Proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE), and 2nd Latin-American Regional Conference of the International Association for Engineering Geology and the Environment (IAEG), La Serena Chile, 2024.

Multiscale analysis of gully erosion in Palmital stream watershed, Minas Gerais (Brazil)

Análise multiescalar de erosão por voçorocas na Bacia do Córrego do Palmital, Minas Gerais (Brasil)

Ádria Kanome Mori Soares
Department of Geotechnical Engineering/São Carlos School of Engineering/University of São Paulo, MSc, Brazil, adriakms@usp.br

Lígia Sampaio Corte Real
Department of Geotechnical Engineering/São Carlos School of Engineering/University of São Paulo, PhD, Brazil

Valéria Guimarães Silvestre Rodrigues
Department of Geotechnical Engineering/São Carlos School of Engineering/University of São Paulo, Professor, Brazil

Silvio Crestana
Embrapa Instrumentation/Brazilian Agricultural Research Corporation, Researcher, Brazil

Rogério Resende Martins Ferreira
Embrapa Territorial/Brazilian Agricultural Research Corporation, Researcher, Brazil

ABSTRACT: Gully erosion can lead to irreversible financial and soil losses, which endorse a detailed study of erosive processes and their conditioning factors in each degraded area. However, studies on a multiscale analysis are relatively lacking. Hence, this study sets out to show how to use an integrated and multiscale approach to assess gully erosion in one gully from the Palmital stream watershed, in Nazareno and Conceição da Barra de Minas (Minas Gerais, Brazil). In the watershed scale (1:50,000), we made anaglyphs and mapped the gullies from 2016 and 2019. In the gully scale (1:5,000), an image of the gully was obtained with a remotely piloted aircraft (RPA). They were analyzed to verify the erosion process and to perform fractal analysis. We also collected soil samples for physical and chemical analysis. Results showed connections between gullies and that the erosive process is still active, occurring on different scales inside the gully, including as tubular erosion in the Cambisol, which destabilizes the Oxisol, enlarging the gully head. Fractal analysis results also showed that both the current state of the gully and the erosion process itself are fractal and self-similar.

KEYWORDS: Soil degradation; Anaglyph; Fractal; Remotely Piloted Aircraft (RPA); Chemical and physical properties.

1. INTRODUCTION

The growing demand for resources, associated with inadequate and/or excessive land use, has resulted in pressures on land, hence instability in essentially physical and socioeconomic environments. Erosion processes cause numerous environmental problems, such as soil loss, decline of soil fertility, and silting of riverbeds (Morgan 2005, Rotta & Zuquette 2015).

The initiation and development of erosion may be related to several erosive agents. Water erosion occurs by raindrop impact, runoff – related to interrill and linear erosion –, subsurface flow, and streambank and coastal erosion, leading to significant consequences. Such an erosion is predominant in Brazil, given the country's climatic characteristics, which include equatorial, tropical, and subtropical climates (Blanco & Lal 2008, Rotta & Zuquette 2015).

Rainfall, vegetation, topography, and soil properties determine the severity of water erosion and the amount, intensity, and frequency of rainfall, as well as the speed, size, and distribution of raindrops sizes influence its efficiency. Vegetation can intercept, absorb, and reduce the energy from raindrops and also increases the mechanical resistance of the soil. However, those conditions depend on the height, continuity, and density of the canopy cover, since the intercepted raindrops may coalesce on the leaves and reach larger and more erosive soil. Topography determines the runoff's velocity, which is higher when the slope is steeper, and convex slopes are more easily eroded. Factors significant to erodibility are texture, aggregate stability, shear strength, infiltration capacity, and organic and chemical content of the soil (Morgan 2005, Blanco & Lal 2008).

Climate characteristics – especially annual rainfall and temperature –, soil texture, and land use control the erosion morphology. Larger features are associated with inter-tropical climate conditions; narrow and long features are found in areas of dense and clayey soils, whereas deep and wide ones are related to sandy soil. Crops and urbanization have bigger erosion features when compared to forests and grasslands (Dube et al. 2020).

Gullies are the most complex form of linear erosion, in which water flow concentrates in channels that grow deeper and wider with time. Both runoff and subsurface flow contribute to the process (Poesen et al. 2003, Blanco & Lal 2008, Rotta & Zuquette 2015). Erosion begins when the shear stress of the flow which is influenced by soil texture, density, clay content, dispersion rate, and topography and land use/land cover, is higher than the critical shear stress of the soil (Blanco & Lal 2008).

The Palmital stream watershed is highly affected by gullies, mainly because of the exposition of Cambisols (high erodibility) after Oxisols (low erodibility) loss by inadequate land use practices (Real et al. 2020a). The complexity of large erosive features requires an integrated study for assessments of the main factors and deflagration agents that influence erosional processes.

Geological and geotechnical investigations must involve a multiscale approach, from regional data to a more detailed scale. It provides a better understanding of the area, in terms of delimitation, characterization, and classification of the processes and their outcomes (Rodrigues et al. 2015). Different scales are necessary for broadening the analyses of environmental problems in experimental and field studies and in simulation research (Pandey et al. 2016). Therefore, a multiscale analysis is essential due to the number of gullies in the watershed (~ 65 gullies) and the complexity of their behavior.

GIS and remote sensing are important tools that organize and add information to those analyses (Pinton & Cunha 2008, Gelagay & Minale 2016). Anaglyphs of satellite images enable a tridimensional visualization of the surface, provided illumination conditions and channel width/depth constraints are fulfilled (Fiorucci et al. 2015). Their application improves the quality of erosion features delimitation since gullies are easily identified if their width is greater than 5 meters (Imwangana et al. 2015). Remotely piloted aircraft (RPA) images can be compared to and complement satellite images in gully erosion studies, providing a more complete investigation of the time variation of such features (Garritano et al. 2018). They also monitor natural resources effectively and provide information for the parameterization and validation of satellite images and models (Acharya et al. 2021).

Although not a new study area, fractal geometry applied to environmental studies, such as those on soil physics, watershed hydrography, and detailed soil properties (Bacchi & Reichardt 1993, Azevedo & Carvalho 2004, Vidal Vázquez et al. 2010), and gully erosion, aims at assessing those complex systems as near their actual forms as possible (Sampaio et al. 2018). Towards simplifying them and the measures to be adopted, researchers and land managers can apply mitigative or recovery measures that, with time, may not stabilize degradation processes and worsen environmental and financial losses (Rotta & Zuquette 2013).

Finally, field surveys and laboratory analysis of the samples supplement data particularly on geologic materials affected by erosion, thus comprehending the context of such a degradation form.

This article addresses the use of an integrated and multiscale approach for assessments of gully erosion in the closest way to its natural behavior employing a gully in the Palmital stream watershed, in Nazareno and Conceição da Barra de Minas municipalities, in Minas Gerais (Brazil). A study that uses GIS, anaglyphs, RPA images, fractal analysis, and field and laboratory survey is innovative; combining different methodologies is important to detail this environmental problem due to the complexity of the gully erosion process.

2. MATERIALS AND METHODS

2.1 *Study Area*

The study area is a gully in the Palmital stream watershed, in the central-eastern region of Nazareno municipality, Minas Gerais state (Brazil) (Figure 1), a region characterized by numerous gully erosions (Ferreira 2005, Ferreira et al. 2008, Ferreira et al. 2011, Sampaio et al. 2013, Sampaio 2014, Ferreira & Ferreira 2015, Cassaro 2018, Real 2019). Previous studies have suggested individual evaluations of the gullies are ineffective because they are interconnected by subsurface flow and water courses. Therefore, the studies have proposed the classification of features as gully complexes towards better results on their stabilization and recovery measures (Real 2019, Real et al. 2020b).

65 gullies were detected in satellite images from 2019 in the entire watershed (Soares, 2022). The gully was chosen as the study area due to the observation of interesting features, such as its form and presence of different soil materials, as well as fault and shear zones.

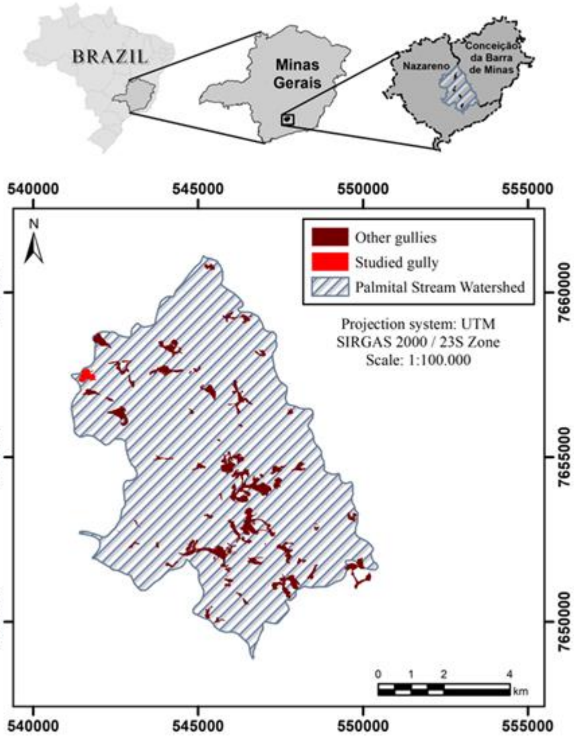

Figure 1. Study area.

Atlantic Rainforest and Brazilian Savannah (Cerrado) used to be the natural vegetation in the area (IBGE 2004) and land uses currently include pasture and crops of soybean, coffee, and corn (Figure 2). The climate is characterized by rainy summers and dry winters, with an approximately 1,350 mm average annual rainfall and temperatures ranging from 8°C to 28°C (INMET 2022). An irregular rainfall distribution has been reported since 2014, when lower volumes of precipitation in January and February started to be recorded, thus resulting in heat waves that decrease soil hydric conditions, since the water absorbed by the soil evaporates before the typical period, impacting the crops growth (INMET 2017). Moreover, climate changes associated with the South Atlantic Convergence Zone (SACZ) have caused intense and persistent rainstorms, twice to three times higher than the average rainfall (INMET 2020, INMET 2021).

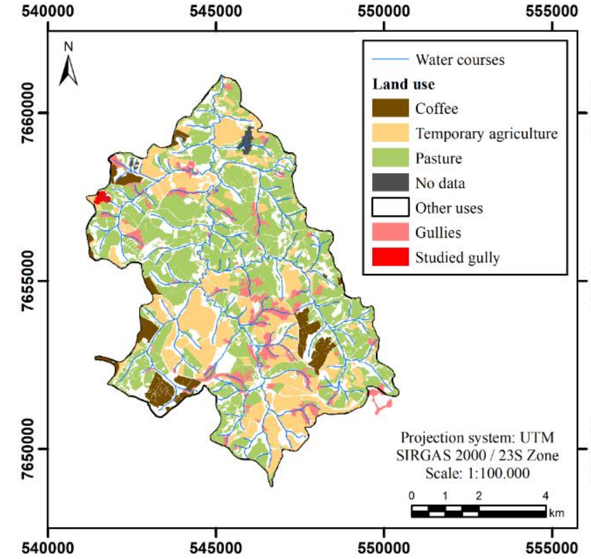

Figure 2. Land use survey of the Palmital stream watershed.

Elevations in the municipality range from 1,140 to 839 m, with strong hilly relief in the gully region (Horta et al. 2009). Cassiterita Orthogneiss, Nazareno Formation, and Represa dos Camargos Metadiorite are the geologic units that occur in the watershed. All of them are from Paleoproterozoic and have an elongated shape with ENE-WSW direction (Ávila et al. 2019). The Lenheiro shear zone is at its southern limits, together with greenstone belts (Ávila et al. 2003). The studied gully is in the northwest portion of the watershed, where Cassiterita tonalite-trondhjemite and orthogneiss rocks are predominant lithotype and essentially composed of plagioclase, quartz, perthitic feldspar, and biotite. Zircon, apatite, allanite, magnetite, ilmenite, molybdenite, pyrite, rutile, epidote, titanite, muscovite, carbonates, and chlorite are accessory and secondary minerals (Ávila 2003, Barbosa et al. 2019, Pinheiro et al. 2020). The Cassiterita Orthogneiss unit exhibits amphibolite facies metamorphism overprinted by retrogressive greenschist metamorphism (Barbosa et al., 2019). The main soil types of the gully area are red-yellow Oxisol, red Oxisol, and Cambisols (Horta et al. 2005, Ferreira 2005, Horta 2006, Horta et al. 2009). Oxisols are classified as dystrophic and clayey soils, with high levels of sesquioxides and aluminum oxides and lower levels of silica and organic matter. Cambisols are dystrophic and alic shallow soils with superficial encrusting and low permeability (Horta 2006, Horta et al. 2009). They are more erodible due to the relief and slope characteristics, slower drainage, stoniness, and fewer vegetation cover in comparison to Oxisols (Ferreira 2005). Oxisols are on top of Cambisols in the area so that if they are removed, Cambisols are exposed to weathering and erosion (Sampaio 2014).

2.2 *SIG and Anaglyphs*

A 2,000 x 2,000 m grid with 29 positions was set up in the Palmital stream watershed towards ensuring an adequate scale. Maxar Technologies satellite images from 07/13/2016 and 01/07/2019, with 3.85 km eye altitude and maximum resolution (4,800 x 2,312 pixels), available in Google Earth PRO, were chosen. Two images of each year were downloaded for every grid position – one centralized on the grid and another with 1,000 m dislocation to the east. They were called “left” and “right” images, respectively. The pairs of images were overlapped with Anaglyph Maker 1.08, creating red-cyan stereographic images (anaglyphs).

The anaglyphs can be correctly visualized with the use of 3D glasses (red and blue lenses), thus enhancing the limits of gullies due to their depths. Surveys were performed in a GIS environment with 1:50,000 scale in ArcMap™ (ESRI ArcGIS®).

2.3 *RPA and Fractal Analysis*

An RPA image of the studied gully (Figure 3) was purchased from AgroSAS ltda, with a 1:1,000 scale and 3.98 cm ground sampling distance (GSD) for improving the analysis and properly delineating the gully’s design by ArcMap™ (ESRI ArcGIS®) as the GIS. The SIRGAS 2000, zone 23S datum was used to maintain the same datum of the RPA image.

Once the gully’s designs had been binarized by ImageJ 1.51j8 (National Institute of Health – NIH), a fractal analysis was conducted according to the box-counting method in FracLac (plugin for ImageJ). Four increasingly refined sizes of sampling elements, twelve grid positions, a minimum pixel number of 0, and a 45% maximum coverage of 45% were used as inputs and the box-counting average fractal dimension (DB) was obtained for the entire gully area and for three parts inside the gully for the assessment of self-similarity.

2.4 *Field Investigation and Characterization*

Field studies and sample collection were performed in the Palmital stream watershed. The soil samples were dried at room temperature, homogenized, and fractioned and the following laboratory tests were conducted for physical and chemical characterization: i) grain size analysis (ABNT NBR 7181:2016) (ABNT, 2018), ii) erodibility (Pejon, 1992), and iii) pHH2O, ΔpH (pKCl – pHH2O) (EMBRAPA, 1997). X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) were performed according to Oliveira (2015) and Sampaio et al. (2016). Figure 3 displays the sampling locations of the different types of soil.

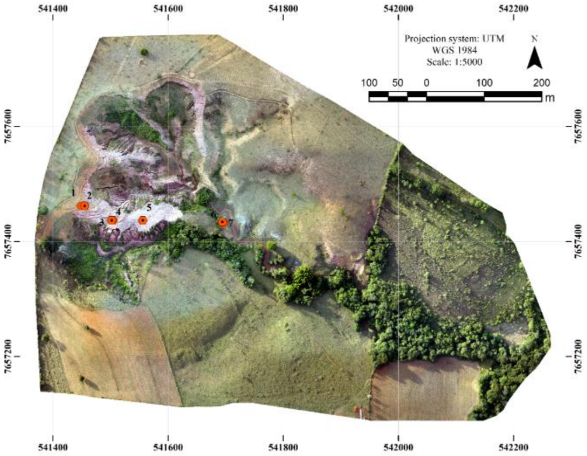

Figure 3. Field sampling location (RPA image).

3. RESULTS AND DISCUSSIONS

3.1 *SIG and Anaglyphs*

Two mosaics of anaglyphs of satellite images from 2016 (Figure 4) and 2019 (Figure 5) were composed for the watershed area. The visual analysis of the texture, color, shape, and depth of the erosive features guided the creation of gully polygons in ArcMAP™.

Figure 6 shows the gullies from 2016 and 2019, on a 1:50,000 scale, displaying some changes in their shape and size and inclusion of three new ones. Cassaro (2018) and Real (2019) mapped 78 gullies in the area using satellite images from 2016 and executing field confirmation. With the application of anaglyphs in our gullies survey in 2016 (Soares 2022), the number of gullies decreased to 63 but the area increased more than 100 ha (from 287.18 ha to 397.93 ha due to this technique), because of the recognition of connections between a part of the gullies (as observed by Real et al. 2020b), and the improvement of feature border's identification (Soares 2022). In 2019, some gullies were grouped, and new ones were delimitated, resulting in 65 gullies of 404.48 ha total area. The evolution of the erosive process was confirmed since the area of the gullies continued growing (Soares 2022).

As observed on the land use map (Figure 2), gullies occur near pasture and in temporary agriculture areas. Such land uses are related to erosion because of the lack of conservative measures in soybean and corn crops and the exposure and compaction of soil in pastures. Since the period between 2016 and 2019, some pasture areas have been replaced with crops, due to rises in grains´ prices (Soares 2022). However, agriculture is not successful in Cambisols since this soil type is poor in nutrients and organic matter.

The assessment of spatial and temporal characteristics of an area affected by erosive processes, especially gullies, has been one of the approaches for studies of their development and supply of information towards contributing to policymaking and decisions on control and recovery of degraded areas.

Remotely sensed data and geoprocessing in GIS are important tools for the identification and preliminary characterization of gullies. The use of satellite images improves the performance of temporal analysis, due to the availability of data from present and previous years, which enable comparisons between quality (length, depth, area, and shape changes) and quantities of features over the period analyzed.

Spatial and temporal studies can be accomplished by methods such as object-oriented analysis (Shruthi et al. 2015), mathematical statistics (Medvedeva et al. 2018, Real et al. 2020a), historical gully assessment with interviews of farmers (Bogale et al. 2020), and fractal analysis (Real et al. 2020a).

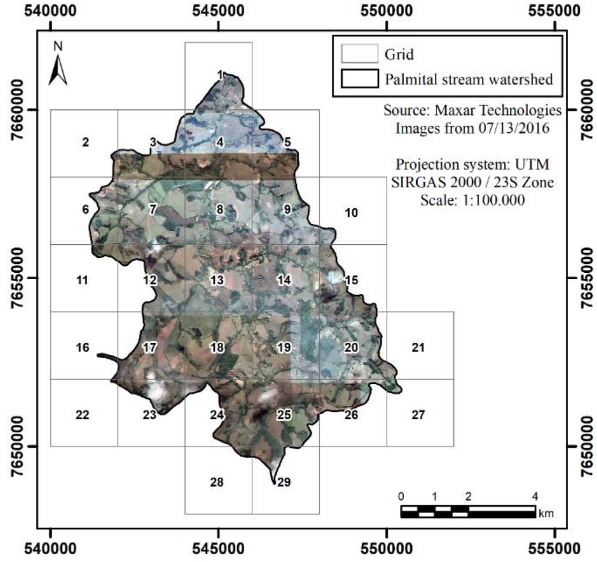

Figure 4. Mosaic of anaglyphs from 2016 in the Palmital stream watershed.

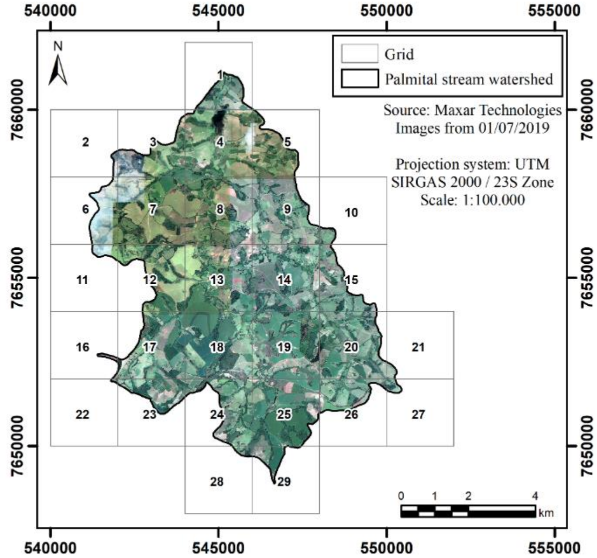

Figure 5. Mosaic of anaglyphs from 2019 in the Palmital stream watershed.

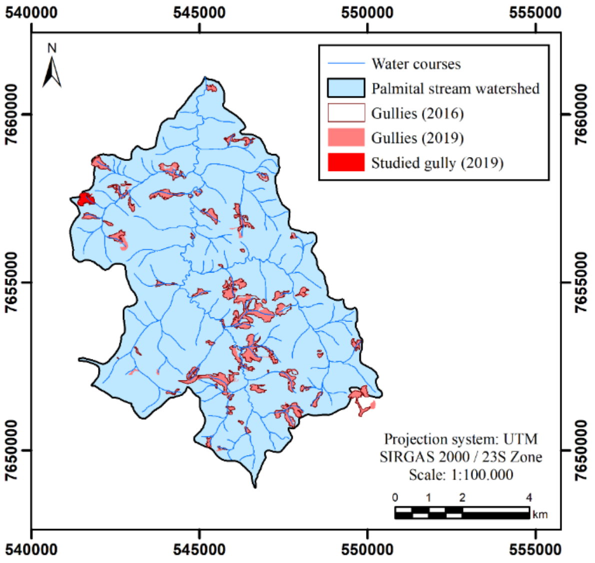

Figure 6. Map of gullies from 2016 and 2019 in the Palmital stream watershed.

3.2 *RPA and Fractals*

The extraction of gully features from satellite images may show uncertainties due to difficulties in the visualization of gully's margins (Shruthi et al. 2015) caused by the presence of vegetation, or the subtleties of texture changes. Moreover, scale and image resolution limitations control the size of the distinguished objects (Imwangana et al. 2015) and the presence of clouds or lack of imagery, thus restricting the visualization of some areas. Therefore, the surveyed elements must be confirmed by other methods such as drones' images and field validation.

The RPA image (Figure 8) shows the prevalence of subterranean soil removal in the gully process, confirming the "stair" form of the gully head. Other features such as drainage and basin systems for stabilizing erosion processes are also delineated; the image shows those systems were not entirely successful, proving different gully recovery measures are still required. Areas to be lost due to erosion processes can also be delineated, since the "stairs" features (soil subsidence) observed in the field are clearly displayed on the image scale. Such areas may collapse and enlarge the eroded area, therefore, vulnerable points of access for animals or people must not be allowed, and it is concerning that the owner would lose land within their property.

The use of drones in soil erosion assessment has been reported as effective for analyses of morphometry aspects, drainage system, and other properties of erosion-affected areas, since they provide high-resolution and accurate imagery (Carollo et al. 2015, Glendell et al. 2017, Koci et al. 2019, Lira-Caballero et al. 2020, Carabassa et al. 2021, Hartwig & Ribeiro 2021, Kariminejad et al. 2021), as observed in the case study.

Fractals can be applied in soil erosion assessments (Ren et al. 2018, Real 2019, Real et al. 2020a, Kabo-bah et al. 2021, Mofidi et al. 2021, Shi et al. 2021) since erosion features are continually changing and are irregular and complex elements. Figure 9 displays the entire gully design used in the fractal study.

According to the results (Table 1), a gully can be described as a fractal, whose DB value is closer to 1.8, i.e., closer to the areal dimension. The smaller parts selected and delimited showed values closer to 1.8 and 1.9, which may mean they are less jagged than the entire gully; however, the values were very close to the that of the entire gully.

Table 1. Results of fractal analysis of the studied gully.

Study Area	D_B	*Standard Deviation*	r^2
Entire gully	1.765	0.010	0.9989
Part 1	1.876	0.008	0.9991
Part 2	1.876	0.011	0.9994
Part 3	1.833	0.014	0.9990

Those values were considered self-similarity fractals, and more rounded shapes were required for representing one of the more evolved erosion stages (values of DB closer to two than one). Therefore, smaller rounded parts would exhibit "the future" of the entire gully, i.e., with no upper red-yellow Oxisol layer, more fragile soil (Cambisol) is exposed and subterranean flow removes the basis that sustains the slope wall, causing it to slide, widening the channel until it reaches a more stable state. Figure 8 shows a schematic of the process. Therefore, if this is a correct argument, then recovery measures comprising only the larger walls outside the gully will not suffice for equilibrium of the entire gully. The smaller channels inside the gully must be stabilized, with the regularization of subterranean flow already reaching the surface in the inner parts of the erosion, i.e., recovery measures must be established inside and outside the gully.

3.3 *Field Investigation and Characterization*

In the field investigation, it was confirmed that the main land use is pasture. As reported by Sampaio et al. (2016), runoff is usually directed to gullies by unpaved compacted roads and crops near them.

Subterranean flow played a major role in the evolution of the gully erosion process, since it removed Cambisol from underneath the more stable red-yellow Oxisol, creating empty subsurface spaces that collapsed, since Cambisols were exposed. An almost hollow "stair" formation (soil subsidence) is observed in the ground (Figure 7) and subsurface erosion is predominant in the gully head (Figure 10).

Figure 7. Part of the gully head: highlights for the "stair" formation on the ground.

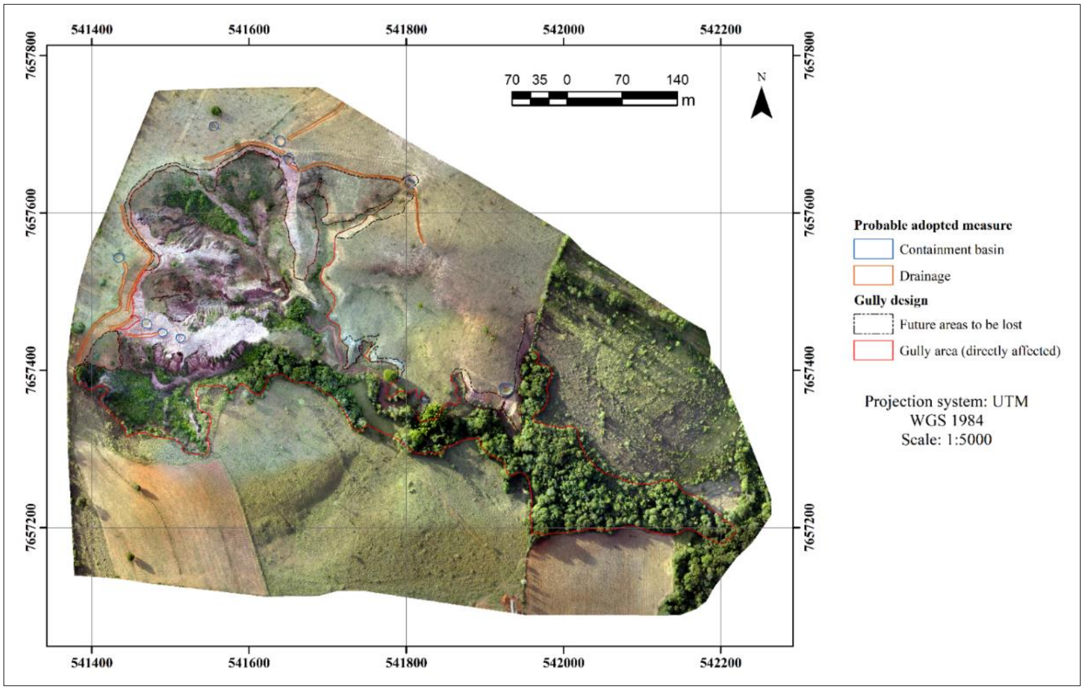

Figure 7. Delimitation of gully features in an RPA image.

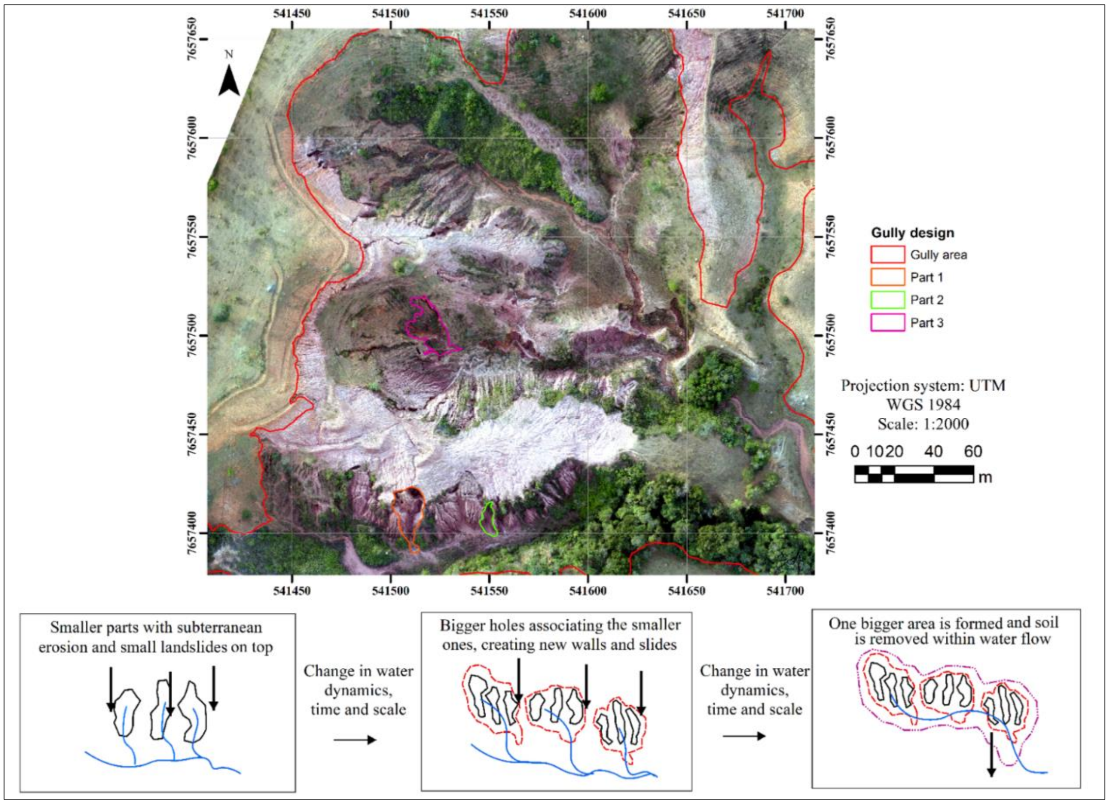

Figure 8. Gully with fractal parts and schematic of the fractal erosion process.

Figure 10. Examples of subsurface erosion over the gully head.

The laboratory results (Table 2) and field study (Figure 11) showed reminiscent structures and minerals from the rock that formed the soil (orthogneiss and tonalite-trondjhemite-granodiorite rocks) e.g., rare earth elements, and that the fault and shear zones also influence the erosion processes in the area. The layer can be considered a weak Cambisol and displays all conditions that worsen subterranean erosion.

Fig. 11 Cambisol inside the gully erosion. Upper left: reminiscent rock structure; lower left: crack following fault direction on soil; right: possible rock structure among Cambisol.

The characteristics of soil samples inside the gully are: (a) Red-yellow oxisol: lateritic soil, more resistant to erosion, homogeneous and permeable; (b) Transition between oxisol and cambisol; (c) "Pink colored" cambisol: more weathered and friable than oxisol, rock characteristics are present; (d) "Pink to white" cambisol: similar to 3, but with white material; (e) "Purple" cambisol: similar to 3, with darker colors resembling purple and more bands; (f) "Yellow" cambisol: closer to the water course, it is clayey and has its boundaries connected to 7; (g) "Gray" cambisol: more friable than 6 and closer to water courses, it is sandier than the others.

The physical and chemical characterization results are shown in Table 2, where particle size analysis is in percentage and pH was done to H_2O.

Table 2. Physical and chemical results for the gully samples.

Sample	*Particle Size Analysis*		*Erodibility*	*pH*	*ΔpH*	*XRD*
1	Clay	35.0	Low	6.7	-0.805	Kaolinite, halloysite, chlorite
	Silt	21.1				
	Fine sand	18.9				
	Medium sand	20.0				
	Coarse sand	5.0				
2	Clay	7.0	High	5.9	-1.815	Kaolinite, quartz
	Silt	35.8				
	Fine sand	27.2				
	Medium sand	25.0				
	Coarse sand	5.0				
3	Clay	3.0	NA	5.2	-0.915	Kaolinite, quartz
	Silt	34.0				
	Fine sand	23.0				
	Medium sand	35.0				
	Coarse sand	5.0				
4	Clay	5.0	High	5.8	-1.580	Kaolinite, quartz
	Silt	47.0				
	Fine sand	25.0				
	Medium sand	20.0				
	Coarse sand	3.0				
5	Clay	5.6	High	5.5	-1.085	Kaolinite, quartz
	Silt	42.4				
	Fine sand	27.0				
	Medium sand	20.0				
	Coarse sand	5.0				
6	Clay	15.0	NA	5.6	-1.040	Kaolinite, illite-chlorite, quartz, mica, muscovite, biotite
	Silt	53.0				
	Fine sand	27.0				
	Medium sand	4.0				
	Coarse sand	1.0				
7	Clay	4.7	High	6.0	-1.435	Quartz, illite, mica, muscovite, polymorphs, biotite
	Silt	41.3				
	Fine sand	30.5				
	Medium sand	22.5				
	Coarse sand	1.0				

NA: not analyzed.

The first sample matches with red-yellow Oxisol, as observed by Ferreira (2005) and Horta et al. (2009). According to the data classification of Cardoso, Fernandes, and Fernandes (2009), red-yellow Oxisol, of clayey sand texture, may have weak acidity (chemical classification) and a high agronomic classification. According to Guerra (1990), in addition to being strongly dependent on organic matter, the erodibility ratio is also dependent on aggregate content, crust formation, shear strength, and soil cohesion.

Santos et al. (2018) claimed such a soil is highly weathered (evolved), with intense ferralitization and resistant clay minerals concentration, including aluminum and iron oxides and hydroxides, with a lower than 17 cmolc kg-1 CEC (see Table 2).

The other samples from beneath the soil (Cambisols) showed erodible (soils 2, 4, 5 and 7; samples of soil 3 and 6 were not analyzed due to difficulties in sampling and applying the methodology). Cambisols are highly weathered and friable, which may grant higher erodibility ratios.

In comparison with sample 1 (Oxysol), Cambisol samples also showed silt and fine sand texture and lower pH, which might be connected to lower cohesion, higher erodibility, and degradation characteristics of the soils. As stated by Cassaro (2018), the lower cohesion of Cambisols cause impermeabilization of the soil surface related to splash of soil particles after raindrop impact. Consequently, water surpasses infiltration rates and runoff is generated, leading to erosion.

According to Figure 10, subterranean erosion occurs in the soil, i.e., the soil erosion mechanism begins inside the gully walls, removing more fragile soil from the slope and letting more resistant soil be exposed to more weathering conditions (differently from the conditions experienced when the soil is exposed), thus increasing its fragility and causing slides.

Lower pH values (more acid soil) can be associated with soil degradation (Bertuani et al. 2017); however, according to Cardoso, Fernandes, and Fernandes (2009), such soils may be adequate for agronomic uses. Matsumoto et al. (2018) demonstrated Al3+ is released from clay minerals, leading to the aggregation of soil particles and significantly decreasing the plastic index (IP) and liquid limit (LL) of the soils when pH ranges between 6.0 and 2.0.

The XRD results were also very similar among the samples. The minerals identified were kaolinite, quartz, illite-chlorite, chlorite, illite, muscovite, biotite, mica, halloysite, and polymorphs. Quartz and biotite are essential minerals to orthogneisses and tonalite-trondhjemites from Cassiterita Orthogneiss. Muscovite and chlorite were also described as accessory and secondary minerals in those rocks (Barbosa et al. 2019). The other minerals found by XRD analysis resulted from the pedologic process and mineral transformations – especially of plagioclase and feldspars.

4 CONCLUSIONS

Subterranean flow is an important factor for the development of gully erosion. Once soil particles from the more erodible layers are detached, the upper layer (in this case, a more stable and resistant soil) loses its basis and is more likely to slide, increasing the gully boundaries. Tubular and piping erosion on the gully head could be used to verify this. Therefore, subterranean flow is of utmost importance and must be considered alongside runoff for stabilizing erosion processes.

The association of satellite images with RPA images and field surveys has proved to better characterize a gully study area, with a more integrated view of features that would be missed if only one or another approach were applied. Gully mapping with the use of anaglyphs from satellite images increases the accuracy of erosion features' borders, shapes, and sizes due to the addition of depth to the visual investigation. The RPA image was highly useful for delimiting details of the gully areas that cannot be visualized in other images on a similar scale (e.g., satellite images) and features such as basins and drainage systems. RPA imagery can also be used in recovery projects due to the easiness for delineating those features in comparison to field observations.

The use of field, laboratory, and imagery analyses enables a wider view of the erosion process. The comprehension of the whole dynamics of gullies is unfeasible with the use of only one scale of analysis, i.e., with only imagery, or only soil analysis. Fractal analysis was also useful, since it revealed a self-similarity behavior within the gully, demonstrating the sue of recovery measures focused on subterranean flow prior to runoff would be more efficient.

5 ACKNOWLEDGEMENTS

The authors acknowledge the financial support from the National Council for Scientific and Technological Development (CNPq) (process numbers: 141835/2015-0 and 420740/2018-0) and the Coordination for the Improvement of Higher Education Personnel (CAPES) (process number: 88887.482750/2020-00), as well as the Brazilian Agricultural Research Corporation for the scientific cooperation.

6 REFERENCES

ABNT (Brazilian Association of Technical Standards). (2018). *NBR 7181:2016 – Soil – Grain size analysis*, 2nd version; ABNT: Rio de Janeiro (RJ), Brazil, 2018. 12 p.

Acharya, B. S., Bhandari, M., Bandini, F., Pizarro, A., Perks, M., Joshi, D. R., Wang, S., Dogwiller, T., Ray, R. L., Kharel, G., Sharma, S. (2021). Unmanned Aerial Vehicles in Hydrology and Water Management: Applications, Challenges, and Perspectives. *Water Resources Research*, 57, e2021WR029925. https://doi.org/10.1029/2021WR029925

Ávila, C. A., Bongiolo, E. M., Vasques, F. S. G., Souza, A. N., Seoane, J. C. S., Rītiņš, J. I. V., Vilela, F. T., Pinheiro, M. A. P., Vasconcelos, F. F., Cardoso, C. D., Silveira, V. S. L., Silva, P. R. S., Simon, M. B., Faulstich, F. R. L., Pires, G. L. C., Stohler, R. C., Oliveira, F. V. C. S. R. S., Tedeschi, M. F. (2019). *Projeto ARIM: Reavaliação das Sequências Metavulcanossedimentares a Sudoeste do Quadrilátero Ferrífero: Mapa Geológico Integrado, escala 1:100.000*. Belo Horizonte: Serviço Geológico do Brasil – CPRM.

Ávila, C. A., Valença, J. G., Moura, C. A. V., Pereira, R. M., Klein, V. C. (2003). *Geoquímica e idade do tonalito/trondhjemito Cassiterita, borda meridional do cráton São Francisco, Minas Gerais, Brasil*. Arquivos do Museu Nacional, 61, 267-284.

Azevedo, R. B., Carvalho, W. A. (2004). Aplicação da análise fractal em bacia hidrográfica: uma contribuição para caracterizar o ambiente. In: Proceedings of 32º Congresso Brasileiro de Educação em Engenharia, Brasília (DF), Brazil. 11 p.

Bacchi, O. O. S., Reichardt, K. (1993). Fractal geometry in soil physics. *Scientia Agricola*, Piracicaba, 50(2), 321-325. https://doi.org/10.1590/S0103-90161993000200021

Barbosa, N. S., Teixeira, W., Ávila, C. A., Montecinos, P. M., Bongiolo, E. M., Vasconcelos, F. F. (2019). U-Pb geochronology and coupled Hf-Nd-Sr isotopic-chemical constraints of the Cassiterita Orthogneiss (2.47 – 2.41-Ga) in the Mineiro belt, São Francisco craton: Geodynamic fingerprints beyond the Archean-Paleoproterozoic Transition. *Precambrian Research*, 326, 399-416. https://doi.org/10.1016/j.precamres.2018.01.017

Bertuani, R. R., Seiberti, L. P., Costa, K. A., Viana, D. G., Junior, P. R. R., Donagemma, G. K. (2017). Uso do pH como indicador da qualidade do solo e níveis de degradação de pastagem na região leste de Minas Gerais. In: Proceedings of 4º Simpósio Mineiro de Ciência do Solo, Viçosa (MG), Brazil. 453-455.

Blanco, H., Lal, R. (2008). *Principles of Soil Conservation and Management*. 1st ed. Springer.

Bogale, A., Aynalem, D., Adem, A., Mekuria, W., Tilahun, S. (2020). Spatial and temporal variability of soil loss in gully erosion in upper Blue Nile basin, Ethiopia. *Applied Water Science*, 10(106). https://doi.org/10.1007/s13201-020-01193-4

Carabassa, V., Montero, P., Alcañiz, J. M., Padró, J. C. (2021). Soil Erosion Monitoring in Quarry Restoration Using Drones. *Minerals*, 11(949). https://doi.org/10.3390/min11090949

Cardoso, E. L., Fernandes, A. H. B. M., Fernandes, F. A. (2009). *Análise de solos: Finalidade e procedimentos de amostragem*. Technical Report n. 79. EMBRAPA: Corumbá (MS), Brazil. 5 p.

Carollo, F. G., Stefano, C. D., Ferro, V., Pampalone, V. (2015). Measuring rill erosion at plot scale by a drone-based technology. *Hydrological Processes*, 29, 3802-3811. https://doi.org/10.1002/hyp.10479

Cassaro, R. (2018). *Análise dos processos erosivos na bacia do Córrego do Forro – Município de Conceição da Barra de Minas (MG): Estudo dos condicionantes geológicos-geotécnicos*. Dissertation (Masters). University of São Paulo. 159 p.

Dube, H. B.; Mutema, M.; Muchaonyerwa, P.; Poesen, J.; Chaplot, V. (2020). A global analysis of the morphology of linear erosion features. *Catena*, 190, 104542. https://doi.org/10.1016/j.catena.2020.104542

EMBRAPA (Brazilian Agricultural Research Corporation). (1997). *Manual de métodos de análise de solo*. 2nd ed. Centro Nacional de Pesquisas de Solos: Rio de Janeiro (RJ), Brazil. 212 p.

Ferreira, R. R. M., Ferreira, V. M. (2015). Levantamento de Áreas Degradadas e seus Atributos Químicos na Bacia Alto Rio Grande, MG. In: Proceedings of 35º Congresso Brasileiro de Ciência do Solo, Natal (RN), Brazil.

Ferreira, R. R. M., Ferreira, V. M., Tavares Filho, J., Ralisch, R. (2008). Levantamento de voçorocas na Bacia Alto Rio Grande, Minas Gerais. In: Proceedings of 8º Simpósio Nacional de Controle de Erosão, São Paulo (SP), Brazil.

Ferreira, V. M. (2005). *Voçorocas no município de Nazareno, MG: Origem, uso da terra e atributos do solo*. Dissertation (Masters). Federal University of Lavras. 84 p.

Ferreira, V. M., Silva, M. L. N., Curi, N., Oliveira, A. H., Silva, M. A., Avanzi, J. C. (2011). Influência antrópica e atributos de solo: inter-relações em ambientes de voçorocas na mesorregião Campo das Vertentes, MG. *Geografia*, Rio Claro, 36(1), 209-219.

Fiorucci, F., Ardizzone, F., Rossi, M., Torri, D. (2015). The Use of Stereoscopic Satellite Images to Map Rills and Ephemeral Gullies. *Remote Sensing*, 7, 14151-14178. https://doi.org/10.3390/rs71014151

Garritano, F. N., Loureiro, H. A. S., Santos, D. S., Martins, V., Guerra, A. J. T. (2018). Monitoramento, mapeamento e caracterização de voçoroca através de imagens do Google Earth Pro e uso de drone. In: Proceedings of 4ª Jornada de Geotecnologias do Estado do Rio de Janeiro, Seropédica (RJ), Brazil.

Gelagay, H. S., Minale, A. S. (2016). Soil loss estimation using GIS and Remote sensing techniques: A case of Koga watershed, Northwestern Ethiopia. *International Soil and Water Conservation Research*, 4(2), 126-136. https://doi.org/10.1016/j.iswcr.2016.01.002

Glendell, M., McShane, G., Farrow, L., James, M. R., Quinton, J., Anderson, K., Evans, M., Benaud, P., Rawlins, B., Morgan, D., Jones, L., Kirkham, M., DeBell, L., Quine, T. A., Lark, M., Rickson, J., Brazier, R. E. (2017). Testing the utility of structure-from-motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion. *Earth Surface Processes and Landforms*, 42, 1860-1871. https://doi.org/10.1002/esp.4142

Guerra, A. J. T. (1990). O papel da matéria orgânica e dos agregados na erodibilidade dos solos. *Anuário do Instituto de Geociências*, 13, 43-52. https://doi.org/10.11137/1990_0_43-52

Hartwig, M. E., Ribeiro, L. P. (2021). Gully evolution assessment from structure-from-motion, southeastern Brazil. *Environmental Earth Sciences*, 80(548). https://doi.org/10.1007/s12665-021-09831-z

Horta, I. M. F. (2006). *Levantamento dos solos e ocupação da superfície do Município de Nazareno, MG*. Dissertation (Masters). Federal University of Lavras. 74 p.

Horta, I. M. F., Costa, A. M., Araújo, A. R., Marques, J. J., Pereira, J. A. A., Oliveira, L. T., Carvalho, L. M. T. (2005). Caracterização dos solos do município de Nazareno - MG. In: Proceedings of 13º Congresso dos Pós-Graduandos da UFLA, Lavras (MG), Brazil.

Horta, I. M. F., Pereira, J. A. A., Marques, J. J., Carvalho, L. M. T. (2009). Digital reconnaissance soil survey of Nazareno, state of Minas Gerais. *Ciência e Agrotecnologia*, Lavras, 33, 1940-1947. https://doi.org/10.1590/S1413-70542009000700042

IBGE (Brazilian Institute of Geography and Statistics). (2004). *Mapa de vegetação do Brasil. Escala 1:5,000,000*. Ministério do Planejamento, Orçamento e Gestão, Diretoria de Geociências. https://ww2.ibge.gov.br/home/presidencia/noticias/21052004biomas.shtm. Accessed 26 Sep 2018.

Imwangana, F. M., Vandecasteele, I., Trefois, P., Ozer, P., Moeyersons, J. (2015). The origin and control of mega-gullies in Kinshasa (D.R. Congo). *Catena*, 125, 38-49. https://doi.org/10.1016/j.catena.2014.09.019

INMET (National Institute of Meteorology). (2017). *Nota técnica 004/17 – Estação chuvosa em Minas Gerais*. http://www.inmet.gov.br/portal/notas_tecnicas/2017/OUTUBRO/Nota_tecnica_CEDEC_04_ 17.pdf. Accessed 16 Jun 2021.

INMET (National Institute of Meteorology). (2020). *Fortes chuvas atingem os Estados do Espírito Santo e Minas Gerais*. https://portal.inmet.gov.br/uploads/notastecnicas/Nota_T%C3%A9cnica_Chuvas_MG_ ES_1.pdf. Accessed 21 Jun 2022.

INMET (National Institute of Meteorology). (2021). *As chuvas na Bahia, Minas Gerais e Espírito Santo*. https://portal.inmet.gov.br/uploads/notastecnicas/Nota_CHUVAS_BA_MG_ES-1_2021-12-28-174949_didl.pdf. Accessed 21 Jun 2022.

INMET (National Institute of Meteorology). (2022). *Banco de dados meteorológicos*. https://bdmep.inmet.gov.br/. Accessed 10 Fev 2022.

Kabo-bah, K. J., Guoan, T., Yang, X., Na, J., Xiong, L. (2021). Erosion potential mapping using analytical hierarchy process (AHP) and fractal dimension. *Heliyon*, 7, e07125. https://doi.org/10.1016/j.heliyon.2021.e07125

Kariminejad, N., Hosseinalizadeh, M., Pourghasemi, H. R., Tiefenbacher, J. P. (2021). Change detection in piping, gully head forms, and mechanisms. *Catena*, 206, 105550. https://doi.org/10.1016/j.catena.2021.105550

Koci, J., Sidle, R. C., Jarihani, B., Cashman, M. J. (2019). Linking hydrological connectivity to gully erosion in savanna rangelands tributary to the Great Barrier Reef using structurefrom-motion photogrammetry. *Land Degradation and Development*, 31(1), 20-36. https://doi.org/10.1002/ldr.3421

Lira-Caballero, V. G., Martínez-Menez, M. R., Romero-Manzanares, A., García-Moya, E., Ríos-Berber, J. D., Rubio-Granados, E. (2020). Morphometry of gullies and bioengineering for sediment retention in the Mixteca Region of Oaxaca, Mexico. *Ecohydrology & Hydrobiology*, 20, 289-300. https://doi.org/10.1016/j.ecohyd.2020.03.001

Matsumoto, S., Ogata, S., Shimada, H., Sasaoka, T., Hamanaka, A., Kusuma, G. J. (2018). Effects of Ph-Induced Changes in Soil Physical Characteristics on the Development of Soil Water Erosion. *Geosciences*, 8(134). https://doi.org/10.3390/geosciences8040134

Medvedeva, R. A., Golosov, V. N., Ermolaev, O. P. (2018). Spatio-Temporal Assessment of Gully Erosion in the Zone of Intensive Agriculture in the European Part of Russia. *Geography and Natural Resources*, 39(3), 204-211. https://doi.org/10.1134/S1875372818030034

Mofidi, S., Torkashvand, A. M., Moeini, A., Pazira, E., Ahmadi, H. (2021). Relationship between fractal dimensions of stream and morphometric characteristics of basin for the soil conservation from water erosion. *International Journal of River Basin Management*. https://doi.org/10.1080/15715124.2021.1981353

Morgan, R. P. C. (2005). Soil Erosion and Conservation. 3rd ed. Blackwell Publishing.

Oliveira, M. P. P. (2015). *Caracterização geológico-geotécnica e propostas de intervenções para estabilização de taludes na Boçoroca do Córrego do Cravo – Nazareno/MG*. Dissertation (Masters). University of São Paulo. 143 p.

Pandey, A., Himanshu, S. K., Mishra, S. K., Singh, V. P. (2016). Physically based soil erosion and sediment yield models re-visited. *Catena*, 147, 595-620. https://doi.org/10.1016/j.catena.2016.08.002

Pejon, O. J. (1992). *Mapeamento geotécnico da folha de Piracicaba-SP (escala 1:100.000): estudo de aspectos metodológicos, de caracterização e de apresentação dos atributos*. PhD Thesis. University of São Paulo.

Pinheiro, M. A. P., Ávila, C. A., Bongiolo, E. M., Magalhães, J. R., Vilela, F. T., Tedeschi, M. F. (2020). *Reavaliação do potencial mineral das sequências metavulcanossedimentares a sudoeste do Quadrilátero Ferrífero – área de Nazareno – MG: texto e mapa geológico integrado, escala 1:100.000*. CPRM: Belo Horizonte (MG), Brazil. 87 p.

Pinton, L. G., Cunha, C.M. L. (2008). Avaliação da dinâmica dos processos erosivos lineares e sua relação com a evolução do uso da terra. *Geociências*, 27, 329-343.

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C. (2003). Gully erosion and environmental change: importance and research needs. *Catena*, 50, 91-133. https://doi.org/10.1016/S0341-8162(02)00143-1

Real, L. S. C. (2019). *Fractal, multifractal e lacunaridade como uma nova ferramenta de análise para voçorocas: um estudo de caso*. PhD Thesis. Universisty of São Paulo.

Real, L. S. C., Crestana, S., Ferreira, R. R. M., Rodrigues, V. G. S. (2020a). Evaluation of gully development over several years using GIS and fractal analysis: a case study of the Palmital watershed, Minas Gerais (Brazil). *Environmental Monitoring and Assessment*, 192, 434-456. https://doi.org/10.1007/s10661-020-08362-7

Real, L. S. C., Crestana, S., Ferreira, R. R. M., Sígolo, J. B., Rodrigues, V. G. S. (2020b). Proposition for a new classification of gully erosion using multifractal and lacunarity analysis: A complex of gullies in the Palmital stream watershed, Minas Gerais (Brazil). *Catena*, 186, 104377. https://doi.org/10.1016/j.catena.2019.104377

Ren, L., Huang, J., Huang, Q., Lei, G., Cui, W., Yuan, Y., Liang, Y. (2018). A fractal and entropy-based model for selecting the optimum spatial scale of soil erosion. *Arabian Journal of Geosciences*, 11(161). https://doi.org/10.1007/s12517-018-3519-1

Rodrigues, V. G. S., Ferreira, M. D., Zuquette, L. V. (2015). Estudos geológicos e geotécnicos de áreas degradadas por mineração e erosão. In L. V. Zuquette (Ed.), *Geotecnia Ambiental* (1st ed., pp. 308-339). Elsevier.

Rotta, C. M S., Zuquette, L. V. (2013). Erosion feature reclamation in urban areas: typical unsuccessful examples from Brazil. *Environmental Earth Sciences*, 72(2), 535-555. https://doi.org/10.1007/s12665-013-2974-y

Rotta, C.M.S., Zuquette, L.V. (2015). Processos Erosivos. In L. V. Zuquette (Ed.), *Geotecnia Ambiental* (1st ed., pp. 308-339). Elsevier.

Sampaio, L. F. (2014). *Estudo geológico-geotécnico dos processos erosivos e proposta de macrodrenagem: Voçoroca do Córrego do Cravo (Nazareno-MG)*. Dissertation (Masters). University of São Paulo.

Sampaio, L. F., Crestana, S., Rodrigues, V. G. S. (2018). Study of gully erosion in south Minas Gerais (Brazil) using fractal and multifractal analysis. In IAEG/AEG Annual Meeting Proceedings, San Francisco, California, United States, 217-222. https://doi.org/10.1007/978-3-319-93142-5_30

Sampaio, L. F., Oliveira, M. P. P., Cassaro, R., Rodrigues, V. G. S., Pejon, O. J., Sígolo, J. B., Ferreira, V. M. (2016). Gully erosion, land uses, water and soil dynamics: A case study of Nazareno (Minas Gerais, Brazil). *DYNA*, 83(199): 198-206. https://doi.org/10.15446/dyna.v83n199.54843

Sampaio, L.F., Oliveira, M. P. P., Gimenes, F. B. Q., Rodrigues, V. G. S., Pejon, O. J. (2013). Utilização de SIG e índices morfométricos para estudo dos processos erosivos em uma bacia do município de Nazareno/MG. In Proceedings of 14º Congresso Brasileiro de Geologia de Engenharia e Ambiental, Rio de Janeiro (RJ), Brazil. p. 1-9.

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araújo Filho, J. C., Oliveira, J. B., Cunha, T. J. F. (2018). *Sistema brasileiro de classificação de solos*. 5th ed. EMBRAPA: Brasília, Brazil. 590 p.

Shi, W., Wang, J., Li, X., Xu, Q., Jiang, X. (2021). Multi-fractal characteristics of reconstructed landform and its relationship with soil erosion at a large opencast coal-mine in the loess area of China. *Geomorphology*, 390, 107859. https://doi.org/10.1016/j.geomorph.2021.107859

Shruthi, R. B. V., Kerle, N., Jetten, V., Abdellah, L., Machmach, I. (2015). Quantifying temporal changes in gully erosion areas with object oriented analysis. *Catena*, 128, 262-277. http://doi.org/10.1016/j.catena.2014.01.010

SOARES, A.K.M. (2022). Análise temporal dos processos erosivos e modelagem da perda de solo na bacia do Córrego do Palmital - Minas Gerais. Dissertation (Masters). University of São Paulo.

Vidal Vázquez, E., Vieira, S. R., Maria, I. C., González, A. P. (2010). Fractal dimension and geostatistical parameters for soil microrelief as a function of cumulative precipitation. *Scientia Agricola*, 67(1): 78-83. https://doi.org/10.1590/S0103-90162010000100011