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Gullies inventory based on Google Earth PRO anaglyph images from Conceição da Barra de Minas, Minas Gerais, Brazil

Inventário de voçorocas baseado em imagens de anaglifo do Google Earth PRO de Conceição da Barra de Minas, Minas Gerais, Brasil

Ádria Kanome Mori Soares[1], Valéria Guimarães Silvestre Rodrigues[1*], Silvio Crestana[2], Rogério Resende Martins Ferreira[3]

[1] Universidade de São Paulo, São Carlos School of Engineering, Department of Geotechnical Engineering. 400 Trabalhador Sãocarlense Ave. 13566-590 – São Carlos, SP, Brazil. (adriakms@usp.br; valguima@usp.br)
[2] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Instrumentation. São Carlos, SP, Brazil. (silvio.crestana@embrapa.br)
[3] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Territorial. Campinas, SP, Brazil. (rogerio.ferreira@embrapa.br)
* Corresponding author

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ABSTRACT

Gullies are erosive features developed through water erosion processes, which combine runoff and subsurface water flow, which can mobilize great volumes of soil and cause severe impacts to both rural and urban areas. The south of Minas Gerais (Brazil) has been affected by soil degradation due to gullying, especially in Nazareno and Conceição da Barra de Minas. It is essential to assess the already eroded areas to obtain information on environmental conditions and deflagrant agents that dominate in the study area. Considering the lack of data in Conceição da Barra de Minas and the inexistence of a gully inventory in this municipality, we used anaglyphs of satellite images from 2023 and 2024 to identify and delimit gullies in 103 cells of 2,000 x 2,000 meters, which were compared with hypsometry, slope, geology, soils, watershed, and land use and land cover maps. The inventory identified 238 gullies, with an area of 727.63 ha. Most gullies were concentrated in the south of the study area, especially in the Palmital stream watershed. These features are situated in altimetric ranges between 940 and over 1,000 meters, occurring on slopes varying from 3 – 8% to 20 – 45%. The gullies are primarily associated with lithologies of the Cassiterita orthogneiss, Represa de Camargos metagranodiorite, and the Nazareno Formation. They develop within Cambisols and red-yellow Oxisols, often near to water springs, and are spatially correlated with regions used for temporary agriculture and pasture activities. These new insights provide tools to both avoid and recover eroded areas in Conceição da Barra de Minas.

Keywords: Erosion; Degraded areas; Environmental cartography.

RESUMO

As voçorocas são feições erosivas desenvolvidas a partir de processos de erosão hídrica, por meio da combinação de fluxo superficial e subsuperficial, que podem mobilizar grandes volumes de solo e causar impactos severos em áreas rurais e urbanas. O sul de Minas Gerais (Brasil) tem sido afetado por degradação do solo devido ao voçorocamento, especialmente em Nazareno e Conceição da Barra de Minas. O estudo de áreas erodidas é essencial para a obtenção de informações sobre os condicionantes ambientais e agentes deflagradores que dominam na área de estudo. Considerando a falta de dados em Conceição da Barra de Minas, e a inexistência de um inventário de voçorocas no município, utilizamos anaglifos de imagens de satélite de 2023 e 2024 para identificar e delimitar voçorocas em 103 quadrículas de 2.000 x 2.000 metros, as quais foram comparadas com os mapas de hipsometria, declividade, geologia, solos, bacias hidrográficas e uso e cobertura do solo. O inventário identificou 238 voçorocas, com área de 727,63 ha. A maioria das voçorocas está concentrada no sul da área de estudo, especialmente na bacia do Córrego do Palmital. Essas feições estão situadas em intervalos altimétricos entre 940 e 1.000 metros, ocorrendo em declividades variando entre 3 – 8% e 20 – 45%. As voçorocas são primeiramente associadas com litologias do Ortognaisse Cassiterita, Metagranodiorito Represa dos Camargos e Formação Nazareno. Elas se desenvolvem em Cambissolos e Latossolos Vermelho-Amarelos, geralmente próximas a nascentes, e são espacialmente correlacionadas com regiões utilizadas para agricultura temporária e pastagem. Estes novos entendimentos fornecem ferramentas tanto para evitar quanto para recuperar áreas erodidas em Conceição da Barra de Minas.

Palavras-chave: Erosão; Áreas degradadas; Cartografia ambiental.

INTRODUCTION

Erosion processes consist of detachment, transport, and deposition of particles, which are naturally occurring as a mechanism of landscape modification (Morgan, 2005). However, they can be accelerated due to specific environmental conditions and/or anthropogenic action (Blanco-Canqui and Lal, 2008; Rotta and Zuquette, 2015), implying that soil loss is higher than the soil formation rate. Among the different types of erosion, there is water erosion, mainly driven by rainwater, runoff, and subterranean flow (Guerra et al., 2007; Blanco-Canqui and Lal, 2008; Rotta and Zuquette, 2015), which predominates in equatorial, tropical, and subtropical regions such as Brazil (Soares et al., 2024a). In this context, gullies are highly complex and the most evolved features of water erosion, developed from the combination of runoff and subterranean flow (piping), with a wide range of impacts, including the loss of large volumes of sediments (Poesen et al., 2003; Morgan, 2005; Blanco-Canqui and Lal, 2008; Rotta and Zuquette, 2015). This is a significant problem, especially in rural areas, where degradation has long-term effects on soil productivity and sustainable agriculture (Morgan, 2005).

Along with the already existing conditions favorable for erosion, climate change has been altering the pattern, volume, and intensity of rain, as well as causing a rise in temperatures. Those alterations affect both the erodibility of geological materials and the erosivity of the rain, which can intensify the development of erosive processes (Latella et al., 2024) even more than changes in land use and land cover (Dash and Maity, 2023). Therefore, it is essential to assess soil erosion by mapping eroded areas to understand the environmental conditions and deflagrators related to erosion development, allowing their characterization and analysis as tools for the prevention and recovery of degraded areas.

Geographic Information Systems (GIS) techniques have been used to manage and analyze environmental information in a geotechnical context (Augusto Filho, 2015), such as to map erosive features (Castillo et al., 2014; Sampaio, 2014; Boardman, 2016; Liu et al., 2018; Golosov et al., 2018; Real, 2019; Real et al., 2020a, 2020b; Soares et al., 2021, 2024a, 2024b; Soares, 2022). There are some difficulties in delimiting erosive features due to the presence of vegetation or other land covers (Real et al., 2020a), which can be overcomed by the application of stereographic images, or anaglyphs, to the survey methodology (Soares et al., 2021, 2024b; Soares, 2022). The use of anaglyphs provides quicker elaboration of maps (Centeno and Silva Junior, 2015), along with better detailing by zooming images and the adjustment of images to include the study area, which is different from conventional stereography using aerial photographs (Ebert, 2015). More importantly to soil erosion assessment, the use of anaglyphs allows a three-dimensional visualization of the images, promoting better delimitation of erosive features, especially gullies, since they have a larger scale and more depth information (Soares et al., 2021, 2024b; Soares, 2022).

The south of Minas Gerais state in Brazil has a wide occurrence of gullies, notably in Nazareno and Conceição da Barra de Minas municipalities. Previous studies were performed in the region, such as in the Alto Rio Grande watershed (Ferreira et al., 2008; Ferreira and Ferreira, 2015; Cassaro et al., 2026) and Nazareno municipality (Ferreira, 2005; Ferreira et al., 2011; Sampaio et al., 2013; Sampaio et al., 2015; Cassaro, 2018; Real, 2019, 2020a, 2020b; Soares, 2024a, 2024b), especially in the Palmital stream watershed. Considering that Nazareno is adjacent to Conceição da Barra de Minas, and the latter municipality also presents many gully occurrences, it is important to investigate the locations where there is gully erosion and what their characteristics are in terms of geological material, vegetation, geomorphology, hydrology, land use and land cover, and climate.

Therefore, this study assesses gully erosion areas in the municipality of Conceição da Barra de Minas (Minas Gerais, Brazil), where 238 gullies were identified and delimited in anaglyphs of satellite images from 2023 and 2024. It is the first gully inventory performed in Conceição da Barra de Minas, which adds to the knowledge regarding erosion processes in the region. This gully assessment also contributes to the validation of the methodology using anaglyphs to improve the identification and delimitation of wide erosive features in areas broader than watersheds. Additionally, the gullies' locations were compared to different environmental characteristics to identify which factors were the most important to their development and evolution. It is of utmost importance to make inventories of gully erosion-affected areas to provide information about where and why they are formed and grow. This kind of study is also necessary in tropical regions to build a global understanding of erosion processes behavior, besides stating baselines for comparisons and prediction of new degradation in similar areas.

OBJECTIVE

This study aims to identify and delimit gullies based on anaglyphs of satellite images in Conceição da Barra de Minas municipality, as well as to recognize the relationship between eroded areas and their environmental conditions..

MATERIALS AND METHODS[1]

Study area

The study area, as shown in Figure 1, corresponds to the Conceição da Barra de Minas municipality and the Palmital stream watershed (included in the territories of Conceição da Barra de Minas and Nazareno municipalities), both in the south of Minas Gerais state, in the southeast region of Brazil. Besides Palmital stream watershed, Conceição da Barra de Minas also comprises Mortes river; Peixe river; Mortes Pequeno river; Mortes river and Serra streams; Sarampo, Ouro, Verde or Barros stream; Bananal, Barro Preto, Lajinha streams and Amaral or Canjica river watersheds. Then, the total area is 30,099 ha.

The geological context of the study area is related to the São Francisco Craton (Bizzi et al., 2003), where a wide range of lithologies occur, including gneissic, greenstone belts, metasedimentary, metamafic, metavolcano-sedimentary, granitoids, mafic-ultramafic, and sedimentary rocks from Paleoarchean to Cenozoic eras (Hasui et al., 2012; Toledo, 2022). The geological units in Conceição da Barra de Minas are Cassiterita orthogneiss, Nazareno Formation, Rio das Mortes Formation, Serrinha Suite, Represa dos Camargos metagranodiorite, Morro do Resende orthogneiss, Ritápolis metagranitoid, and Brumado metagranodiorite (Ávila et al., 2019). The area shows the majority of strong to mountainous reliefs, with large hills with convex-concave ridges (Brasil, 1983; Baruqui et al., 2006). Cambisols, red-yellow Oxisols, and red Oxisols are the typical soil types, with minor occurrence of litholic Neosols, fluvic Neosols, Gleysols, and red Argisols (Horta et al., 2005, 2009; Ferreira, 2005; Horta, 2006; UFV et al., 2010; Ferreira et al., 2011; Cassaro, 2018; Real, 2019; Soares, 2022).

The climate is described as dry winters and rainy summers (Baruqui et al., 2006), with an average of 1,476.5 mm of rainfall and mean temperatures ranging from 14.8 to 27.1°C. However, comparisons between 30 years of climate data and the last 5 years data show a rise of more than 0.5°C in mean annual temperature, with records of up to 38.2°C in 2023 (INMET, 2025). The land use and cover are represented by agricultural activities with corn, soybean, coffee, beans, rice, sugar cane, passion fruit and eucalyptus cultivation; cattle raising, especially dairy production; and mining of non-metallics, tin, manganese, and iron ores (Ferreira, 2005; Real et al., 2020a; Soares, 2022).

The region has been affected by extensive soil erosion, which motivated various studies, with emphasis on Nazareno municipality, which comprises half of Palmital stream watershed and is adjacent to Conceição da Barra de Minas municipality, both objects to the present work. The gullies in Nazareno were mapped by Ferreira (2005), Ferreira et al. (2011) and Pereira et al. (2014). A smaller area from Nazareno and Conceição da Barra de Minas, corresponding to the Palmital stream watershed, had gullies assessment performed by Real (2019), Real et al. (2020a, 2020b) and Soares et al. (2024a, 2024b). Inside Palmital stream watershed, other subwatersheds were studied, such as Forro stream watershed (Cassaro, 2018), Charuteiro stream watershed (Real, 2019), and Cravo stream watershed (Sampaio, 2014; Cassaro, 2015; Oliveira, 2015). Another study was performed in Cafundão stream watershed (Sampaio et al., 2013), near the urban area from Nazareno. In a wider context, the gullies in the Alto Rio Grande watershed were also mapped by Ferreira et al. (2008) and Ferreira and Ferreira (2015). These surveys and their results are summarized in Table 1.

Data acquisition and processing

The present work followed the steps summarized in Figure 2.

Topographic and political elements were obtained from Nazareno (SF-23-X-C-I-2), São João del Rei (SF-23-X-C-II-1), Itutinga (SF-23-X-C-I-4), and Madre de Deus de Minas (SF-23-X-C-II-3) topographic maps, scale 1:50,000, from Brazilian Institute of Geography and Statistics (IBGE) (IBGE, 1975a, 1975b, 1975c, 1975d), and

1 AI tools were not applied to this work.

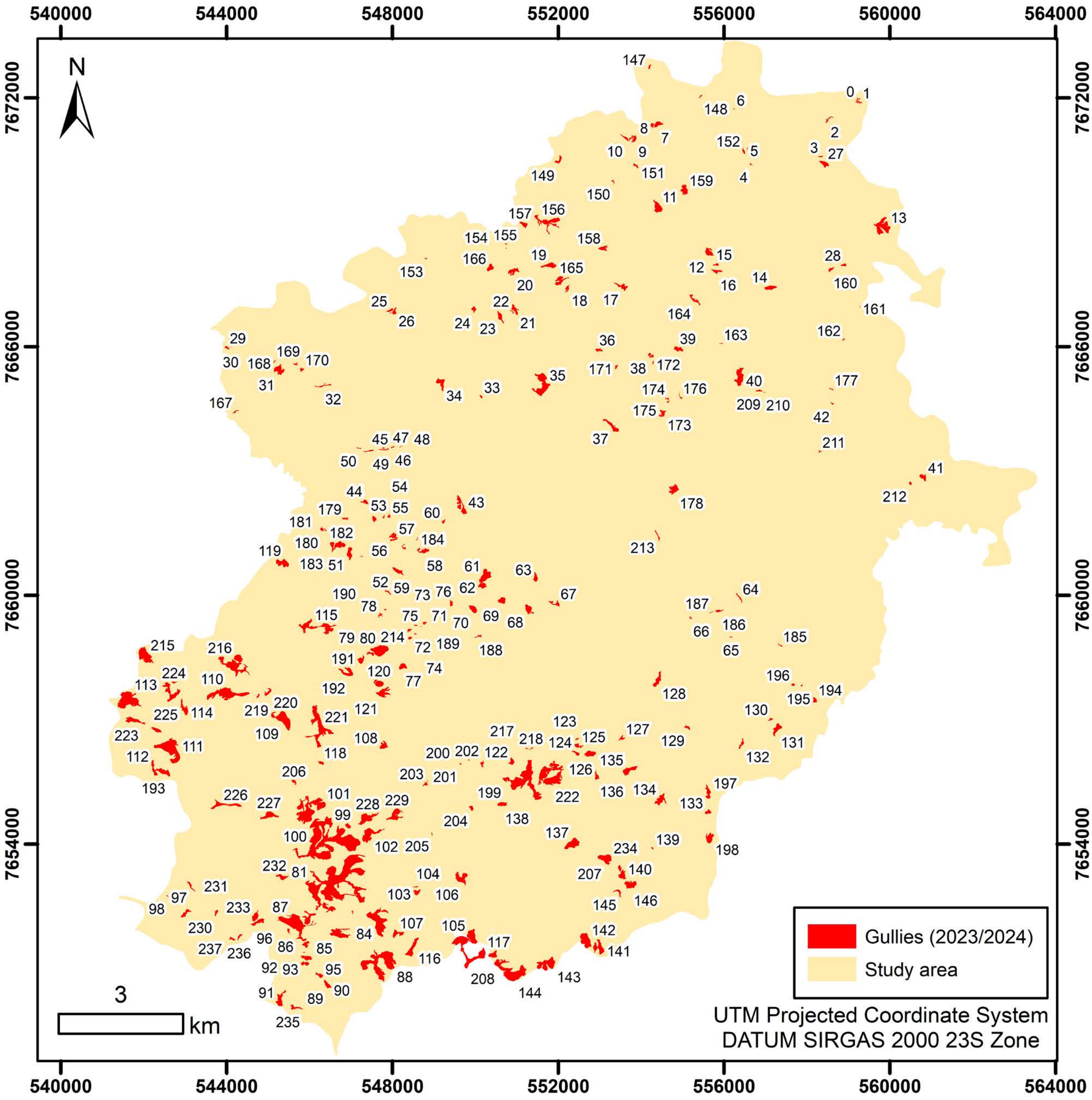

Figure 1. Map of the study area.

Table 1. Gullies surveys performed in the region of Conceição da Barra de Minas and Nazareno municipalities.

Publication	Study area	Year and number of mapped gullies	Area of mapped gullies (km²)	Area of mapped gullies (ha)
Ferreira et al. (2008)	Alto Rio Grande watershed	2000: 1,150	20.175	2,017.5
Ferreira and Ferreira (2015)	Alto Rio Grande watershed	2009: 798	30.29	3,029.00
Ferreira (2005)	Nazareno	2003 – 2004: 57	3.446	344.6
Ferreira et al. (2011)	Nazareno	2003 – 2004: 96	-	-
Sampaio et al. (2013)	Cafundão stream watershed	2007: 8	-	-
Real (2019)	Palmital stream watershed	2016: 60	-	-
Soares (2022)	Palmital stream watershed	2016: 63 2019: 65	2016: 3.98 2019: 4.04	2016: 397.93 2019: 404.48

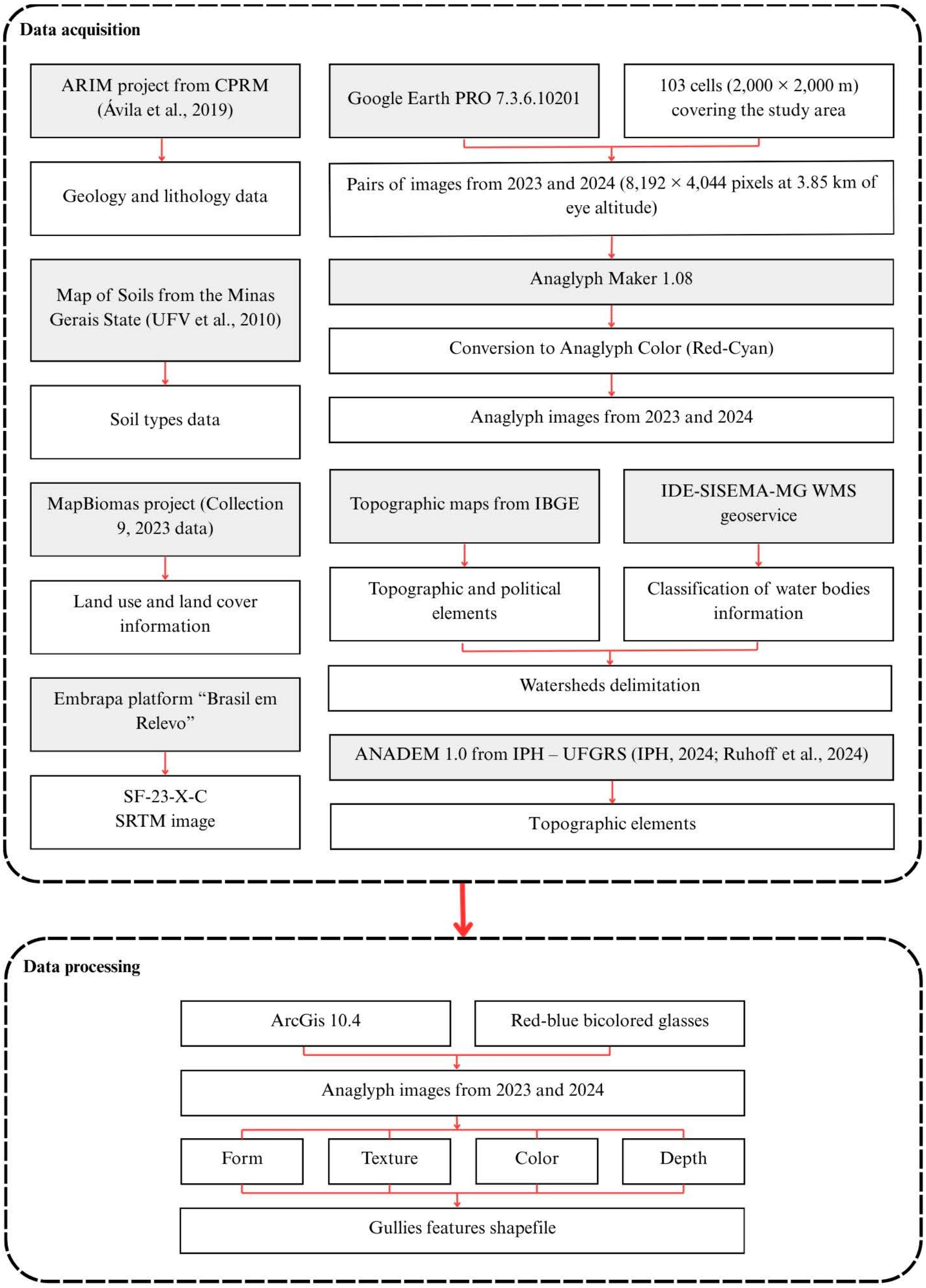

Figure 2. Flowchart of the methodology.

SF-23-X-C SRTM image, scale 1:250,000, from Embrapa platform "Brasil em Relevo" (Miranda, 2005). Additional topographic elements (slope, hypsometry, and solar radiation) were derived from ANADEM version 1.0, 30 m spatial resolution, a digital terrain model (DTM) based on digital elevation model (DEM) Copernicus GLO-30 with vegetation effects remotion through combination with altimetric data from Global Forest Canopy Height (GEDI) and Landsat-8, validated with ICESat-2 altimetry data, acquired in the platform Large Scale Hidrology (Hidrologia de Grande Escala) from the Hydraulic Research Institute from Federal University of Rio Grande do Sul (IPH – UFGRS) (IPH, 2024; Ruhoff et al., 2024). Land use and land cover information were acquired in MapBiomas platform, corresponding to Collection 9 based on 2023 data (Projeto MapBiomas, 2024). Geology data were obtained in Geology and Mineral Resources Map from ARIM Project: Revaluation of Metavolcano-sedimentary Sequences Southeast from Quadrilátero Ferrífero, scale 1:100,000 (Ávila et al., 2019). Soil data were acquired in the Map of Soils from the Minas Gerais State, scale 1:650,000 (UFV et al., 2010). The watersheds delimitation was based on the topographic maps from IBGE (IBGE, 1975a, 1975b, 1975c, 1975d) and the classification of water bodies in the hydrographic jurisdiction of the Rio Grande "vertentes" (GD2) from the IDE-SISEMA-MG WMS geoservice (SISEMA-MG, 2019). The methodology for image acquisition, anaglyph making, and gully delimitation was based on the approaches outlined by Soares (2022, 2024b) and Real (2020a, 2020b).

The study area was divided into 103 grids, each measuring 2,000 × 2,000 meters (Figure 3), to facilitate the acquisition of satellite images using Google Earth PRO 7.3.6.10201. Satellite imagery from Maxar Technologies was captured at an eye altitude of 3.85 km, ensuring maximum resolution (8,192 × 4,044 pixels). For each grid, a pair of slightly displaced images was obtained: the central image, referred to as the "left image", and a second image shifted eastward, designated as the "right image". The images had pixel width of 0.54 meters and were from 2023 (September 21st and December 11th) and 2024 (June 20th and July 3rd), since 2023 images were not available for the two last columns (grids 17, 27, 37, 46, 47, 56, and 57) and were only partially available for the second to last column (grids 4, 9, 16, 26, 36, 45, 55, 67, and 77).

The acquisition of a pair of images enabled the elaboration of anaglyphs using the free software Anaglyph Maker, 1.08 version, where the left and right images were set and their dislocation was manually adjusted to get the tridimensional visualization in the adequate scale of analysis. The type of anaglyph was "Anaglyph Color (Red-Cyan)", best viewed with red-blue bicolored glasses, allowing enhanced depth perception in stereographic visualization. After saving the anaglyphs in TIF format, they were georeferenced in ArcMap 10.4.

The gullies delimitation considered patterns of form, texture, color, and depth as applied before by Cassaro (2018), Real (2019), Soares (2022) and Soares et al. (2024a, 2024b). After their identification, the gullies were delineated with the "Create features" tool in ArcMap 10.4.

To get the geometry information about the mapped gullies, we calculated the area in m², km², and ha, along with the perimeter in meters using the "Calculate Geometry…" function in Attribute Table. Additionally, we applied the "Minimum Bounding Geometry" Spatial Analyst tool to create a feature class of rectangles enclosing each input features of mapped gullies, along with measurements of width (shorter side of the resulting rectangle), length (longer side), and orientation of the length. Then, it was possible to obtain the dimensions of each mapped gully. The status of each gully was determined through the interpretation of

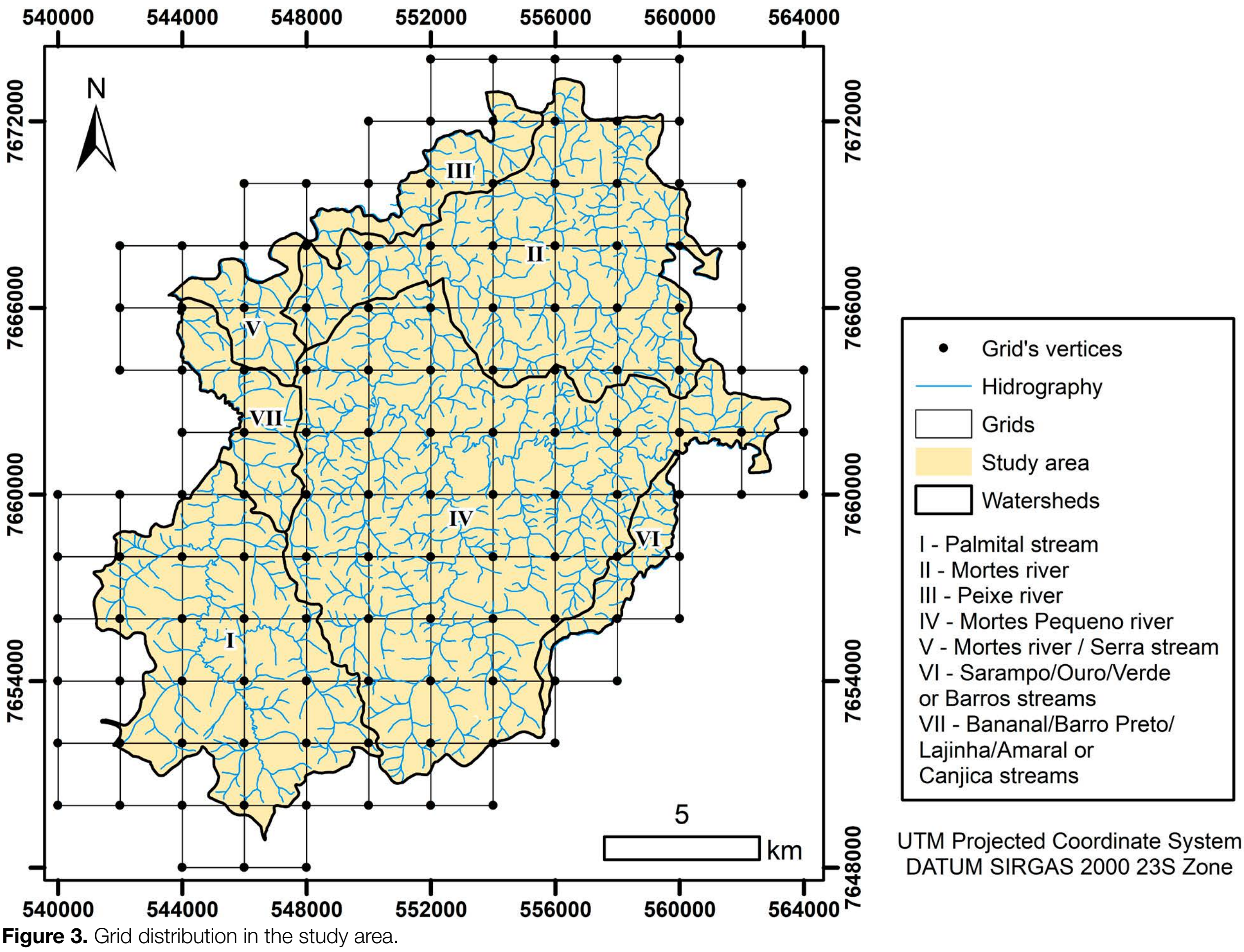

Figure 3. Grid distribution in the study area.

anaglyphs. Gullies were classified as stable when they were fully vegetated or occupied by other land use types, and as active when they exhibited evidence of recent erosional processes, such as exposed soil or visible incisions resulting from soil loss. The positional distribution of gullies along the slopes was determined by generating an aspect map and subsequently clipping it to the gully shapefile, which enabled the identification of the predominant slope orientation associated with each gully, thereby providing insights into the directional patterns of gully development.

The relationships between the gullied areas and environmental conditions related to topography (altitude, contours, and slope), solar radiation, soil types, lithology, and land use and land cover were assessed through a spatial overlay of the respective shapefiles in ArcGIS 10.4. Thematic data were also clipped to the gully polygons, and the area (ha) and proportional representation (%) of each class within the gullied zones were calculated and exported to a .xlsx file. Those procedures enabled the identification of classes most frequently associated with erosion, thereby highlighting the environmental conditions predominantly linked to gully development in the study area.

All elements, vector and raster, were georeferenced to SIRGAS 2000 23S.

RESULTS AND DISCUSSION

The region was assessed before by gully inventories performed in Alto Rio Grande watershed (Ferreira et al., 2008; Ferreira and Ferreira, 2015); Nazareno municipality, adjacent to Conceição da Barra de Minas (Ferreira, 2005; Ferreira et al., 2011); Cafundão stream watershed (Sampaio et al., 2013); Forro stream watershed (Cassaro, 2018) and Palmital stream watershed, both part of the present work's study area (Real, 2019; Real et al., 2020a, 2020b; Soares et al., 2021, 2024a, 2024b; Soares, 2022). The application of anaglyphs to map the gullies in the area was proposed by Soares et al. (2021) and Soares (2022), as their use in environmental assessment was already set for geological mapping (Herbert et al., 2014; Silva et al., 2017), geological faults mapping (Patria et al., 2021; Goto et al., 2022; Shnizai et al., 2024), mass movements mapping (Abdallah et al., 2005; Chen and Chen, 2012; Razak et al., 2013; Bucci et al., 2021; Xia et al., 2021; Albano et al., 2023; Ardizzone et al., 2023; Cinosi et al., 2023), and erosive features study (Sattar et al., 2010; Kandrika and Dwivedi, 2013; Fiorucci et al., 2015; Imwangana et al., 2015; Kornejady et al., 2022). Anaglyphs are stereoscopic images generated by partially overlapping two consecutive photographs to enable three-dimensional visualization through binocular vision (Britannica, 2019). Traditionally, aerial survey imagery was printed and examined using stereoscopic instruments equipped with internal mirrors, which replicated the optics of human vision to provide a perception of depth (Chiossi et al., 2013). An alternative technique involves the combination of an image in red and another in blue, which are then visualized using glasses with corresponding red and blue lenses. Through this optical arrangement, the red lens filters out the red image, rendering the blue image in black, while the blue lens filters out the blue image, rendering the red image in black. The superimposition of these filtered images produces a composite that conveys a three-dimensional effect to the observer (Watch, 1895). The elaboration of digital anaglyphs is relatively straightforward, requiring only a few minutes to produce, and facilitates the analysis of extensive areas, including those that are difficult to access either in person or through conventional aerial photography. Furthermore, the process is cost-effective, as it can be performed using freely available or low-cost software and imagery (Centeno and Silva Junior, 2015). Digital anaglyphs also offer additional advantages, such as the ability to zoom into specific features, enable simultaneous interpretation by multiple operators, and adjust the imagery to align with the spatial coordinates of the study area (Ebert, 2015). Then, the anaglyphs allow the tridimensional observation of satellite images, as well as drone imagery, which provide better conditions for identification and delimitation of gullies, increasing the mapped areas in almost 40% (Soares et al., 2021, 2024b; Soares, 2022). It corresponds to an improvement in the methodologies applied to assess the area, which is complex and shows evidence of connectivity between the gullies, as observed by Real et al. (2020b). Additionally, vegetation developed inside gullies may be evidence of their stabilization; however, their presence hinders the recognition of gullies' borders in satellite images (Real et al., 2020a), which can be bypassed by applying anaglyphs to the mapping. Therefore, this methodology was also applied to assess gullies in Conceição da Barra de Minas municipality, as advance to the previous inventories performed in Palmital stream watershed both by the expectation of higher precision in mapping and by identifying erosive features in non-mapped areas.

The inventory provided the identification of 238 gullies (108 active and 130 stable), with an area of 727.63 ha, as observed in Figure 4. Other information regarding gullies identification number map, year of mapping, area (ha), perimeter (m), width (m), length (m), length orientation (degrees), and status (if active or stabilized) are described in the Supplementary Document, and the main statistics are shown in Table 2.

The area affected by gully erosion is significant in comparison with the total area of 30,099 ha, especially considering the predominance of cattle raising and agricultural activities in the study area, which are highly impacted by soil loss. Thematic maps for hypsometry and contours (Figure 5), slope (Figure 6), solar radiation (Figure 7), soil types (Figure 8), lithology (Figure 9), and land use and land cover (Figure 10) were built to better understand the study area and to establish spatial relationships between them and erosion features development.

Lower altitude is mostly related to the Peixe, Mortes, and Mortes Pequeno rivers, along with the Palmital stre-

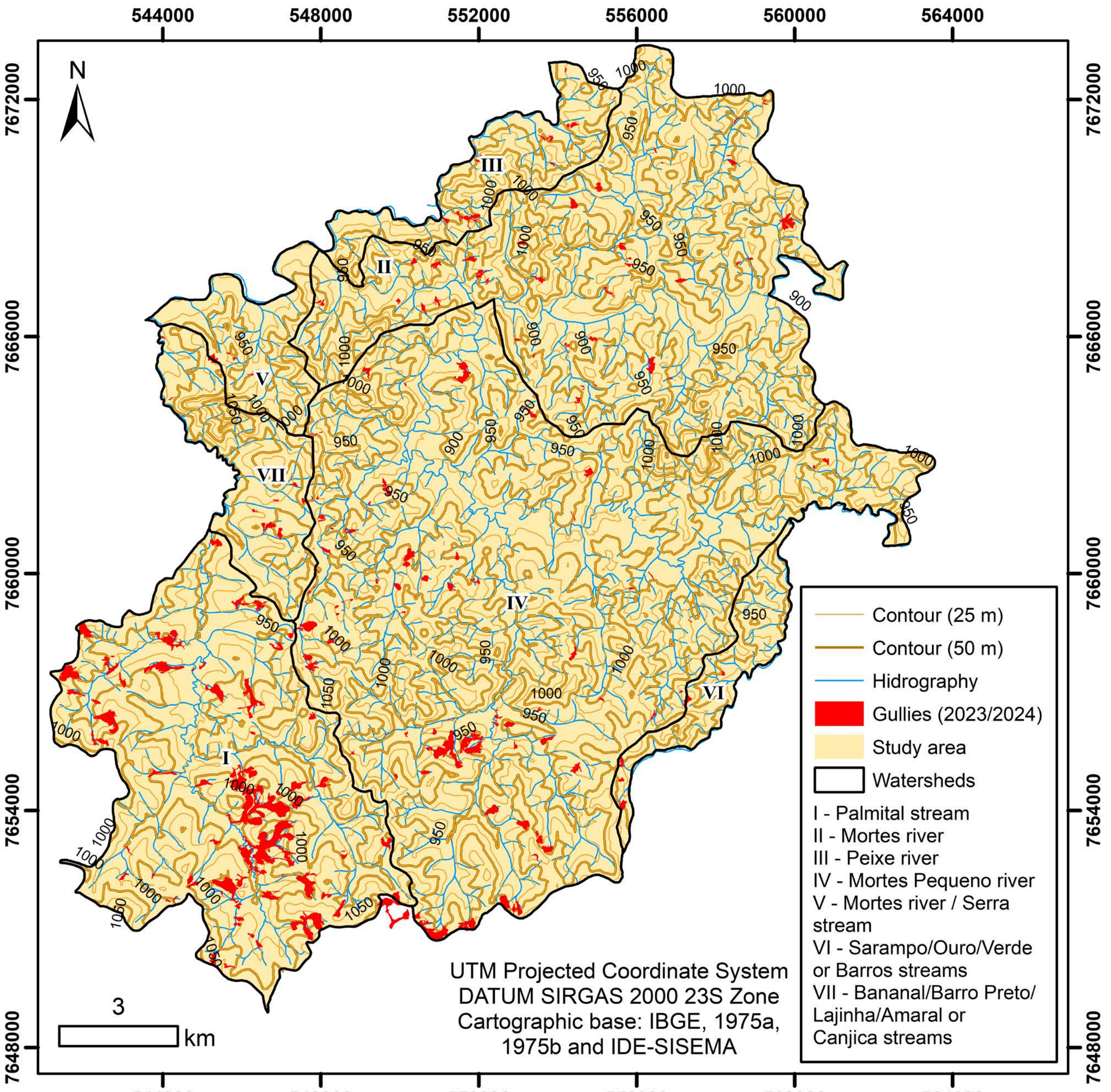

Figure 4. Gully inventory of Conceição da Barra de Minas (Minas Gerais, Brazil) based on images from 2023 and 2024.

Table 2. Statistics of gullies mapped in 2023-2024 images in Conceição da Barra de Minas and Palmital watershed.

Statistics	Area (ha)	Perimeter (m)	Width (m)	Length (m)	Length Orientation
Maximum	65.76	12,891.3	1,172.5	1,649.1	178°
Minimum	0.01	50.5	9.6	21.3	1°
Mean	3.06	966.4	144.9	266.1	91°
Median	1.04	604.1	99.3	201.6	92°

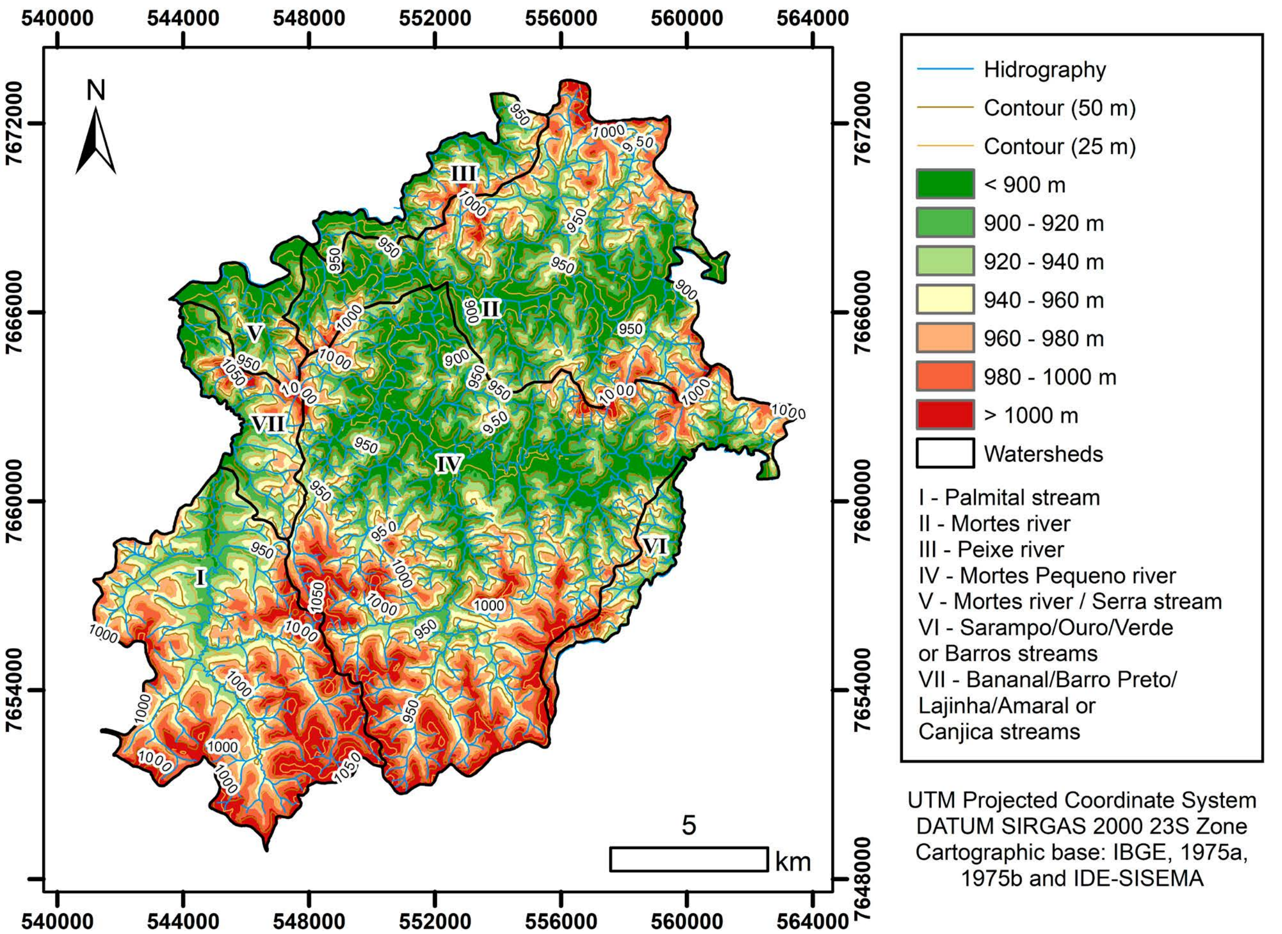

Figure 5. Hypsometry and contours map of study area.

am, whereas higher altitude is concentrated in the south of the study area, as well as in smaller portions in the north. Higher slope percentages were more expressive up to the north of the study area, especially in the northeast portion. The three highest slope ranges are 8 – 20%, 20 – 45%, and 3 – 8%. The solar radiation ranges from 525.48 – 795.68 kWh/m² in the study area, with a mean of 747.79 kWh/m². Lower values were associated with the Mortes river adjacencies. There is dominance of Cambisols and Oxisols in Conceição da Barra de Minas, with Cambisols mostly in the northern portion and Oxisols in the southern portion of the study area, according to 1:650,000 scale soil data (UFV et al., 2010), which may have differences in more detailed scales. Regarding lithology, there is a great complexity of rock types, ages, and properties in the region. The central part of the study area is dominated by Cassiterita orthogneiss, while the southern part mostly shows the metamafic, metaultramafic, and quartzite rocks from Nazareno Formation, with relevant intrusions of Serrinha Suite and Represa dos Camargos metagranodiorito in the south and Brumado metadiorite, Ritápolis metagranitoid, along with Morro do Resende orthogneiss in the north of the study area. Additionally, there are seven watersheds in the study area, which are related to the (a) Palmital stream, (b) Mortes river, (c) Mortes Pequeno river, (d) Mortes river and Serra stream, (e) Peixe river, (f) Bananal, Barro Preto, Lajinha, Amaral/Canjica streams, and (g) Sarampo, Ouro, Verde/Barros streams. Land use and land cover in the study area are represented by pasture (17,684.10 ha), forest formation (4,089.52 ha), other temporary crops (3,176.65 ha), mosaic of uses (2.893,21 ha), grassland (1,357.87 ha), forest plantation (349.31 ha), coffee (293.31 ha), river, lake and ocean (164.73 ha), urban area (63.44 ha), other non-vegetated areas (19.53 ha), and other perennial areas (6.34 ha), with around 59% of the study area corresponding to pasture. Other prevalent classes are forest formation and other temporary crops areas, which correspond to 13.6% and 10.55% of the study area, respectively. Considering that forest plantation consists of 1.16% of the study area, the total forested area equals to 4,438.83 ha, or 14.75% of the study area.

Most gullies, especially the widest forms, are concentrated in the south of the study area, where there is altimetry of 940 m to higher than 1,000 m and slopes between 3 – 8% to 20 – 45%. Although higher slopes are linked to greater erosive potential (Blanco-Canqui and Lal, 2008), the 45 – 75% slopes are predominant in the north of the study area, where there are gully occurrences, but smaller in number

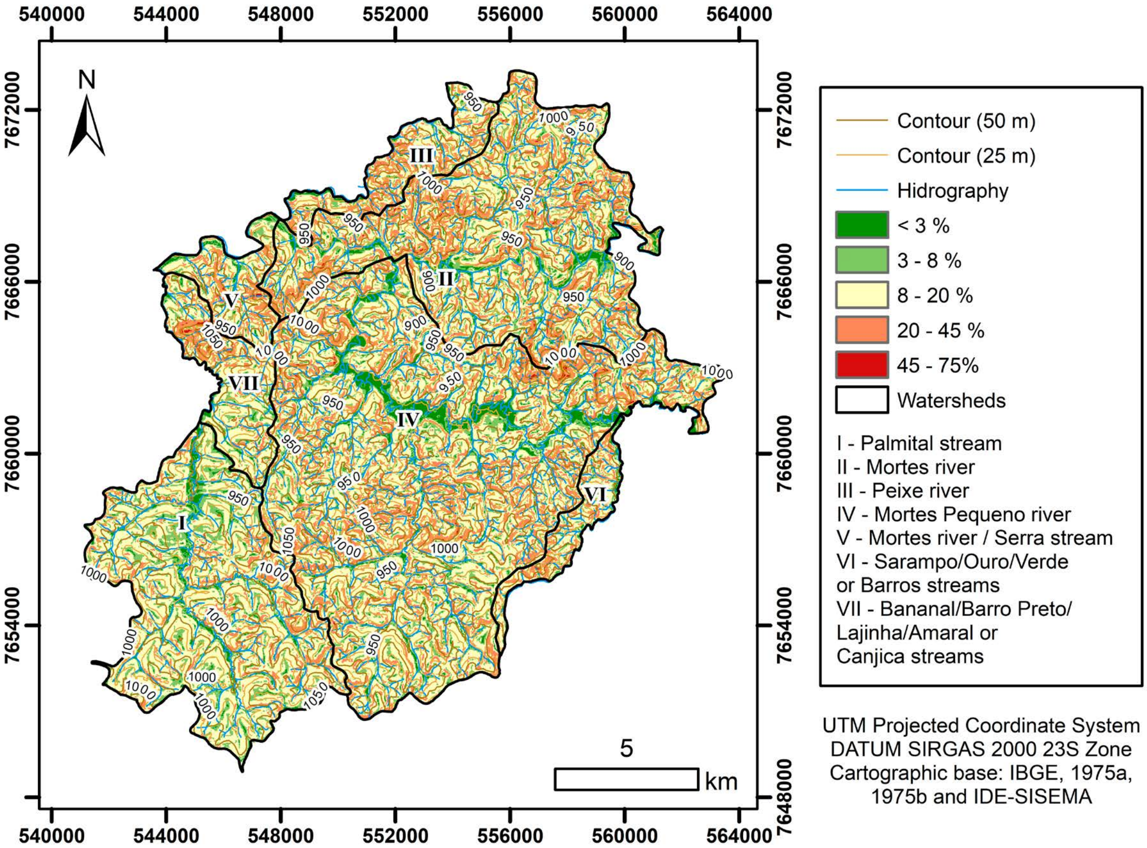

Figure 6. Slope map of study area.

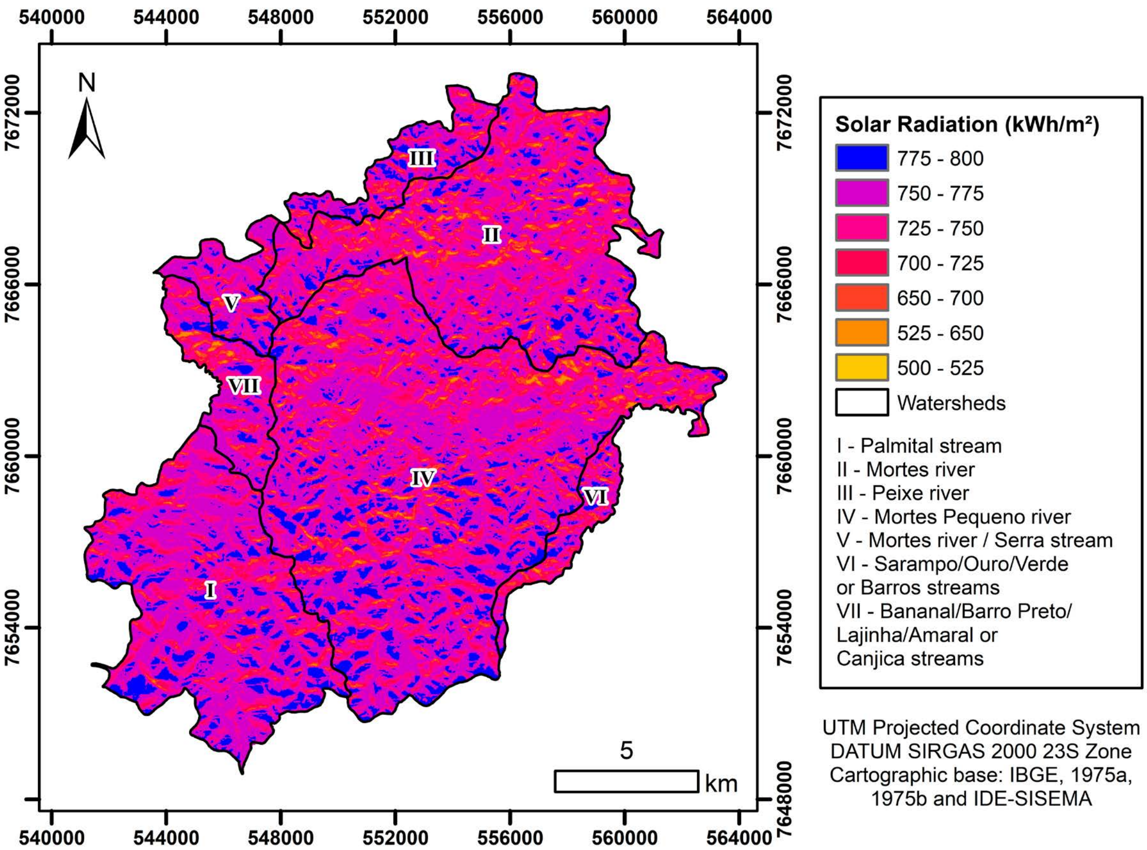

Figure 7. Solar radiation map of study area.

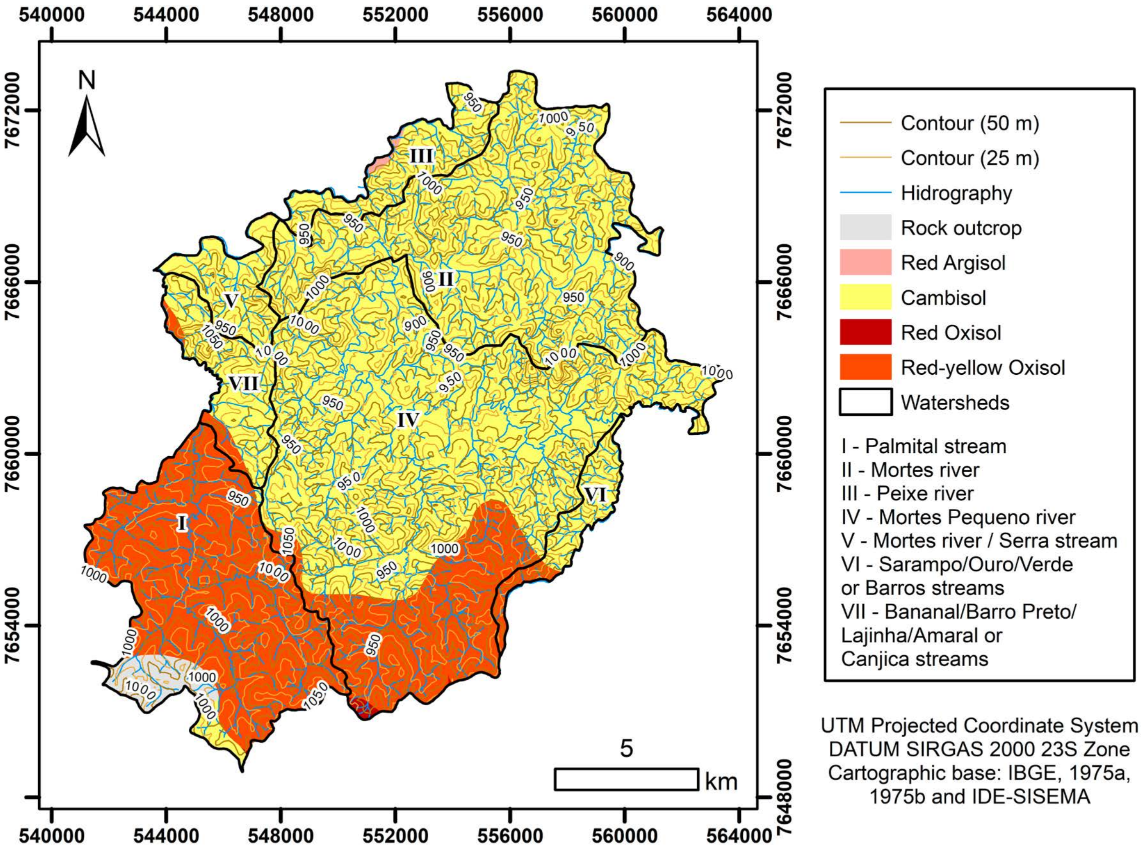

Figure 8. Soil types map of study area.

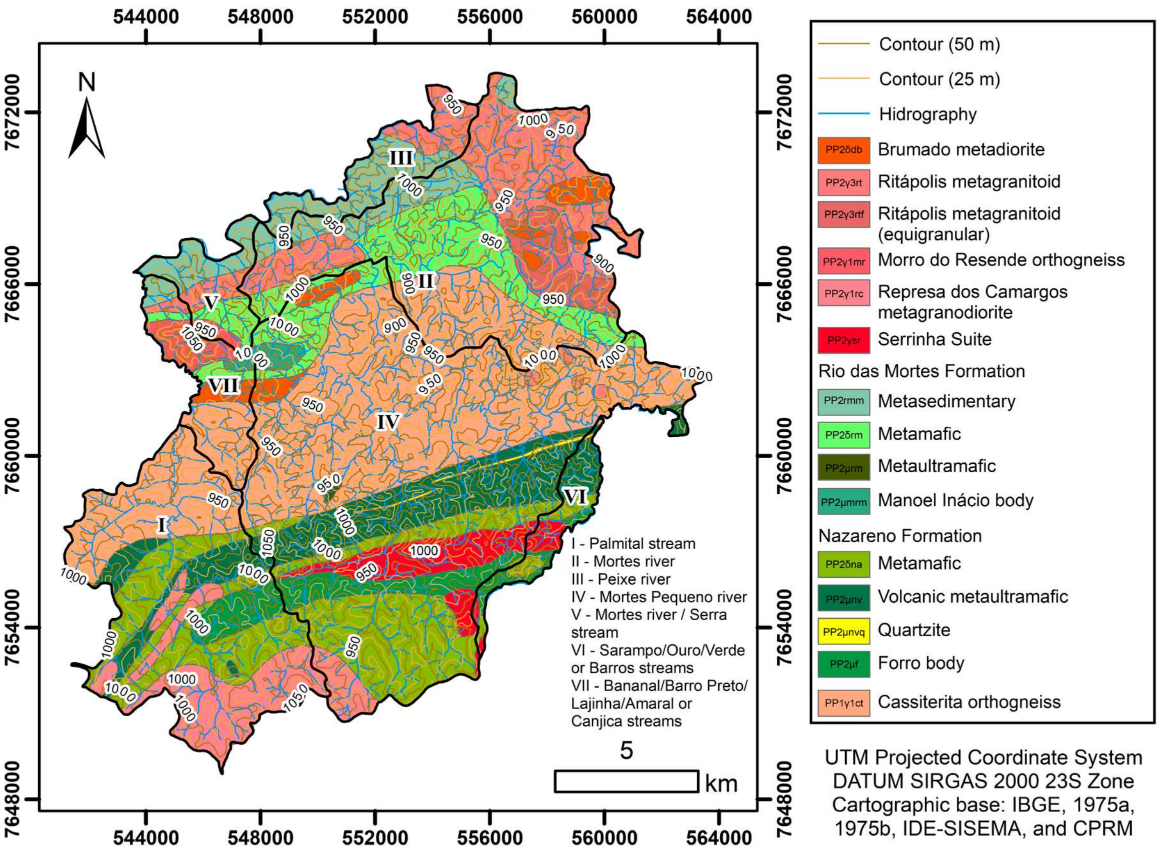

Figure 9. Lithology map of study area.

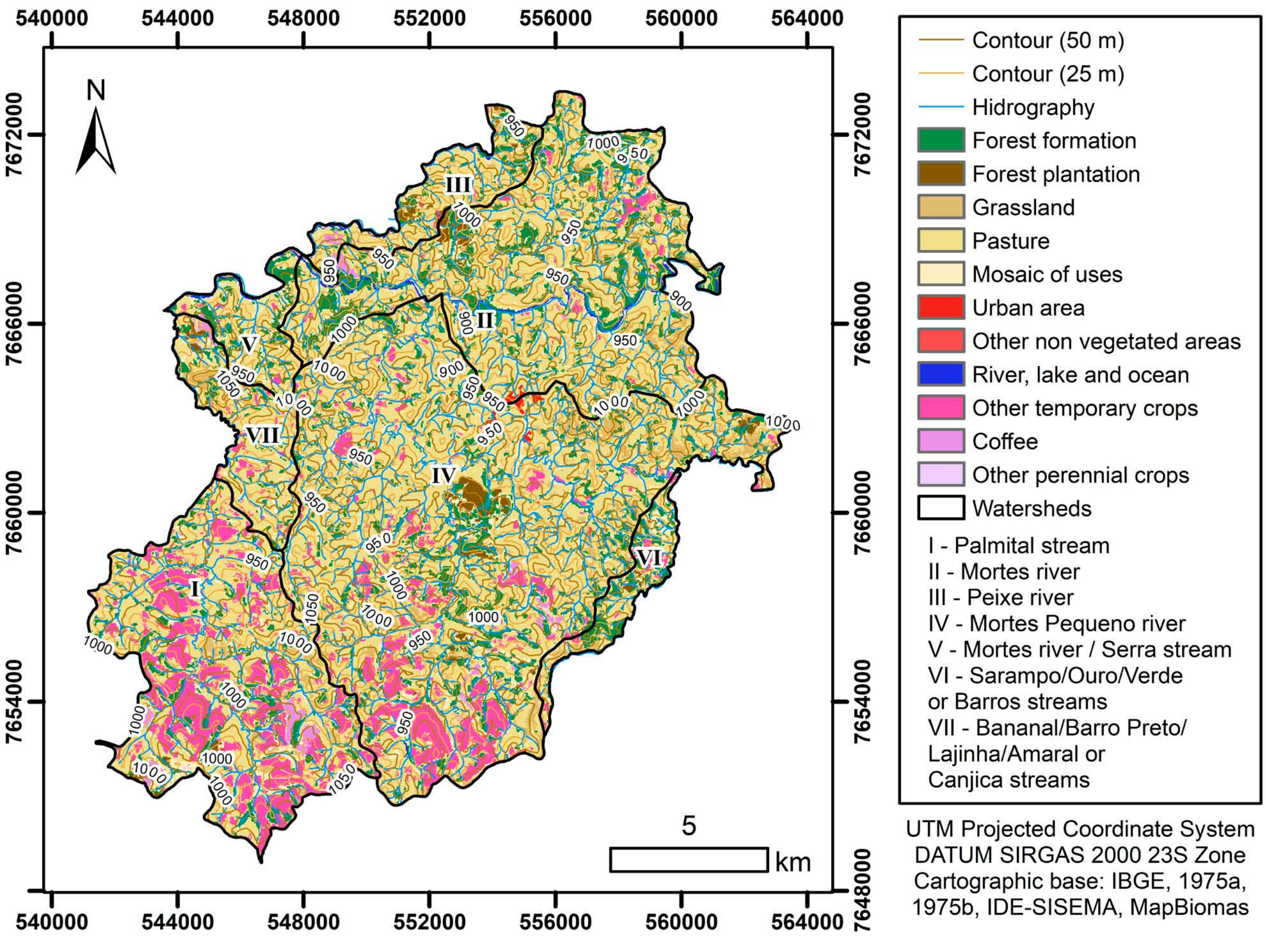

Figure 10. Land use and land cover map of study area.

and area. Therefore, it is inferred that slope is not the most important factor affecting soil erosion in the region, but other factors combination, notably land use and land cover. The gullied areas showed solar radiation values ranging from 595.2 to 793 kMw/m², but most of the values were between 725 – 750, 750 – 775, and 775 – 800, in descending order of dominance. Observations of the wider gullies in the southwest of the study area showed a spatial trend wherein solar radiation intensity increases progressively from the northern to the southern extent of each individual gully feature. Regarding geological materials, most of the eroded area is associated with Cassiterita orthogneiss (187.90 ha of gully erosion), Represa de Camargos metagranodiorite (147.50 of gully erosion), metamaphic member (143.09 ha of gully erosion) and Forro body (112.44 ha of gully erosion) from Nazareno Formation. However, most of the surface is composed of soil, notably haplic Cambisol, with 159 gullies (222.1 ha), and red-yellow Oxisol, with 83 gullies (454.17 ha). There are also 11 gullies (27.88 ha) in areas classified as rock outcrops and 2 gullies (17.17 ha) in red Oxisol. It is important to note that Cambisols are less competent soils against erosion, and their exposition not only causes their own erosion but also subsidence of Oxisols that occur upon them (Real et al., 2020a; Soares et al., 2024b). Additionally, almost all gullies are linked to surface water courses, especially in first and second order; then, their occurrence may be related to their water springs.

Considering the land use and land cover classes from MapBiomas collection 9 (MapBiomas, 2024), up to 40% of the eroded area is correspondent to pastures, followed by 22.6% of grasslands, 18% of mosaic of uses, 15.5% of forest formation, 2.9% of other temporary crops, and 0.1% of other non-vegetated areas. Previous research identified associations between gullies development and land use and land cover patterns, such as inadequate agricultural practices, including uncontrolled fire, monoculture, excessive exploration, deforestation to implement pasture activity, and pasture in steep areas (Sampaio et al., 2013, 2016; Sampaio, 2014; Cassaro, 2015, 2018; Ferreira and Ferreira, 2015; Real, 2019; Real et al., 2020a, 2020b; Soares, 2022). Additionally, coffee plantations can also direct runoff from more elevated areas to the gullies (Sampaio, 2014). With respect to the land use and management factor (c factor), which ranges from 1 (indicating maximum probability of erosion) to 0 (indicating minimum probability of erosion), pastures are associated with a value 0.200 (Marques et al., 2003), whereas grasslands and temporary agriculture correspond to 0.013 (Azevedo, 2017) and 0.290 (Beskow et al., 2009), respectively. Despite grasslands representing the second most eroded land cover category within the study area, their comparatively low c factor suggests that erosion in this class is not primarily driven by LULC characteristics, but to other environmental conditions. Then, if these areas were replaced into land cover types such as pastures or temporary crops, both of which exhibit higher susceptibility to erosion, or even bare soil, representing the maximum exposure to erosion agents, the likelihood of gully initiation and subsequent widening would be considerably greater. Furthermore, previous studies identified an increase of temporary agriculture replacing former pasture areas between 2016 and 2019, due to the rise of grains prices; however, the soil is exposed for longer periods under temporary agriculture than under perennial agriculture, which favors erosion development (Soares, 2022; Soares et al., 2024). Moreover, many of the pasture areas are underlain by Cambisols rather than Oxisols, which are characterized by low nutrient availability and a high proportion of coarse fragments, along with being more susceptible to erosion; then, agricultural productivity in these areas was limited, and this trend of LULC change may further increase the likelihood of gully development.

Although most of the gullies developed in rural areas, there are gullies near to the urban area of Conceição da Barra de Minas, as showed in Figure 11, which may pose a risk to the population, as their progression has the potential to compromise paved roads and built infrastructure, particularly residential edifications. As stated by Soares et al. (2024), urban areas and paved roads have the highest mean erosion (8.39 t/ha year), excluding gullies and exposed soil, which implies higher soil loss that may negatively affect the urban area.

Other anthropogenic alterations are linked to gully formation, such as unpaved roads (Sampaio, 2014) and ditches opened as an old practice for marking the boundaries of rural properties (Ferreira et al., 2011; Cassaro, 2018). In this context, the soil loss models performed in Palmital stream watershed by Soares et al. (2024a) showed higher mean erosion in exposed soil (10.89 t/ha year), urban areas and paved roads (8.37 t/ha year), temporary agriculture (2.61 t/ha year), and pasture (2.20 t/ha year). Considering our study area, most of the use of soil is related to pasture and temporary agriculture areas, which are prone to erosion, along with other environmental conditions and the contribution of erosive agents, notably runoff.

When comparing the gullies mapped using imagery from 2023 and 2024 with those documented in earlier years and studies, notable differences emerge. No previous investigations were conducted specifically within the municipality of Conceição da Barra de Minas; prior research focused instead on the Forro stream watershed (Cassaro, 2018)

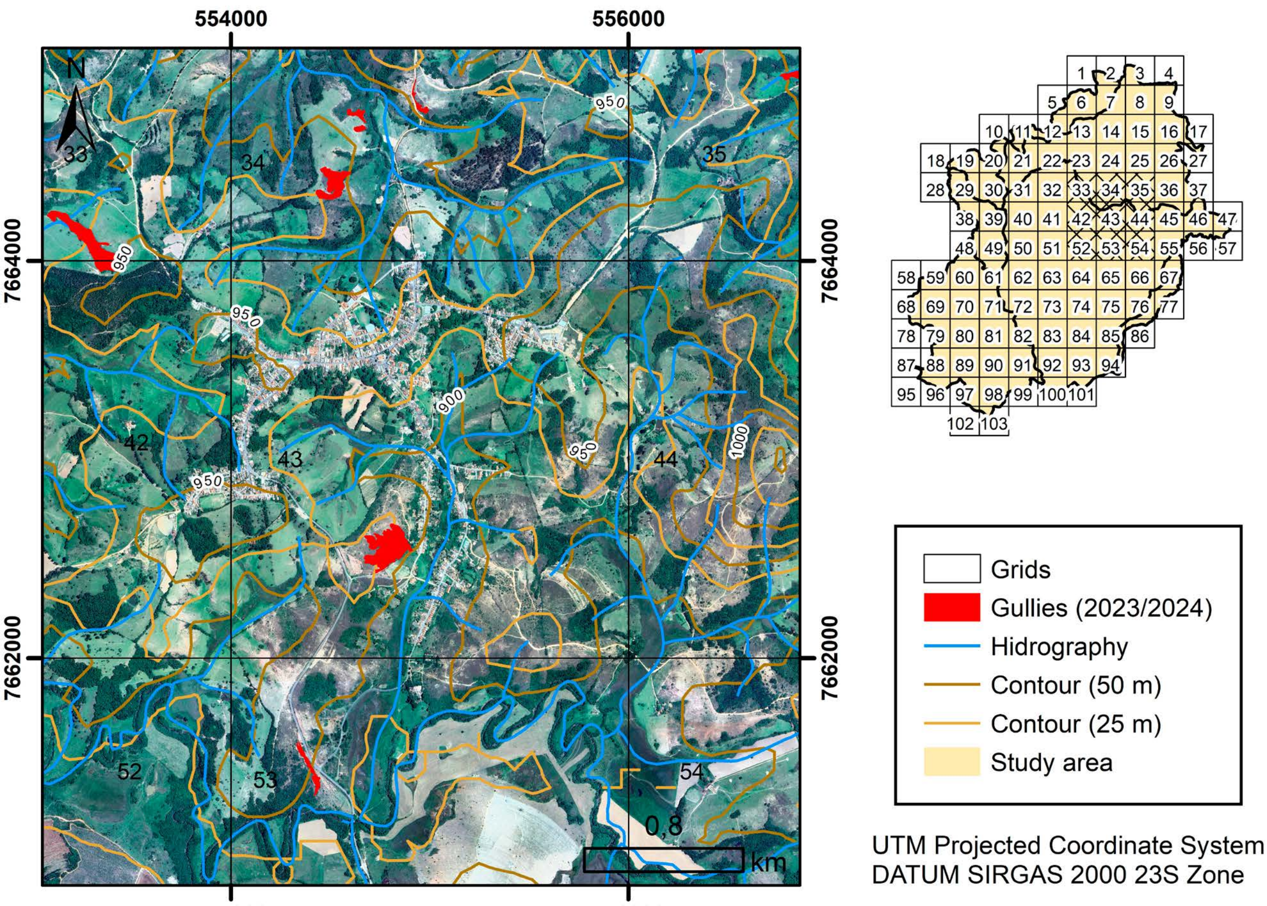

Figure 11. Gullies near to the urban area of Conceição da Barra de Minas.

and the Palmital stream watershed (Real, 2019; Real et al., 2020a, 2020b; Soares et al., 2021, 2024a, 2024b; Soares, 2022), both of which partially overlap with the present study area but do not encompass the entire municipality. Consequently, direct comparisons are limited to less than half of the study area. In addition, methodological advances and improvements in image resolution have significantly enhanced gully identification. Specifically, the incorporation of anaglyphs and the availability of higher-resolution imagery have facilitated more precise delineation of gully boundaries. Even when using the same source (Google Earth Pro), the resolution of images from 2019 differs from those of 2023 and 2024, with the latter providing clearer visualization and more reliable boundary detection. However, if examining the gullies mapped in previous studies, based on earlier imagery and/or different methodological approaches, with those identified in the present analysis, it is possible to observe that new gullies were detected in areas where they had not been previously mapped, while others exhibited evidence of widening. Conversely, a reduction in the number of gullies was observed in certain locations, largely attributable to the use of higher-resolution imagery, which enabled more precise boundary delineation and reduced the generalization inherent in earlier datasets.

Finally, the involvement of local communities and stakeholders must also be considered as an important component of gully management. Given that the methodology employed for gully mapping relies on free software to generate anaglyphs from accessible imagery, the approach can be readily disseminated and shared. This enables community members and stakeholders to actively participate in mapping and monitoring gully development by applying the same procedures, therefore fostering collaborative knowledge exchange and enhancing long-term erosion management strategies.

CONCLUSIONS

No prior development of a gully inventory has been conducted for Conceição da Barra de Minas (Minas Gerais, Brazil) municipality. Therefore, this study introduces new insights into the gullies within the study area, by presenting detailed maps, which enable evaluation of their geometry, extent of erosion, and relationships with environmental characteristics such as hypsometry, slope, geology, soils, watersheds, and patterns of land use and land cover. The application of anaglyphs to the mapping methodology also reiterates its efficiency to identify and delimit gully features, despite the presence of vegetation in their borders, which hinders the outlining of gullies. This new information about gully development in Conceição da Barra de Minas provide tools to stakeholders and decision makers to avoid further evolution of erosive processes, as well as to recover already eroded areas in the municipality, its adjacencies, and other similar areas.

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