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Research Article

Gullies in Brazil: a spatiotemporal approach between 2000 and 2020

Voçoroca no Brasil: uma abordagem espaço-temporal entre os anos 2000 e 2020

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Abstract: This article proposes to conduct a bibliographic review of the scientific production on gullies, approaching the conceptual, methodological, and dimensional aspects and their spatial distribution in Brazil. Therefore, the database available on the Brazilian Journal of Geomorphology (RBG, https://rbgeomorfologia.org.br/rbg/index) was used, along with the articles, expanded and simple abstracts from the National Geomorphology Symposium (SINAGEO, http://lsie.unb.br/ugb/sinageos). The analyzed period for the RBG was from 2003 to 2020, and that for the SINAGEO was from 2000 to 2018. Overall, the southeastern region concentrates most of the works, focusing on the hydrological processes that contribute to gullying. Regarding the definitions, there is considerable diversity, with studies that value only the dimensional criteria, the combination of shape and dimensions, or the connectivity with the drainage network. A change in monitoring techniques is currently evident with the use, often combined, of unmanned aerial vehicles (UAVs), terrestrial laser scanning (TLS), and satellite/aerial photography, making it possible to know the spatiotemporal evolution and the current evolutionary stage of gullies. Lastly, the works point out that the occurrence of gullies in rural and urban areas arises from the imbalance between the energy and matter available in the system.

Keywords: Geomorphology; Erosion; Gully.

Resumo: Este artigo propõe realizar uma revisão bibliométrica da produção científica da temática voçoroca, abordando os aspectos conceituais, metodológicos, dimensionais e sua distribuição espacial no Brasil. Para tal, utilizou-se apenas o banco de dados disponível no site https://rbgeomorfologia.org.br/rbg/index na Revista Brasileira de Geomorfologia (RBG) e os trabalhos completos, resumos expandidos e simples do Simpósio Nacional de Geomorfologia (http://lsie.unb.br/ugb/sinageos). O período de análise dos dados é para a RBG de 2003 até 2020 e para o Sinageo de 2000 até 2018. De maneira geral, a maior concentração dos trabalhos é na região Sudeste, abordando os processos hidrológicos que contribuem para a formação de voçorocas. Quanto às definições, existe uma considerável diversidade, desde aquelas que valorizam apenas o critério dimensional, a forma e dimensão juntas ou a conectividade com a rede de drenagem. Também, evidencia-se uma mudança nas técnicas de monitoramento, sendo atualmente, utilizados Veículo Aéreo Não Tripulado (VANT) e *Laser Scanner Terrestre* (LST) e imagens de satélites/fotografias aéreas, que por vezes são utilizadas combinadas, possibilitando conhecer a evolução espaço-temporal e, o estágio evolutivo atual das voçorocas. Por fim, os trabalhos salientam que a ocorrência das voçorocas em áreas rurais e urbanas, são oriundas do desequilíbrio do balanço entre a energia e a matéria disponível no sistema.

Palavras-chave: Geomorfologia; Erosão; Voçoroca.

1. Introduction

Gullies are erosive features found in different parts of the Earth, originating from natural processes, with different frequencies and magnitudes, resulting from a dynamic adjustment between the energy and the material available in the hydrogeomorphic system (MORGAN, 2005).

Despite this, human activity on Earth has been contributing to the alteration of the dynamic balance between energy and material available in the system, leading to an increase in the occurrence of gullies in both rural and urban landscapes. Over the past two decades, gullies in urban landscapes have become a global-scale problem (WALLING, 1999; CASTILLO; GÓMEZ, 2016; ROBERTS et al., 2022).

Regarding the factors that contribute to the occurrence of gullies, we can highlight those associated with natural aspects, such as rainfall (intensity and frequency), topographic characteristics (length, shape, orientation, slope, among others), soil characteristics (texture, structure, bulk density, porosity, permeability, aggregate stability, among others) (VIEIRA, 1978; GUERRA, 1995; PIMENTEL, 2006; MANSTRETTA, PERILLO, PICCOLO, 2023), geological characteristics (lineaments, joints, and fractures) (DI-RANE; VIEIRA, 2014; LI et al., 2022; ZHAO et al., 2022), and those associated with human actions resulting from changes in land use and land cover (agricultural practices without soil management and conservation, land impermeabilization, among others).

One of the earliest studies on quantifying gully erosion dates to Charles Lyell's visit to Georgia, United States, in 1846, when he conducted a physiographic description (IRELAND, 1939). Since then, the 'Lyell' gully has been revisited several times in the works of Ireland (1939) and Horton (1945), with the latter referring to it as a 'rill channel.'

According to Augustin and Aranha (2006), at the international level, studies on gullies were in their early stages until the 1970s, with a greater emphasis in the 1980s, research on this erosive feature increased. Notable works in chronological order include those of Tricart (1966), Young (1972), Carson and Kirkby (1972), Kirkby (1978), Imeson and Kwaad (1980), Crouch and Blong (1989), Poesen and Govers (1990), Bull and Kirkby (1997), Poesen et al. (2003), Valentin, Poesen, and Yong (2005), Goudie (2006), Gómez-Gutiérrez, Schnabel, and Felicísimo (2009), Gómez-Gutiérrez et al. (2012), Castillo and Gómez (2016), and Vanmaercke et al. (2016, 2021). Additionally, Valentin, Poesen, and Yong (2005) noted that international conferences held in Leuven, Belgium, and Chengdu, China, contributed to the increase in publications on the topic.

In Brazil, as reported by Augustin and Aranha (2006), the first specific publications on gullies began to appear in the 1950s, with more systematic studies emerging in the 1970s. Since then, there has been a growing number of publications on the topic of gullies, encompassing studies of morphological and morphometric characteristics, hydrological aspects (surface and subsurface water), those utilizing both traditional and recent techniques for monitoring their evolution, and those associated with the effects of human activity on the landscape. Some notable references include Fiori and Soares (1976), Vieira (1978), Fleury (1983), Bigarella and Mazuchowski (1985), Coelho Netto, Fernandes, and Deus (1988), Oliveira (1999), Coelho Netto (1995), Paisini and Oliveira (2001), Vrieling, Rodrigues, and Sterket (2005), Bacellar, Coelho Netto, and Lacerda (2005), Drumond and Bacellar (2006), Salgado et al. (2008), Magalhães et al. (2012), Marchioro, Andrade, and Oliveira (2016), Julian and Nunes (2020), and Loureiro, Guerra, and Andrade (2020), among many others.

In this context, Ab'Saber (1968), Carson and Kirkby (1972), Kirkby (1978), Imeson and Kwaad (1980), and Dotterweich et al. (2012) emphasize that throughout geomorphological history, gullies have been recognized as a morphogenetic process that operates on landscapes and, due to anthropogenic activities, have become one of the major environmental degradation issues. Therefore, considering the historical perspective of knowledge about the gully topic, this article conducts a critical bibliometric analysis of scientific production related to the subject in Brazil, considering publications in the Brazilian Journal of Geomorphology and the National Symposium on Geomorphology.

2. Materials and Methods

Given the diversity of bibliometric sources available today, this article chose to focus on the Brazilian Journal of Geomorphology (RBG), which was classified as Qualis A2 during the period from 2013 to 2016 and as Qualis A1 from 2017 to 2020. Additionally, publications available from the National Symposium on Geomorphology (Sinageo) (http://lsie.unb.br/ugb/sinageos) were used. The analysis period for RBG is from 2003 to 2020, and for Sinageo is from 2000 to 2018.

This choice of journal and symposium is due to the fact that they are the only specific sources for geomorphology in Brazil, affiliated with the Brazilian Geomorphology Union, which is, in turn, associated with the International Association of Geomorphologists (IAG). However, it should be emphasized there is a wide variety of national and international journals that also address the topic but were not considered in this article.

To identify and quantify articles related to the topic of gullies, initially, works with the terms "voçoroca or gully" and/or "gullies or voçorocamento" in the title, abstract, and keywords were selected. Once identified, they were analyzed for spatial and historical distribution, methods and techniques used, dimensional aspects, and conceptual aspects. Subsequently, descriptive statistical analyses were conducted, and graphs and maps were elaborated to represent the research conducted in Brazil.

3. Results and Discussion

3.1. Spatial Distribution of Gully Studies

Regarding gully studies in Brazil, a total of 10 articles were identified in the RBG during the period from 2003 to 2020, with spatial concentration in the Southeast and South regions (Figure 1). The highest occurrence of publications took place in 2020 (Figure 2). It is also noteworthy that the institutions with the highest number of publications were the Federal University of Rio de Janeiro (UFRJ) and the São Paulo State University "Júlio de Mesquita Filho" (Figure 3).

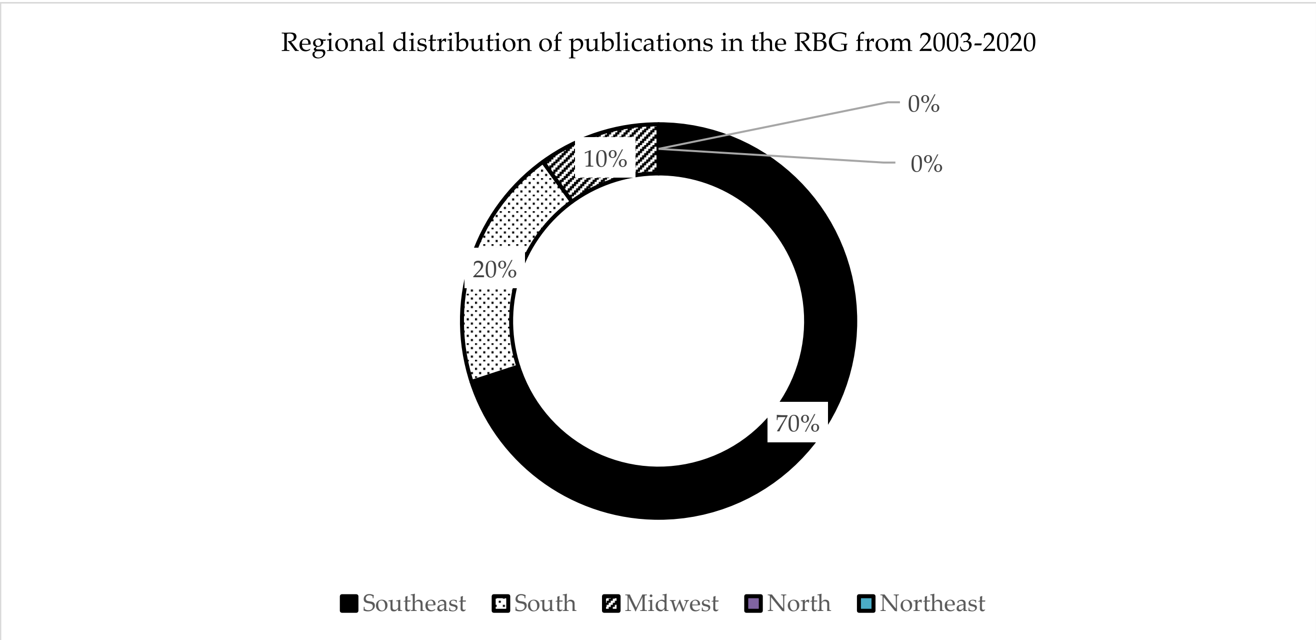

Figure 1. Spatial distribution of publications on gullies in the RBG. Source: Compiled by the authors.

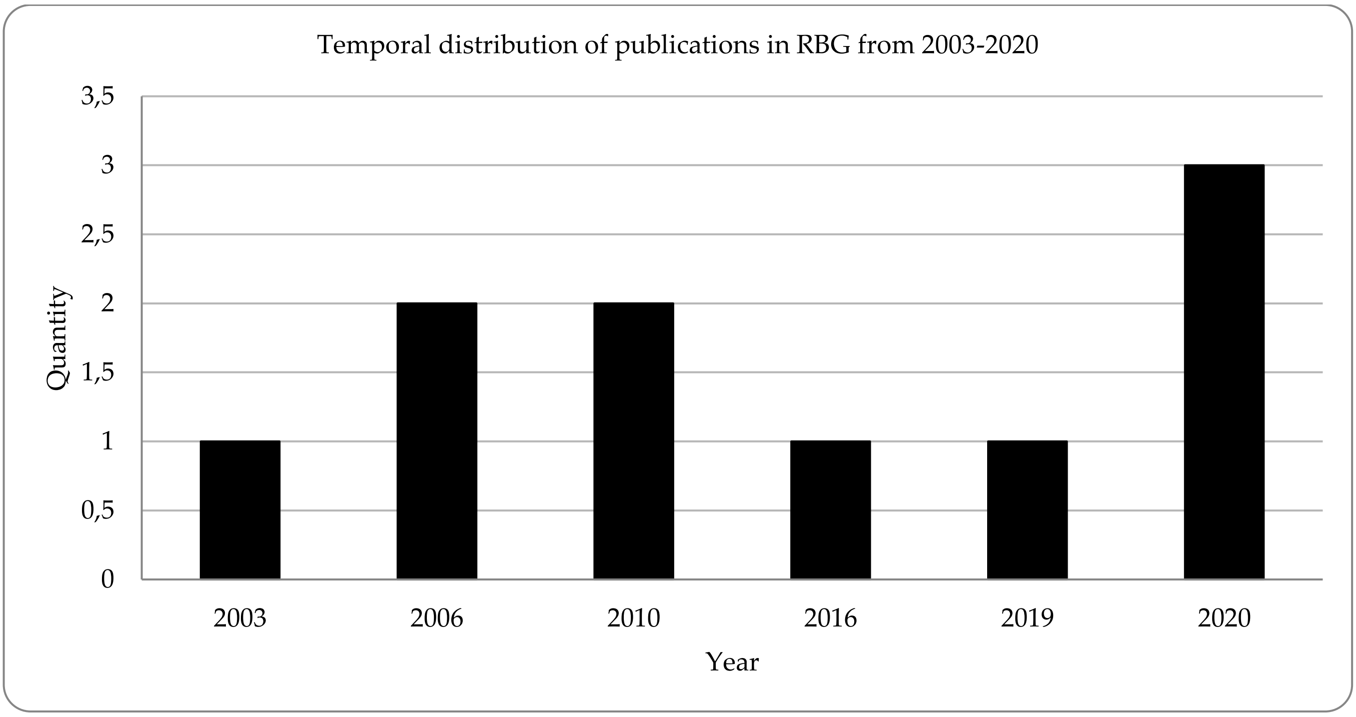

Figure 2. The temporal distribution of publications on gullies in RBG. Source: Compiled by the authors.

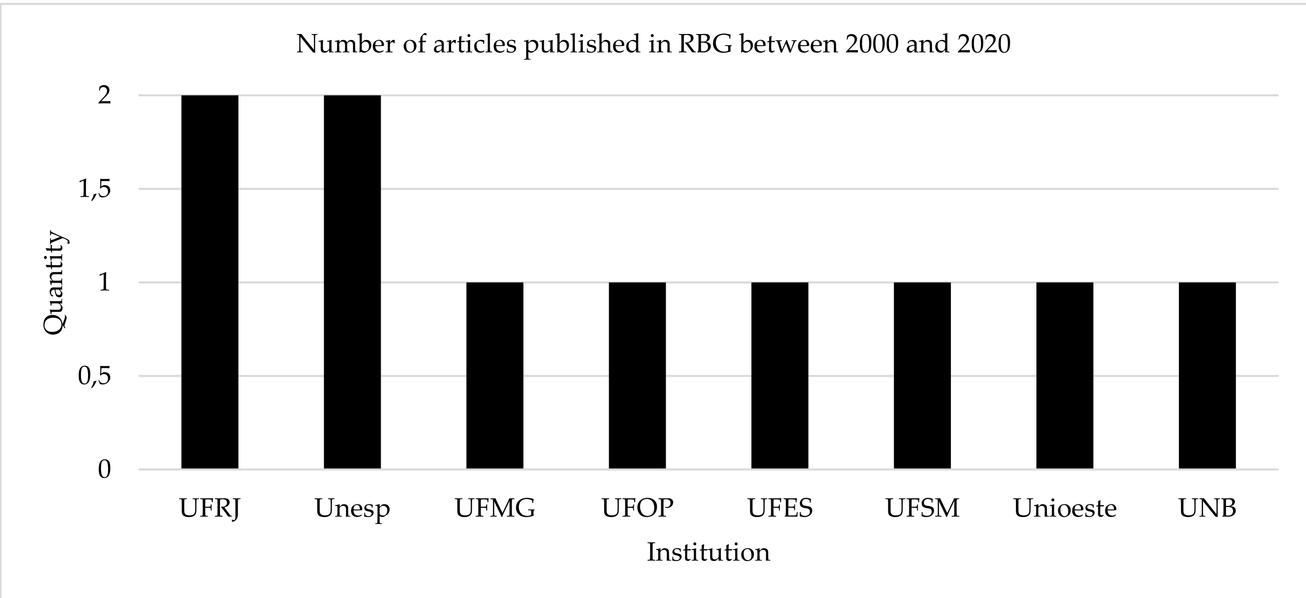

Figure 3. Institutions where publications on the topic of gullies in the RBG were found. Source: Compiled by the authors.

Regarding Sinageo, from 2000 to 2018, 107 works with the term "gully" were identified, with the years 2000 and 2006 having the highest occurrence of the term in the publications on the subject (Figure 4). In terms of spatial distribution, the highest concentration is repeated in the Southeast region, followed by the North region, accounting for a combined 62.62% of publications in Sinageo (Figure 5). It is noteworthy that, as observed in the publications, new data acquisition technologies for gullies are being used, such as satellite images, unmanned aerial vehicles (UAVs), and terrestrial laser scanning (TLS). This allows the integration of techniques with different spatial and temporal scales.

Furthermore, the highest occurrence of works on the subject in the Southeast region of Brazil may be linked to greater financial investment in research by institutions over historical periods, which strengthened research groups in universities from that region. Another aspect that contributed to this strengthening over time is the geo-environmental conditions, including rainfall, topography, soils, and land use, which can contribute to the advancement or emergence of gullies. These gullies notably affect both rural and urban geographical spaces, requiring researchers to develop studies on the subject.

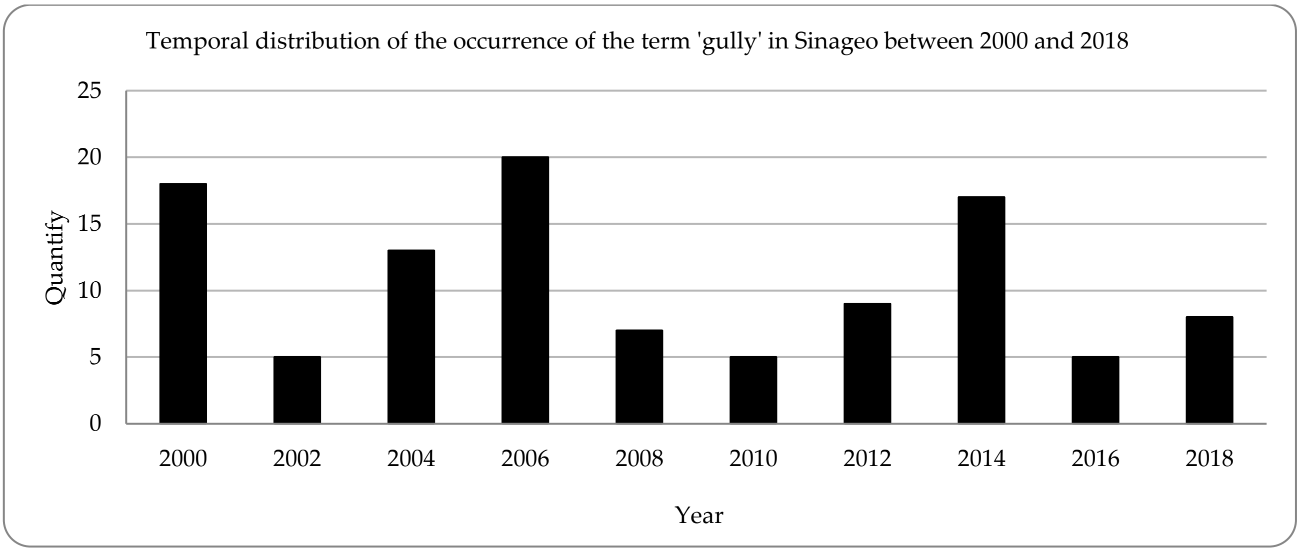

Figure 4. Temporal distribution of the occurrence of the term "gully" in publications in Sinageo. Source: Compiled by the authors.

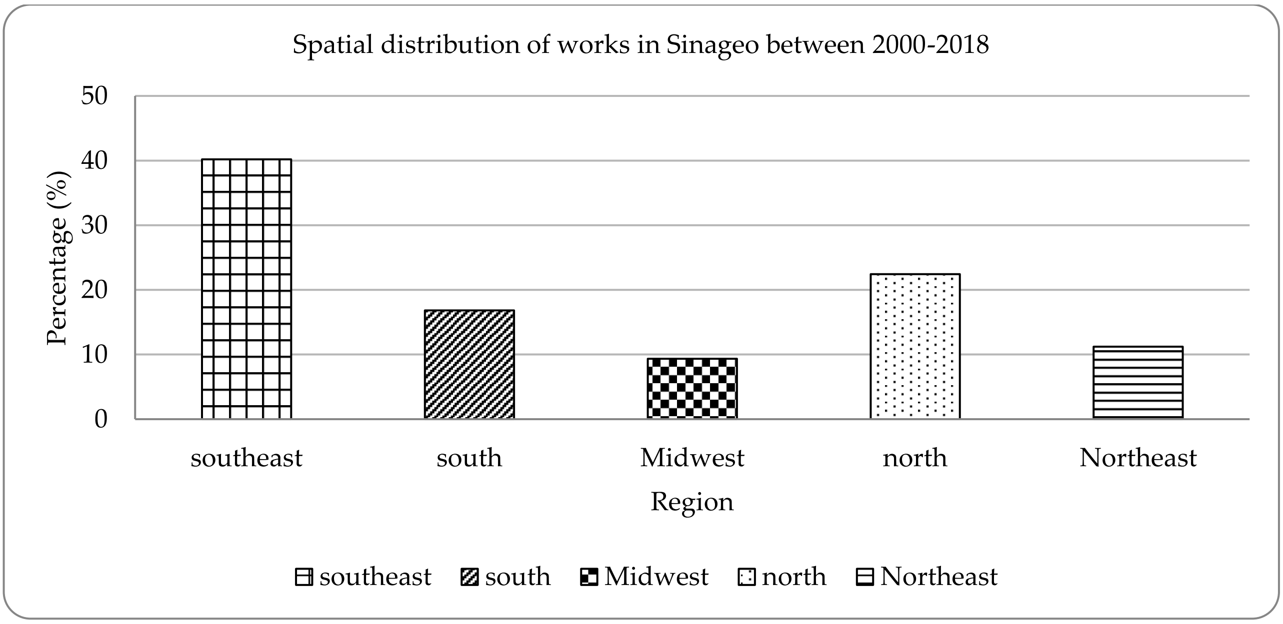

Figure 5. The spatial distribution in percentage of studies on gullies in Sinageo. Source: Compiled by the authors.

Regarding the geographical areas where the studies were conducted, it can be stated that, in 44.86% and 50% of publications in Sinageo and 50% of the articles in RBG, respectively, the term is present in rural research areas, associated with the absence of soil management and conservation practices and "natural" processes. Sinageo and RBG comprise 34.57% and 20% of the articles in urban areas, respectively, reflecting how soil impermeabilization and the concentration of hydrological flows contribute to the occurrence of gullies. It is noteworthy to mention that, in Sinageo, studies associating mining activities as a triggering mechanism for gully erosion were identified, which was not observed in the publications of RBG.

3.2. The term "gully": from its origin to its derivations

In Brazil, the term gully or "voçoroca" originates from "boçoroca," which is derived from Tupi-Guarani: "ibi-çoroc," where "ibi" means land and "çoroc" means fissure or rift, in other words, "land with rifts." This term was widely used until the late 1980s by authors such as Ab'Saber (1968), Furlani (1969), and Vieira (1978), among others. However, at present, it is less commonly used in the Brazilian scientific community, despite, according to Francisco (2018), no plausible argument being presented for minimizing the use of the term "boçoroca."

In light of this, a question arises regarding gully studies in Sinageo and RBG: do the articles provide any definition of the erosive feature?

Considering the analyzed period, the total number of articles that provided the adopted definition in the publication is 28.03%, a percentage considered low. This is driven by the earlier Sinageo editions that included publications in the form of simple abstracts and/or extended abstracts, which limited the use of definitions. Regarding articles in RBG, few include a concept of the geomorphological feature or a review of the concept itself, as seen in works such as those by Francisco, Nunes, and Tommaselli (2010), Marchioro, Andrade, and Oliveira (2016), and Julian and Nunes (2020).

The definitions found in the works of Sinageo and RBG mostly emphasize surface and subsurface hydrological processes as significant factors in the formation of gullies, such as a) as presented by Gomes et al. (2014) and in accordance with the NBR 6502 standard (ABNT, 1995, p.18), a gully is described as "an erosive form, shaped by surface erosion and undercutting caused by underground erosion, typically in sandy terrains"; b) Sato et al. (2012) describe gullies as "[...] erosions caused by the exfiltration of groundwater"; c) Julian and Nunes (2020) emphasize that gullies are "caused by concentrated surface runoff until it reaches the level of the suspended water table," which contrasts with the definition provided by the Technological Research Institute of São Paulo State (IPT); d) Salgado et al. (2008) classified gullies based on whether they are connected or disconnected from the drainage network; and e) Dirane and Vieira (2014) defined gullies as erosive features with a flat bottom, dimensions greater than 1.5 m in depth, and width and length exceeding 3 m.

There are also studies that emphasize the importance of geological lineaments and structures in the process of gully formation, as presented by Coelho Netto (2003), Dummer and Verdum (2016), Abreu, Vieira, and Frota Filho (2012), and Souza, Litholdo, and Lupinacci (2018). However, Abreu, Vieira, and Frota Filho (2012) point out the need for more studies to investigate the relationship between geological structures and lineaments with gullies in the city of Manaus, which is a research topic that can also be expanded to other regions and cities in Brazil.

Still considering the definitions, in those articles that did not provide an explicit definition, it was possible to observe the discussion of the processes that form gullies. This was done based on the hydrogeomorphic conditions in rural and urban areas, highlighting the importance of process-oriented studies.

The use of different criteria to define gullies is not exclusive to the publications of Sinageo and RBG since various criteria for their classification can be found in the international literature, as presented by Goudie (2006), including a) morphological and topographic criteria: characterized by relatively steep walls, relatively deep incisions with poorly vegetated surroundings, and a catchment area of 10 km² or less; b) surface and subsurface hydrological criteria (MORGAN, 2005); c) criteria related to agricultural practices: channels with depth and width that do not allow for agriculture (FAO, 1965); and d) instability criteria: recently formed incisions within a valley where there was previously no well-defined channel (BETTIS III; THOMPSON, 1985).

These variations in concepts found in Sinageo and RBG can, in general, contribute to difficulties in categorization within Geomorphology and other areas of scientific knowledge, nationally and internationally.

3.3. The dimensions of the gullies

Considering the dimensional criterion, the areas comprised from the gullies among the set of works presented to Sinageo and the RBG were as follows: a) the average total area was 7,662.05 m², b) the minimum area was 149.33 m², and c) the maximum was 69,884.09 m². Given the data presented in Table 1 and considering the regional diversities of climatic, tectonic, lithological, and regolith characteristics, it can be emphasized that dimension alone may not be the best criterion to define gullies in Brazil due to its continental size and multiple hydrogeomorphic systems, which require the incorporation of shape criteria into hydrogeomorphic processes for a better definition.

Table 1. Depth, width, length, and dimension of the works from Sinageo and RBG on gullies.

Parameter	**Dimension** (m)	**Source**
Minimum depth	2.00	(MASCARELLO; CAMARGO FILHO, 2006)
Maximum depth	40.00	(COSTA et al., 2018)
Average depth	9.07	*
Minimum width	2.50	(MASCARELLO; CAMARGO, 2006)
Maximum width	72.59	(CABRAL; NUMMER; BETEIRA, 2020)
Average width	23.28	*
Minimum length	42.00	(VIEIRA; MOLINARI; MUNIZ, 2004)
Maximum length	1,200.00	(BESERRA NETA; TAVARES JUNIOR; COSTA 2014)
Average length	27.03	*
Minimum total area	149.33	(VIEIRA; MOLINARI; MUNIZ, 2004)
Maximum total area	69,884.80	(CABRAL; NUMMER; BETEIRA, 2020)
Average total area	7,662.05	*

Note: Prepared by the authors. * Average values were obtained from publications in Sinageo and RBG.

Aiming to improve the concept and with the intention of considering morphological aspects in defining gullies, Oliveira and Braga (2008) align with the approach, emphasizing that a gully consists of a relatively permanent feature on the slope, with deep and steep walls, generally with a flat bottom. Vieira (2008) points out that a "gully" is an erosional feature with a flat bottom, with dimensions exceeding 1.5 m in depth and with a width and length exceeding 3 m.

When comparing the concepts found in Sinageo and RBG with what is observed worldwide, it can be said that there is also no consensus on dimensions to define a gully. Poesen et al. (2003) suggest that a gully is a feature with a minimum area of 1 m2 without specifying minimum width and depth. Heede (1970) and Imeson and Kwaad (1980) suggest that gullies can have widths and depths of 50 cm. According to the FAO (1965), gullies are erosional features that cannot be obliterated by human action or machinery, indicating a small dimension without specifying it.

The dimensions of the gullies obtained from the works of Sinageo and RBG raise questions for possible reflections: a) Is it possible to consider the dimensional criterion in regions with different regoliths as a determining factor in defining what a gully is? b) Is it possible to incorporate regional characteristics of regoliths into the definition of a gully based on dimensional criteria? c) Are there sufficient data on gullies in Brazil to establish an average dimension for the country or by geographical region? d) Is it possible to compare the dimensions of Brazilian gullies with different regions of the world without considering their climatic, geomorphological, tectonic, and pedological characteristics?

Based on what has been exposed thus far, there is a need to regroup and/or expand the efforts of the geomorphological community and related fields. This is essential for the search of a scientific approach capable of minimizing the nuances of the concept across different areas of geosciences and for different parts of the planet. Based on these reflections, we aim to get closer to the so-called “universal” concept. However, is it possible?

3.4. Methods and techniques used over time

Despite the evolution of scientific knowledge and technical information systems, this topic aims to depict the transformations that have occurred in the monitoring techniques of gullies over time.

In general, the gully monitoring works published in Sinageo and RBG adopted erosion stakes or pins, aerial photographs, satellite images, unmanned aerial vehicles (UAVs), terrestrial laser scanners (TLSs), GeoRadar, ground penetrating radar (GPR), piezometers, and morphometric conditioning studies to understand the occurrence of gullies.

In Sinageo and RBG, studies using the technique of erosion stakes or pins are predominantly distributed in the Southeast, Northeast, and South regions, as seen in the works of Francisco, Nunes, and Tommaselli (2010), Loureiro and Guerra (2012), and Viana and Bezerra (2018). The use of this technique is largely due to its low cost and its potential for geospatial monitoring of erosional feature evolution. However, the need for continuous field visits to obtain data over time may become a challenging task, limiting the monitoring period to a few years. Another aspect highlighted by Loureiro, Guerra, and Andrade (2020) is that gully monitoring with erosion pins requires a high point density to capture the spatial variability of features more accurately, as well as an extended monitoring period to generate more reliable extrapolations.

Studies using aerial photographs, such as those conducted by Drumond and Bacellar (2006), Oliveira and Braga (2008), Leal et al. (2008), Salgado et al. (2008), Nascimento et al. (2012), and Marchioro, Andrade, and Oliveira (2016), demonstrate the relevance of using aerial photographs and satellite images to assess the evolutionary changes in the studied gullies. This type of photointerpretation allows for the assessment of gully shape and dimensions over a span of up to 50 years or more, depending on the availability of photographs or satellite images. However, it is important to note that sometimes these images may not have the same spatial resolution and temporal consistency, potentially requiring significant investments due to their spatial resolution.

To understand the mechanism behind gully formation, Augustin and Aranha (2006) used GeoRadar or Ground Penetrating Radar (GPR) to study some types of pipes and their association with gullies, highlighting a monitoring technique for gully triggering mechanisms that contribute to the study of elements involved in the origin of the feature. Other works, such as Coelho Netto (2003), aimed to understand the nature of geomorphological processes responsible for gullies, and Pinto et al. (2008) used digital terrain models of morphometric parameters and/or accumulated flow maps to detect areas susceptible to gully occurrence.

Other studies, such as Loureiro, Guerra, and Andrade (2020), presented methodological and analytical potentials for gully monitoring using terrestrial laser scanners (TLSs) combined with UAV imaging to monitor and diagnose gully erosion. Cabral, Nummer, and Bateira (2020) combined radar images and WorldView-2 satellite images to classify the shape and obtain morphometric parameters. Julian and Nunes (2020) used UAVs to calculate the volume of soil loss in gullies.

Considering the breadth of materials and methods observed in gully studies during the analyzed period, it is emphasized that, whenever possible, detailed field observations should be combined with contemporary techniques and dating methods to reconstruct the conditions that lead to incision, development, and filling of gullies, as also noted by Poesen (2011) and Torri and Poesen (2014).

The analysis of the texts for the preparation of this work points to the near absence of articles that deal with the filling of gullies and many that seek to understand their development. The work of Biffi and Paisani (2019) is one of the rare studies that determine the micromorphological properties of colluvial-alluvial deposits that filled established paleogullies on the Pinhão/Guarapuava summit surfaces, suggesting that different sediment concentration and flows were involved in the filling of these paleogullies. Another work in this line is Salgado et al. (2008), in which physical properties of sedimentary/pedological coverings associated with gully occurrence were analyzed.

Regarding the time spent on gully monitoring, short-term monitoring reveals momentary recession rates, which can be significantly different from the rates that would be observed in the long term, for example, via satellite images. Thus, this justifies the combination of research methods and techniques for different temporal scales, especially for broader space-time monitoring.

Therefore, considering the diversity of methods and techniques (Table 2) observed throughout Sinageo and RBG, it can be emphasized that these detailed studies on gullies over time are crucial not only for reconstructing the past but also for learning from it, with a focus on the present and the future of scientific knowledge.

Table 2. Proposal for a relationship between techniques, temporal scale, investments, resolution, and spatial coverage for gully monitoring, considering the reading of Sinageo and RBG works.

Method/Technique	Timescale	Cost	Spatial resolution	Spatial coverage
Erosion stakes or pins	Current time (months and a few years)	Low	Variable	Hillslope
Aerial photographs	Historical time (subject to availability).	Variable depending on the resolution	Variable	Watershed
Satellite images	Historical time (dependent on availability)	Variable depending on the resolution	Variable	Watershed
Unmanned Aerial Vehicles (UAV)	Current time (months and a few years).	High	High	Watershed and hillslope
Terrestrial laser scanners (TLSs)	Current time (months and a few years).	High	High	Hillslope

Note: Table prepared by the authors based on manuscripts from Sinageo and RBG.

4. Final considerations

Considering the evolutionary process and the causative mechanisms of gullies, it is beneficial, when possible, to use different scientific information methods that support the development of studies with various spatiotemporal scales, allowing for the understanding and assessment of characteristics over historical and current times.

The development and intensification of agriculture without proper management and conservation practices, along with urbanization in its various phases, have contributed to the emergence and/or enlargement of gullies by disrupting the energy balance between erosivity and the regolith's resistance to erosion.

In general, the works that have been published in RBG and Sinageo emphasize the formation mechanism and evolutionary process associated with surface and subsurface hydrological processes. However, there is still a scarcity of studies that seek to evaluate the filling process, which could contribute to future research on the topic.

Finally, it is relevant to establish a research network on gullies in Brazil capable of providing support and exchanging experiences based on case studies in different regions of the country. Such a network could enhance and expand monitoring and knowledge on the subject.

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