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Spatiotemporal analysis of gullies and environmental controlling factors in the municipality of Alegre (state of Espírito Santo, southeastern Brazil)

Análise espaçotemporal de voçorocas e fatores ambientais controladores no município de Alegre (Estado do Espírito Santo, Sudeste do Brasil)

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Abstract

Water erosion of soil slopes causes several environmental, economic, and social losses worldwide every year, particularly, when it reaches more advanced stages, leading to the formation of gullies. The municipality of Alegre, in the state of Espírito Santo (southeastern Brazil), has numerous gullies, which stand out in the landscape by their impressive proportions and environmental impacts. Nevertheless, very few studies have been published on the subject and most focus on specific erosion features. Therefore, this study aimed at mapping out the gullies to create an inventory and at qualitatively evaluating the environmental factors controlling gully development from 2009 to 2019. Terrain elevation, slope angle, aspect, surface curvature, lithology, soil types, rainfall erosivity, and land cover were considered gully causative factors. Google Earth Pro imagery and classical Geographic Information System (GIS) techniques were used to locate the gullies and to process/evaluate the environmental factors. The number of gullies in the study area remained approximately constant over the past ten years. Results revealed that the gullies may have started at different periods and are still active and evolving. Finally, the spatial distribution of the gullies is not random, but controlled by geomorphological, geological, and land cover factors.

Keywords: Soil erosion; Environmental impacts; Nitisol; Geoprocessing; Soil conservation.

Resumo

A erosão hídrica do solo em encostas é responsável por causar uma série de prejuízos ambientais, econômicos e sociais em todo o mundo a cada ano, principalmente quando atinge estágios mais avançados, levando à formação de voçorocas. O município de Alegre, Estado do Espírito Santo (Sudeste do Brasil), possui inúmeras delas, que se destacam na paisagem por suas impressionantes proporções e impactos ambientais. Apesar disso, ainda são poucos os estudos publicados sobre o assunto, e a maioria enfoca voçorocas específicas. Diante disso, o objetivo deste estudo foi realizar um inventário das voçorocas e analisar qualitativamente os fatores ambientais que controlam o desenvolvimento das mesmas para o período de 2009 a 2019. Elevação do terreno, declividade, aspecto, curvatura da superfície, litologia, tipos de solos, erosividade da chuva e uso da terra, foram considerados fatores causadores de voçorocas. Imagens do Google Earth Pro e técnicas clássicas de Sistema de Informação Geográfica (SIG) foram usadas para localizar as voçorocas e processar/avaliar os fatores ambientais. O número de voçorocas na área de estudo permaneceu aproximadamente constante nos últimos dez anos. Os resultados revelaram que as voçorocas parecem ter começado em períodos diferentes e ainda estão ativas e evoluindo. Por fim, a distribuição espacial das voçorocas não é aleatória, mas sim controlada por fatores geomorfológicos, geológicos e de uso da terra.

Palavras-chave: Erosão do solo; Impactos ambientais; Nitossolo; Geoprocessamento; Conservação do solo.

INTRODUCTION

Water erosion is a natural process of landscape evolution. However, human activities, in general, tend to amplify and accelerate this process. As a consequence, soil erosion causes several environmental, economic, and social losses worldwide and, when not controlled, it can damage roads, railways, agricultural lands, and urban areas (Morgan, 1995; Poesen et al., 2003; Telles et al., 2011). In addition, water erosion causes large soil losses and, consequently, sediment accumulation in river channels, which, in turn, negatively affect flooding phenomena (Robinson and Blackman, 1990). Therefore, the study of the soil erosion process is of paramount importance for land use and natural resource management in both urban and rural areas (Pinto, 2018).

Water erosion is controlled by several environmental factors, such as surface topography, rainfall, slope angle, geology, soil properties, land use and land cover, surface curvature, etc. (Bigarella and Mazuchowski, 1985; Silva et al., 1993; Valentin et al., 2005; Chaplot, 2013; Rahmati et al., 2016; Mararakanye and Sumner, 2017). The process starts with the impact of rain drops on the surface land (splash effect), followed by surface runoff and sediment transport, and finally the accumulation of detached sediments (Guerra et al., 1999; Gao, 2013; Rotta and Zuquette, 2015). When surface water flow is concentrated, surface incisions may develop and lead to the formation of rills and gullies (DAEE/IPT, 1990). Gullies involve both surface and subsurface erosion processes (e.g., piping) according to Bernatek-Jakiel and Poesen (2018) and DAEE/IPT (1990), and represent the most advanced and complex stage of the phenomenon. According to Guerra et al. (1999) and SSSA (2008), gullies are well-defined surface incisions, which are meters to tens of meters in depth, width, and extent. In the municipality of Alegre, located in the state of Espírito Santo (Figure 1), a large proportion of its territory has been used for cattle raising and coffee plantations over the last decades.

The municipality of Alegre has a large number of gullies spread all around its urban and rural areas, which are massive in size and contrast with the natural and anthropic landscape (Figure 2). Despite that, very few studies have been published on the subject and most of these studies focus on specific erosion features (Marchioro and Oliveira, 2014; Marchioro et al., 2016). Therefore, this study aimed at: mapping out the gullies in the municipality of Alegre from 2009 to 2019, and qualitatively evaluating the environmental factors controlling gully development.

STUDY AREA

The municipality of Alegre is located in the southern region of the state of Espírito Santo (southeastern Brazil) (Figure 1). According to the 2019 census (IBGE, 2019), it has 30,084

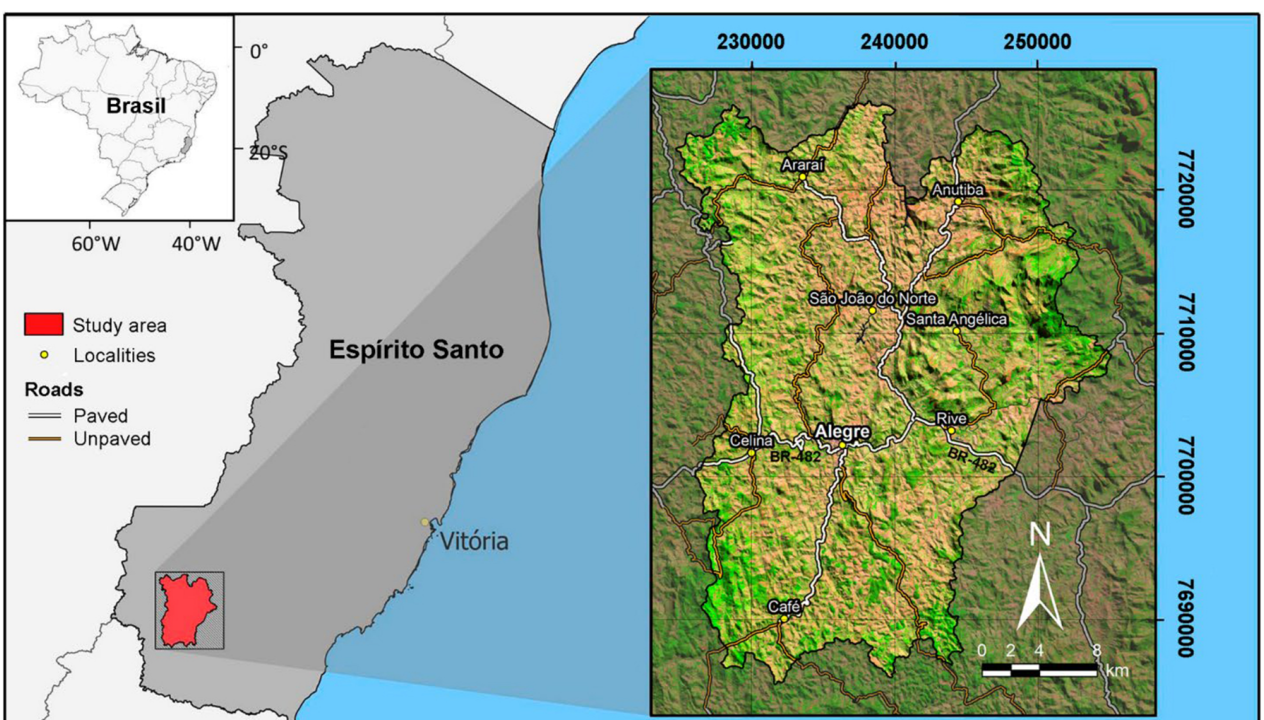


Figure 1. Study area with indication of localities and main roads.

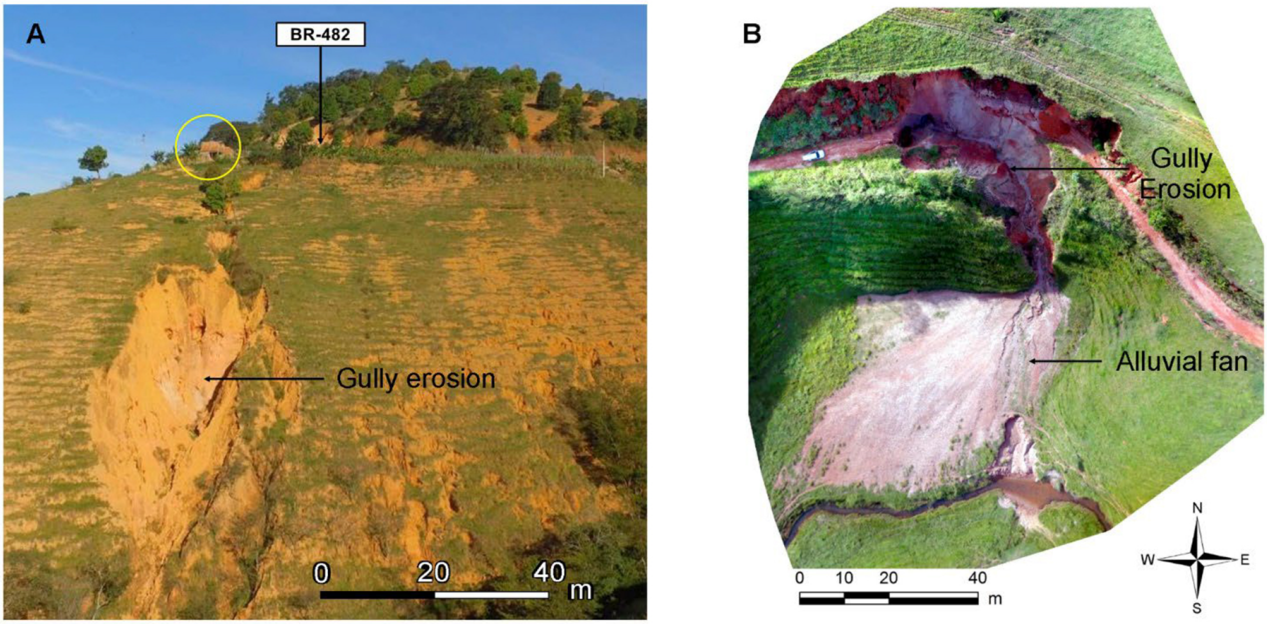


Figure 2. Illustrations of the gullies in the municipality of Alegre: (A) residences (yellow circle) and BR-482 highway (between the municipality of Alegre and the district of Celina) threaten by a large gully (oblique view), and (B) unpaved road cut by a gully with the formation of an adjacent alluvial fan-shaped deposit (plan view).

inhabitants. The average annual rainfall is 1,341 mm and the average annual temperature is 23.1 degrees Celsius (Lima et al., 2008). The climate is classified, according to Koppen and Geiger (1936), as Aw (savanna climate), with dry winters and hot and rainy summers. The study area is 772 km^2 and elevation ranges from 91 to 1,438 m.a.s.l.

Currently, most of the original vegetation cover (semi-deciduous forest) has been replaced with pasture for raising cattle and family farming. After the economic decline of coffee crops in the 1930s, many farmers in the region migrated to the livestock sector, which required large areas for grazing (SEAG, 2008). Since then, land use has been mainly focused on livestock farming and coffee plantation.

The geomorphology of the study area is characterized by dissected landforms with average elevations around 600 m.a.s.l., aligned valleys, and bare rocky domes (inselbergs) (IJSN, 2012). According to Cunha et al. (2016), the study area comprises different types of soil, such as nitisol, latosol, oxisol, cambisol, and neosol.

The geology of the study area was described by Vieira (1997) and comprises a set of high-grade metamorphic ortho- and paragneisses, which can be locally milonitized and/or migmatized, mylonites, and igneous rocks. According to Vieira (1997), paragneisses are included in the Paraíba do Sul Complex, which also comprises amphibolites, quartzites, and marbles. Orthogneisses represent pre- to syn-collisional granitoids with tonalitic and granodiorite dominating compositions. Post-collisional rocks involve acid and basic igneous rocks grouped into the Santa Angélica Intrusive Complex, as well as isolated intrusive charnockite plutons. The northwestern region of the study area exposes high-grade mylonites and ultramylonites included in the NE-trending Guaçuí Shear Zone (Hartwig et al., 2020). All the above-mentioned geological units belong to the southern part of the Neoproterozoic Araçuaí-West Congo Orogen (Pedrosa-Soares and Wiedmann-Leonardos, 2000).

MATERIAL AND METHODS

The methodology of this study involved the application of GIS techniques (Conforti et al., 2011; Pinheiro and Redivo, 2016; Igwe et al., 2020). We followed two steps: elaboration of gully erosion inventories for the years 2009 and 2019; and spatial analysis of the environmental factors controlling gully development. All maps shown in this study were prepared in the ArcGIS 9.5 (ESRI) software. The Universal Transverse Mercator (UTM) coordinate system and the World Geodetic System 1984 (WGS-84) ellipsoid were used.

Gully erosion inventory maps were prepared based on a visual inspection of Google Earth Pro imagery (Boardman, 2016; Igwe et al., 2020; Zhou et al., 2021). The inventory includes gully location, area, and morphology. The eroded area of each gully was determined by manual digitization in Google Earth Pro (Casalí et al., 2015). The gully erosion area was classified by the natural breaks method (Jenks, 1977) as follows:

- very small (< 280 m^2);
- small (281 – 650 m^2);
- moderate (651 – 1,600 m^2);
- large (1,601 – 2,800 m^2);
- very large (> 2,800 m^2).

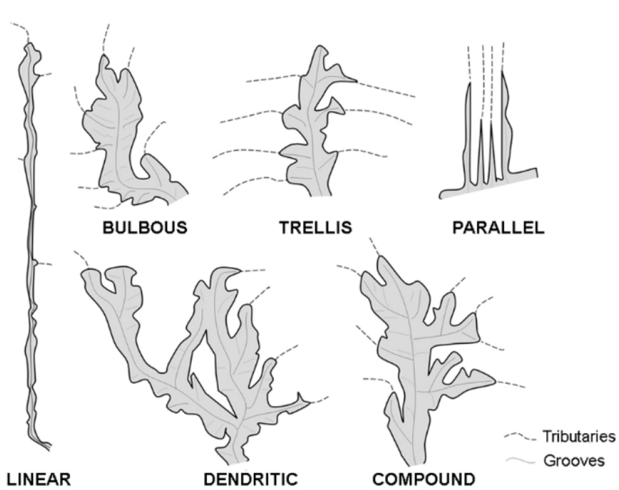
Gully erosion morphology was classified based on the classical study of Ireland et al. (1939) (Figure 3). Field surveys in selected places were carried out in order to confirm the gully inventory map.

Spatial analysis of the environmental factors controlling gully development included the preparation of maps grouped into five categories:

- topographical (elevation, slope, surface curvature, and aspect);
- environmental (land cover);
- geological (lithology);
- soil properties (type of soil);
- hydrological (rainfall erosivity).

Besides that, a gully erosion density map was prepared to evaluate spatial patterns in gullies distribution. The gully erosion density map was elaborated using the kernel density function with a search radius equal to 4 km. Elevation, slope angle, aspect, and surface curvature maps were derived from a 2-meter Digital Elevation Model (DEM) resampled to 25 meters. The DEM was produced from aerial triangulation of stereopairs and is available at https://geobases.es.gov.br/. Elevation and rainfall maps were classified based on the natural breaks method. Slope angle was classified according to Embrapa (1999) as:

- flat (< 3%);
- gently undulating (3 – 8 %);
- undulating (8 – 20%);
- strongly undulating (20 – 45%);
- hilly (45 – 75%);
- steep terrain (> 75%).



Source: adapted from Ireland et al. (1939).

Figure 3. Gully erosion morphologies.

The aspect map indicates the orientation of slope faces and ranges from 0 to 360 degrees, being classified clockwise as:

- flat;
- north;
- northeast;
- east;
- southeast;
- south;
- southwest;
- west;
- northwest.

The slope aspect controls vegetation cover type and distribution due to slope sunlight exposure, and also expresses the influence of geological structures. Surface curvature comprises both plan and profile curvature maps. The plan curvature map describes the surface water concentration downslope; and the profile curvature map, the surface water acceleration/deceleration. Regions where surface water concentrates at high speeds are prone to water erosion (Bernard et al., 2010). Surface curvature is classified as concave, convex, and linear. The plan curvature is negative for the concave shape and positive for the convex shape. The profile curvature is positive for concave shape and negative for convex shape. Null values indicate linear slopes. Land cover maps were generated using the MAXVER (maximum likelihood) classification algorithm (Vale et al., 2018; Santos et al., 2019). For this purpose, satellite images with similar lighting conditions and spatial resolutions were chosen. Two different red, green, blue (RGB) compositions were used to create land cover maps for the years 2009 and 2019, respectively: 5R4G3B (Landsat 5 TM) and 6R5G4B (Landsat 8 OLI). The following land cover classes were determined: urban areas; outcrops; water bodies; bare soil; pasturage/plantation; and forest. It is well known that vegetation cover plays a key role in the susceptibility to soil erosion as it intercepts rainfall before reaching the land surface, reducing water erosion capacity. The opposite is also true. The map accuracy was evaluated by the overall accuracy and the Kappa coefficient (Centeno, 2003; Lillesand et al., 2015).

The lithological map was prepared based on Vieira (1997). The soil type map was obtained from Cunha et al. (2016), which is based on the Brazilian Soil Classification System (Embrapa, 1999). The rainfall erosivity map makes it possible to evaluate the potential of rainfall to cause soil erosion (Bertoni and Lombardi Neto, 1999). For such map, we used rainfall data from 22 pluviometric stations (Figure 4) available at http://www.snirh.gov.br/hidroweb/apresentacao. Cassol et al. (2008) recommend using a time series of at least

20 years, but the available data were restricted to the last decade. The rainfall erosivity index was calculated according to the Equation 1 (Bertoni and Lombardi Neto, 1999):

$$EI = 67{,}355\left(\frac{r^2}{R}\right)^{0{,}85} \quad (1)$$

Where:
EI = is the average annual soil erosion (MJ.mm.ha^{-1}.h^{-1}.y^{-1});
r = is the average monthly rainfall (mm);
R = is the average annual rainfall (mm).

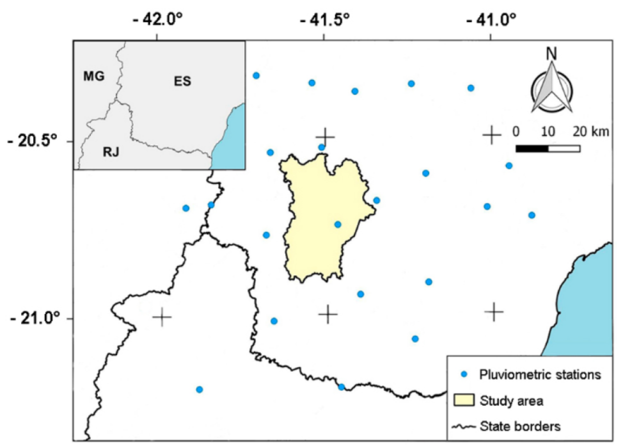


Figure 4. Location of the pluviometric stations used for the calculation of rainfall erosivity.

The rainfall erosivity index was determined for each pluviometric station and then spatially interpolated by the spline interpolation method.

RESULTS AND DISCUSSION

Gully erosion inventory mapping

A total of 70 gullies were mapped out in 2009 and 73 in 2019 in the municipality of Alegre. However, because of the presence of shadow areas, limited spatial resolution in rural areas, poor image contrast, vegetation cover (restoration process), hillside geometry (e.g., aspect and slope angle), and fieldwork surveys, the number of mapped gullies is actually smaller than the actual number. The visual interpretation of Google Earth Pro imagery has indicated that three gullies were rehabilitated through geotechnical engineering stabilization methods, such as benching, slope protection, and surface drainage system (Figure 5).

Figure 6 shows the histograms of gully surface area for the years 2009 and 2019. It shows that 75% were classified as very small to small (< 650 m^2) in 2009 and 78% were classified as small to large (650 – 2,800 m^2) in 2019. The total gully area for the years 2009 and 2019 were 72,454 m^2 and 79,311 m^2, respectively. Despite the slight increase in the eroded area (9.5%), the erosion process has been active in the period. Hartwig and Ribeiro (2021) recently published

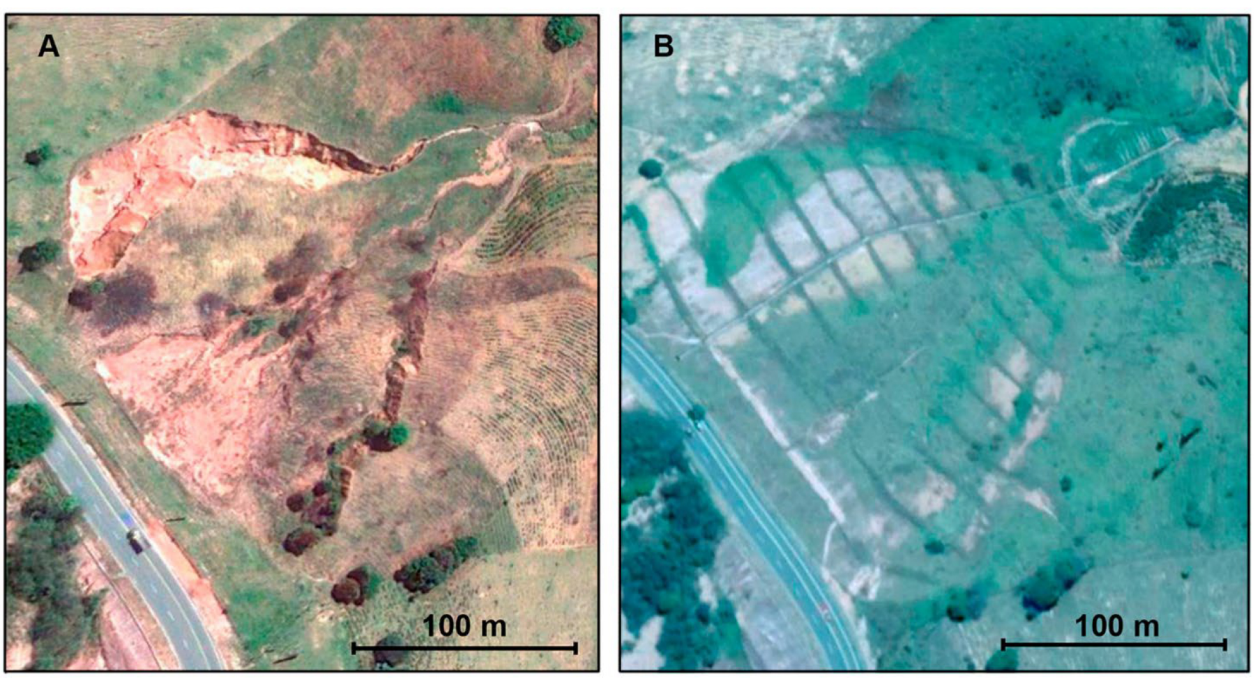


Figure 5. Rehabilitation of the gullies adjacent to BR-482 highway between the municipality of Alegre and the district of Celina: (A) 2009 and (B) 2019.

volume estimates for part of the gullies shown in this study. However, it is worth mentioning that distortions in Google Earth Pro imagery due to georeferencing process may lead to inaccuracy when determining gully surface area (Batista et al., 2019). The data also showed large variations in gully surface area (96 to 6,801 m^2). This suggests that gullies may have started at different periods since most of them have been carved in nitisols. Figure 7 illustrates the gully erosion density map for 2019, showing two spots of major concentration, one to the north and the other around the municipality of Alegre, both showing > 0.43 gully per square kilometer. Figure 7 shows that gullies occurred as clusters aligned in the northeast direction. Oliveira (2011) recognized a similar gully distribution pattern in the Brasília region (Federal District). According to the author, this clustered pattern would be associated with local environmental factors and also with human activities.

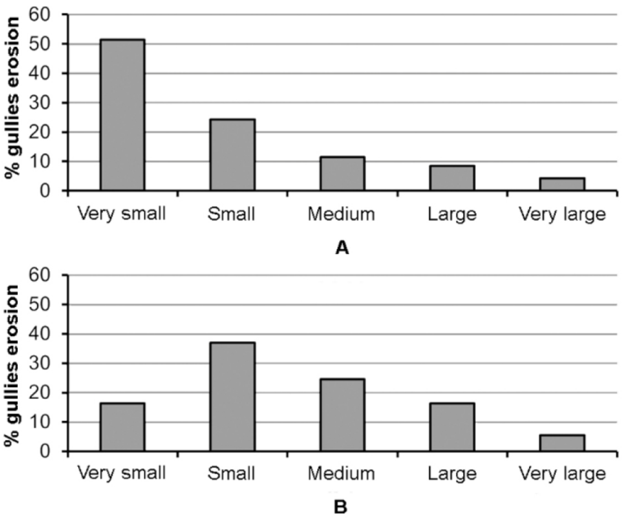


Figure 6. Histograms for gully surface area for the years (A) 2009 and (B) 2019.

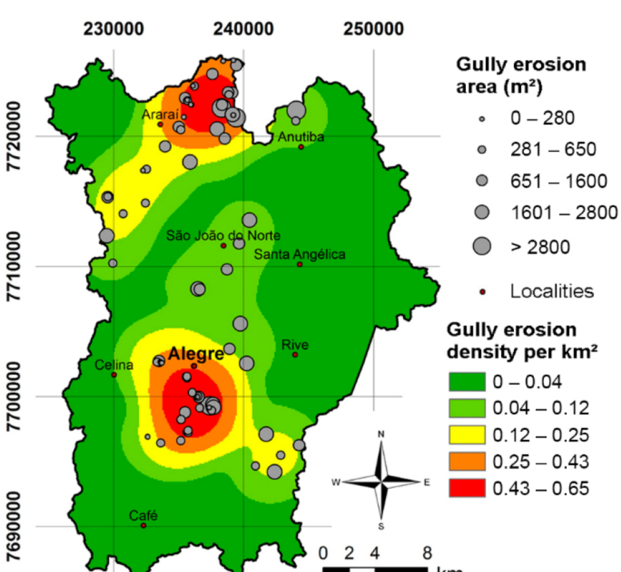


Figure 7. Gully erosion density map for the year 2019.

According to Cabral (2018), gully morphology can reveal the evolutionary state of gully erosion. Linear forms are considered the least evolved and compound forms the most evolved ones. In the study area, bulbous forms predominate (Figure 8), suggesting that the gullies found in Alegre are relatively young. In addition, Figure 8 shows a significant reduction in the number of linear gullies and an increase in the number of compound gullies between 2009 and 2019, which demonstrates that the erosion process was active during this period.

Environmental maps

Elevation, slope, aspect, and surface curvature maps

Figure 9A shows the elevation map for the study area. Elevations ranged from 55 to 1,475 m.a.s.l. Highlands occupy west and northeast areas (e.g., Santa Angélica locality). The gullies occurred in the range of 321 to 641 m.a.s.l. Figure 9B reveals a wide spectrum of slope angles in the study area, with slope angles > 20% being predominant. Steep slopes (> 75%) are preferentially concentrated to the northeast and northwest of the municipality. Figure 10A shows that 40% of the gullies occur in hillsides with slope angles between 40 and 53%. According to Cabral (2018), higher slope angles do not necessarily imply a greater incidence of gullies. Steep slopes usually show thin soil covers, which means that less soil mass is available for gully erosion. Morgan (1995) states that there is a non-linear relationship between water erosion and slope angle. As the slope angle changes from mild to moderate (up to about 20%), the erosion process rapidly increases, decreasing

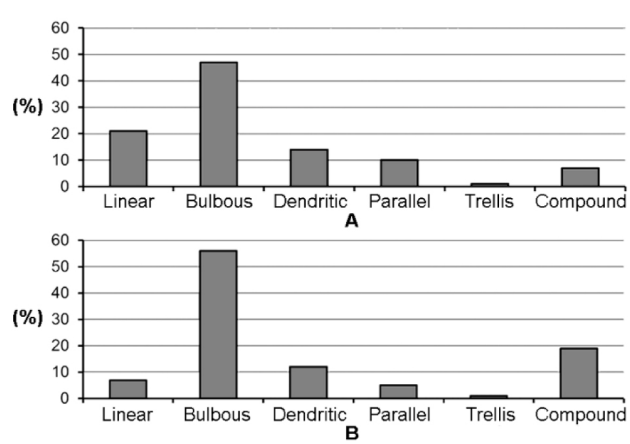


Figure 8. Histograms for gully erosion morphology for the years (A) 2009 and (B) 2019.

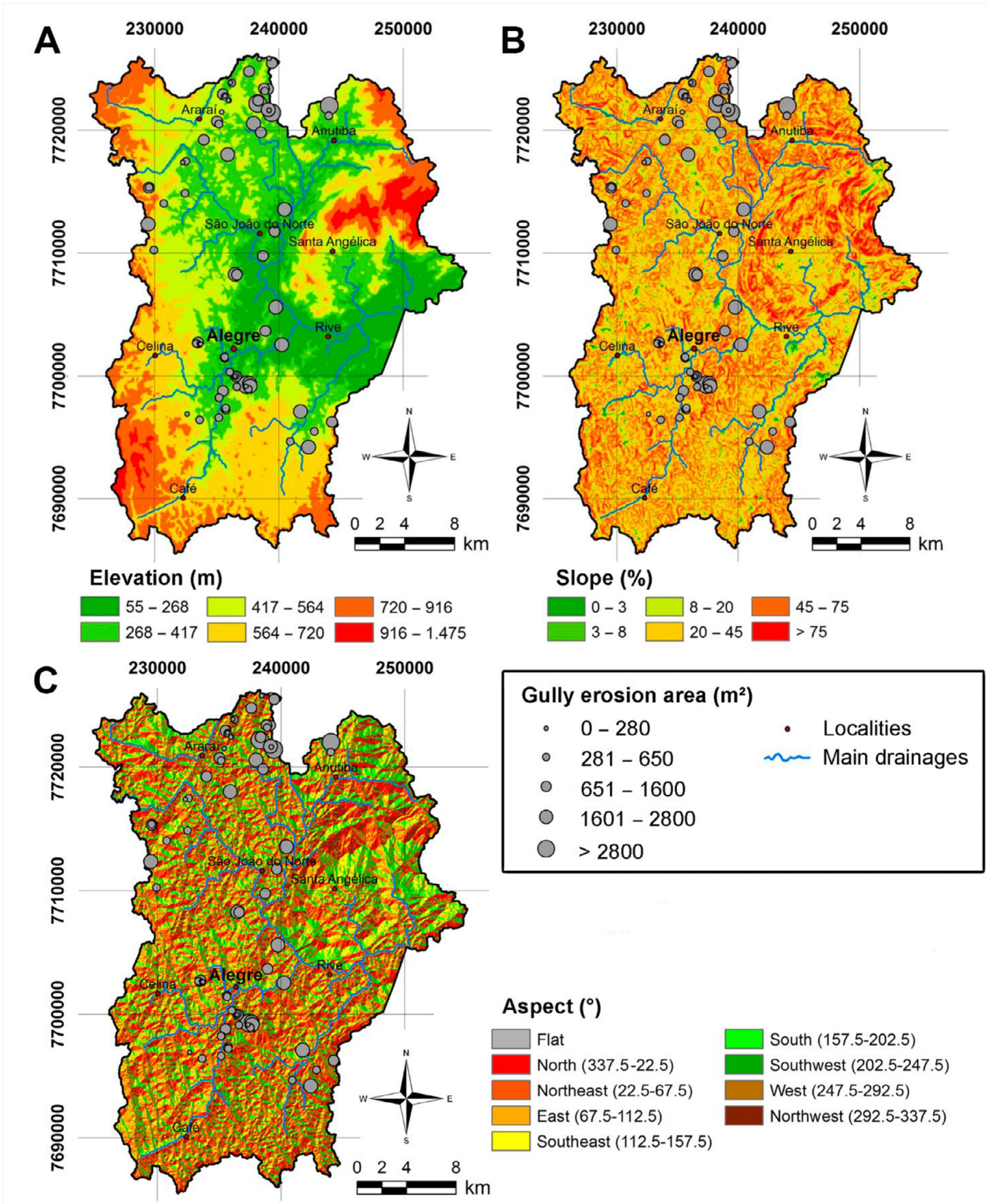


Figure 9. Environmental maps: (A) elevation map; (B) slope angle map; (C) aspect map.

for higher slope angles. A similar response was found for the study area, but with a slope angle threshold of approximately 50%. Figure 9C depicts the aspect map for the study area and Figure 10B indicates that the gullies cut hillsides with a wide range of slope orientations. The profile and plan curvature surface maps (Figure 11) show that linear surface curvatures have restricted occurrence in the study site. According to Zevenbergen and Thorne (1987), this is expected as null curvature values are rare to be found. Figure 10C reveals the prevalence of concave profile curvatures (> 57%). Sanchez et al. (2009) state that hillsides with concave profile curvatures are subjected to erosion and deposition in the upper and lower slope, respectively. Oliveira (1990) recognized a concentration of gully erosion on concave slopes in Bananal (state of São Paulo, Brazil). Figure 10D indicates that there is an equal proportion between concave and convex plan curvatures.

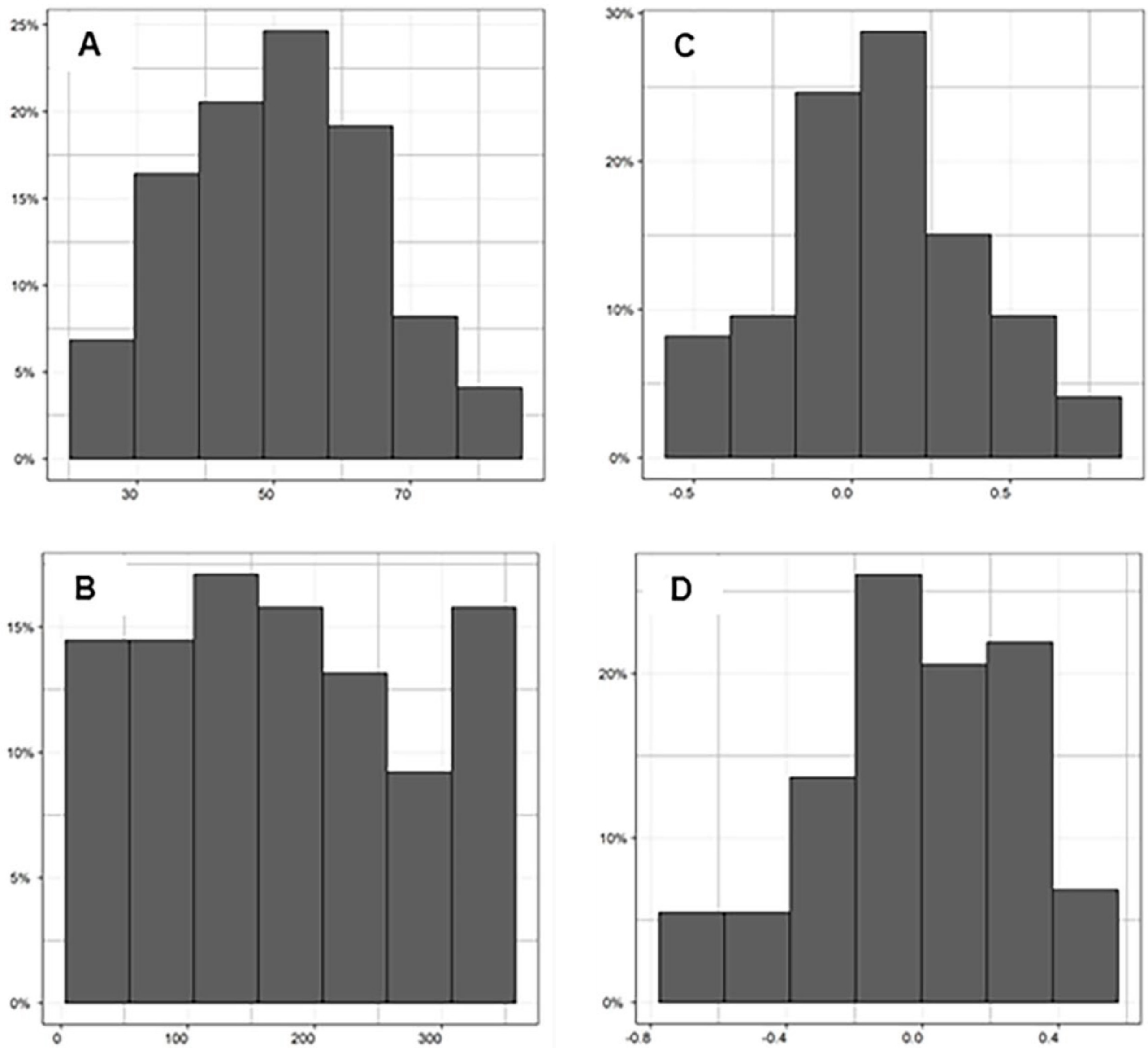


Figure 10. Histograms for (A) slope angle, (B) aspect, (C) profile surface curvature, and (D) plan surface curvature for active gullies in the year 2019.

Lithological and soil maps

Figure 12A shows the lithological map for the study area. The gullies occurred in three of the six lithological units: paragneiss from the Paraíba do Sul Complex (34 occurrences), orthogneiss (20 occurrences), and mylonites (19 occurrences). The post-collisional igneous rocks occupy a great proportion of the Alegre territory. Nevertheless, gullies have not been recorded in this geological unit. Post-collisional igneous rocks are well exposed in the study area and are covered by thin soil horizons, which could explain the lack of gullies. In addition, this region has a low population density and more (dry) weather conditions (e.g. Cactus plants are very common). The largest gullies (> 1,600 m^2) are evenly distributed over para- and orthogneisses. In addition, Figure 12A shows that the gullies follow the NE-trending of the Precambrian basement rocks, revealing structural control. According to Figure 12B, most of the gullies are associated with red nitisol (72.6%). Silva and Alvares (2005) argue that nitisol erodibility is considered moderate. However, in the study area, nitisol profile is very thick and inherits structural and mineralogical evidence from the parent rock (paragneisses). Thus, nitisol is enriched in quartz and mica minerals and has a

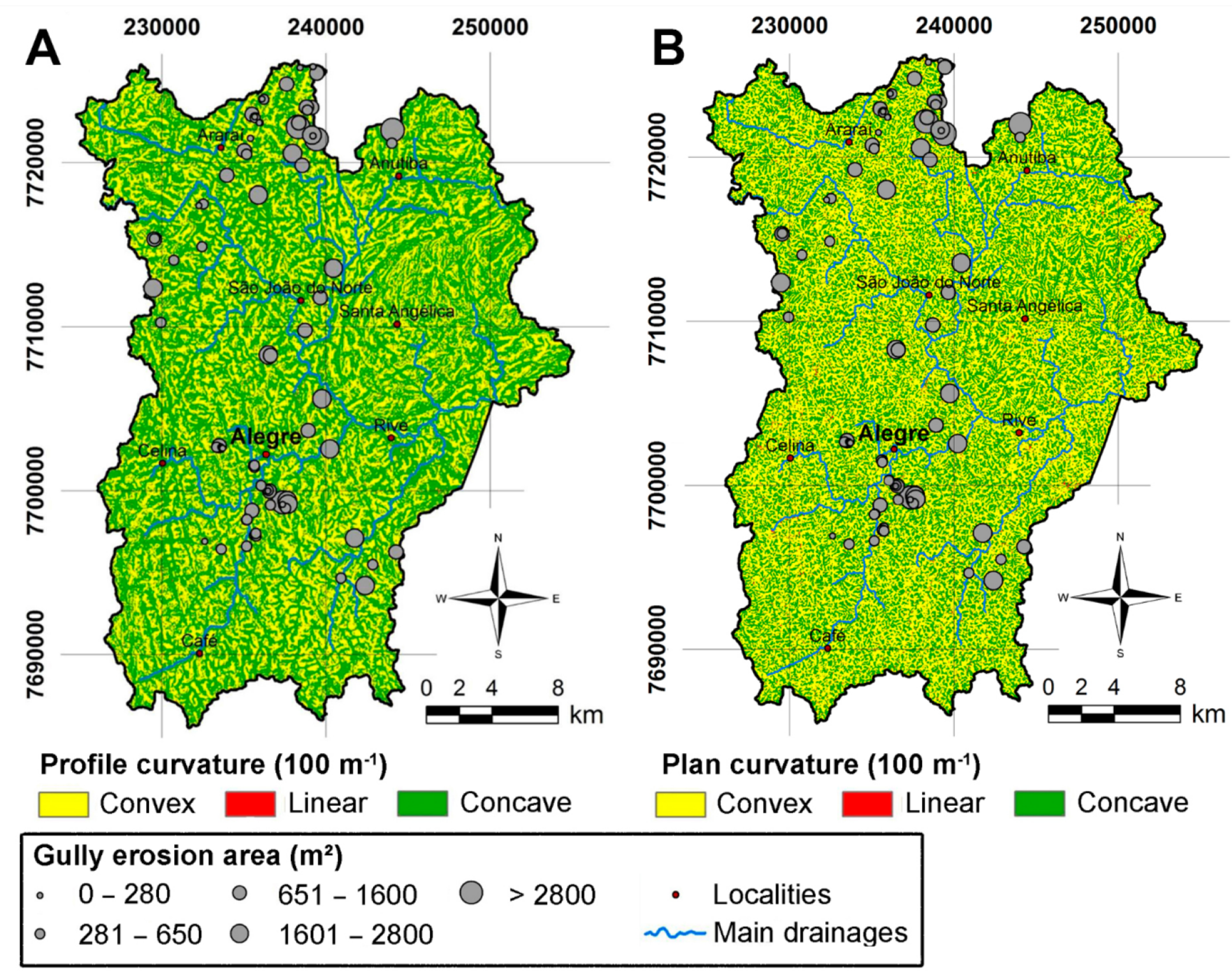


Figure 11. Surface curvature maps: (A) profile curvature and (B) plan curvature.

silty-sand texture, which makes it susceptible to water erosion, according to Camargo and Larach (1983). Gullies were not found over lithic neosol, which covers post-collisional igneous rocks. According to Alho et al. (2007), lithic neosol is associated with strongly hilly landforms.

Rainfall erosivity map

The rainfall erosivity map (Figure 13) shows that higher erosivity occurs in the northwest and northeast, which coincides with the highlands (Figure 9A). According to Melo Júnior et al. (2006), rainfall shows a positive correlation with elevation. Carvalho and Assad (2005) state that when wet winds from the coast reach mountainous areas, they rise, and their temperature drops. As a result, rain clouds form and rainfall occurs. In the state of Espírito Santo, Silva et al. (2011) found higher rainfall and rainfall erosivity values associated with the highlands. Despite that, gullies were not recorded above 641 m.a.s.l, but are largely distributed close to the city of Alegre, where rainfall erosivity is low. As already described, a reason for this behavior is that steep slopes usually show poorly developed soil cover, which means less soil volume available for water erosion.

Land cover map

Figure 14 shows the land cover maps for 2009 and 2019. An increase in bare soil from 2009 to 2019 can be clearly observed, particularly in the north-central part of the study area. The land cover maps for 2009 and 2019 had overall accuracy of 95.9 and 93.5%, and k = 0.92 and 0.91, respectively. Table 1 summarizes the proportion of gullies (in percentage) per class of land cover. The gullies were concentrated over pasture/plantation and bare soil land classes, respectively. Only about 8% were found in forested

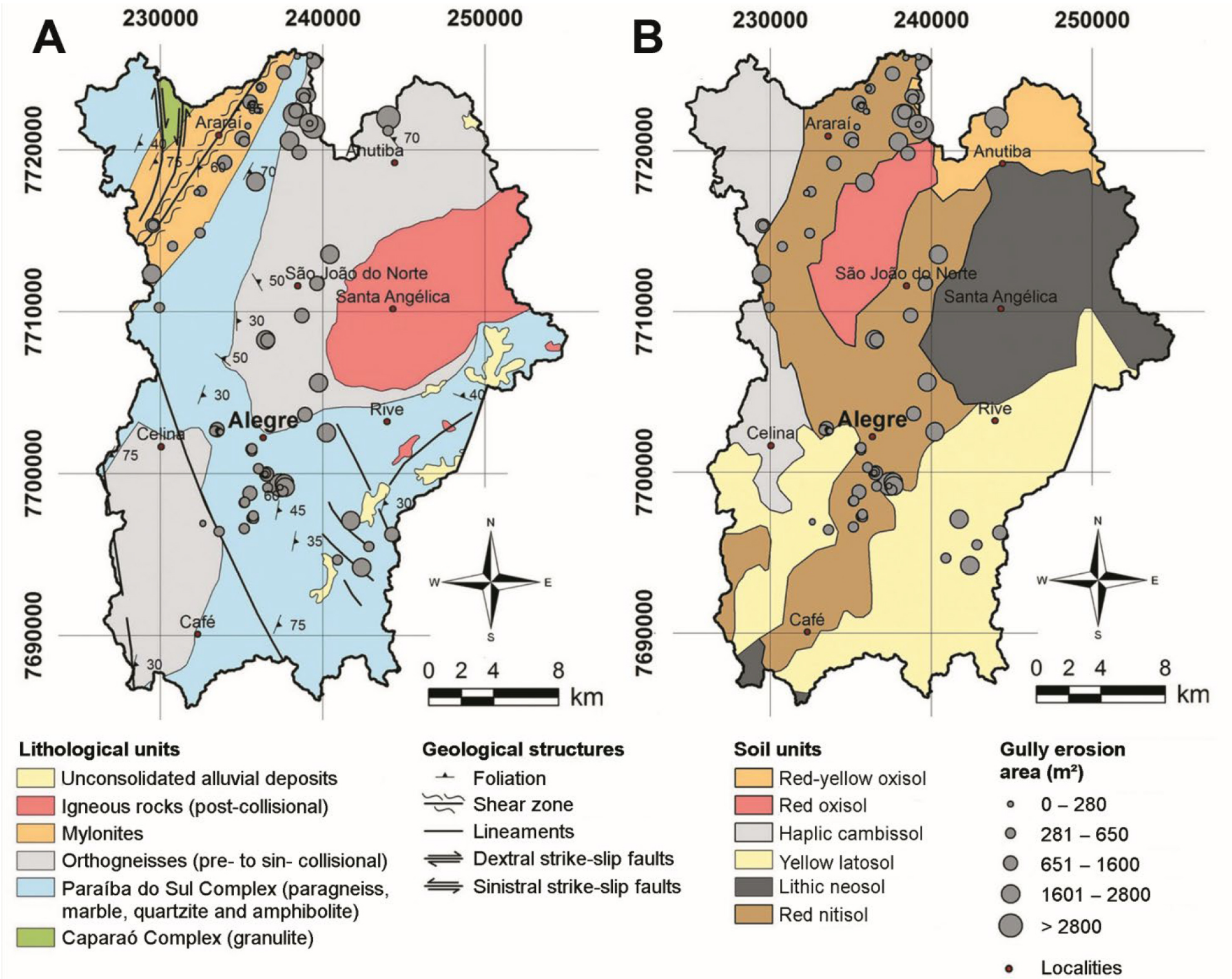


Figure 12. Lithological map (A) and soil map (B).

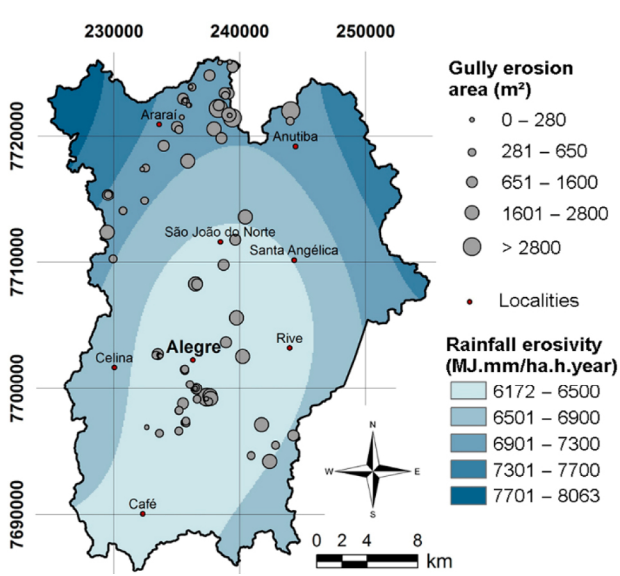


Figure 13. Rainfall erosivity map.

areas, which points out the impact of human activities (e.g. deforestation) on the erosion process. Viero (2004) and Castro et al. (2010) reported that areas used for grazing may enhance the water erosion process. According to Oliveira (2014), the use of fire over the years — a common soil management practice in Brazil — and overgrazing may also increase the rate of water erosion.

The interpretation of Google Earth Pro imagery revealed that about 38% of the gullies in the municipality of Alegre are associated with roadway slopes. As mentioned by Marchioro et al. (2016), this is due to ineffective rainwater drainage systems and lack of maintenance thereof. Field surveys also revealed a lack of erosion control measures in most roadways in the study area. Salomão and Iwasa (1995) described several simple and inexpensive erosion and sediment control measures for roadway construction in rural areas, such as slope protection, water collectors, energy dissipators, waterways, etc.

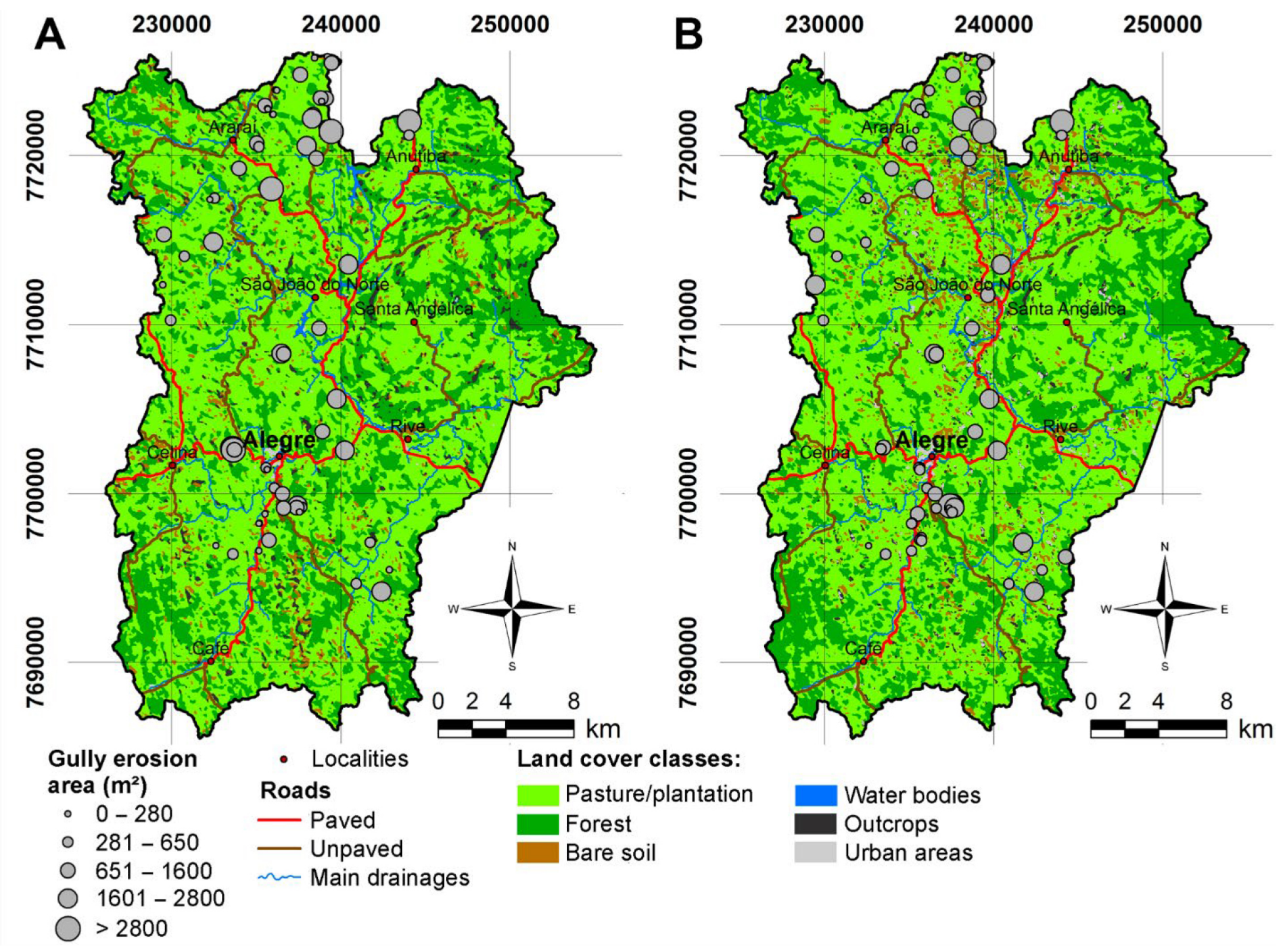


Figure 14. Land cover maps for years (A) 2009 and (B) 2019.

Table 1. Proportion of gullies (%) per class of land cover for the years 2009 and 2019.

Year	Land cover classes	%
	Pasture/plantation	80
2019	Bare soil	11.4
	Forest	8.6
	Pasture/plantation	75.4
2009	Bare soil	16.4
	Forest	8.2

CONCLUSIONS

Mapping out gullies and understanding their controlling factors is key for territory planning, conservation, and environmental management purposes. In this study, gullies were mapped out and inventoried for the first time in the municipality of Alegre (southeastern Brazil) and the controlling factors have been analyzed. Our findings revealed a large number of gullies spread out in the study area. The data indicate that these may have started at different periods in time and that they have not reached their ultimate stage of development. Gully distribution in the investigated area is not unpredictable, but rather controlled mainly by terrain elevation (321 to 641 m.a.s.l.), soil types (nitisol), land cover (pasture/plantation and bare soil), lithology (paragneiss), and also geological structures (i.e., NNE-trending fabrics associated with deformed Precambrian rocks). Surface curvature and rainfall erosivity factors were inconclusive concerning gully distribution. Finally, the results demonstrate that a large proportion of the gullies (38%) have developed due to the lack of erosion control measures on local roadways.

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