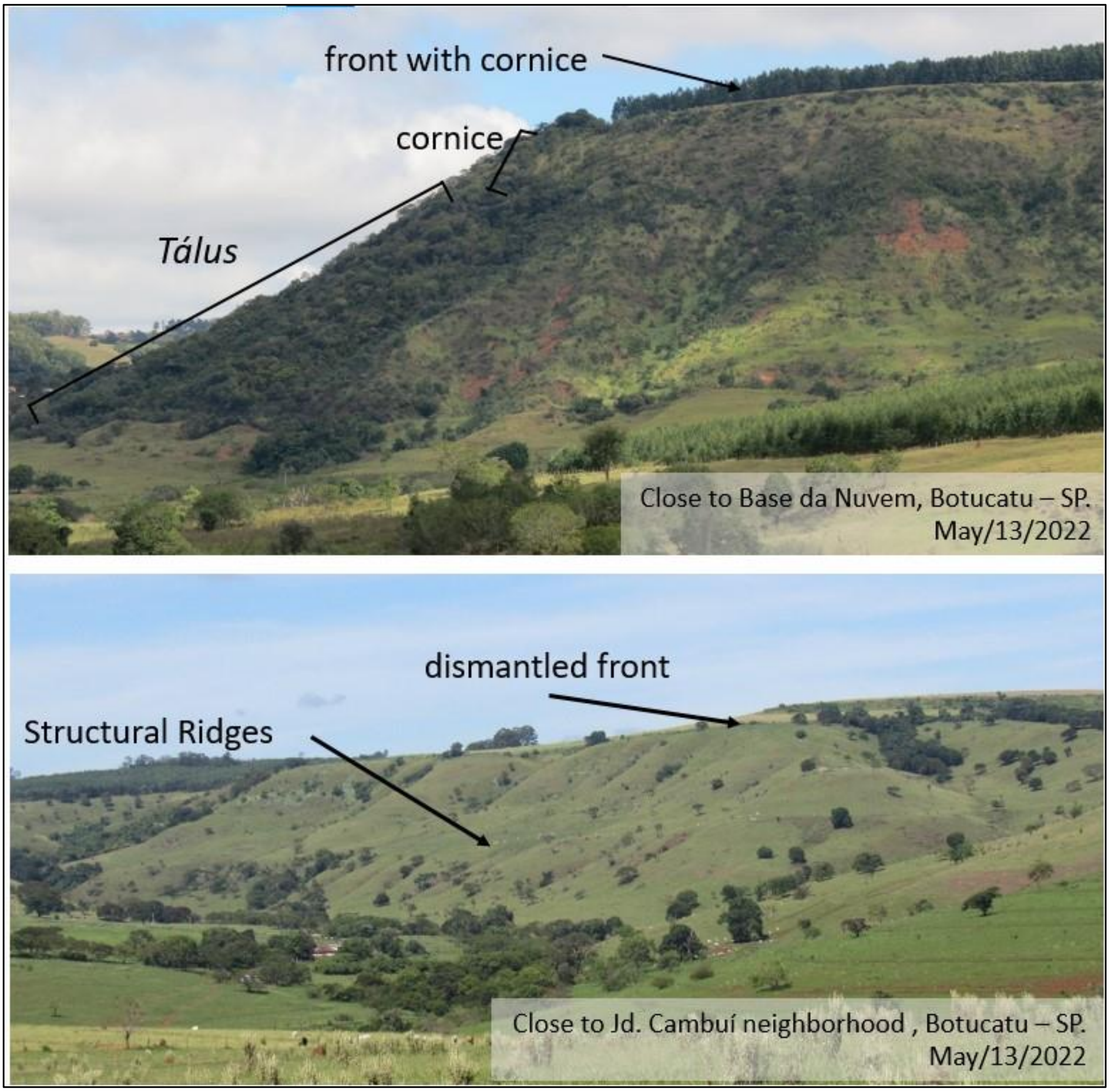


Figure 5. Morphological characteristics of the cuesta front in Botucatu. Source: the authors

The spatial crossover between the relief, lithology and soil mappings with the linear erosion features density map from 1972 and 2010 (Figure 6) highlighted the existence of some differences in the density of linear erosion features mapped in the two scenarios, which are due to changes in land-use patterns that occurred in this 38-year interval. However, both scenarios were analyzed in a complementary manner in order to support the analyses regarding the influence of physical variables on erosion dynamics.

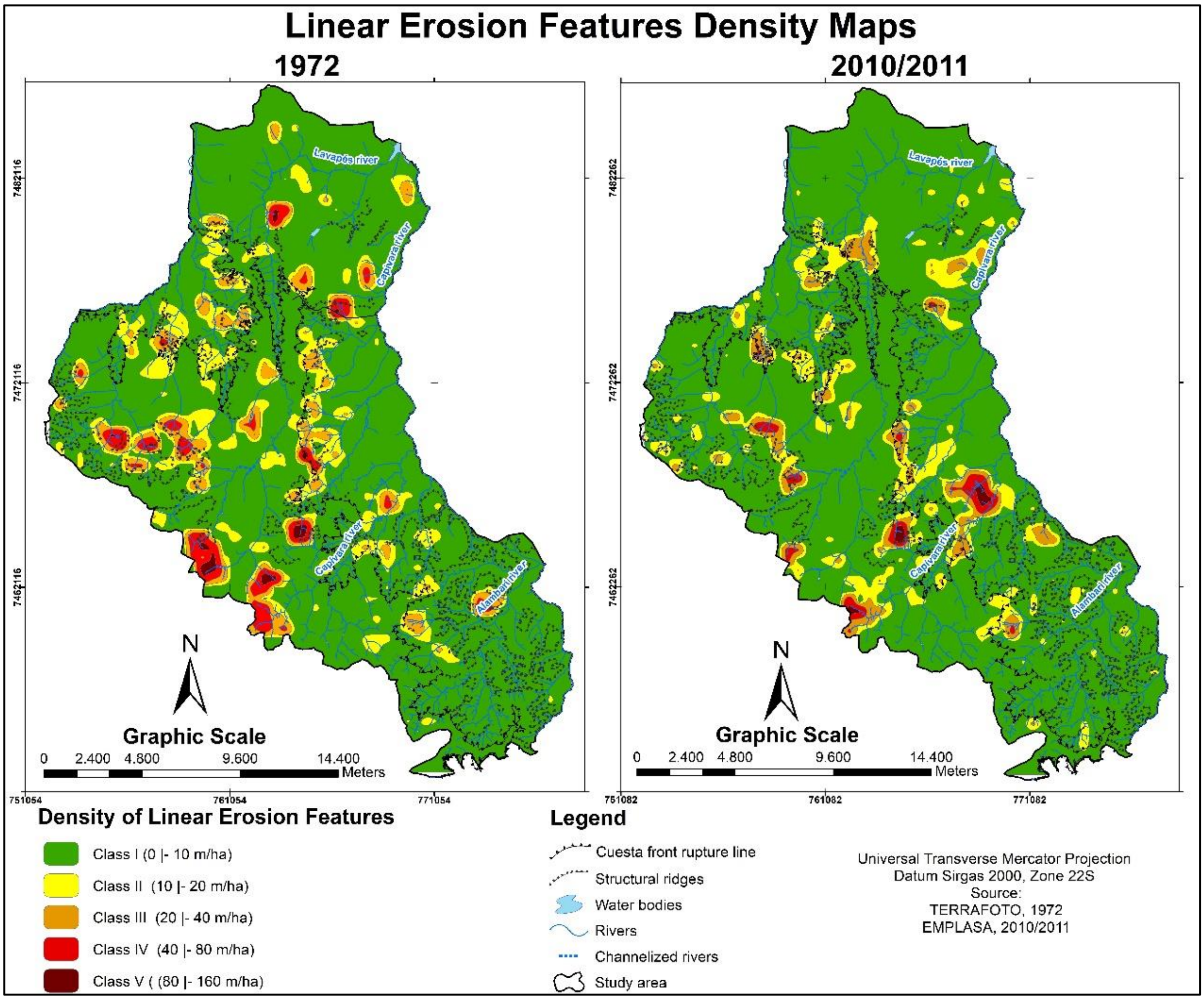


Figure 6. Linear Erosive Features Density map from 1972 and 2010

Regarding the spatial relationships between the compartments of the cuestiform relief and the density of linear erosion features, Table 1 indicates that the highest classes were identified in the reverse, which houses 73.1% of the Class IV area and 85.9% of Class V for the 1972 scenario (Table 1; Figure 7). However, this trend was not repeated in the 2010 scenario, when the reverse became home to 54.1% of Class IV and 48.7% of Class V, which had a greater representation in the Peripheral Depression (Table 1; Figure 8). The data indicate the high potential of the cuestifa reverse to develop of linear erosion features, based on the identification of the many and extensive gullies in the headwaters of the Araquá and Capivara rivers and the Lavapés stream (Figure 9a). The occurrence of gullies in drainage headwaters is already known in the bibliography and pointed out as a frequent trend (DANIEL; VIEIRA, 2015), especially on concave slopes due to the concentration of surface and subsurface flows (NÓBREGA et al, 2023). However, in the case of the Botucatu cuestas, the high density classes of linear erosion features on the reverse follow the contact between the Marília and Serra Geral formations, in several sectors marked by the presence of structural ridges, or Pliocene-Pleistocene deposits with the Marília and Serra Geral Formations (Figure 9).

Table 1. Distribution of erosion features density classes by cuesta relief compartment

Cuestas relief compartments	Total Area	Linear Erosive Features Density									
		Class I		Class II		Class III		Class IV		Class V	
		1972	2010	1972	2010	1972	2010	1972	2010	1972	2010
Peripheral Depression	43.6%	48.6%	46.0%	25.1%	32.5%	25.9%	23.6%	16.8%	39.4%	8.5%	51.3%
Talus	16.4%	13.6%	14.6%	32.8%	24.2%	24.6%	36.1%	9.8%	6.4%	5.6%	0.0%
Residual Features	0.6%	0.4%	0.7%	1.7%	0.4%	1.1%	0.5%	0.4%	0.2%	0.0%	0.0%
Reverse	39.4%	37.4%	38.7%	40.4%	42.9%	48.4%	39.8%	73.1%	54.1%	85.9%	48.7%

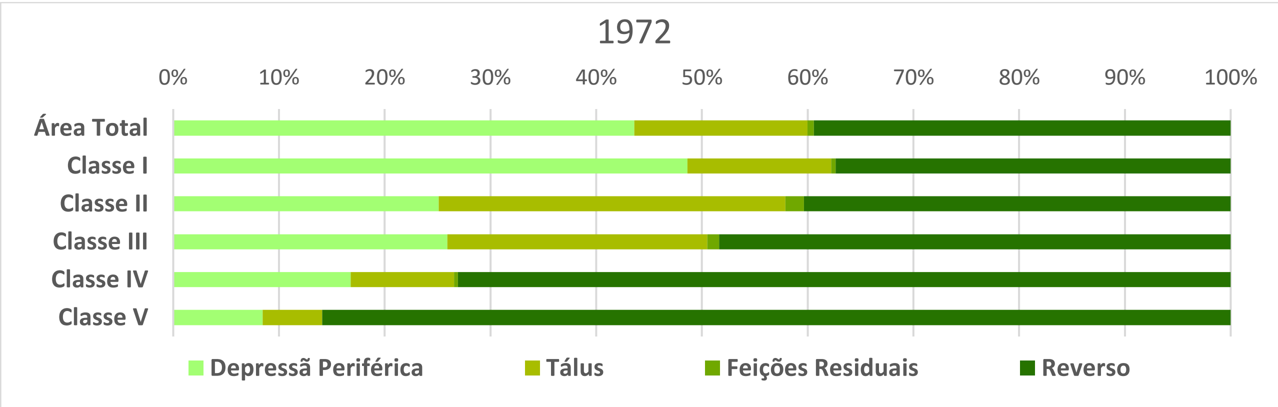


Figure 7. Distribution of erosion features density classes by cuesta relief compartment in 1972

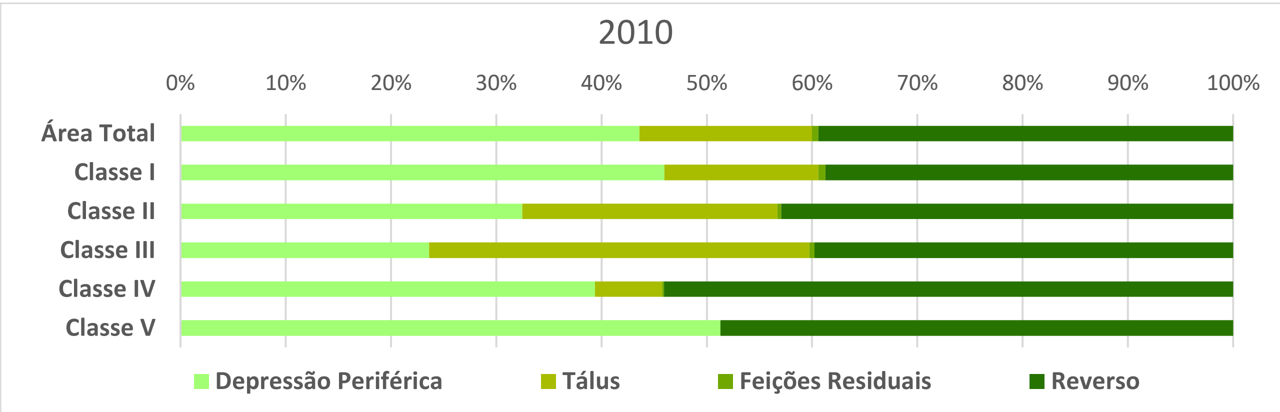


Figure 8. Distribution of erosion features density classes by cuesta relief compartment in 2010

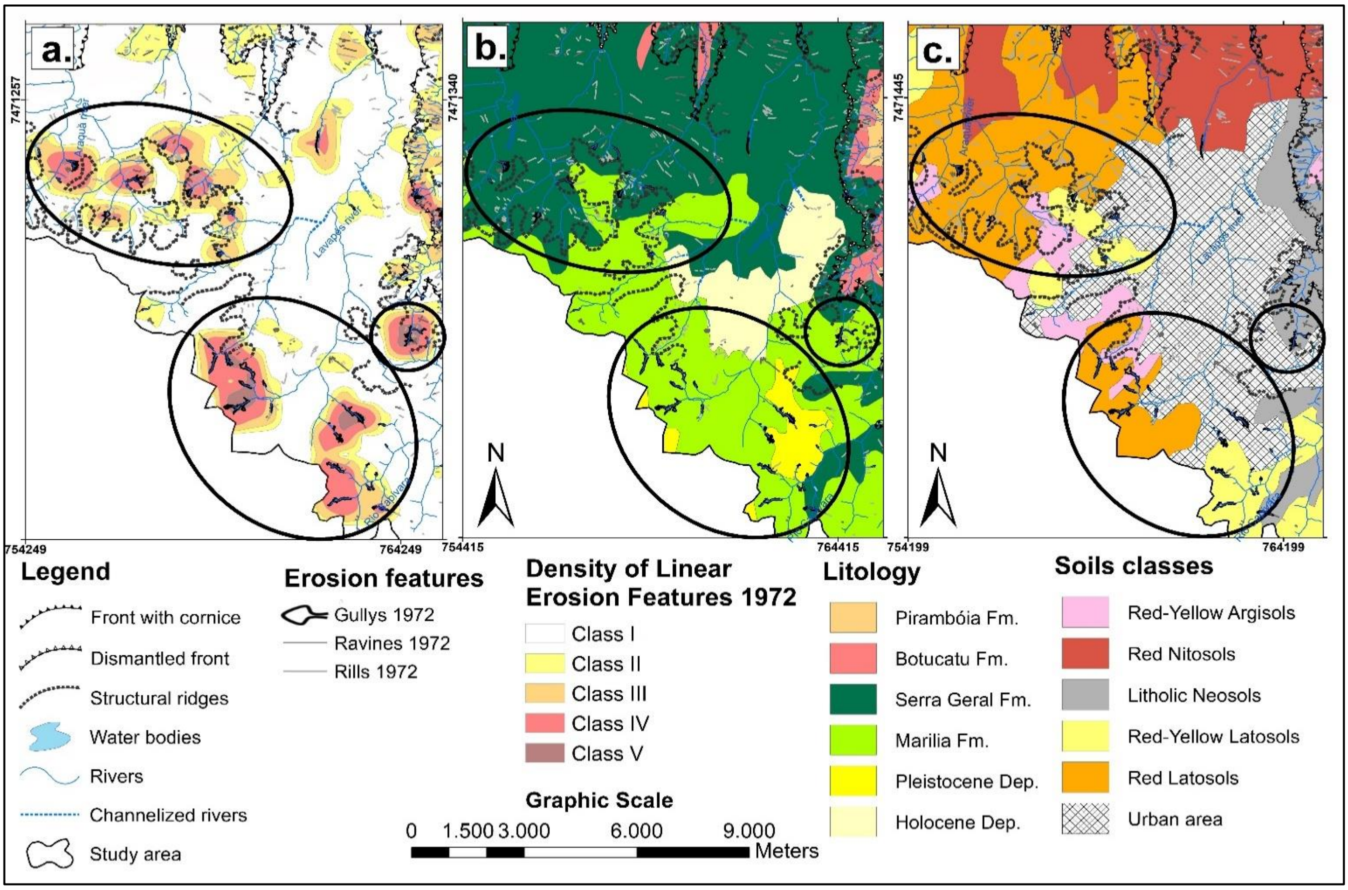


Figure 9. Erosive features, lithology and soils in the cuesta reverse. Source: São Paulo, 1984; Rossi, 2017

Regarding the overlap of the linear erosion features density, with the talus, this compartment, which occupies 16.4% of the study area, housed 32.8% of Class II and 24.6% of Class III in 1972, and in the 2010 scenario, these values reach 24.2% of Class II and 36.1% of Class III (Table 1, Figures 7 and 8). Despite this expressive representation in both classes, the same does not occur in the highers classes, IV and V. These data demonstrate that the talus is more prone to concentration of rills, ravines and small gullies (Figures 10 and 11), which are the types of features most frequently associated with classes II and III (ANDRADE; LUPINACCI, 2023). Conversely, large gullies associated with classes IV and V were rarely identified on the talus. This fact may be associated with the steeper slope and the length of the slopes, which enhance the energy of surface runoff, making the surface materials (soils and colluvium) shallower, generating rills and ravines, but without sufficient depth for gullies. Furthermore, the fact that the talus is made up of recent and unconsolidated colluvial material, deposited from geomorphological processes in varied climatic conditions (PINHEIRO; QUEIROZ NETO, 2017), makes these terrains more susceptible to the development of erosive forms (DANIEL; VIEIRA, 2015; SHEEHAN; WARD, 2018).

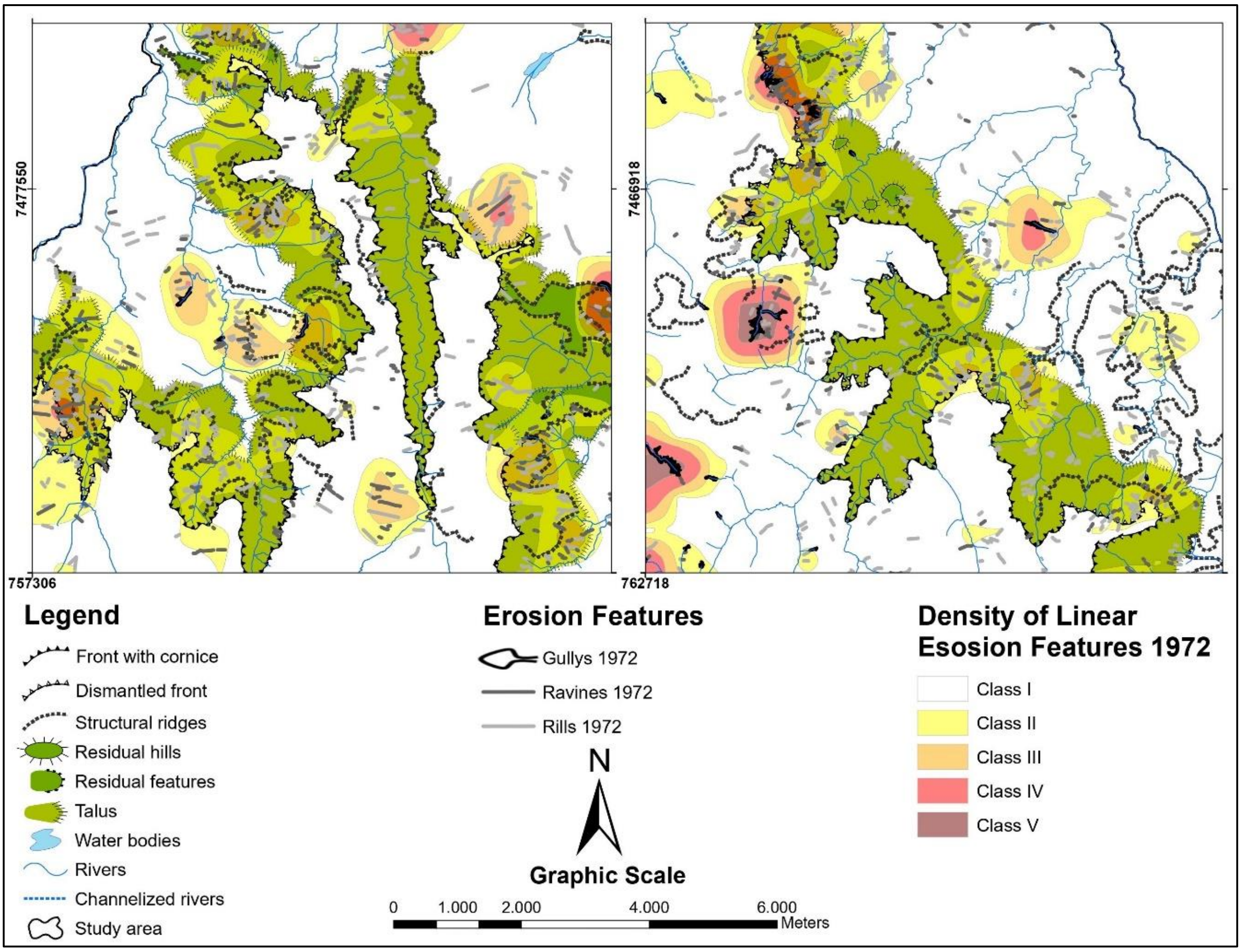


Figure 10. Linear erosion features density classes on the talus.

In the case of the Peripheral Depression, the overlap with the largest density classes of linear erosion features is low in the 1972 scenario, supporting 16.8% of the terrains in class IV and 8.5% of those in class V, which are more associated with the reverse (Table 1, Figure 7). However, due to the decrease in erosion features on the reverse, concomitantly with the increase in gullies in the Peripheral Depression in the 2010/2011 scenario, this sector now houses 39.4% of Class IV and 53.3% of Class V (Table 1; Figure 8). This increase is very well marked by the development of large gullies in one place, possibly due to local lithological and pedological characteristics (Figure 12).

Figure 11. Erosive features on the cuesta front. Source: The authors

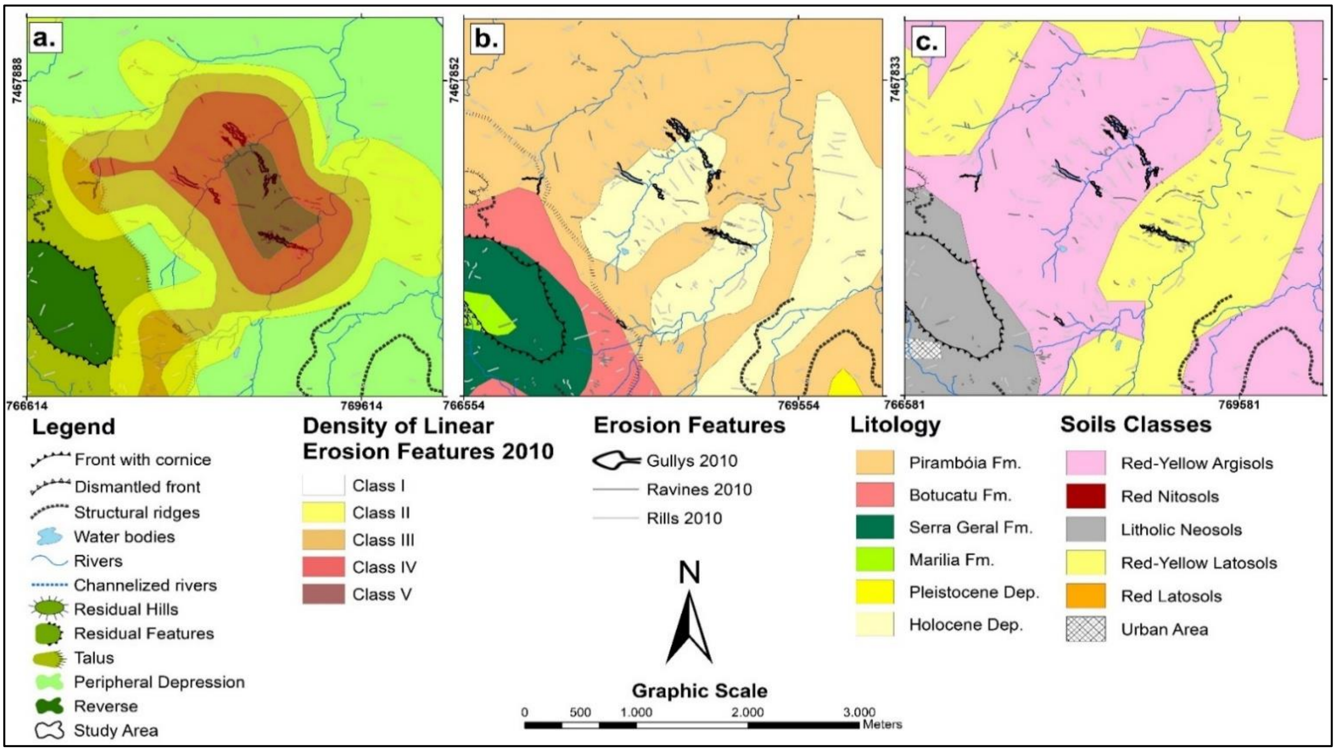


Figure 12. Erosive features in the Peripheral Depression (a); lithology (b) and soils (c). Source: São Paulo, 1984; Rossi, 2017

Regarding the influence of the lithology on the development of linear erosion features, a strong relationship was identified between class IV and the Marília and Serra Geral Formations, which respectively support 43.1% and 38.9% of the area included in this class (Table 2, Figure 13) in the 1972 scenario. In the case of class V, 76.8% (Table 2, Figure 14) are concentrated on the Marília Formation for the same scenario. Furthermore, in the 1972 scenario, the Pliocene-Pleistocene deposits, which occupy 3.6% of the study area, present 4.7% of class IV and 5.6% of class V (Table 2, Figure 13). In 2010, despite some similarities, an increase in classes IV and V was noted over the Pirambóia Formation and Holocene Deposits, as a result of the intensification of gullies in the Peripheral Depression. In this scenario, the proportion of overlap of Class IV with the Marília Formation is 35.9% and 19.4% for the Serra Geral Formation. In the case of Class V, the overlap value with the Marília Formation is 48.2% (Table 2, Figure 14).

Table 2. Lithology embasement of linear erosion feature density classes in1972 and 2010

Lithology	Total Area	Density of Linear Erosive Features									
		Class I		Class II		Class III		Class IV		Class V	
		1972	2010	1972	2010	1972	2010	1972	2010	1972	2010
Pirambóia Fm.	36.7%	41.7%	39.7%	19.1%	21.7%	17.0%	18.1%	9.7%	24.6%	4.0%	15.9%
Botucatu Fm.	10.2%	8.9%	9.2%	18.3%	15.3%	15.1%	20.4%	2.8%	2.1%	4.4%	0.0%
Serra Geral Fm.	31.9%	29.0%	30.5%	45.0%	43.1%	43.3%	36.9%	38.9%	19.4%	9.4%	0.2%
Marília Fm.	12.1%	10.6%	11.5%	10.5%	11.6%	18.9%	18.1%	43.1%	35.9%	76.8%	48.2%
Holocene Dep.	5.4%	6.1%	5.6%	4.1%	3.1%	2.9%	3.0%	1.0%	15.0%	0.0%	35.4%
Pliocene-Pleistocene Dep.	3.6%	3.7%	3.5%	3.1%	5.1%	2.9%	3.6%	4.7%	3.0%	5.4%	0.3%

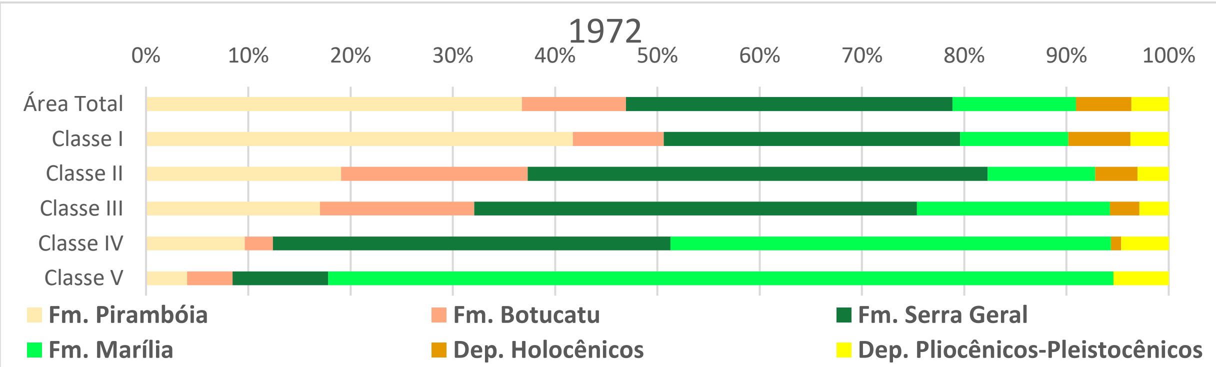


Figure 13. Lithology embasement of linear erosion feature density classes in 1972

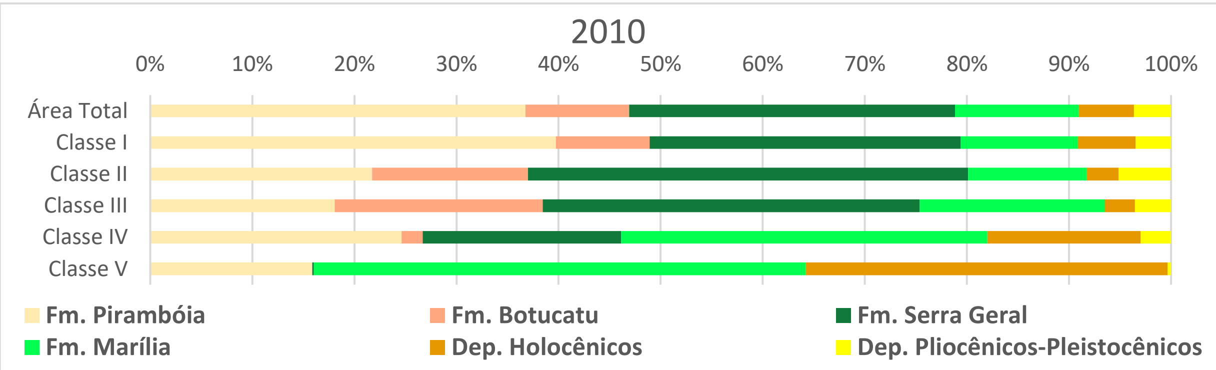


Figure 14. Lithology embasement of linear erosion feature density classes in 2010

Quantitative data, combined with qualitative analyses of the places where the highest classes are concentrated in both scenarios, reinforce the understanding that the lithological contacts of Marília and Serra Geral formations in the drainage headwaters create conditions for the intense development of linear erosion processes in the cuesta regions (Figure 9b). This is probably due to the change in infiltration rates in the transition between the formations, which change from a more permeable sandstone texture to a less permeable basaltic embasement, favoring the outcrop of subsurface waters. These conditions lead to the occurrence of a large number of springs, making these locations more fragile. In addition, the sandy characteristics of the Marília Formation and the Pliocene-Pleistocene deposits and, consequently, the lower resistance of these formations, also increase the susceptibility of these terrains to accelerated erosion by gullies and the evolution of these features upstream. Furthermore, the lower number of rills and ravines in these sectors reinforces the understanding that these are places more prone to processes linked to subsurface flow.

The sandy aspect of the Marília Formation gives rise to equally sandy and fragile soils from an erosion perspective (BEZERRA et al, 2009; ARRAES; BUENO; PIZARRA, 2010). This fact, associated with the contact with the less permeable basalts at the base, can intensify the erosion process. Regarding the structural ridges observed at some points of contact between the Marília and Serra Geral formations, it was noted that these increased erosion due to the steeper slope. However, in these locations, less extensive gullies were observed compared to those seen in places where the lithological contacts were not marked by structural ridges. These analyses suggests that the greater lithological resistance, evidenced by the presence of structural ridges, dynamizes the erosion process due to the slope, while the gullies are less developed upstream, with fewer branches. In contacts where there were no structural ridges, which suggests less resistance of the parent rock, the erosion features are more extensive.

Regarding the overlaps between the inear erosion features density classes and the Botucatu and Serra Geral formations, results similar to those associated with the talus were identified. Despite corresponding to 10.2% of the studied area, the Botucatu Formation supports 18.3% of Class II and 15.1% of Class III, while the Serra Geral Formation, which extends over 31.9% of the analyzed area, houses 45% of the Class II terrains and 43.3% of Class III terrains in the 1972 scenario (Table 2; Figure 13). In 2010/2011, the Botucatu sandstones underlie 15.3% of the Class II area and 20.4% of Class III, while the Serra Geral Formation supports 43.1% of the terrains inserted in Class II and 36.9% of those inserted in Class III (Table 2, Figure 14).

In addition to the quantitative data, the relationship between erosion features density and the contact areas between Serra Geral and Botucatu formations were also noted, suggesting that the transition between these heterogeneous structures enhances erosion dynamics (Figure 15a). Thus, in addition to the increase in erosion potential due to the slope of the front and structural ridges, these contacts imply discontinuities in infiltration rates, leading to the occurrence of springs, which, without the maintainence of the original vegetation, can lead to the development of gullies. Furthermore, these lithological formations gives rise to soils with distinct textural properties, which can impact the surface runoff dynamics.

Regarding the Pirambóia Formation and linear erosion dynamics, a weak relationship with the largest classes of erosion feature density was observed in 1972. Although it occupies 36.7% of the analysis area, the overlap with classes IV and V is, respectively, 9.7% and 4.0%, due to the concentration these features on the reverse in 1972 (Table 2; Figure 13). In 2010, these values reach 24.6% in Class IV and 15.9% in Class V, while the relationship with the Holocene deposits, which extend over only 5.4% of the study area, in the 2010 scenario supports 15% of the sectors included in Class IV and 35.4% of Class V (Table 2, Figure 14). These values are mainly reached in the sector where the greatest increase in gullies was observed (Figure 12b) and may also be associated with the lithological contact between these formations and the local pedological characteristics.

Regarding the pedological coverage, it was found that the highers densities of linear erosion features on the reverse were established on the Red and Red-Yellow Latosols. The Red Latosols, which occupy 10.4% of the analysis area, are mostly on the reverse and support, respectively, 36.2% and 41.6% of the areas of classes IV and V in 1972, however this value drops to 19.5% and 0% in the 2010 scenario (Table 3, Figures 16 and 17). The Red-Yellow Latosols are mostly distributed throughout the Peripheral Depression, but are also identified on the reverse, where they support extensive gullies in both scenarios (Figure 9c). The overlap of Red-Yellow Latosols with classes IV and V is, respectively, 19.0% and 0.1% in the 1972 scenario and 30.2% and 39.9% in 2010 (Table 3, Figures 16 and 17). However, it is worth noting that in the 2010 scenario, a large part of these overlaps are established in the Peripheral Depression.

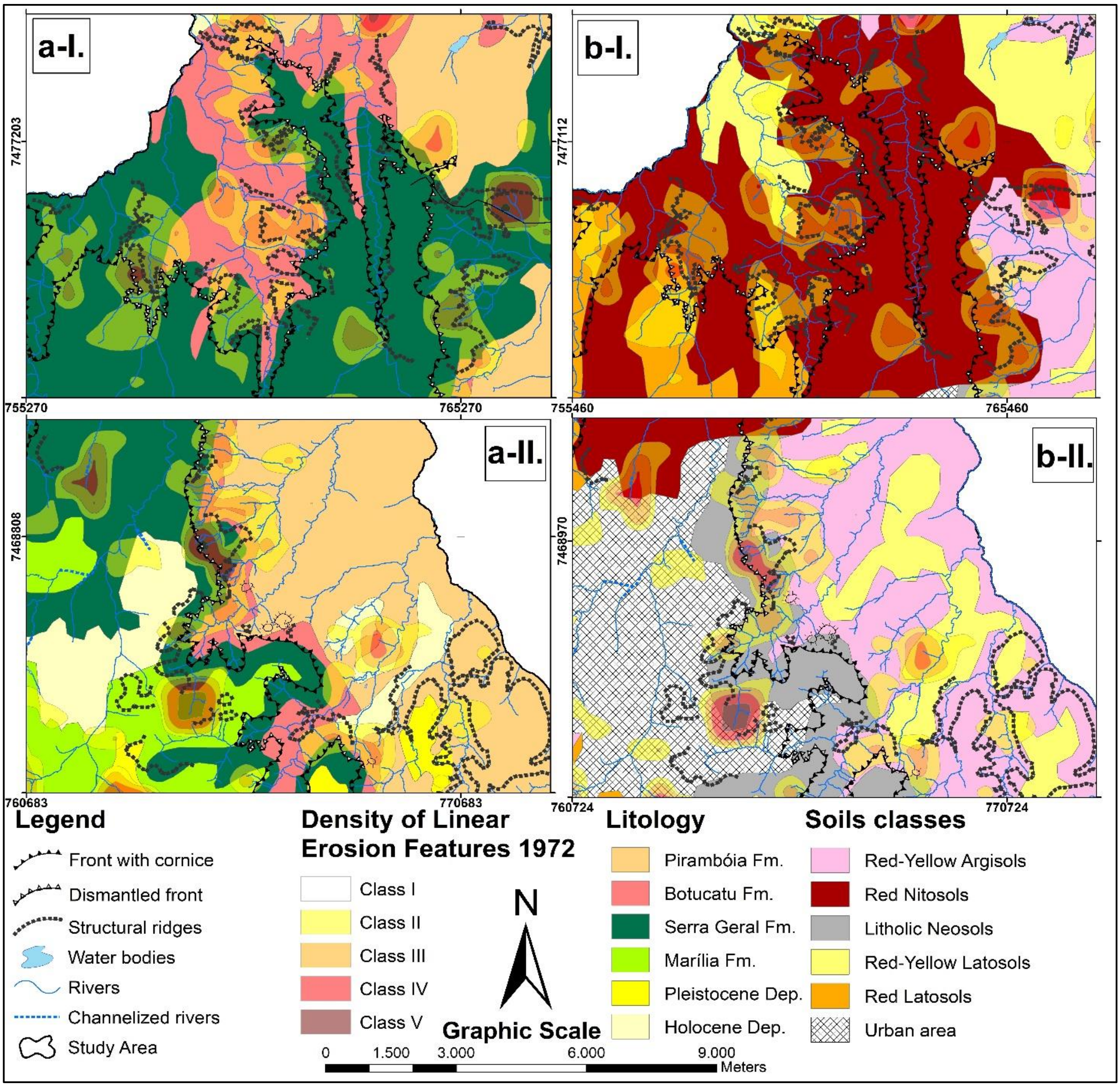


Figure 15. Linear erosion features density near to the contacts between the Serra Geral and Botucatu Formations (a) and on the Nitosols and Litholic Neosols (b). Source: São Paulo, 1984; Rossi, 2017.

Table 3. Soils distribution in the linear erosion features density classes in 1972 and 2010

Soils	Total Area	Density of Linear Erosive Features									
		Class I		Class II		Class III		Class IV		Class V	
		1972	2010	1972	2010	1972	2010	1972	2010	1972	2010
RED LATOSOL	10.4%	7.9%	9.8%	15.8%	11.1%	20.4%	18.5%	36.2%	19.5%	41.6%	0.0%
RED-YELLOW LATOSOL	21.7%	23.2%	21.8%	14.6%	19.9%	18.4%	21.9%	19.0%	30.2%	0.1%	39.9%
LITHOLIC NEOSOLS	11.1%	11.2%	10.5%	10.3%	15.5%	11.9%	12.6%	8.9%	10.2%	25.2%	26.1%
RED NITOSOL	16.4%	15.0%	15.8%	25.7%	21.1%	21.3%	21.3%	8.4%	1.8%	0.0%	0.0%
RED-YELLOW ARGISOL	31.0%	33.8%	32.7%	23.4%	23.2%	17.8%	19.8%	14.6%	26.3%	12.1%	26.0%
URBAN AREA	9.3%	8.9%	9.5%	10.3%	9.1%	10.2%	5.8%	12.8%	11.9%	20.9%	8.1%

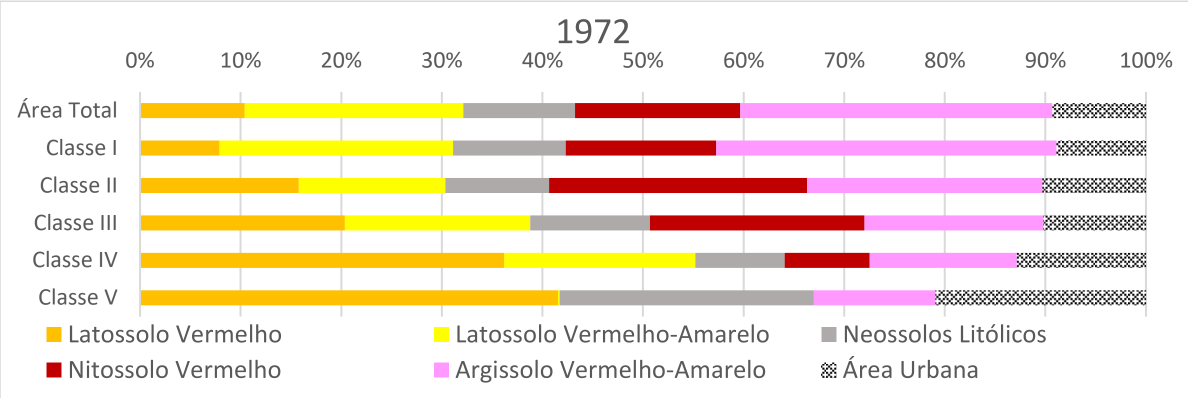


Figure 16. Soils **d**istribution in the linear erosive features density classes in 1972

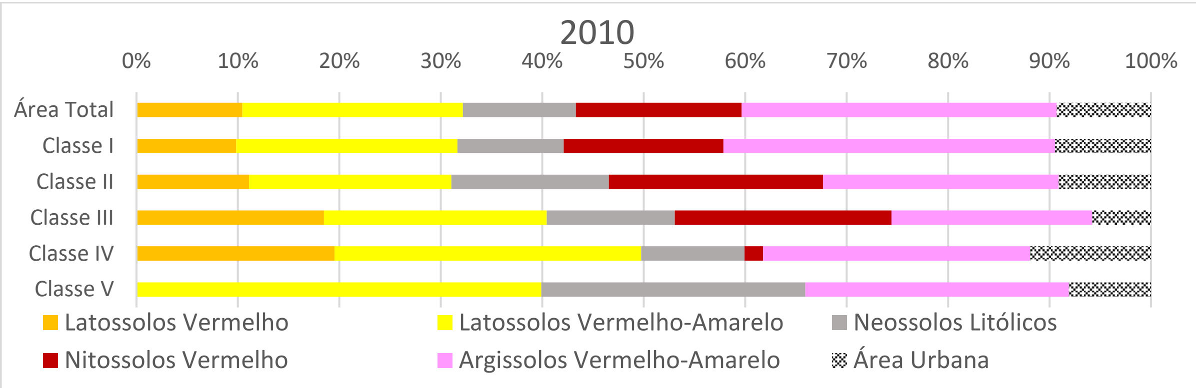


Figure 17. Soils **d**istribution in the linear erosion features density classes in 2010

The Red Latosols are associated with the Serra Geral and Marília formations and have textures that vary from more clayey to more sandy (IAC, 2014; ROSSI, 2017). Such characteristics can influence the dynamics and shape of the erosion features identified on this soil. The analysis of the cartographic documents demonstrated that the gullies identified on the Red Latosols near the contacts between the Serra Geral and Marília formations are smaller and less developed upstream, unlike those observed near the contact between the Marília Formation and the Pliocene-Pleistocene deposits, which are branched and well developed (Figure 18). This diversity identified in the morphodynamics of the erosion features corroborates the analyses of Nóbrega et al (2023), according to which the characteristics of origin and evolution of the gullies are associated with a set of local factors.

These findings suggest a more clayey and resistant Red Latosols identified near the Serra Geral-Marília contact. Furthermore, in these areas, higher concentrations of rills and ravines were also observed (Figure 9), which suggests a greater occurence of surface runoff processes, enhanced by the steep slopes associated with the structural ridges. On the other hand, the characteristics of the gullies identified in the Red Latosols over the Marília Formation, more extensive and with more upstream branches, similar to those identified over the Red-Yellow Latosols (Figures 9 and 18), suggests a more sandy content of the Red Latosols in these locations. This condition makes them more susceptible to the development of gullies due to subsurface runoff flows, similar to the conditions identified by Arraes, Bueno and Pissarra (2010) and IAC (2014). According to them, the high permeability and low cohesion make the sandy Red-Yellow Latossols especially prone to gullie erosion.

In the case of Red Nitosols and Litholic Neosols, the overlap with the erosion freatures density classes presents similarities with the dynamics recorded on the front and on the Botucatu and Serra Geral formations. Litholic Neosols correspond to, respectively, 10.3% and 11.9% of the lands under classes II and III, while Red Nitosols have, respectively, 25.7% and 21.3% of overlap with the same classes for the year 1972 (Table 3, Figure 16). Concomitantly, in 2010, Litholic Neosols support, respectively, 15.5% and 12.6% of the area of Classes II and III, while Nitosols support, respectively, 21.1% and 21.3% of the area of these same classes (Table 3, Figure 17).

Even with the clayey texture of Red Nitosols and Litholic Neosols when of basaltic origin (IAC, 2014; ROSSI, 2017), in Botucatu the erosion features associated with these coverings can develop due to the high slopes, as well as due to the proximity with sandier surfaces (Figure 15b). This condition was described by Stefanuto et al (2022) in a study of erosion features on the cuesta front in Analândia (SP), in transitions between more clayey soils associated with the basaltic basement and more sandy soils originated from the Botucatu and Passa Quatro sandstones. According to the authors, the more clayey soils have lower infiltration rates during the wet season, adding energy to the surface runoff that, when reaching the neighboring sandier and less-resistant coverings causes the development of rills and ravines.

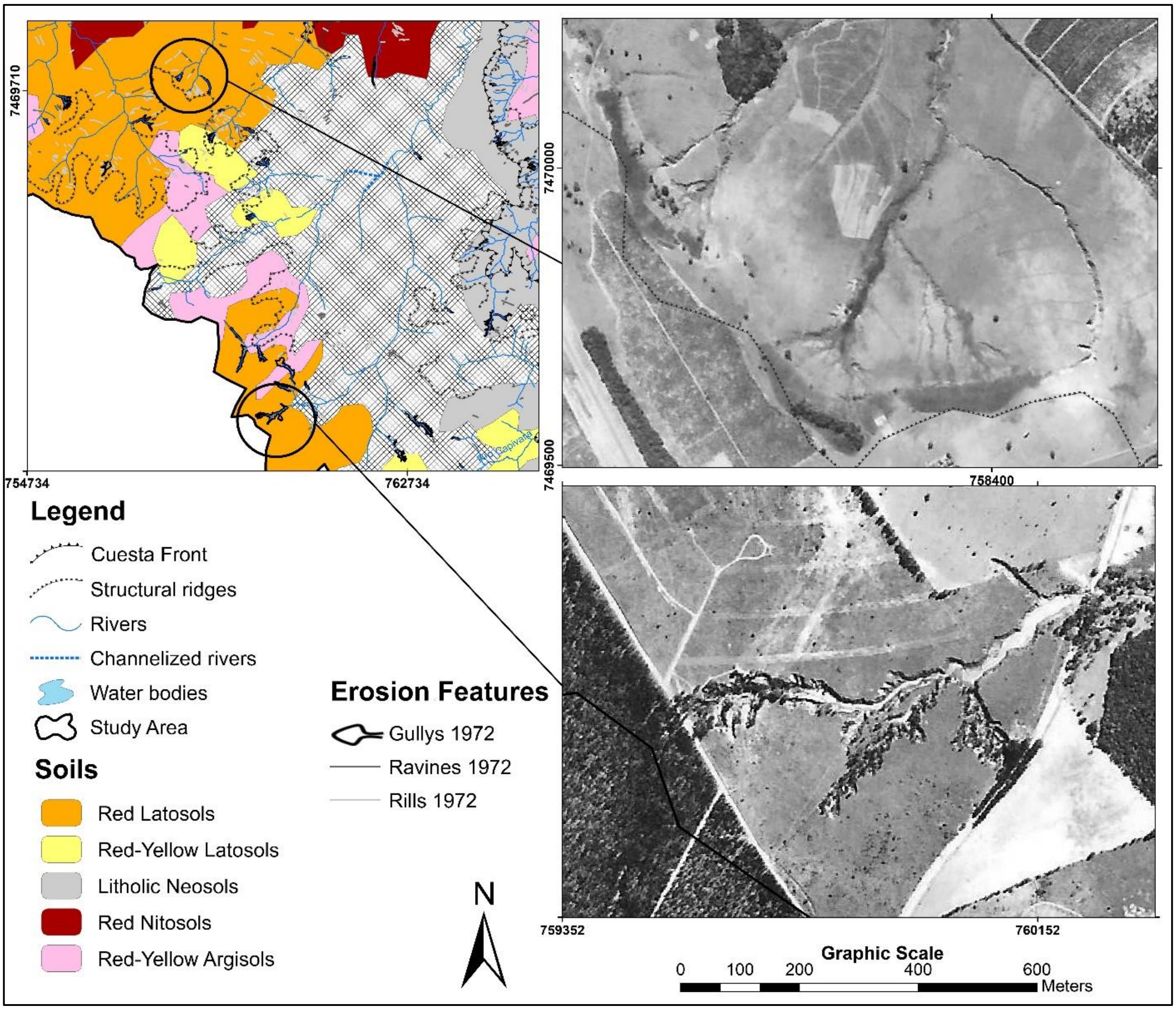


Figure 18. Erosive features on Red Latosols. Source: Terrafoto, 1972; Rossi, 2017

In the case of Litholic Neosols, their shallow depth and low cohesion (IAC, 2014) also contribute to their greater susceptibility to the development of linear erosion features in cuesta relief regions. Daniel and Vieira (2015) identified Neosols with a sandstone matrix at the base of the São Pedro cuesta (SP) that are especially prone to gullie erosion. Similarly, Bezerra et al (2009) found high erosive susceptibility in sandy and unconsolidated material, enhanced by the relief energy over colluvial deposits at the base of the Marília Plateau.

Another influence of Litholic Neosols and Red Nitosols on the linear erosion dynamics at the cuesta front is related to the morphodynamic characteristics of the erosion features itselfs. In addition to the greater frequency of rills and ravines due to the slope, the gullies in these places tend to be smaller, narrower and with fewer branches (Figure 11), unlike the widened, branched and deeper gullies found on the reverse and the Peripheral Depression latosols. This fact is probably related to the greater resistance of the Red Nitosols and the shallower depth of the Litholic Neosols found in the steepest terrains.

In the case of pedological influence on erosions in the Peripheral Depression, as it was observed the grater concentrantion of erosion features on the contacts between the Red-Yellow Argisols and the Red-Yellow Latosols.

In 1972, the Red-Yellow Argisols supported 14.6% of the area of Class IV and 12.1% of the area of Class V (Table 3, Figure 16). In the 2010 scenario, an intensification of the linear erosive features in the Red-Yellow Argisols was noted, causing them to support 26.3% of the lands in Class IV and 26.0% of the lands in Class V (Table 3, Figure 17).

The consulted bibliography indicates that the São Paulo Argisols are characterized by their high or medium to very high erodibility (SILVA; ALVAREZ, 2005; IAC, 2014; CORRÊA; MORAES; PINTO, 2015; ROSSI, 2017). This characteristic would be mainly associated with the low cohesion of the more sandy surface horizons and the low permeability of the subsurface horizons, with a higher clay content. It, provides greater susceptibility to the development of erosive processes as a result of the variation in the textural gradient between the horizons (IAC, 2014; DEMARCHI; ZIMBACK, 2014; CORRÊA, MORAES, PINTO, 2015; SILVA; LUPINACCI, 2021).

However, what was identified is that the largest linear erosion features density are associated with Red-Yellow Argisols in the contact with Red-Yellow Latosols (Figure 12c). Possibly, the transition from latosols to argisols is associated with subsurface granulometric variations that enhance the development of erosive processes, either due to the textural gradient or due to the lower resistance of the latosols (Figure 19). According to Nóbrega et al (2023), variations in the textural gradient between horizons increases the occurrence of subsurface water flows and, consequently, the widening and branching of the feature upstream due to the pipping process.

Figure 19. Erosive features in the Peripheral Depression on Red-Yellow Latosols. Near the Indiana Plant (Botucatu – SP). Source: The authors, 05/31/2021

5. Conclusions

The cross-referencing of cartographic documents identified a high concentration of gullies on the cuesta reverse, in the drainage headwaters, strongly associated with contacts between more sandy lithologies (Marília Formation or Pleistocene-Pliocene deposits) with less permeable lithologies, such as Serra Geral. These contacts may also be marked by structural ridges, enhancing the erosive action due to the slope. In addition, the pedological characteristics of the reverse also played an important role in the erosive dynamics, since in the drainage headwaters, gullies were recorded mainly on Red and Red-Yellow Latosols. In addition to being susceptible to the development of these processes, these soils influence the morphodynamics of the features due to their propensity for evolution, widening and branching.

Another area where linear erosion features are concentrated, mainly rills, ravines and small gullies, is the cuesta front. These erosive features are enhanced by the steep slope, the length of the hillslopes and the colluvial material at the base, which is less resistant. The lithology and the pedological coverings also stimulate these processes. The relationship between Red Nitosols and Litholic Neosols and the linear erosion features density classes suggests that the transition from more clayey and less permeable coverings to more sandy and less resistant ones is a factor that enhances the development of features associated with surface runoff.

In the Peripheral Depression, large gullies were also identified in areas of lithological and pedological transitions, in the case of the Pirambóia Formation and Holocene deposits and Red-Yellow Argisols and Red-Yellow Latosols. These results suggest that this contact favors the development of these features due to the textural discontinuity between the horizons, which may interfere with the dynamics of subsurface runoff.

Thus, the slope in the front and the lithological and pedological contacts influence the development of linear erosion features in the cuesta region of Botucatu. The transition between heterogeneous formations and coverings, typical of cuesta reliefs, due to the high geodiversity of these environments, is a fundamental element for understanding and preventing environmental degradation by accelerated soil erosion. Furthermore, it is necessary to reaffirm that land use should be analyzed in future studies since it can constitute a decisive factor in soil degradation. For this reason, knowledge about the morphodynamics of cuesta regions is essential to support an environmental policy that considers their specificities, in order to guarantee the preservation and conservation of soils and other natural resources and processes.

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