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Analysis of the sidewall dynamics of a gully system: causes and processes

Análise da dinâmica do talude erosivo de um sistema em voçorocamento: causas e processos

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Abstract

Globally, gullies appear to be a complex phenomenon due to their multi-causal and non-coincidental conditions, with variations in their temporal and spatial dimensions. In this sense, the aim is to evaluate the evolutionary dynamics of the sidewall gullies system, aiming to understand its interaction with rainfall events, as well as the active dynamization mechanisms. For this, a gully system was selected with differentiated morphology, presenting a sidewall organized into two levels, located in the Paulista Peripheral Depression in the Corumbataí city, São Paulo. The sidewall was monitored from stakes installed around them over an 11 quarter period. In this way, it was verified that two evolutionary dynamics act on the sidewall, namely the loss of material associated with the undermined blocks, erosion by waterfalls and the action of the water channel, and the expansion of the material related to undermined blocks processes in progress, as well as the expansion of the materials by hydration and the occupation of the reading points by grasses. It was also found that the presence of cattle may have contributed to greater sidewall dynamics, since most of the monitoring periods, after the removal of the cattle, showed a reduction in the values of material loss. Finally, rainfall is also a variable of interest, with part of the analyzed quarters showing consonance between increased rainfall and increased material loss, and part showing an inverse relationship between rain and material loss, which may be associated to the little intense rains and the antecedent wetness.

Keywords:
Gully erosion, Erosion monitoring, Material loss and expansion, Rainfall intensity

Resumo

Globalmente, as voçorocas se evidenciam como um fenômeno altamente complexo devido a sua condição multicausal e não coincidente, apresentando variações em suas dimensões temporais e espaciais. Neste sentido, tem-se como objetivo avaliar a dinâmica evolutiva do talude erosivo de um sistema em voçorocamento, visando compreender sua interação com os eventos pluviométricos, assim como os mecanismos de dinamização atuantes. Para tal, selecionou-se um sistema em voçorocamento com morfologia diferenciada, apresentando talude erosivo organizado em dois patamares, localizado na Depressão Periférica Paulista, no município de Corumbataí (SP). Os taludes erosivos foram monitorados a partir de estacas instaladas em seu entorno, durante o período de 11 trimestres. Desta forma, verificou-se que duas dinâmicas evolutivas atuam no talude erosivo, sendo estas a perda de material, associada ao solapamento da base, erosão por quedas d'água e atuação do canal hídrico; e a expansão do material, relacionada a processos de solapamento em curso, a expansão dos materiais por hidratação e a ocupação dos pontos de leitura por gramíneas. Também se averiguou que a presença de gado pode ter contribuído para maior dinâmica do talude, uma vez que grande parte dos períodos de monitoramento, posteriores a retirada do gado, apresentaram redução nos valores de perda de material. Por fim, a chuvas também se apresentam como uma variável importante para a análise, sendo que parte dos trimestres evidenciaram consonância entre aumento do volume pluviométrico e aumento da perda de material e parte evidencia relação inversa entre chuva e perda de material, a qual pode estar associada às chuvas poucos intensas e a umidade antecedente.

Palavras-chave: Voçoroca, Monitoramento erosivo, Perda e expansão de material, Intensidade de chuva.

I. INTRODUCTION

Globally, gullies are a highly complex phenomenon due to their multi-causal and non-coincidental conditions, presenting variations in their temporal and spatial dimensions, factors which require a series of methodologies for measurement, monitoring and analysis (CASTILLO; GOMÉZ, 2016). In this context, the question arises: What is the contribution of gullies to the general loss of soil and sediment production at various temporal and spatial scales and under different climatic conditions and land uses? The responses to such an erosive phenomenon are broad and reinforce the complex attribute. For example, Poesen et al. (2003), when analyzing the production of sediments from water erosion in different parts of the world, found that gullies can contribute between 10% to 94% of the total sediment arising from this erosion process. It is also worth highlighting that studies that consider gullies as an object of analysis date back to the beginning of the 20th century (RUBEY, 1928), a fact that guarantees approximately 100 years of research on the subject, providing a range of theories and methodologies on the occurrence and evolution of gullies.

Some research narrows the relationship between the occurrence and evolution of this feature with land use and cover, highlighting the removal of native vegetation and the conversion of land into agricultural areas as a determining factor (TEBEBU et al. 2010). Rural practices such as livestock farming, when carried out continuously and excessively, act as a forcing element causing the perversion of physical attributes of the terrain and accelerating the dynamics of erosion processes, which can give rise to gullies (ZANATTA et al., 2019). Old overgrazed sectors (150 years old) can still be associated with roads and passage routes (BOARDMAN, 2014), a situation that intensifies soil degradation, causing preferential paths for surface flows. Rural roads (unpaved) located on the boundary between planting areas (sugar cane) and forest fragments may experience recurrence of permanent gullies. Such erosive features, for the most part, begin on the roads themselves or on their lower banks (considering the direction of hillslope) and enter the forest sectors (BEZERRA et al., 2020). Still, seeking to specify the analysis, attention should be paid to the points of intersection between roads and agricultural terraces, as according to Bezerra et al. (2020), in research applied to the tributary river basins of the Barro Frio stream (Piracicaba - SP) along 104 intersections, 38 of these (37%) coincide with erosion features. In these sectors, the concentrated flow from the volume of water accumulated along the agricultural terrace gutter contributes, through overflow and runoff along the sides, to the formation of erosion features such as gullies.

Thus, in degraded areas, surface runoff is considerably higher than in sectors, for example, that are well vegetated. Therefore, in the face of rainfall events with high volumes (e.g. 100 mm), significant flows are evident in the gully channel (BOARDMAN, 2014), presenting a high potential to boost the evolution of sidewalls. In this way, analysis of the relationship between rain and gullies is an important element, making it possible to categorize the action of rain into single events and multiple or extended events (ANDERSON et al., 2021). Single events are associated with high-intensity rainfall, which presents a high volume of water in a short period. During these events, attention should be paid to concentrated flows, which dynamize the evolution of the gully (ANDERSON et al., 2021) through processes such as the removal of material from the base of the sidewall (formation of alcoves), providing an environment conducive to cracking and undermining of the material (WELLS et al., 2013), the latter process being represented by blocks falling due to shearing failure, toppling failure and/or stress failure (WANG et al., 2016). Multiple events can affect gullies in possibly more profound ways than single short events (ANDERSON et al., 2021). According to Karimov et al. (2015), in a study applied to the agricultural area, gullies show significant headwater evolution when rainfall events are recorded in soils saturated by previous rains. Wells et al. (2013) highlighted that if the sidewall soils are waterlogged, there is an increase in the weight of the material, and due to erosion at the foot of the sidewall, it can collapse prominently. Other authors highlight the dry period, drawing attention to clayey soils, in which the formation of drying cracks and crevices can occur, which can facilitate the erosive evolution of the sidewall during the first rains of the wet period (MENDES, 1993).

Thus, despite the gullies being an object of research with years of analysis (RUBEY, 1928), scientific gaps still persist, requiring new research. With this, Castillo and Goméz (2016) indicated the need for more studies to provide long-term data and with a high frequency of surveys, thus increasing reliability, since the data tends to be widely variable. Dube et al. (2020) stated that recurring data in the bibliography about gullies still needs adjustments and deepening, such as on the effects of climate, topography, land use and/or change in land use and soil mineralogy. Furthermore, the authors highlighted the need for more information about dry seasons, addressing the duration and maximum amounts of rain and/or intensity.

Therefore, the objective of this article is to evaluate the evolutionary dynamics of sidewalls of a gully system, aiming to understand its interaction with rainfall events, as well as the active dynamization mechanisms. This gully system presents a different morphology, with sidewalls organized into two levels, with only the lower level in contact with the water course, a fact that, in principle, can highlight the multi-causal and non-coincidental conditions (CASTILLO; GOMÉZ, 2016). It is also noteworthy that during erosion monitoring the area presented periods with livestock and periods without livestock, allowing a more precise analysis of the influence of agriculture on gully systems.

II. MATERIALS AND METHODS

The study area and the field monitoring technique used to measure the erosion dynamics of the gully's sidewalls are presented below, as well as the collection and organization of secondary rainfall data.

CHARACTERIZATION OF THE STUDY AREA

The study area is located in the eastern sector of the Paraná Sedimentary Basin in the Peripheral Depression province, more specifically in the Middle Tietê Zone (Figure 1). This zone consists mainly of sedimentary rocks, with significant intrusions of basalt rocks. The slope of the sedimentary layers highlights more resistant rocks, with elevated areas still occurring in the relief resulting from basaltic intrusions. The other forms are quite smooth, with local unevenness that rarely exceeds 200 meters. According to IPT (1981), this is characterized as the Morrotes Relief, which presents interfluves without preferential orientation, angular and flat tops and ravine hillslopes with rectilinear profiles (IPT, 1981, p.58). It is located on the Piramboia Formation (IG, 1984), which is overlying the shales and siltstones of the Corumbataí Formation and underlying the sandstones of the Botucatu Formation, with both contacts discordant (CORTÊS; PERINOTTO, 2015). The soils are predominantly characterized by Dystrophic Red Yellow Argisols, from the Serrinha unit (KOFFLER et al., 1992), which present an abrupt textural change characterized by a textural B horizon. On the surface there is a domain of fine-grained sand (OLIVEIRA; PRADO, 1984). In relation to morphometry, the sub-basin mostly presents a slope of 5% to 12%, showing a slope class of 12-30% upstream of the erosion system (SILVA; LUPINACCI, 2021).

Regarding the energy of the relief, the sub-basin has a predominance of medium and moderately strong energy, with the upstream portions of the system having an energy class classified as strong (SILVA; LUPINACCI, 2021).

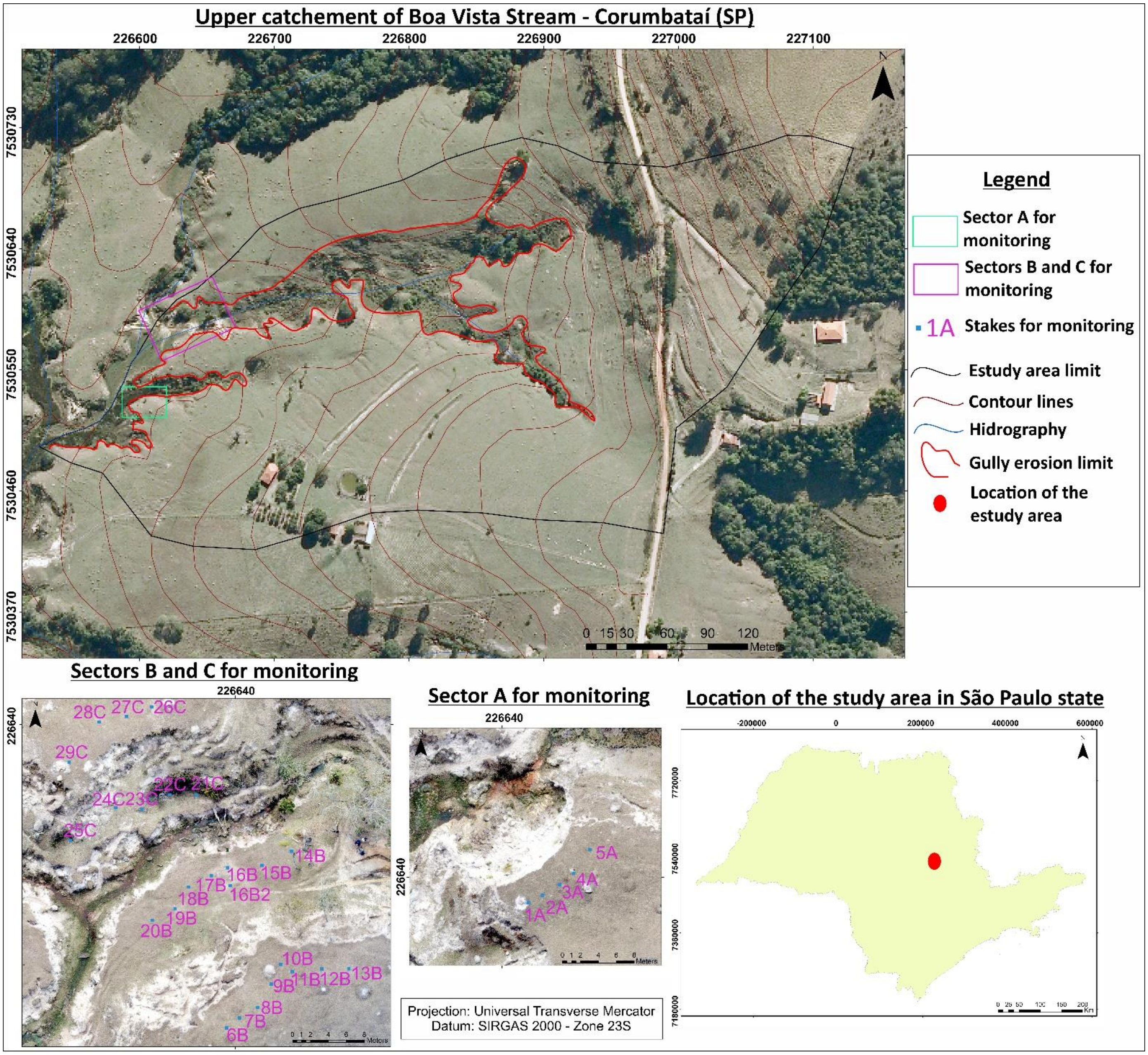

Figure 1 -Identification of the study area. Image source of the upper basin: EMPLASA (2010). Cartographic base source: IGCSP (1979).

Regarding rainfall dynamics, the month of January is the rainiest month and August is the driest month. In a historical analysis (1983 to 2012), the year 1983 presented the highest recorded rainfall volume (2,299.3 mm), with 2003 being the year with the lowest volume (1,232.5 mm; Figure 2). In this period, the months of

January and February present the maximum volumes recorded, with 600.7 mm falling in January 1999 and 618.8 mm in February 1995 (MELLO, 2014, p.40-42).

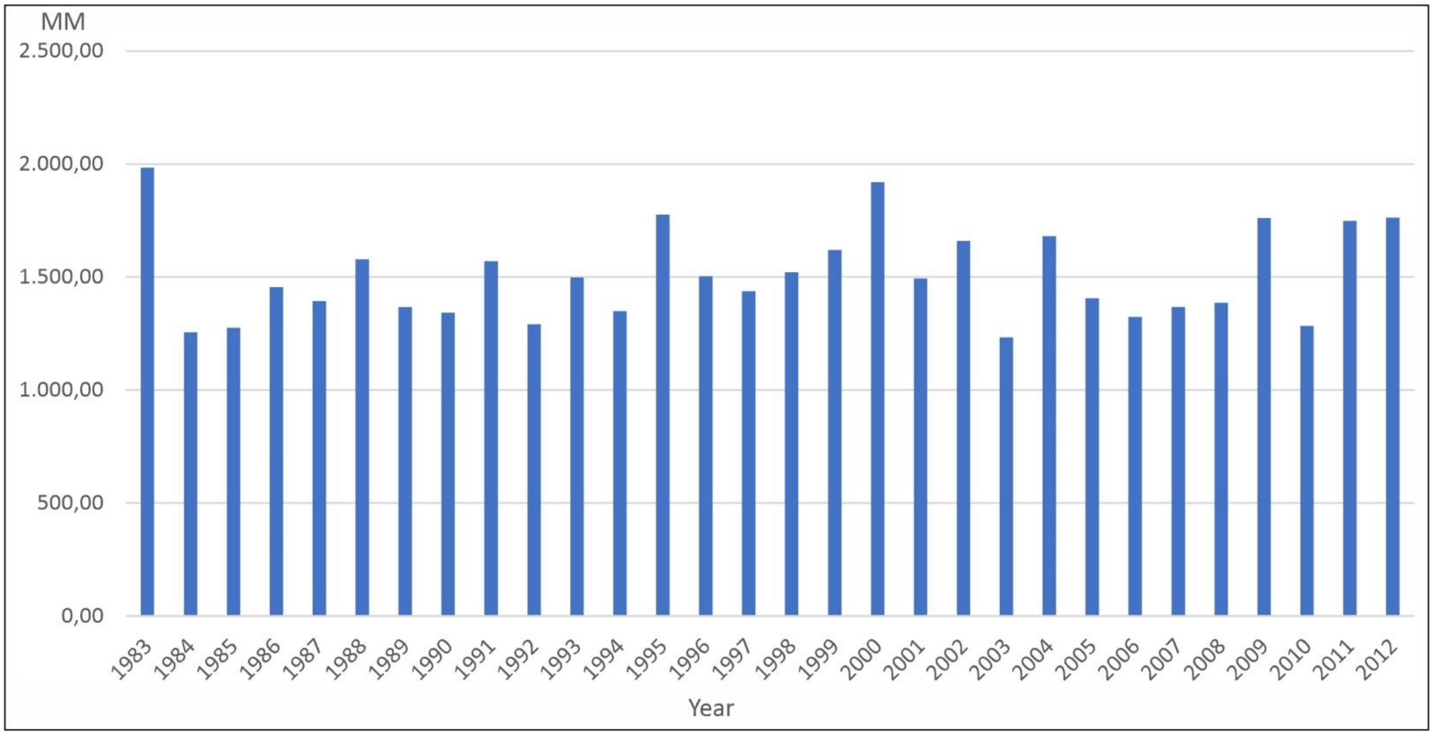

Figure 2 – Historical series of annual precipitation in Corumbataí (SP) – 1983 to 2012. (Source: Mello, 2014)

MONITORING OF THE SIDEWALLS

The sidewalls of the gully system analyzed were monitored based on the proposal by Guerra (2002), which indicates the measurement of the evolution of features using stakes installed in their surroundings. For this research, some adaptations were necessary, aiming to provide greater precision to the technique. The stakes were installed in Corumbataí on May 7, 2020, with the last monitoring carried out on February 8, 2023. The monitoring frequency was quarterly, aiming to cover the interaction of sidewalls with the dry and wet seasons and their respective transitions.

In total, 29 stakes were installed. As the area presents a complex and extensive gully system, some sectors were selected for monitoring using, as a criterion, the degree of dynamicity of the sidewall, represented by undermined blocks and bare sidewall. Three sectors located in the middle course of the erosion system were selected, being classified as “A, B and C” (Figure 1). Furthermore, sectors B and C were assigned the designations “inferior” and “superior”, depending on the morphology of the sidewalls, taking into account the topographic position. Sector A has a prominent sidewall, with an elevation difference of approximately 14 m from the top to the channel. Sectors “B and C” present a sidewall divided into two levels (upper and lower), with the lower one

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in contact with the channel and the upper one in contact with the top of the lower level. Sectors "B and C" are in a mirrored dynamic, with B on the left bank of the channel and C on the right bank.

Thus, considering the characteristics of each monitored sector and the conditions of the terrain, the lateral distance between the installed stakes was varied, being approximately 2 m or 3 m in relation to neighboring stakes (Figure 3a). Regarding the distance from the stake to the sidewall, the stakes were installed 3 m from the upper limit of the sidewall (Figure 3b), aiming to provide a safety margin during intense developments. To guarantee a measurement standard and reduce interference, pins were added in an aligned manner between the stake and the sidewall, ensuring a straight line was obtained (Figure 3c) and, consequently, a standard reading point between monitoring (Figure 3d).

With the help of a ruler aligned parallel to the left side of the pins, the reading points on the sidewall were identified (Figure 3d), positioning the reading ruler (Figure 3e) level over the points. The reading ruler made it possible to project the sidewall, allowing a suspended straight line to be drawn up to the monitoring stakes, disregarding possible irregularities in the terrain. It is noteworthy that at each survey the stakes were leveled crosswise (Figure 3f), in order to reduce noise in the measurements. With the stakes leveled, the Leica DISTO^{TM} D5 laser measuring tape was positioned over the head of the stake, with its reading sensor at the edge of the face facing the sidewall (Figure 3g). Thus, measurements of the distance between the stakes and the sidewalls were obtained.

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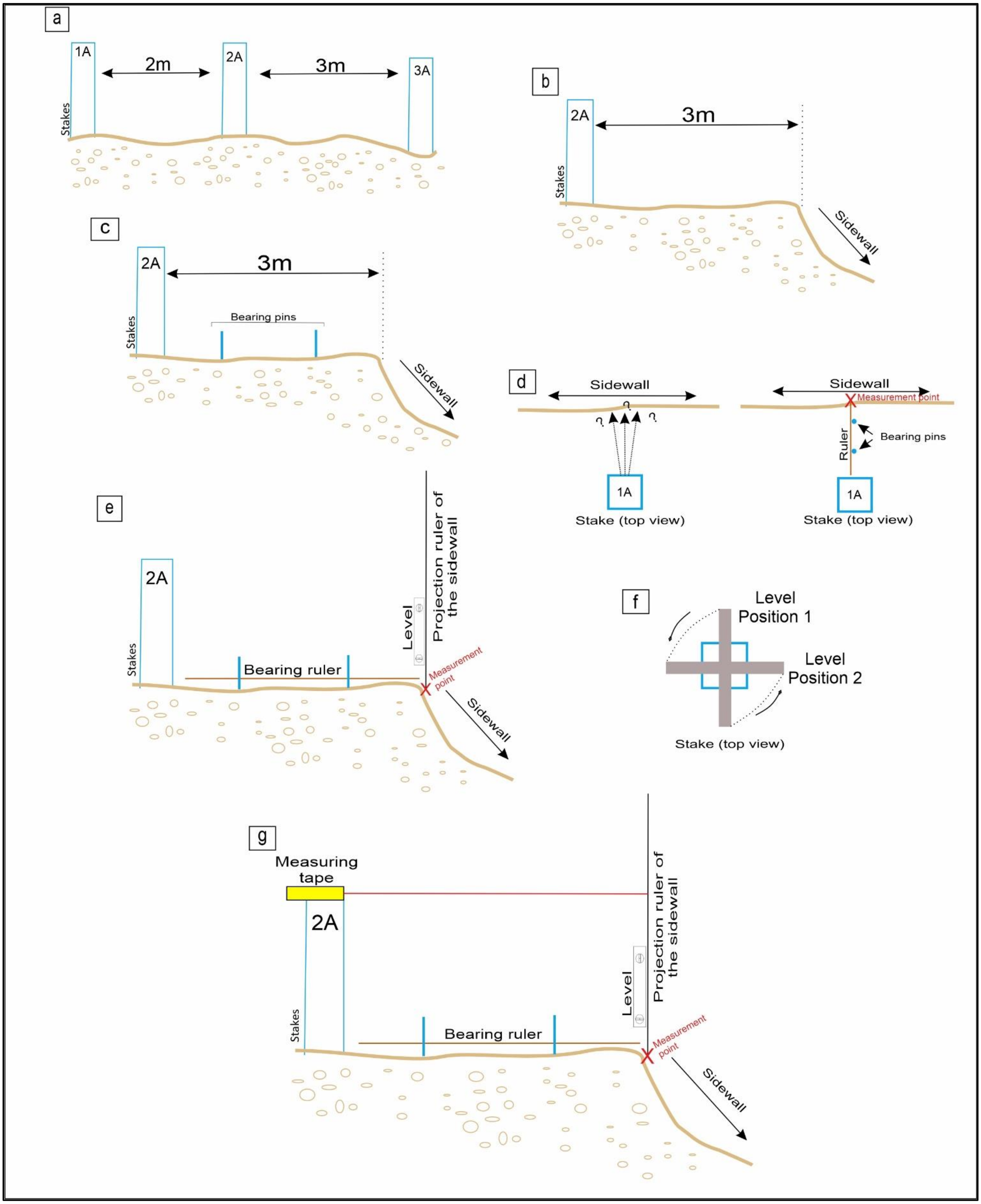

Figure 3 - Parameters used to install the stakes and to read the evolutionary dynamics of the sidewalls. (Source: the authors)

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PLUVIOMETRY

Rainfall data were collected from the Hydrological Database of the Department of Water and Electric Energy – DAEE. The collection station has the prefix D4-125 and is located at UTM coordinates 228344 and 7528546, with a straight line distance of 2.6 km from the study area. Furthermore, the data provided by DAEE presents a *deficit* of a few months, with the latest data provided going until July 2022. Thus, aiming to equate the monitoring periods of the erosion sector with the rainfall data, the missing months were completed with data from the Integrated Center for Agrometeorological Information – CIIAGRO, until the last monitoring (02/08/2023), using information from a station located in Corumbataí (UTM 228393 and 7538858) 9 km from the study area. The CIIAGRO station was chosen based on the Thiessen method (Figure 4), applied through ArcMap, using the *Create Thiessen Polygons* tool. Finally, the rainfall data was organized according to the time interval stipulated for erosion monitoring (quarterly), aiming for a comparative analysis.

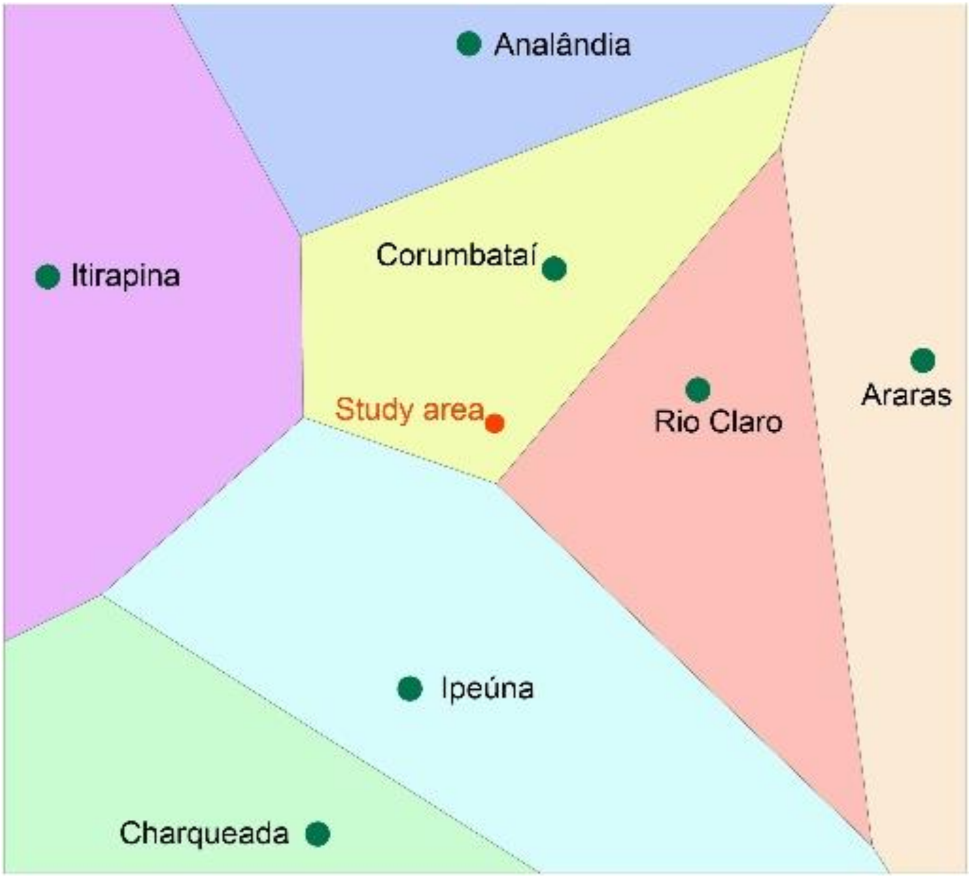

Figure 4 – Identification of a meteorological station with a good spatial correspondence with the study area using the Thiessen method. The green dots correspond to CIIAGRO stations within a 25 km radius of the study area. The color variation indicates the spatial influence zone of each station. (Source: the authors)

III. RESULTS

DATA FROM MONITORING THE SIDEWALL

The monitored sidewall presented a dynamic factor, which is evidenced by the field characteristics (Figure 5) and by measurements that indicated loss (values in red) and expansion of material[1] (values in green in Table 1). In general, four quarters held relevance in relation to the total loss values, these being: February 2021 (2.93 m of sidewall retreat), May 2021 (2.33 m), November 2021 (3.42 m) and February 2022 (2.83 m). In contrast, the periods with the lowest material loss are recorded before and after the period of most significant material loss highlighted, these being: November 2020 (0.19 m), May 2022 (0.22 m) and August 2022 (0.14 m). The most significant expansion dynamics were concentrated sequentially in the months of November 2020 (0.69 m), February (0.44 m) and May (0.26 m) 2021, with the less significant expansion values recorded in November 2022 (0.07 m) and in August 2021 (0.13 m) (Table 1).

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[1] The expansion of the material is characterized by an increase in the distance between the monitoring stake and the reading point, on the edge of the sidewall.

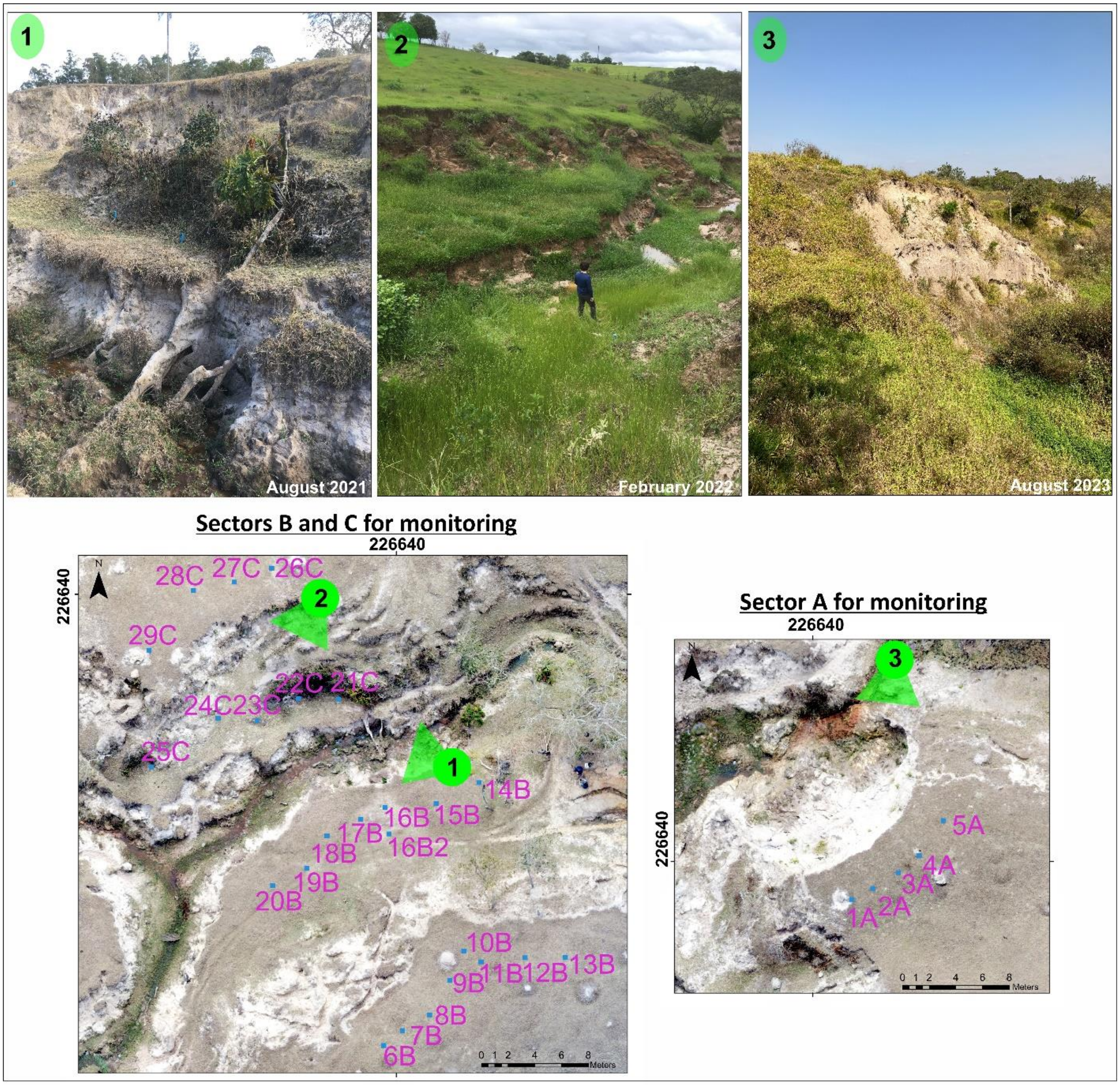

Figure 5 – Characterization of the monitored erosion system. (Source: the authors)

Table 1 – Monitoring data from the sidewall of the gully located in Corumbataí. Legend: Identi: Identification of the stake; Dist. (M): Distance in meters; Evo. (M): loss or expansion in meters.

	08/03/2020		11/04/2020		02/08/2021		08/05/2021			08/07/2021		11/06/2021		02/05/2022		05/06/2022			08/04/2022		11/09/2022		02/08/2023	
	Sector A		Sector A		Sector A		Sector A			Sector A		Sector A		Sector A		Sector A			Sector A		Sector A		Sector A	
Identi.	Dist. (M)	Evo. (M)	Dist. (M)	Evo. (M)	Dist. (M)	Evo. (M)	Dist. (M)	Evo. (M)	Identi.	Dist. (M)	Evo. (M)	Dist. (M)	Evo. (M)	Dist. (M)	Evo. (M)	Dist. (M)	Evo. (M)	Identi.	Dist. (M)	Evo. (M)	Dist. (M)	Evo. (M)	Dist. (M)	Evo. (M)
1A	2,90	0,10	2,91	0,01	2,91	0,00	2,91	0,00	**1A**	2,90	0,01	2,90	0,00	2,91	0,01	2,90	0,01	**1A**	2,91	0,01	2,91	0,00	2,91	0,00
2A	2,90	0,10	2,88	0,02	2,88	0,00	2,88	0,00	**2A**	2,86	0,02	2,87	0,01	2,78	0,09	2,80	0,02	**2A**	2,81	0,01	2,55	0,26	2,56	0,01
3A	3,00	0,00	2,94	0,06	2,73	0,21	2,74	0,01	**3A**	2,74	0,00	2,74	0,00	2,74	0,00	2,72	0,02	**3A**	2,72	0,00	2,72	0,00	2,73	0,01
4A	3,00	0,00	3,00	0,00	3,02	0,02	3,02	0,00	**4A**	3,02	0,00	2,94	0,08	2,92	0,02	2,92	0,00	**4A**	2,93	0,01	2,93	0,00	2,94	0,01
5A	3,00	0,00	2,99	0,01	3,00	0,01	3,02	0,02	**5A**	3,01	0,01	3,01	0,00	3,01	0,00	3,00	0,01	**5A**	3,02	0,02	3,01	0,01	3,02	0,01
	Sector B upper		Sector B upper		Sector B upper		Sector B upper			Sector B upper		Sector B upper		Sector B upper		Sector B upper			Sector B upper		Sector B upper		Sector B upper	
6B	3,00	0,00	3,00	0,00	3,00	0,00	3,01	0,01	**6B**	3,02	0,01	2,99	0,03	3,01	0,02	3,01	0,00	**6B**	2,98	0,03	2,97	0,01	2,97	0,00
7B	3,00	0,00	3,00	0,00	3,02	0,02	3,04	0,02	**7B**	3,00	0,04	3,02	0,02	3,00	0,02	3,00	0,00	**7B**	2,99	0,01	2,99	0,00	3,00	0,01
8B	3,00	0,00	3,05	0,05	3,07	0,02	3,08	0,01	**8B**	3,01	0,07	3,02	0,01	3,05	0,03	3,06	0,01	**8B**	3,05	0,01	3,05	0,00	3,06	0,01
9B	3,00	0,00	3,06	0,06	3,08	0,02	3,08	0,00	**9B**	3,05	0,03	3,06	0,01	3,05	0,01	3,05	0,00	**9B**	3,06	0,01	3,07	0,01	3,03	0,04
10B	3,00	0,00	3,00	0,00	3,06	0,06	3,06	0,00	**10B**	3,05	0,01	3,04	0,01	3,06	0,02	3,06	0,00	**10B**	3,09	0,03	3,05	0,04	3,05	0,00
11B	2,96	0,04	3,00	0,04	3,00	0,00	2,95	0,05	**11B**	2,95	0,00	2,92	0,03	2,85	0,07	2,84	0,01	**11B**	2,85	0,01	2,87	0,02	2,84	0,03
12B	3,00	0,00	3,00	0,00	3,01	0,01	2,95	0,06	**12B**	2,96	0,01	2,95	0,01	2,96	0,01	2,89	0,07	**12B**	2,90	0,01	2,92	0,02	2,89	0,03
13B	3,00	0,00	3,06	0,06	3,03	0,03	3,05	0,02	**13B**	3,02	0,03	3,03	0,01	3,05	0,02	3,05	0,00	**13B**	3,04	0,01	3,04	0,00	3,02	0,02
	Sector B lower		Sector B lower		Sector B lower		Sector B lower			Sector B lower		Sector B lower		Sector B lower		Sector B lower			Sector B lower		Sector B lower		Sector B lower	
14B	2,80	0,20	2,82	0,02	2,82	0,00	2,89	0,07	**14B**	2,90	0,01	2,36	0,54	2,05	0,31	1,99	0,06	**14B**	2,01	0,02	1,95	0,06	1,95	0,00
15B	2,89	0,11	2,87	0,02	2,91	0,04	2,52	0,39	**15B**	2,50	0,02	1,42	1,08	0,77	0,65	0,78	0,01	**15B**	0,78	0,00	0,78	0,00	0,78	0,00
16B	3,03	0,03	3,08	0,05	2,19	0,89	1,60	0,59	**16B**	1,60	0,00	1,66	0,06	1,11	0,55	1,11	0,00	**16B**	1,11	0,00	1,11	0,00	1,12	0,01
17B	2,93	0,07	2,92	0,01	2,88	0,04	2,91	0,03	**17B**	2,90	0,01	2,18	0,72	2,18	0,00	2,20	0,02	**17B**	2,19	0,01	2,15	0,04	2,18	0,03
18B	3,05	0,05	3,10	0,05	2,85	0,25	2,85	0,00	**18B**	2,86	0,01	2,52	0,34	2,51	0,01	2,53	0,02	**18B**	2,56	0,03	2,54	0,02	2,52	0,02
19B	3,00	0,00	3,00	0,00	3,02	0,02	3,05	0,03	**19B**	3,02	0,03	3,03	0,01	3,04	0,01	3,04	0,00	**19B**	3,05	0,01	3,04	0,01	3,05	0,01
20B	3,00	0,00	3,05	0,05	3,16	0,11	2,71	0,45	**20B**	2,72	0,01	2,73	0,01	2,40	0,33	2,44	0,04	**20B**	2,45	0,01	2,30	0,15	2,28	0,02
	Sector C lower		Sector C lower		Sector C lower		Sector C lower			Sector C lower		Sector C lower		Sector C lower		Sector C lower			Sector C lower		Sector C lower		Sector C lower	
21C	3,03	0,03	3,07	0,04	2,13	0,94	2,17	0,04	**21C**	2,18	0,01	1,92	0,26	1,19	0,73	1,20	0,01	**21C**	1,18	0,02	1,13	0,05	1,16	0,03
22C	2,55	0,45	2,57	0,02	2,32	0,25	2,16	0,16	**22C**	2,14	0,02	2,17	0,03	2,22	0,05	2,20	0,02	**22C**	2,17	0,03	2,07	0,10	2,07	0,00
23C	3,03	0,03	3,06	0,03	3,16	0,10	2,67	0,49	**23C**	2,71	0,04	2,71	0,00	2,75	0,04	2,77	0,02	**23C**	2,79	0,02	2,77	0,02	2,81	0,04
24C	3,03	0,03	3,10	0,07	2,88	0,22	2,85	0,03	**24C**	2,86	0,01	2,84	0,02	2,83	0,01	2,82	0,01	**24C**	2,81	0,01	2,81	0,00	2,83	0,02
25C	3,00	0,00	3,04	0,04	3,02	0,02	2,96	0,06	**25C**	2,96	0,00	2,71	0,25	2,71	0,00	2,70	0,01	**25C**	2,70	0,00	2,71	0,01	2,56	0,15
	Sector C upper		Sector C upper		Sector C upper		Sector C upper			Sector C upper		Sector C upper		Sector C upper		Sector C upper			Sector C upper		Sector C upper		Sector C upper	
26C	3,02	0,02	3,06	0,04	3,06	0,00	3,05	0,01	**26C**	3,05	0,00	3,03	0,02	3,04	0,01	3,04	0,00	**26C**	3,04	0,00	3,04	0,00	3,04	0,00
27C	3,00	0,00	3,04	0,04	3,03	0,01	3,01	0,02	**27C**	3,02	0,01	2,99	0,03	2,99	0,00	2,99	0,00	**27C**	2,99	0,00	3,00	0,01	3,01	0,01
28C	2,96	0,04	2,98	0,02	2,90	0,08	2,88	0,02	**28C**	2,89	0,01	2,89	0,00	2,88	0,01	2,89	0,01	**28C**	2,88	0,01	2,80	0,08	2,81	0,01
29C	3,00	0,00	2,93	0,07	2,93	0,00	2,93	0,00	**29C**	2,91	0,02	2,92	0,01	2,90	0,02	2,90	0,00	**29C**	2,90	0,00	2,89	0,01	2,89	0,00
Total loss of material		1,11		0,19		2,93		2,33			0,32		3,42		2,83		0,22			0,14		0,86		0,31
Total material expansion		0,19		0,69		0,44		0,26			0,13		0,18		0,22		0,16			0,20		0,07		0,22

Source: the authors

The points located in the lower sectors B and C stand out in terms of material loss per period: 15B (1.08 m sidewall retreat in November 2021), 21C (0.94 m in February 2021 and 0.73 m in February 2022) and 16B (0.89 m in February 2021) (Table 1); and by the total values of material loss in the analyzed period (Figure 6). The lower sectors are also highlighted in terms of expansion, since the highest values recorded in the period are associated with points 20B (0.11 m increase in the distance from the stake to the sidewall in February 2021), 23C (0.10 m in February 2021) and 24C (0.07 m in November 2020). Finally, the stability recorded in the upper sectors B and C is highlighted, which is evident, in the first case, by 63% of the points presenting values equal to or greater than 3 m (initial distance of installation of the stake) and, in the case of the second, because 50% of the monitoring points present such dynamics.

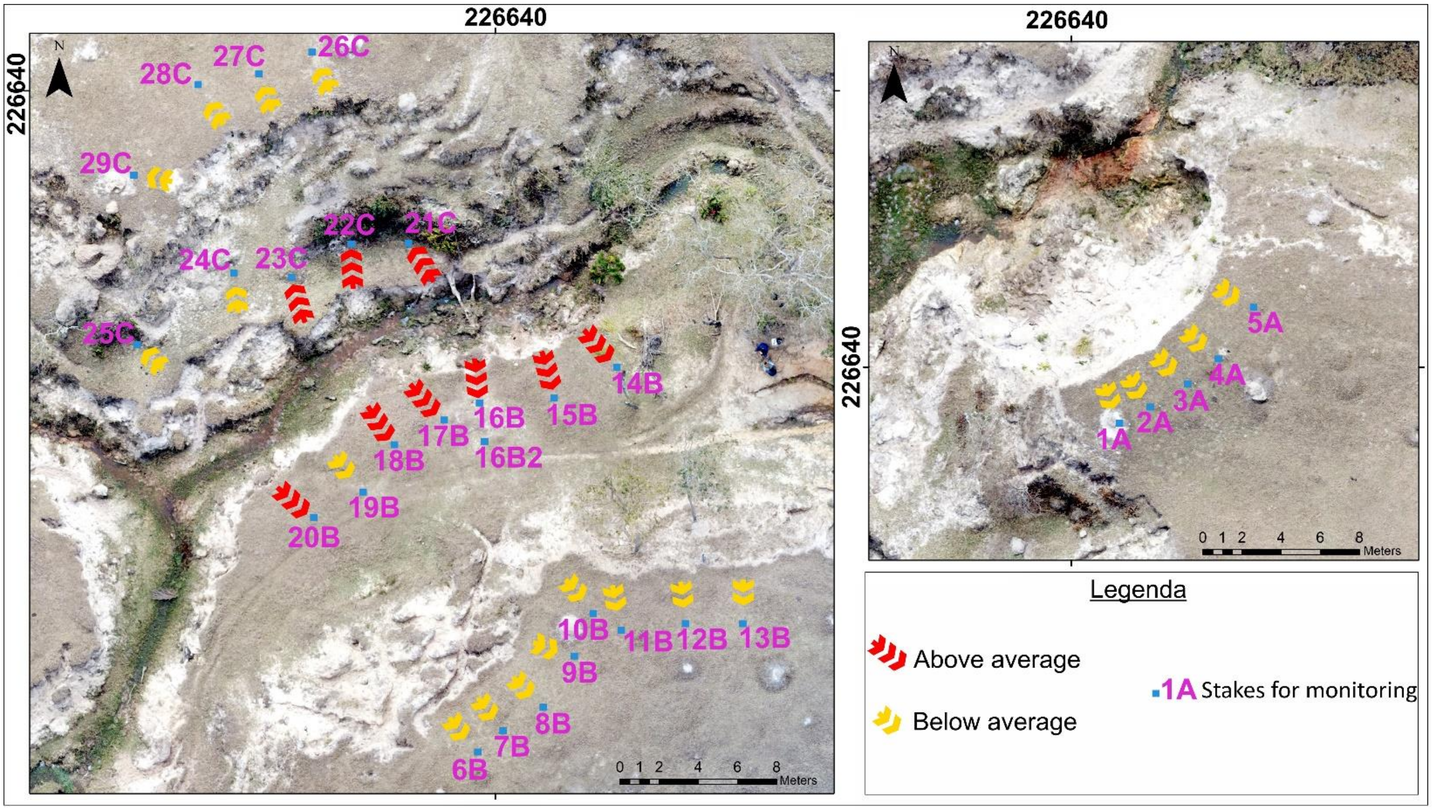

Figure 6 – Sectors of the sidewall and its respective dynamics. The total average loss of material during the analyzed period was 0.50 meters. (Source: the authors)

RAINFALL DATA

The quarters with the most significant volumes were those ending in February 2020, 2021 and 2022, with the maximum volume of rain in the period recorded in 2021 (762.7 mm, Table 2). Regarding the intensity of rainfall events, the highest intensity daily rainfall was recorded in December 2020 with 34.4 mm/day, in November 2021 with 90.8 mm/day and in January 2022 with 60.2 mm/day, with such events being in line with the period of most significant volumes (November to February). Regarding the periods, the following are worth highlighting: from 19 to 20 November 2021 (average of 63.5 mm/day) and from 29 to 31 January 2022 (38.4 mm/day).

The quarters ending in August 2020, 2021 and 2022 were those with the lowest rainfall, with an extreme of 1.5 mm in the respective quarter of 2022. Thus, considering the driest periods, it appears that from May to November 2020, 134.7 mm of rain was registered in the same period; in 2021 it was 192.5 mm and in 2022, 203.7 mm.

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Table 2 - Corumbataí rainfall data organized by quarter.

Month/Year/ Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Maximum rainfall month (mm)	Total rainfall in the quarter (mm)
05/2020	0	0	0	0	0	0	0	0	0	0	0	0	0	5,5	0	0	0	0	0	0	0	0	15,3	0	0	0	0	0	0	0	0	15,3	
06/2020	0	0	3,1	0	2,8	0	6,1	0	0	16,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18,5	0	0	0	---	18,5	77,7
07/2020	0	7,7	0	0	2,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7,7	
08/2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27,8	0	8,3	0	0	0	0	0	0	0	0	0	0	0	27,8	
09/2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6,2	0	0	0	0	0	0	0	0	---	6,2	134,7
10/2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.3	0	0	0	0	27,7	17,9	10,7	0	0	0	0	0	0	0	32.8	0	32,8	
11/2020	0	0	0	0	0	0	0	0	0	0	4,7	11,3	0	32,3	1.6	13,2	0	12,3	33.9	3,2	0	0	0	0	0	0	0	27,9	0	0	---	33,9	
12/2020	8.5	0	0	24,7	1,7	8,9	34,4	14,7	5,8	0	6,5	0	34,4	0,5	0	0	14,7	6.4	9,7	0	0	0	22,4	0	5,2	0	21,5	33,4	4,7	20	0	34,4	596,3
01/2021	27,7	0	5,5	0	0	0	0	0	0	24,4	0	0	0	44,3	24,7	3,4	2,8	0	0	0	0	0	0	0	0	15,2	0	17,3	0	0	0	44,3	
02/2021	0	0	7,3	0	5,2	0	0	0	10,1	5,7	0	0	13,1	8,5	0	0	9,3	0	0	0	0	5,2	0	0	12,3	0	19,8	40,5	---	---	---	40,5	
03/2021	0	0	0	0	7.5	22,3	0	19,4	0	13,4	0	0	7,2	0	0	0	0	58,3	0	0	0	0	0	0	0	0	0	15,8	31,2	0	0	58,3	319,1
04/2021	0	0	0	0	0	13,7	0	0	0	0	5,8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	---	13,7	
05/2021	0	0	0	0	0	0	0	0	0	0	0	4.6	0	0	0	0	0	0	0	0	0	0	14,4	0	0	0	0	0	3,7	0	0	14,4	
06/2021	0	2,5	0	0	0	5,8	0	0	0	15,9	0	0	0	0	0	0	0	0	0	0	0	0	7,1	0	0	0	0	0	0	0	---	15,9	70,9
07/2021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9,4	0	7,5	0	0	0	9,4	
08/2021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5,1	0	0	5,1	
09/2021	0	0	0	0	0	0	0	0	3,8	0	0	0	12,3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	---	12,3	192,5
10/2021	0	0	0	28,8	0	0	34,3	0	0	4	0,2	0	0	12,4	0	10,7	2,5	0	17.2	6,3	0	0	0	7,2	5,5	0	12,6	24,5	0	0	0	34,3	
11/2021	5.1	0	0	0	0	0	0	0	0	8,5	0	0	0	0	0	0	0	0	36.3	90,8	0	0	0	0	0	0	30,6	0	0	8,5	---	90,8	
12/2021	8.6	0	0	3,6	0	0	0	0	2,6	0	0	0	0	34,5	20,6	23,2	2,3	16,2	0	0	0	0	9,7	0	0	0	0	20,7	0	0	---	34,5	762,7
01/2022	9,5	0	14,4	0	13,8	17,2	57,3	0	0	0	9,3	10,7	0	0	60,2	16,9	12,1	0	34,1	0	0	12,2	0	0	0	0	0	8,5	54,8	15,2	45,1	60,2	
02/2022	5,7	11,6	22,3	2,4	12,7	13,9	8,3	0	11,5	0	3,9	0	0	13,7	0	0	0	0	0	9,1	0	0	0	0	0	0	0	0	---	---	---	22,3	
03/2022	0	0	0	0	0	0	7,2	0	0	0	27,3	23,5	22,3	9,3	0	0	9,2	0	0	0	0	0	0	0	0	0	0	8,2	2	0	0	27,3	187,2
04/2022	8,3	0	0	0	0	0	0	0	5,8	0	0	0	0	0	0	0	3,7	0	0	0	0	0	0	0	0	0	0	0	0	0	---	8,3	
05/2022	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1,5	1,5	
06/2022	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	---	0	1,5
07/2022	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
08/2022	0	0	0	0	0	0	0	3,8	3,3	9,1	0,3	0	0	0	0	0	0	0	0	0	0	0,3	0	0	0	0	0	0	0	0	0	9,1	
09/2022	0	0	0	0	0	0	13,0	7,9	0	0	0	0	0	3,8	7,9	---	0	0	0	0	0	14,7	1,5	0	0	0,0	11,4	1,0	10,2	0,3	---	14,7	203,67
10/2022	7,6	0	0	0	0	0	22,6	0	0	1,0	3,0	0,25	0	0	0	0	0,8	0	11,2	11,4	16,0	0	0	0	0	0	0	6,6	0,3	17,0	0,3	22,6	
11/2022	17,3	0,0	0,0	0	0	0	0	0	0	0,0	0	19.3	0	3,3	12,2	0	0	0	0	0,0	0,8	0.3	11,2	20,8	0,0	0	0	0	5.8	4,6	---	20,8	
12/2022	2.3	0,2	4,1	11,7	2	12,4	11,4	28,4	0	0	0	3.6	5,6	16,8	0	2,3	2,8	0	0	0,8	7,4	0	0	11,7	0	32.5	6,4	3,3	34,8	1	18,5	34,8	480,5
01/2023	23,9	3,6	2,8	3,8	11,7	3,0	0	0	0,0	13,7	3,0	7,1	0,0	4,8	1,3	2,5	0	10,2	0	0,3	24,1	3,8	1,0	7,9	0	0	0	0	0,0	2,0	4,3	24,1	
02/2023	17,8	6,6	5,3	2,8	0	0	0,5	14,5	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	17,8	

Source: the authors

INTERACTION OF EROSION MONITORING DATA AND RAINFALL DATA

Figure 7 is presented to analyze the influence of rainfall data on the total loss of material from sidewall. Coherence is observed between rainfall and material loss data in 7 of the 10 quarters analyzed. All monitoring carried out in May and August of the respective years supports this statement, and monitoring in February and November does not present such a metric. As a result, 3 quarters (November 2020, February 2022 and February 2023) show a distinct relationship between material loss and rainfall volume. The most disparate variations occur in the months of February 2022 and 2023, with rainfall data for the first period rising from a level of 200 mm (Nov. 2021) to a level of 750-800 mm and material loss data decreasing from elevation from 1.00-1.25 m to 0-0.25 m; the second period also presents a similar relationship, with rainfall data rising from 200 mm (Nov. 2022) to 450-500 mm and material loss data decreasing from 0.75-1.0 m (Nov. 2022) to 0.25-0.50 m.

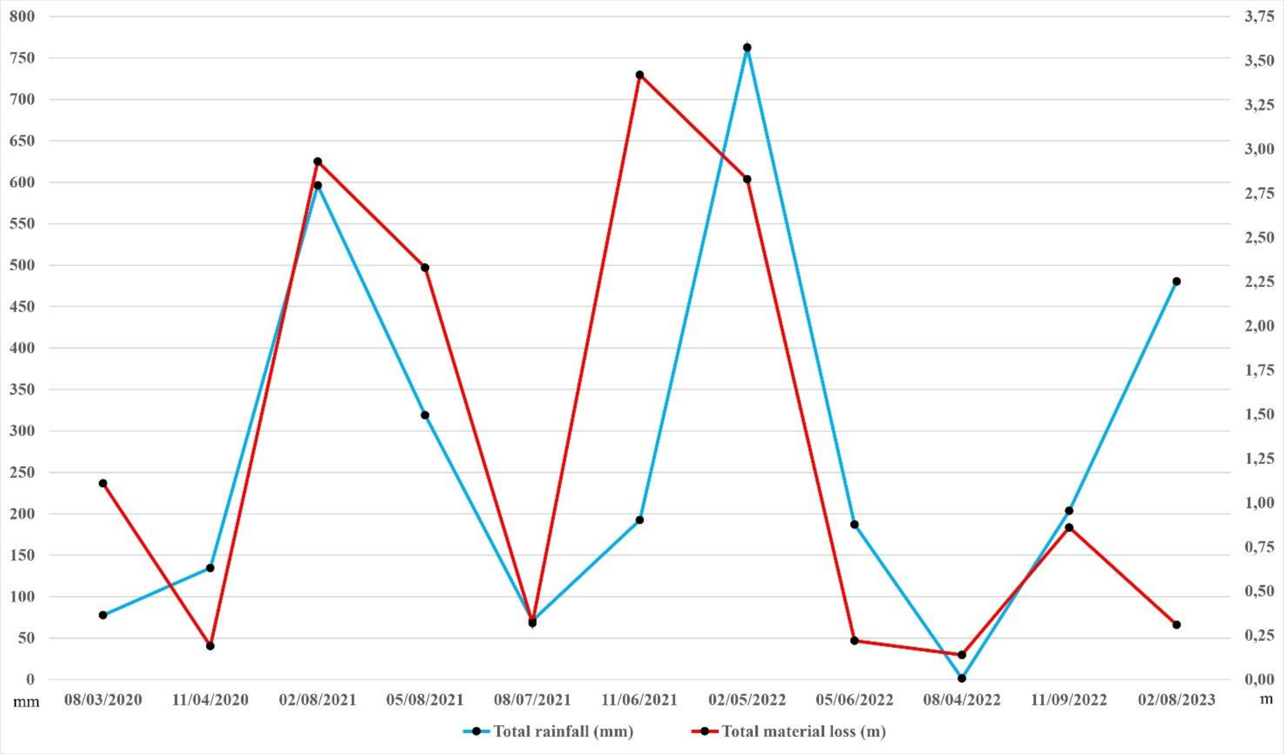

Figure 7 – Interaction between rainfall and material loss data by quarter. (Source: the authors)

IV. DISCUSSION

The loss of material is a classic characteristic of the sidewalls of gullies with a significant degree of dynamicity, in which materials become detached, accumulating or being transported by the channel. According to Bigarella (2003), the morphological evolution of gully sidewalls is intrinsically linked to surface and subsurface flows, which contribute to the loss of material via liquefaction, causing mass movements and step-shaped morphologies as well as excavations at the base of shell-shaped embankments with subsequent undermining. According to Wang et al. (2016), the undermining process can occur due to shearing failure, toppling failure and/or stress failure (Figure 8). Oliveira (1999) already highlighted the dynamic nature of the process of erosion by waterfalls (plunge pool erosion), which can occur on sidewalls that are more cohesive at the top and less cohesive at the bottom, and in the entry process of the flow in the erosive system, causes flow lines that create a vortex, with a reversal of the flow direction at the base of the sidewall, generating a process of material removal. Furthermore, surface flows with reduced volumes cause water films on the sidewalls, generating features called subvertical streams of surface flow (OLIVEIRA, 1999).

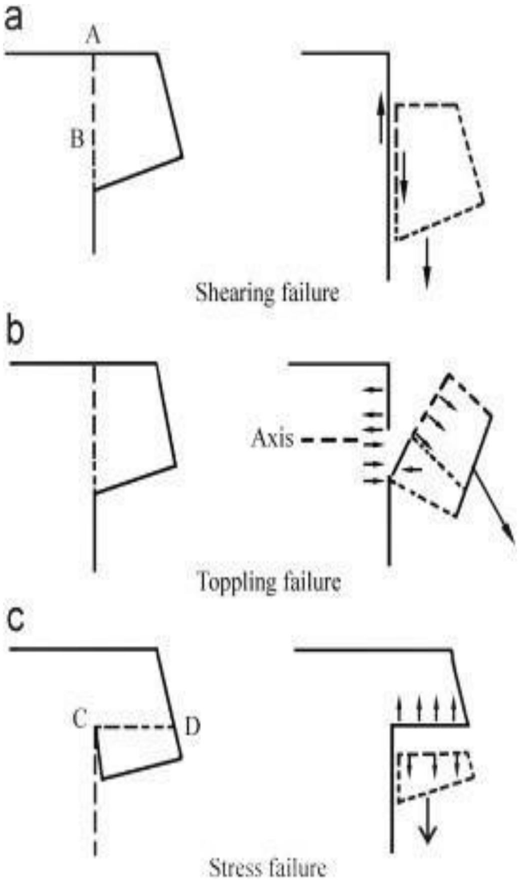

Figure 8 – Types of undermining. (Source: WANG et al., 2016)

Still, in relation to material loss, the fact that the lower sectors B and C are more dynamic may be associated with the channel's performance. According to Wells et al. (2013), the volume of water in the channel will have a determining interaction with the sidewalls. If the water column is acting at the top of the sidewall, it may exert confining pressure, which will tend to keep the material in place. Shallow water columns, in comparison to the height of the sidewall, may act at the base of it, causing the removal of material, making such sidewalls more susceptible to the presence of gravitational processes (WELLS et al., 2013). Another factor that contributes to the hypothesis of the channel's role in the loss of material is the data from upper sectors B and C, which are not in contact with the channel and show that a large part of the monitored sectors are stable or have low dynamicity.

The expansion of sidewall is a dynamic little explored in the literature, and its study is only possible through detailed monitoring techniques of the sidewall. In this sense, the toppling process (WANG et al., 2016) can constitute a path of analysis, since, prior to undermining, the upper part of the sidewall can incline towards the interior of the gullies, and depending on the monitoring technique used, the distance between the stake and the reading point on the sidewall may increase. Some monitoring points confirmed this information (Table

1). For example, Point 20B showed a 0.11 m increase in the distance from the stake to the sidewall in February 2021 (the most significant value in the analysis period), and in the following monitoring (May 2021), a sidewall retreat of 0.45 m was recorded; Point 23C showed a 0.10 m increase in distance in February 2021, recording a material loss of 0.49 m in May 2021 (the following monitoring); at Point 24C an expansion of 0.07 m was recorded in November 2020, culminating in a 0.22 m retreat in the following monitoring (February 2021); at Point 16B, a 0.06 m of expansion was recorded in November 2021, with a 0.55 m of expansion in February 2022; and at Point 14B, with emphasis on the non-linear factor in the process and response, there was a subsequent expansion of 0.07 m (May 2021) and 0.01 (August 2021), culminating in a material loss of 0.54 m in November 2021.

However, not all data/points presented a direct relationship between expansion and subsequent undermining. Therefore, it is also important to analyze the dynamics based on the phenomena of material expansion due to hydration and occupation of the sidewall reading point by grasses. Regarding the expansion of the material via hydration, it is noted in soils with high percentages of silt and clay (COCCO et al., 2015). The soils in the analyzed sector are predominantly characterized as Dystrophic Red Yellow Argisols, from the Serrinha unit (KOFFLER et al., 1992), which present an abrupt textural change represented by a textural B horizon. On the surface there is a domain of fine-grained sand (OLIVEIRA; PRADO, 1984). Therefore, according to the pedological map (KOFFLER et al., 1992), the occurrence of final fractions (silt and clay) in the sector is possible. In turn, regarding grasses, these can have significant variations in leaf mass index and consequently phytomass, based on water availability and season (VIANA et al., 2007), a fact that, as they are located in points (reading ruler positioning point), may interfere and vary the measurement by a few centimeters. In the field, the occurrence of grass fringes superimposed on the upper part of the sidewall (Figure 9) was observed, and it is worth noting that even in dry periods (August 2021) the fringes appear over the reading points, causing interference.

Figure 9 - Grass fringe over reading points in August 2021. (Source: the authors)

It is also noteworthy that the study area was predominantly covered by pastures intended for livestock, with cattle in a free grazing system, without rotation. According to data obtained from the owner, the study area had cattle until 11/26/2021, with the gully area being fenced on 06/07/2022. It is noteworthy that in the subsequent monitoring period (Figure 10) the removal of cattle (February 2022) showed a marked total loss of material (retreat of 2.83 m from the sidewall); however, it is understood that the vegetation cover may take a few months to restore its vitality and significantly cover the soil, an element that, in principle, justifies part of the loss of material recorded in February 2022 even within the sector without livestock. In the following monitoring, from May 2022 to February 2023, the total values of material loss showed significant reductions based on the comparative analysis between the periods before and after the removal of cattle and fencing.

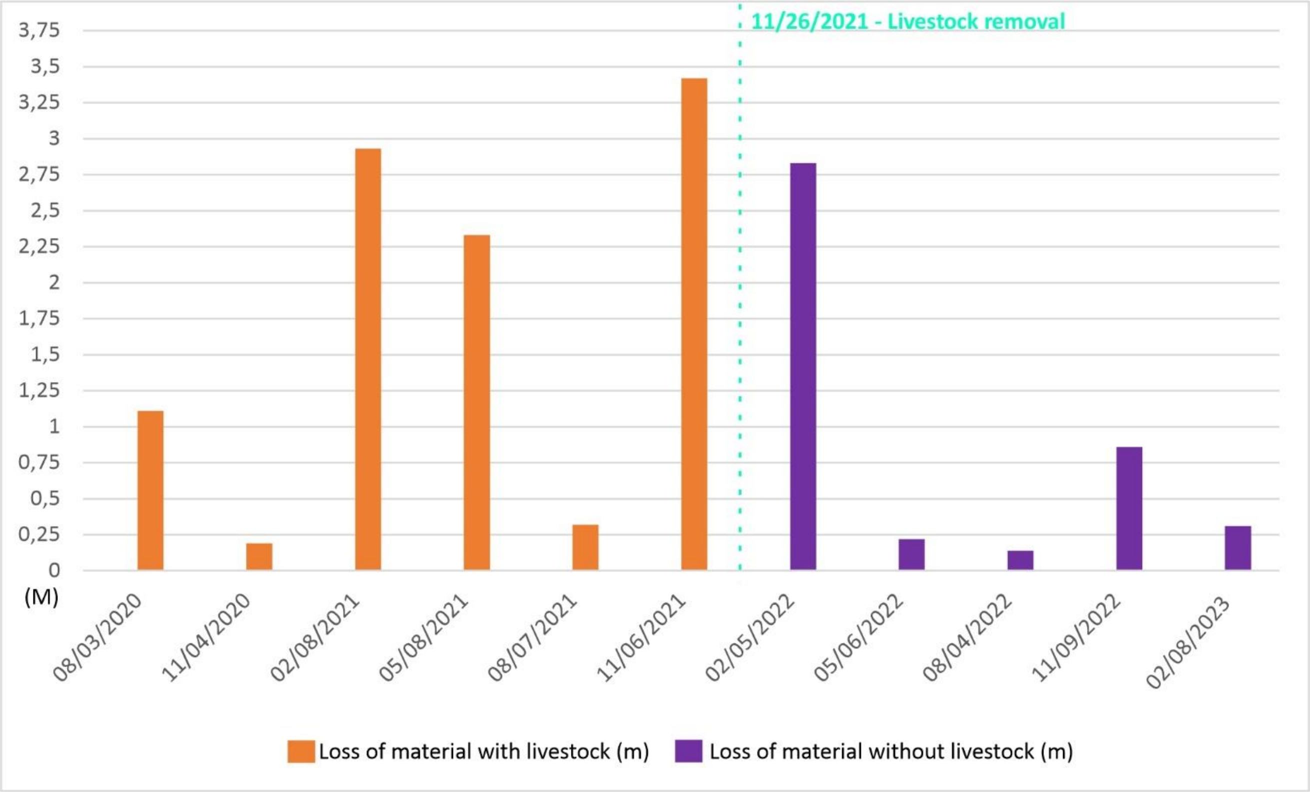

Figure 10 – Material loss data for periods without and with cattle accessing the monitored erosion system. (Source: the authors)

In this sense, the research by Zanatta et al. (2019), in a study applied to Marabá Paulista (SP), located in the Pontal do Paranapanema region, reinforces the relationship between gullies and pasture areas intended for livestock. According to the authors, since 1963 the mapped linear erosion features have been intrinsically related to pastures classified as “clean” and “dirty”, with dirty pasture being constituted by poorly maintained pasture sectors, characterized by grasses interspersed with shrubby plant species. In this context, gullies constitute the linear feature with the most determining relationship with pastures, since in 1997, 100% of the mapped features occurred in pasture areas (ZANATTA et al., 2019). Therefore, it is understood that the removal of cattle from the study area of this research has influenced the reduction of material loss from the sidewall.

Regarding rainfall data and the relationship with material loss, the consonance identified between the increase in rainfall and the loss of material in seven quarters constitutes an expected dynamic and is widely debated in the bibliography (ANDERSON et al., 2021). As evidenced by Oliveira (1999), processes such as erosion due to waterfalls and forms such as subvertical streams of surface runoff confirm the action of flows from rain on sidewalls. It is worth mentioning that the response of sidewalls to rainfall flows is also influenced by internal wear of the gullies. According to an analysis of erosion systems installed in the Burdekin River basin – Northeast Australia, Daley et al. (2023) found that rainfall flows can cause vertical wasting rates of up to 10-2m/year^{-1}, which can represent up to 160 t/ha of erosion, which can contribute up to 80% of the erosion recorded in the balance of sediment from monitored erosion systems.

In the quarters with a different relationship between rainfall and material loss, it appears that in November 2020 the rainfall data did not present a very significant volume/day (Table 2). This fact may have contributed to the lower loss of material from the sidewalls, justifying, in principle, the increase in rainfall with the reduction in material loss (Figure 7) in this respective period. As of February 2022 and 2023, the analysis can be directed to the issue of antecedent humidity (KARIMOV et al., 2015). As can be seen in Figure 7, the rise of the rainfall data curve begins between the monitoring of August and November 2021 and 2022. With this, it is understood that such rains hydrate the soil, providing greater aggregation of particles and consequently greater resistance of materials (KARIMOV et al., 2015). Therefore, even with increasing rainfall volumes in February 2022 and February 2023, the soils in the monitored area show greater aggregation as a result of the previous humidity, causing the total material loss values to drop.

V. CONCLUSIONS

The data points to two evolutionary dynamics of the gully's sidewall. The loss of material constitutes a classic and well-known dynamic linked to the undermining of the base, erosion by waterfalls and the action of the canal. The expansion of the material is a topic little explored in the bibliography, and in this article the hypotheses of analysis were based on expansions associated with ongoing undermining processes; the expansion of materials by hydration, a typical characteristic in materials with a significant composition of silt and clay; and the occupation of reading points by grasses, both in the dry and humid periods. Furthermore, the removal of cattle from the study area proved to be an important variable for understanding the dynamics of the respective erosion system, since most of the monitoring periods following the removal of cattle showed a reduction in material loss values. Finally, rainfall is also a variable of interest for understanding the dynamics of sidewalls in 7 of the 10 quarters analyzed, this fact being evidenced by the consonance between the increase in rainfall volume and the increase in material loss. However, three quarters showed an inverse relationship between rainfall and material loss, with this dynamic being associated with low rainfall events in the precipitation/day ratio (November 2020 period), and related to the antecedent soil moisture in relation to periods of February 2022 and 2023, and humidity which can cause greater soil cohesion, triggering a scenario less susceptible to the occurrence of material loss on sidewalls.

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