



ZERO-ORDER CHANNELS: CONTRIBUTIONS TO MANAGEMENT IN THE PIAVA RIVER ENVIRONMENTAL PROTECTED AREA, UMUARAMA, PARANÁ

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Abstract: *The Piava River Watershed Station, in Umuarama (Paraná) is the only source of public water supply for the municipality, benefiting more than 100,000 people and thus assuming a fundamental role in the city's sustainability. Although strategically important for regional water security, the watershed is under the influence of anthropogenic pressures related to urban expansion, predominant livestock production, soil compaction, riparian vegetation removal, and the intensification of erosive processes. Zero order channels play an environmentally relevant role, as they are areas of convergence of surface and subsurface flows are often associated with temporary zones of water saturation, wetlands, and the onset of incision erosive processes. The aim of the study was to evaluate the use of geotechnologies and morphometric indices for identifying these channels in the Piava River Environmental Protection Area (APA), particularly through the Topographic Wetness Index (TWI) and the Maximum Flow Index (MFI) – the latter derived from the Digital Terrain Model processed in QGIS and SAGA GIS. Differences were observed between official topographic maps at the 1:50,000 scale and what was represented through geoprocessing and field validation, highlighting the underestimation of naturally vulnerable sites. It is concluded that the inclusion of zero-order channels in environmental planning is crucial for reviewing vegetative margins, for the mitigation of siltation and for the consolidation of integrated watershed management.*

Keywords: *Environmental management; watershed; geotechnology; indices.*

CANAIS DE ORDEM ZERO: CONTRIBUIÇÕES PARA O MANEJO NA APA DO RIO PIAVA, UMUARAMA-PR

Resumo: A Estação da Bacia Hidrográfica do Rio Piava, em Umuarama (PR), é a única fonte de abastecimento público do município, beneficiando mais de 100 mil pessoas e assumindo, assim, um papel fundamental para a sustentabilidade da cidade. Embora de importância estratégica para a segurança hídrica regional, a bacia está sob a influência de pressões antropogênicas relacionadas à expansão urbana, à produção pecuária predominante, à compactação do solo, à remoção da vegetação ribeirinha e ao aumento dos processos erosivos. Os canais de ordem zero desempenham um papel importante ambientalmente, uma vez que são áreas de convergência de fluxos superficiais e subsuperficiais, e associam-se frequentemente às zonas temporárias de saturação hídrica, às áreas úmidas e ao início de processos erosivos de incisão. O objetivo do estudo foi avaliar a utilização de geotecnologias e índices morfométricos para a identificação desses canais na APA do Rio Piava, em especial por meio do Índice Topográfico de Umidade (ITU) e do Índice de Fluxo Máximo (IMF) – este último derivado do Modelo Digital de Terreno processado no QGIS e no SAGA GIS. Foram observadas diferenças entre as cartas topográficas oficiais na escala 1:50.000 e o que foi representado por geoprocessamento e validação em campo, evidenciando a subestimação dos sítios naturalmente vulneráveis. Conclui-se que a inclusão dos canais de ordem zero no planejamento ambiental é crucial para revisão das margens vegetacionais, para a mitigação do assoreamento e para a consolidação da gestão integrada do manancial.

Palavras-chave: Gestão ambiental; bacia hidrográfica; geotecnologia; índices.

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1 Introduction

Zero-order channels correspond to temporary or ephemeral hydrological features located upstream from first-order channels, formed by the convergence of surface and subsurface runoff in headwater areas. These features represent transition zones between hillslope processes and fluvial processes and are mainly activated during intense rainfall events or during periods of higher soil saturation. According to Silva et al. (2024), ephemeral channels and drainage headwaters have received increasing attention in watershed management studies because they directly influence hydrological connectivity and the initial transport of sediments. Although they do not always present a well-defined bed or permanent flow, they play a relevant role in transferring water, sediments, and solutes from hillslopes to the drainage network (Silva; Kobiyama, 2004).

The importance of zero-order channels has gained prominence in recent environmental debates, especially in view of the intensification of extreme precipitation events, the expansion of agricultural and livestock uses over sensitive areas, and the need to improve territorial planning instruments. Recent studies on hydrosedimentological connectivity, remote sensing, and digital terrain modeling have demonstrated that drainage headwaters are fundamental areas for water regulation, sediment production, and the maintenance of water quality in watersheds. Topographic indices derived from digital terrain models are important tools for identifying saturation zones and areas of greater hydrological connectivity in headwater basins. From this perspective, the identification of ephemeral channels, temporary wetlands, and saturation zones becomes relevant for the management of water sources, especially in watersheds used for public water supply (Schlesner, 2022; Souza; Castelo Branco, 2020).

In the Environmental Protection Area of the Rio Piava Watershed, located in Umuarama, Paraná, this discussion is particularly relevant, since the Rio Piava is the main surface water source for the municipality's public supply. The watershed presents natural fragilities associated with the occurrence of sandy soils and sandstones of the Caiuá Formation, in addition to anthropogenic pressures related to the predominance of pastures, soil compaction, suppression of riparian vegetation, rural roads, and urban expansion. According to Bento, Ribeiro, and Kopp (2025), changes in land use in Brazilian watersheds may modify hydrological responses, increasing erosion, surface runoff, and sediment loads. These factors may intensify surface runoff, linear erosion, sediment transport, and the silting of the main channel (Pericinoto, 2021; Bento; Ribeiro; Kopp, 2025).

Despite their importance, zero-order channels are generally not represented on official topographic maps, especially at medium scales such as 1:50,000. This absence creates a gap between the actual hydrological dynamics of the watershed and formal environmental planning



instruments, which tend to consider only permanent or intermittent watercourses and point springs. According to Bortolin, Mendes, and Caneppele (2021), the use of geotechnologies has proven essential for complementing traditional cartographic databases, particularly in studies that require greater spatial detail. Thus, hydrologically active and environmentally vulnerable areas may remain without adequate protection when they are not analyzed through morphometric and geospatial methods (Bortolin; Mendes; Caneppele, 2021).

In this context, this study aims to evaluate the application of geotechnologies and morphometric indices in identifying potential areas of occurrence of zero-order channels in the Environmental Protection Area of the Rio Piava Watershed. For this purpose, the Topographic Wetness Index and the Stream Power Index were used in association with Digital Terrain Model analysis, land use and land cover data, and field validation. According to Ribeiro et al. (2021), the integration of hydrological modeling, spatial analysis, and empirical validation strengthens the interpretation of environmental processes in watersheds. Thus, this study seeks to contribute to the improvement of environmental management in the Environmental Protection Area and to the protection of the water source used for public supply in Umuarama (Pericinoto, 2021).

2 Watershed, Hydrological Connectivity, and Zero-Order Channels

The watershed constitutes an appropriate physical-territorial unit for environmental planning and water resource management, as it integrates climatic, geomorphological, pedological, hydrological, and anthropogenic processes. Changes occurring on hillslopes, recharge areas, springs, and headwaters may affect the entire drainage network, influencing discharge, water quality, sediment transport, and channel stability. According to Costa, Dupas, and Pons (2020), the assessment of environmental fragility in watersheds must consider the interaction between natural characteristics and forms of land use, since the main environmental conflicts emerge from this combination. For this reason, watershed management requires a systemic approach capable of considering both mapped fluvial channels and the contributing areas that condition their functioning (Christofolletti, 1980; Tucci, 2001; Costa; Dupas; Pons, 2020).

The drainage network is traditionally represented by hierarchical ordering systems, such as the Strahler method, in which first-order channels are those that have no mapped tributaries. Although widely used in geomorphological and hydrological studies, this model has limitations when applied to headwater areas, as it tends to disregard diffuse, ephemeral, or temporarily connected features of the hydrographic network. According to Souza and Castelo Branco (2020), the interpretation of geomorphological connectivity in tropical landscapes requires attention to discrete forms of linkage between hillslopes, channels, and depositional areas. It is precisely within



this interval between the hillslope and the first-order channel that zero-order channels occur (Strahler, 1952; Strahler, 1957; Souza; Castelo Branco, 2020).

Zero-order channels are features located at the beginning of the drainage network, frequently associated with concavities, elongated depressions, temporary wetlands, incipient rills, and exfiltration zones. Their activation depends on the combination of rainfall, antecedent moisture, infiltration capacity, slope, contributing area, and land use conditions. Topographic wetness indices contribute to identifying sectors where soil saturation may increase connectivity between headwater areas and fluvial channels. During dry periods, these features may remain poorly defined; during rainfall events, however, they may act as preferential pathways for runoff and sediment transport (Beven; Kirkby, 1979; Schlesner, 2022).

The notion of hydrological connectivity is central to understanding the importance of these features. Connectivity expresses the degree to which different landscape compartments — such as hillslopes, roads, agricultural areas, wetlands, and channels — are functionally linked by the flow of water and sediment. According to Almeida and Correa (2020), sediment connectivity in agricultural watersheds may intensify the transfer of soil particles to watercourses, especially when vegetation cover is low and conservation practices are insufficient. In watersheds subjected to agricultural and livestock use, soil compaction, reduced vegetation cover, and the presence of rural roads may increase this connectivity, creating preferential runoff routes toward zero-order channels and, subsequently, toward the main channel (Bracken; Croke, 2007; Almeida; Correa, 2020).

Recent studies on watershed management and water resilience have reinforced that headwater areas, riparian zones, and ephemeral drainages perform essential environmental functions, such as sediment retention, flood attenuation, groundwater recharge, pollutant filtering, and the maintenance of aquatic and terrestrial biodiversity. The disregard of ephemeral channels in management policies may compromise the interpretation of water and sediment flows in watersheds subjected to climate change and land use alterations. Therefore, the protection of permanent watercourses, although necessary, is not sufficient to ensure the hydrological integrity of the watershed; it is also necessary to incorporate the areas responsible for the generation and initial concentration of runoff (Silva et al., 2024).

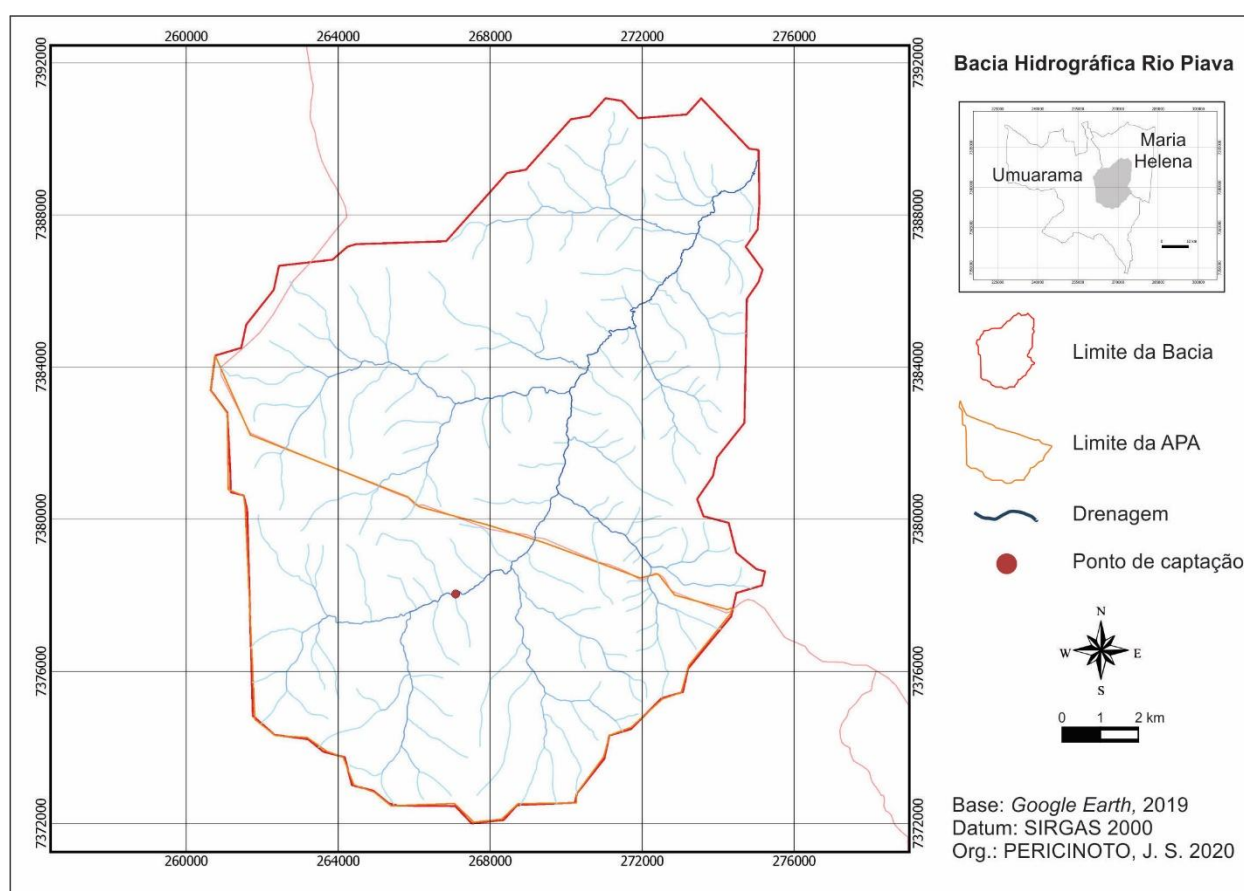
In Brazil, environmental legislation establishes protection criteria for Permanent Preservation Areas associated with watercourses, springs, palm swamps, and wetlands. However, the application of these rules often depends on the cartographic or visual identification of permanent or clearly defined hydrological features. Changes in land use may substantially increase erosion rates, demonstrating the need for preventive management instruments in environmentally fragile areas. This aspect may limit the protection of ephemeral channels and temporary wetlands,

even when they perform relevant hydrological functions (Brasil, 2012; Sampaio; Passos; Alves, 2024).

3 Characterization of the Study Area

The study area is the Environmental Protection Area (APA) of the Rio Piava Watershed, located in northwestern Paraná State, mainly within the municipality of Umuarama and, to a lesser extent, in the municipality of Maria Helena, as shown in Figure 1.

Figure 1 – Location of the Rio Piava APA



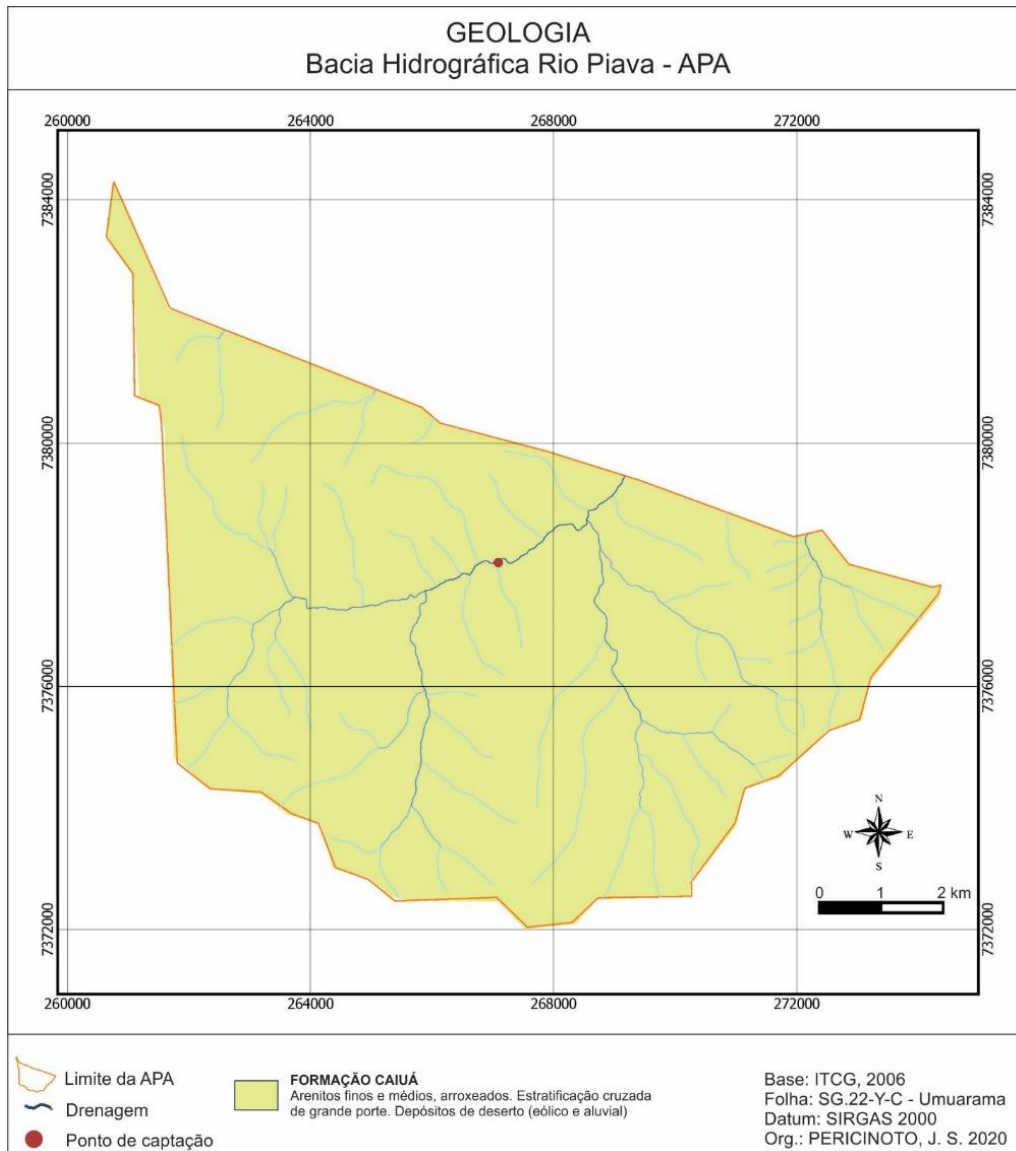
Source: Pericinoto, 2021.

The Rio Piava is of strategic importance because it constitutes the main surface water source used for public supply in Umuarama, serving a population of more than 100,000 inhabitants. According to Tundisi and Tundisi (2008), the conservation of water sources requires coordination among environmental protection, land use control, and integrated water resource management. This condition makes watershed conservation essential for municipal water security, especially in the face of extreme climate events, such as prolonged droughts and intense rainfall (Pericinoto, 2021; Tundisi; Tundisi, 2008).

The Rio Piava APA was created with the purpose of regulating land use and protecting the natural resources associated with the water source. Initially established by Municipal Decree No. 050/1998, the unit was later expanded by Municipal Law No. 3,849/2012, covering approximately 8,344.66 hectares. According to Costa, Dupas, and Pons (2020), territorial units subjected to multiple uses require environmental diagnoses capable of identifying areas of greater fragility and conflicts between conservation and production. As it is a sustainable-use conservation unit, economic activities are allowed, provided that they are compatible with conservation objectives. This makes greater control of headwater areas, hillslopes, and direct contributing zones necessary (Costa; Dupas; Pons, 2020; Pericinoto, 2021).

Geologically, the watershed is located in an area of sandstones of the Caiuá Formation, which is part of the Bauru Group, as shown in Figure 2.

Figure 2 – Geological map of the APA



Source: Pericinoto, 2021



From a physical and natural perspective, the watershed is located within the domain of sandstones of the Caiuá Formation, which belongs to the Bauru Group. These materials have a predominantly sandy texture and low cohesion, characteristics that favor the disaggregation and transport of particles when the soil is exposed or subjected to inadequate management. According to Almeida, Panachuki, and Oliveira (2018), sediment production in Brazilian watersheds is strongly associated with the combination of soil erodibility, inadequate land use, and the absence of conservation practices. The soil cover is mainly composed of Red Latosols and Red-Yellow Argisols, in addition to localized occurrences of sandy soils and areas under hydromorphic influence, a condition that may favor subsurface lateral flows and moisture concentration in specific sectors of the landscape (Santos et al., 2018; Almeida; Panachuki; Oliveira, 2018).

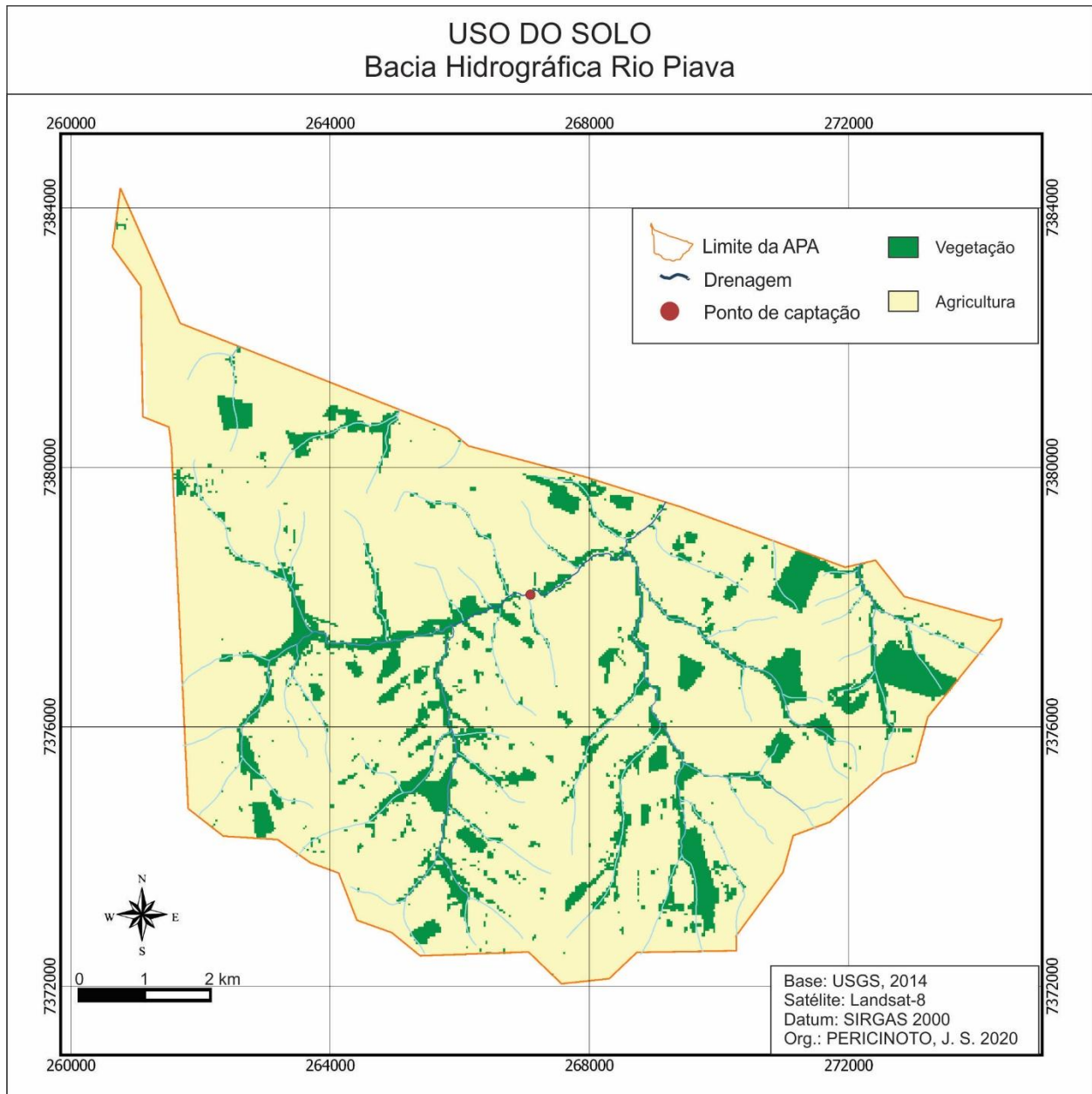
The regional climate is classified as humid subtropical, with an average annual rainfall of approximately 1,670 mm and an average temperature around 22 °C. Although rainfall occurs throughout the year, it is more concentrated in spring and summer, which favors the temporary saturation of soils in headwater areas, valley bottoms, and concavities. According to Silva et al. (2020), rainfall erosivity and hydrological vulnerability in Brazilian watersheds are essential factors for understanding terrain response to precipitation and sediment transport. During intense rainfall events, these areas may show a rapid expansion of runoff, increasing connectivity between hillslopes and fluvial channels (Silva et al., 2020; Pericinoto, 2021).

The local geomorphology is characterized by predominantly gently undulating relief, with long hillslopes, concave sectors, and transitions between middle and lower slopes. Although slopes are not steep in much of the watershed, hillslope morphology and topographic convergence contribute to the concentration of water flow. In headwater areas, topographic convergence may be as relevant as slope in defining temporary wetlands and preferential runoff pathways. This characteristic is fundamental for the identification of zero-order channels, since these features tend to occur in areas where water accumulates or converges before the formation of more defined channels (Schlesner, 2022).

The drainage network of the Rio Piava presents a hierarchical pattern typical of medium-sized watersheds, with the river's main watercourse classified as a fifth-order channel according to Strahler. However, conventional representation tends to emphasize more clearly defined watercourses, omitting ephemeral or temporary features in headwater areas. This is a central point of the present study, since zero-order channels are not indicated on official topographic maps, although they play a very important role in the hydrological and sediment dynamics of the watershed (Pericinoto, 2021).

Land use and land cover are dominated by pastures, followed by agriculture and fragments of native vegetation, as shown in Figure 3.

Figure 3 – Land Use and Land Cover



Source: Pericinoto, 2021

Land use and land cover are marked by the predominance of pastures, followed by agricultural areas and fragments of native vegetation. The presence of pastures in hydrologically sensitive areas may intensify surface compaction due to cattle trampling, reduce infiltration, and increase surface runoff. Changes in vegetation cover and the expansion of agricultural and livestock uses may significantly increase erosion rates, especially when they occur on vulnerable soils. When associated with sandy soils and the absence of adequate riparian vegetation, this condition favors linear erosion, sediment transport, and the silting of the Rio Piava (Pericinoto, 2021; Sampaio; Passos; Alves, 2024).



Thus, the study area reveals the presence of a combination of natural and anthropogenic elements that justify the use of geotechnologies for the study of hydrological dynamics. The existence of a sandy substrate, relief with convergence areas, concentrated precipitation, dominant agricultural and livestock use, and direct dependence on the water source impose the need to identify hydrologically sensitive areas. In this sense, zero-order channels acquire strategic environmental importance, as they indicate regions where the drainage network forms or expands temporally, directly influencing erosion, infiltration, and sediment load processes.

4 Materials and Methods

The methodology was structured into five main stages: organization of the geospatial database, generation of the Digital Terrain Model, calculation of morphometric indices, spatial overlay with land use and land cover, and field validation. This sequence made it possible to identify areas with a greater tendency toward water saturation, higher runoff energy, and a higher probability of occurrence of zero-order channels in the Environmental Protection Area of the Rio Piava Watershed. According to Ribeiro et al. (2021), the integration of spatial modeling, environmental data, and empirical validation increases the reliability of analyses applied to watershed management.

Initially, a database was organized in a Geographic Information System environment using QGIS software, version 3.4, with support from the GRASS GIS and SAGA GIS modules. Topographic maps at a 1:50,000 scale, hydrographic data, APA boundaries, geological and pedological information, and Landsat-8/OLI satellite images were incorporated. According to Bortolin, Mendes, and Caneppele (2021), the use of geotechnologies in watershed management makes it possible to integrate data from multiple sources and generate spatial diagnoses that are more compatible with environmental complexity. All layers were reprojected to the same spatial reference system, clipped to the boundary of the study area, and checked for topological consistency (Bortolin; Mendes; Caneppele, 2021).

The Digital Terrain Model was produced from contour lines from the topographic maps, with a vertical interval of 20 meters. Interpolation was performed in the GRASS GIS environment, generating a raster matrix with a spatial resolution of 10 meters. The quality of the digital terrain model directly influences the estimation of topographic indices, especially in low-slope areas and diffuse headwaters. After generating the model, hydrological correction procedures were carried out, such as filling spurious depressions and adjusting flow continuity, in order to reduce inconsistencies in the calculation of flow direction and flow accumulation (Schlesner, 2022).

To represent the distribution of runoff over the surface, flow direction algorithms available



in SAGA GIS were used, with preference given to multiple-flow direction methods, which are suitable for gently undulating relief areas. This type of algorithm allows flow to be distributed to more than one neighboring cell, reducing the artificial concentration typical of single-flow direction methods. According to Ribeiro et al. (2021), the appropriate choice of flow algorithm is decisive for representing hydrological processes in watersheds with poorly dissected relief. This choice was considered important for identifying diffuse wetlands, concave headwaters, and incipient channels (Ribeiro et al., 2021).

The identification of areas with a greater propensity for water saturation was carried out using the Topographic Wetness Index, calculated from the relationship between the specific contributing area and the local slope. The equation used was:

$$ITU = \ln \left(\frac{A_c}{\tan \beta} \right)$$

Where A_c represents the specific contributing area and β represents the local slope expressed in radians. According to Beven and Kirkby (1979), this index makes it possible to estimate variable contributing areas and sectors with a higher probability of saturation. Recent studies also reinforce its usefulness in identifying wetlands, hydrologically active headwaters, and zones of surface and subsurface connectivity (Schlesner, 2022).

The erosive potential associated with concentrated runoff was estimated using the Maximum Flow Index, equivalent to the Stream Power Index. The equation used was:

$$IMF = A_c \cdot \tan \beta$$

In the equation, A_c represents the specific contributing area and β corresponds to the local slope in radians. High MFI values indicate sectors where flow has greater energy to remove, transport, and deposit sediments. Areas of greater sedimentological connectivity in agricultural watersheds tend to coincide with preferential runoff and particle transport routes. These locations were interpreted as areas with greater potential for the formation of rills, gullies, and incipient erosive channels (Almeida; Correa, 2020).

After calculating the indices, the TWI and MFI maps were classified into relative low, medium, and high susceptibility classes, based on the statistical distribution of the values obtained for the study area. Subsequently, a spatial overlay was performed among the indices, the official hydrographic network, topographic maps, and the land use and land cover map. According to Costa, Dupas, and Pons (2020), the overlay of environmental variables is an appropriate strategy for identifying areas of fragility and supporting management decisions. Potential areas of occurrence of zero-order channels were considered to be those that presented medium to high TWI



values, topographic connection with first-order channels, linear or convergent morphology, and absence of representation as permanent watercourses in official databases (Costa; Dupas; Pons, 2020).

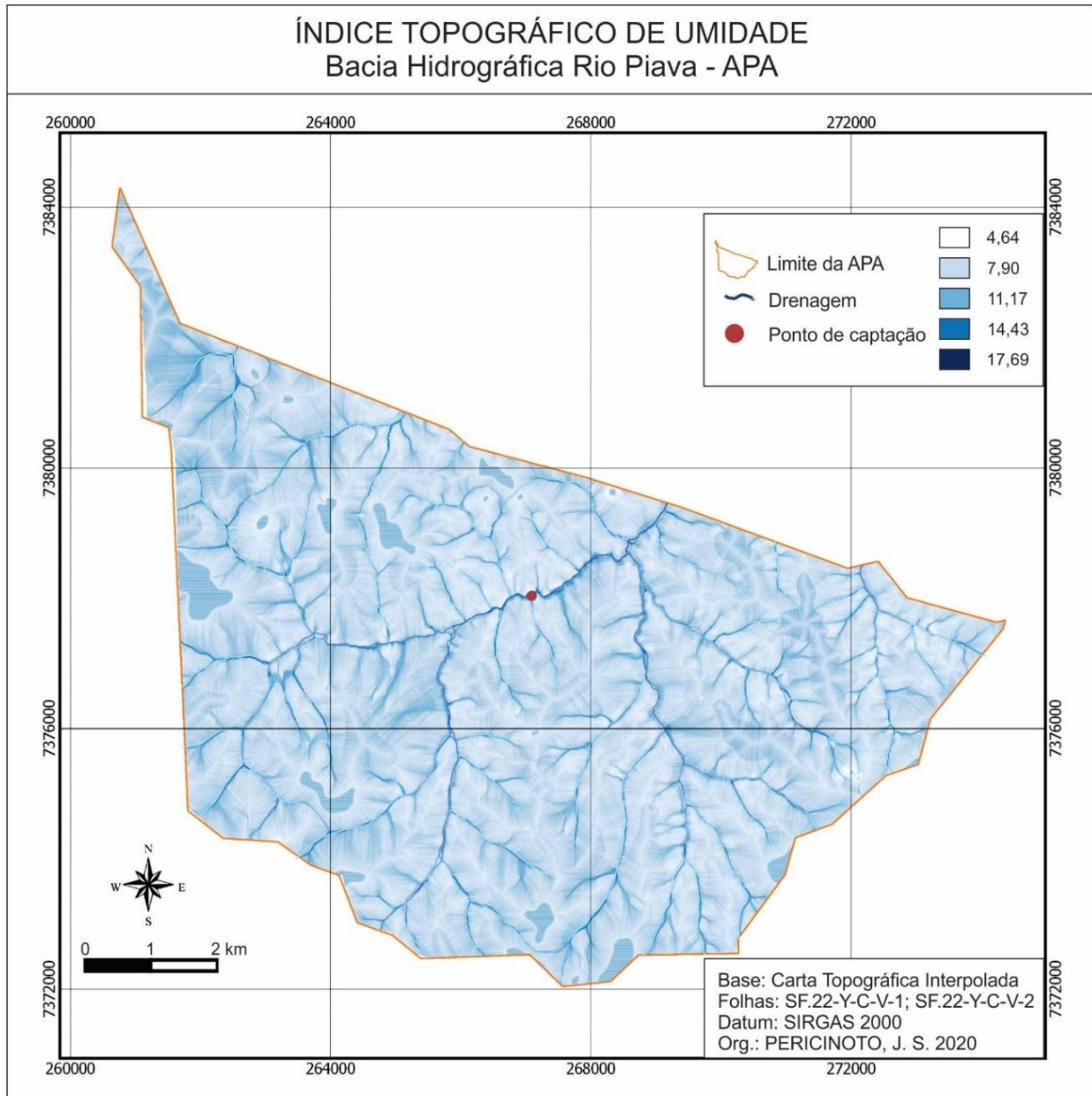
Field validation was carried out based on the selection of representative points indicated by the morphometric indices. The points were chosen according to four criteria: presence of high TWI and/or MFI values, proximity to first-order channels, diversity of land uses, and ease of access. According to Bortolin, Mendes, and Caneppele (2021), empirical validation is a fundamental step for reducing uncertainties in diagnoses produced through geoprocessing. During the field visits, aspects such as hillslope morphology, presence of concavities, surface moisture, vegetation indicative of wet environments, signs of concentrated flow, erosive rills, sediment deposition, soil compaction, presence of cattle, and interference from rural roads were observed (Bortolin; Mendes; Caneppele, 2021).

5 Results and Discussion

The morphometric analysis of the Rio Piava APA demonstrated that the hydrological vulnerability of the watershed is not conditioned solely by slope, but by the combination of hillslope form, contributing area, soil type, vegetation cover, and land use. Although gently undulating relief predominates, specific sectors with greater flow concentration were identified, especially in concave headwaters, valley bottoms, and transitions between middle and lower slopes. Areas of topographic convergence may have high hydrological importance even when located in low-slope terrain. These results indicate that areas that appear to be only slightly inclined may show high environmental sensitivity when associated with water convergence and sandy soils of low cohesion (Schlesner, 2022; Pericinoto, 2021).

The TWI allowed the identification of areas more susceptible to water saturation, especially in valley bottoms, concave headwaters, and stretches connected to the drainage network, as shown in Figure 4.

Figure 4 – Topographic Wetness Index – TWI

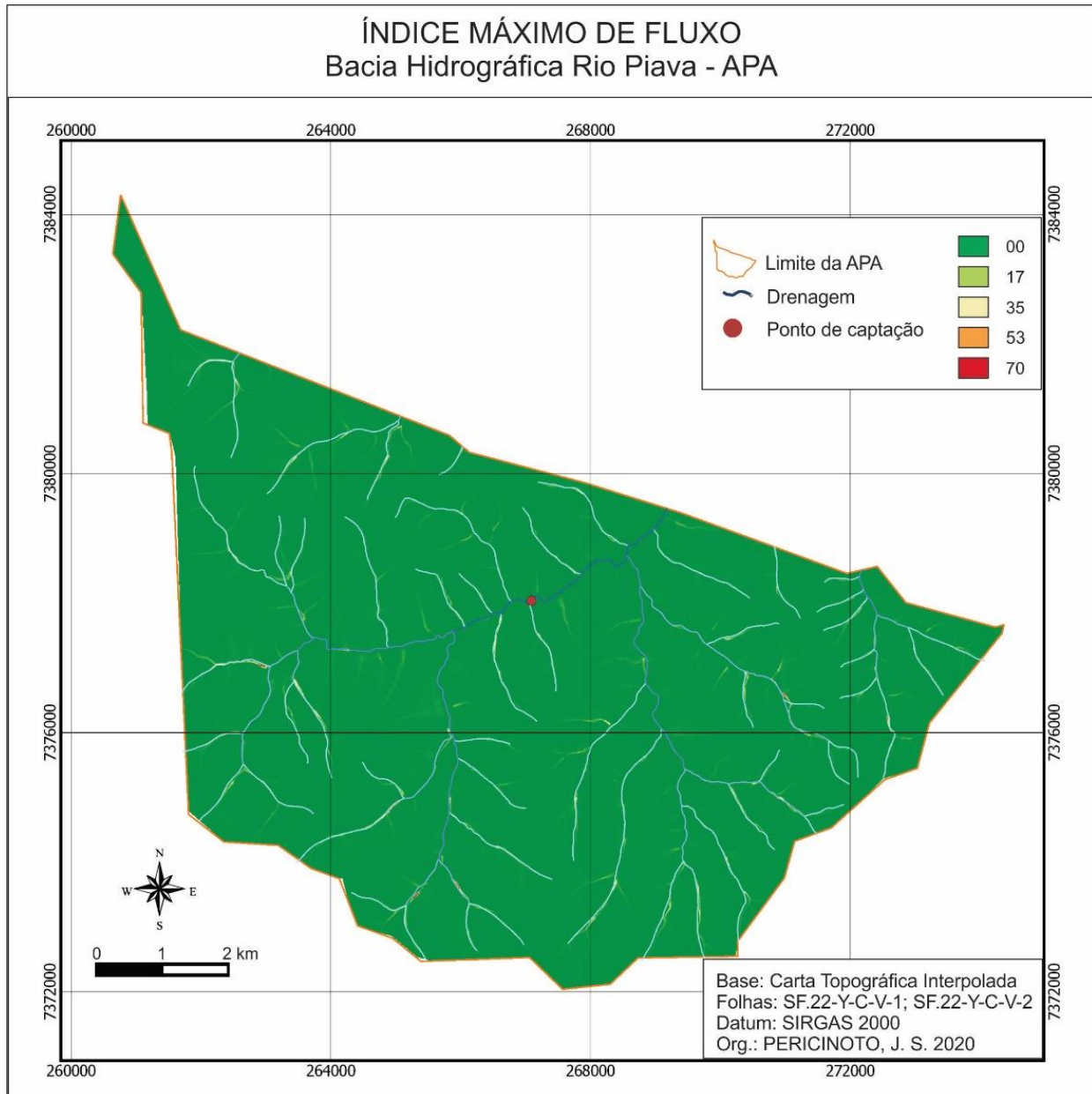


Source: Pericinoto, 2021

The occurrence of high TWI values in these sectors indicates the presence of hydrologically active areas, which may function as zones of temporary storage, exfiltration, or subsurface flow. According to Silva et al. (2024), headwater areas and ephemeral channels can be rapidly activated during rainfall events, expanding the functional drainage network. This result is relevant because it shows that the watershed's functional drainage network expands during wet periods, exceeding the limits represented by official cartography.

The MFI highlighted the sectors most prone to erosion and sediment transport, mainly in areas of flow convergence and between hillslopes and valley bottoms, as shown in Figure 5.

Figure 5 – Maximum Flow Index



Source: Pericinoto, 2021

The highest MFI values occurred at flow convergence points and in transition areas between hillslopes and valley bottoms, where water accumulated in the upper portions of the watershed tends to concentrate. According to Almeida, Panachuki, and Oliveira (2018), sediment transport in Brazilian watersheds is associated with the interaction among runoff energy, soil erodibility, and land-use patterns. Although these sectors occupy relatively small areas, their environmental importance is high, as they may function as sediment source areas and initiate incision processes that later connect to the main channels (Almeida; Panachuki; Oliveira, 2018).

The integration between TWI and MFI made it possible to identify priority areas with potential occurrence of zero-order channels. Locations where high topographic wetness values



coincided with greater flow energy were interpreted as critical sectors, as they combine favorable conditions for both soil saturation and the formation of concentrated runoff. According to Almeida and Correa (2020), sediment connectivity is intensified when sediment source areas are functionally linked to channels through preferential runoff pathways. This combination indicates a greater probability of the emergence of ephemeral channels, incipient rills, and temporary wetlands connected to first-order channels (Almeida; Correa, 2020).

The comparison between the products generated through geoprocessing and the official topographic maps at a 1:50,000 scale revealed important limitations of conventional cartography. Several areas indicated by the indices as hydrologically sensitive were not represented as drainage features on the official maps. On the other hand, some mapped features did not present, in the field, characteristics compatible with permanent channels. According to Bortolin, Mendes, and Caneppele (2021), the integration of cartographic databases, remote sensing, and fieldwork is essential for refining environmental diagnoses. This divergence reinforces that medium-scale maps may generalize or omit ephemeral features, especially in headwater areas, where hydrological dynamics vary according to seasonality and rainfall events (Bortolin; Mendes; Caneppele, 2021).

Field observations confirmed a significant part of the interpretations obtained through modeling. In sectors with high TWI values, concavities, greater surface moisture, vegetation associated with wet environments, and evidence of temporary flow were observed. In areas with high MFI values, signs of concentrated runoff, exposed soil, small rills, sediment deposition, and the influence of rural roads were identified. According to Ribeiro et al. (2021), field validation makes it possible to verify whether modeled patterns correspond to processes that are effectively observable in the landscape. These elements indicate that morphometric indices not only represent topographic patterns, but also express observable hydrological and geomorphological processes (Ribeiro et al., 2021).

Land use showed a strong relationship with the vulnerability of zero-order channels. The predominance of pastures in headwater areas and flow convergence zones contributes to soil compaction, reduced infiltration, and increased surface runoff. Changes in land use and land cover may cause significant increases in erosion rates, especially when natural covers are replaced by agricultural and livestock uses. Animal trampling and low vegetation cover favor flow concentration, increasing erosion potential in areas that are already naturally fragile (Sampaio; Passos; Alves, 2024; Pericinoto, 2021).

The discussion of the results allows zero-order channels to be understood as strategic components of the hydrographic network, even when they do not present permanent flow. Their function is related to moisture regulation, the connection between hillslopes and channels,



sediment production, and the hydrological response of the watershed during rainfall events. According to Souza and Castelo Branco (2020), the analysis of geomorphological connectivity makes it possible to understand how different landscape compartments contribute to sediment dynamics. In water-supply catchments such as the Rio Piava, the degradation of these areas may increase water turbidity, intensify silting, and raise treatment costs.

These results are consistent with recent studies that emphasize the need to integrate headwater areas, temporary wetlands, and ephemeral drainages into environmental planning. Management based only on the permanent hydrographic network tends to underestimate critical areas of runoff and sediment generation. Changes in land use in Brazilian watersheds may simultaneously alter hydrological and sedimentological processes, requiring preventive management measures. Therefore, the TWI and MFI maps can be used as complementary instruments to define priority areas for restoration, improve rural roads, guide conservation practices, and review protection zones in sustainable-use conservation units (Bento; Ribeiro; Kopp, 2025).

6 Conclusion

The study demonstrated that the application of geotechnologies and morphometric indices is suitable for identifying hydrologically sensitive areas in the Environmental Protection Area of the Rio Piava Watershed, especially those related to the potential occurrence of zero-order channels. The Topographic Wetness Index was effective in indicating sectors with a greater tendency toward saturation, while the Maximum Flow Index made it possible to recognize areas with greater runoff energy and erosive potential. According to Schlesner (2022), topographic indices are relevant tools for interpreting the spatial organization of moisture and connectivity in headwater areas. The integration of these indices provided a more complete interpretation of headwater dynamics, making it possible to identify critical areas not represented by official cartography.

The results confirm that zero-order channels play a relevant role in the hydrological and sediment connectivity of the watershed. Even when they present only temporary flow, these features act as initial zones of water concentration and may connect hillslopes to first-order channels during rainfall events. Ephemeral channels are important components of the functional drainage network, especially in scenarios of land-use change and intensification of extreme events. For this reason, disregarding them in environmental planning may contribute to increased erosion, sediment transport, silting, and turbidity of the water captured for public supply (Silva et al., 2024).

The predominance of pastures in headwater areas and flow convergence zones aggravates



the environmental vulnerability of the APA, especially due to soil compaction, reduced infiltration, and intensification of surface runoff. This condition is intensified by the presence of sandy soils and friable materials associated with the Caiuá Formation, which makes the watershed particularly sensitive to erosive processes. According to Almeida, Panachuki, and Oliveira (2018), the combination of susceptible soils, agricultural and livestock use, and the absence of conservation practices increases sediment production in watersheds. Therefore, the management of these areas should be treated as a priority to reduce impacts on the water source (Almeida; Panachuki; Oliveira, 2018).

The protection of zero-order channels should be incorporated into the environmental management strategies of the Rio Piava APA. It is recommended that the planning of the conservation unit consider not only permanent watercourses and point springs, but also temporary wetlands, headwater concavities, and sectors of high hydrological connectivity identified through morphometric modeling. According to Costa, Dupas, and Pons (2020), the identification of environmentally fragile areas contributes to reducing land-use conflicts and guiding conservation policies. This incorporation may contribute to the revision of protection zones, prioritization of restoration areas, improvement of rural roads, control of concentrated runoff, and reduction of sediment input into the water source (Costa; Dupas; Pons, 2020).

Finally, future studies are recommended to use higher-resolution altimetric databases, drone imagery, field surveys in different seasonal periods, and soil moisture monitoring. According to Ribeiro et al. (2021), the combination of geospatial data, hydrological modeling, and empirical validation tends to improve environmental diagnoses and increase their applicability in watershed management. This information may refine the delimitation of zero-order channels and strengthen the formulation of public policies aimed at water security in Umuarama (Ribeiro et al., 2021).

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