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Papers

Integrated Assessment of the Proliferation of Small Dams and Erosion Susceptibility: The Ivaí River Watershed, Southern Brazil

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Keywords
Dam
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Abstract
The proliferation of small dams in watersheds has raised growing concerns about their potential impacts on the connectivity of fluvial systems, particularly regarding sediment transport, flow variability, and the integrity of aquatic habitats. In this context, this study investigated the distribution of hydroelectric dams and the erosion susceptibility, using the Ivaí River Watershed, Paraná state, Brazil, as a case study to assess geomorphological implications at the watershed scale. The Ivaí River is the largest free-flowing river in Southern Brazil, and also stands out as the main unregulated tributary of the Paraná River, granting it a strategic role in maintaining the hydro-sedimentological and ecological integrity of the Upper Paraná River watershed. The analyses in the Ivaí River Watershed were conducted using cadastral data from hydroelectric projects and geoprocessing techniques based on map algebra. A total of 21 projects, either operational or approved for construction, were identified. Their drainage areas represent 13.7% of the watershed, mostly concentrated in the upper course, characterised by dissected relief, the presence of Neosols, and high rainfall indices. Currently, its main course remains free-flowing; however, studies for future projects threaten the river integrity. The overlap between areas of high geomorphological vunerability and project concentration indicates potential cumulative risks to fluvial dynamics. The results show that even smaller-scale dams, when located in sensitive areas, can disrupt fluvial connectivity and morphodynamic processes with cumulative effects. This scenario highlights the need for territorial planning policies that integrate the conservation of fluvial systems essential to maintaining ecosystem services in their decision-making.

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INTRODUCTION

The construction of dams has been a topic of global discussion. One of the main reasons for studying the impacts of dams on rivers is the consequent changes in sediment load and flow amplitude (Latrubesse *et al.*, 2017; Guo *et al.*, 2018; Coelho, 2008; Figueiredo; Gomes, 2024; Chong *et al.*, 2021). Dams can prevent the transport of more than half of the sediment, with implications for the fluvial landscape (e.g., inhibition of bar and island formation), mainly downstream of the structures (Yang *et al.*, 2022; Quang; Viet, 2023). The longitudinal channel connectivity, and the other dimensions of water and sediment flow connectivity (Zanandrea *et al.*, 2020), are drastically altered by the sediment retention caused by dams. For example, Latrubesse *et al.* (2017) highlight that dams built on mainstem rivers and tributaries, without foreseeing cumulative consequences, can lead to large-scale degradation. In this regard, not only dams on the main channel but also on the tributaries become potential threats to the water and sediment flows that sustain the physical integrity and ecosystems of the rivers.

In Brazil, dams for hydroelectricity production are classified by Agência Nacional de Energia Elétrica – ANEEL (National Agency of Electric Energy) (ANEEL Normative Resolution N° 875, 2020) as a Hydropower Plant (HPP), Small Hydropower Plant (SHP), and Reduced-Capacity Hydroelectric Generating Facility (CGH). Currently, CGHs correspond to hydropower developments whose capacity is equal to or less than 5,000 kW (ANEEL Normative Resolution N° 875, 2020). SHPs fall into the range of installed capacity greater than 5,000 kW and equal to or less than 30,000 kW, without specifications regarding the reservoir size. Finally, HPPs fall into the range of installed capacity greater than 30,000 kW, subject to authorization grants, and installed capacity greater than 50,000 kW, subject to concession grants (ANEEL Normative Resolution N° 1.070, 2023).

Despite the diverse research on the impact of dams from hydroelectric projects, there are still few studies at the watershed scale, mainly regarding the distribution and potential impacts of the proliferation of small developments in tributaries (Csiki; Rhoads, 2010; Fencl *et al.*, 2015; Chong *et al.*, 2021). CGHs and SHPs, although having lower installed capacity, have recently received attention for their deleterious effects on fluvial systems (Paes *et al.*, 2019; Cardoso *et al.*, 2015).

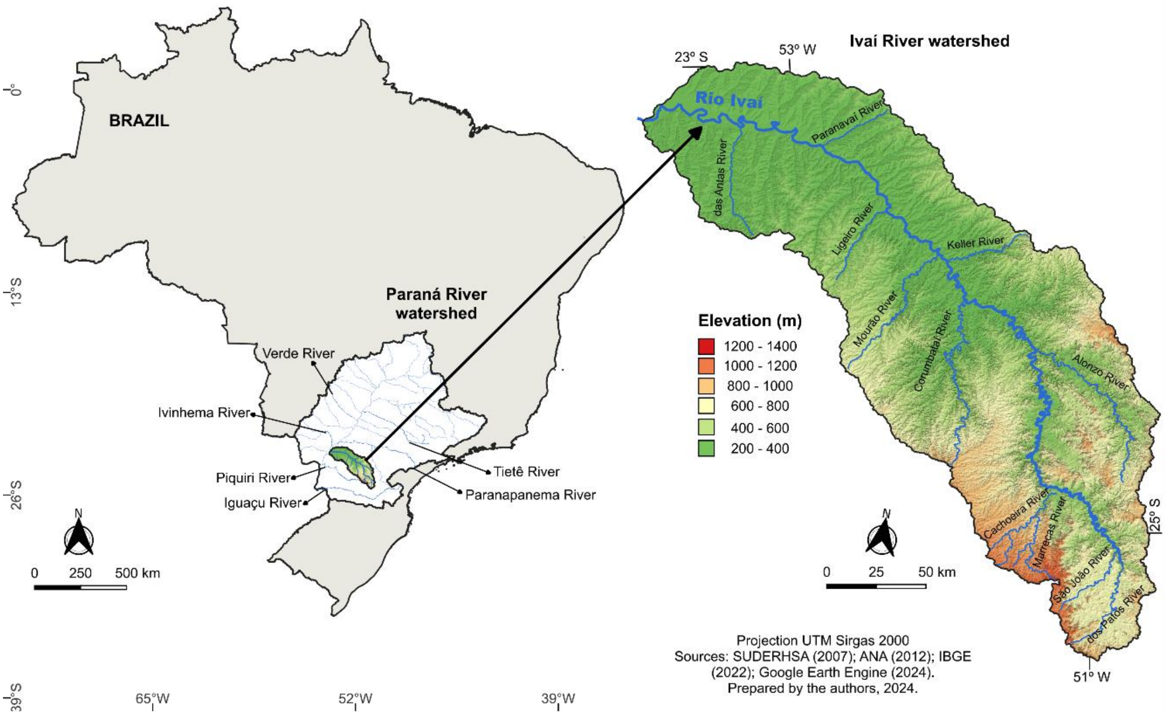
The state of Paraná, like much of Brazil, exhibits geomorphological and hydrological characteristics favorable to the installation of hydroelectric dams. The river characteristics, such as slope and discharge, that make energy generation viable, position Paraná as the third state with the highest potential for electricity generation in the country (Kliemann; Delariva, 2015). The Ivaí River, which has the largest watershed entirely within the state, presents high hydroelectric potential and the main channel is free of dams. However, there is a series of dams in operation and under licensing on its tributaries. This condition differs from other rivers in Southern Brazil, such as the Paraná, Uruguai, and Iguaçu rivers, whose dams have drastically impacted their functioning (Panta *et al.*, 2023; Leli *et al.*, 2017; Rocha, 2010).

This study aims to characterize the areas of influence of existing and planned dams in the Ivaí River watershed and, consequently, to evaluate the sediment production in these areas using the qualitative approach of Natural Erosion Potential (NEP). In this context, considering the sediment production in the Ivaí River watershed, in relation to the hydroelectric plants, is essential for evaluating the impacts associated with these landscape transformations.

STUDY AREA

The Ivaí River watershed (Figure 1) has a drainage area of 36,587 km² covering approximately 20% of the Paraná territory (Fujita, 2009) and is considered the second largest in the state of Paraná (Fujita, 2009; Santos, 2015). The Ivaí River is considered the largest genuinely Paraná river because its drainage area is entirely within the Paraná territory, comprising 107 municipalities (Parolin *et al.*, 2010; ITCG, 2009). Its formation occurs from the confluence of the Patos River with the São João River, in the municipality of Prudentópolis, with the Patos River being its main source (Parolin *et al.*, 2010; Fujita, 2009), and it flows into the Paraná River at an elevation of 240 m (Fujita, 2009), between the municipalities of Querência do Norte on the right bank and Icaraíma on the left bank (Parolin *et al.*, 2010).

Figure 1 - Location of the Ivaí River watershed within the Paraná River watershed, Southern Brazil



Source: SUDERHSA (2007); ANA (2012); IBGE (2022); Google Earth Engine (2024). Prepared by the authors (2024).

In geological terms, the Ivaí River watershed is located within the Paraná Sedimentary Basin (Santos, 2015), and is mainly represented by rocks from the Caiuá Group (26.2%), Serra Geral Group (47.9%), and sedimentary rocks from the Mesozoic and Paleozoic eras (21.3%), such as the Rio do Rasto, Teresina, Serra Alta, and Irati Formations (Passa Dois Group) and Rio Bonito and Palermo Formations (Guaíra Group) (Bresser *et al.,* 2021). The basin extends between the subtropical (upper course) and tropical (middle and lower courses) zones, with a predominant Köppen Cfa climate (Santos, 2015; IAPAR, 1994; Parolin *et al.,* 2010). According to Santos (2015), the Second Paraná Plateau corresponds to the upper course of the Ivaí River watershed, while the Third Paraná Plateau corresponds to the middle and lower courses. The pedological soil classes present in the study area are: Nitisol, Latosol, Neosol, Argisol, Cambisol, Gleysol, and Organosol (EMBRAPA, 2008).

MATERIALS AND METHODS

The study was developed in two stages: (i) mapping and characterization of the dams and their respective drainage areas, using data from ANEEL (2022; 2023); and (ii) calculation of the Natural Soil Loss Potential, based on the physical factors of the Universal Soil Loss Equation (USLE). The analyses were performed using a geographic information system the QGIS 3.22.6 (2022).

In the first stage, data on HPP, SHP, and CGH projects were obtained from ANEEL (2022; 2023). The drainage areas were delineated based on the axis of each dam. The built dam made available by ANEEL (2022; 2023) were confirmed with satellite images from Google Earth Pro.

The hydroelectric projects across Brazil are made available in shapefile format by ANEEL (2023). The projects in the Ivaí River watershed were subsequently grouped into studies and post-studies. The studies phase projects include: Available Axis (*Eixo Disponível*), Authorization Grant Intention Registration Dispatch (DRI), and Executive Summary Adequacy Registration Dispatch (DRS). The post-studies projects are: Construction, Construction Not Started, and Operation (ANEEL, 2024).

The approved Hydroelectric Inventory Studies class identifies hydropower developments with unit capacity greater than 5,000 kW and that offer the best cost-energy ratio. The Available Axis refers to developments identified in an approved hydroelectric inventory for any interested party to conduct their study. After this inventory study stage, the interested party must indicate which hydropower development locations they are interested in further studying with a view to seeking the project's grant. For this to occur, authorization from ANEEL (2024) is required.

Projects with capacity less than 50,000 kW (SHPs and Authorized HPPs) require a basic design, and authorization is granted through the issuance of the Authorization Grant Intention Registration Dispatch (DRI – SHP or DRI – HPP). The Basic Design, along with other documents, makes up the Executive Summary, delivered to ANEEL. If the Summary is compatible with the Hydroelectric Inventory Studies and the use of the hydraulic potential, the DRS will be published. The DRS allows ANEEL to request the Water Availability Reserve Declaration (DRDH), and the interested party to request Environmental Licensing with the competent bodies, with the possibility of anticipating actions immediately after the publication of the DRI, when applicable. After obtaining the DRDH and Environmental Licensing, the authorization grant is issued with a validity of 35 years (ANEEL, 2024).

In the second stage, the Natural Erosion Potential (NEP) map was prepared. The methodology was based on the Universal Soil Loss Equation (USLE) (Wischmeier; Smith, 1978), utilizing the physical factors R (erosivity), LS (topographic), and K (erodibility), based on the methodologies of Bloise *et al.* (2001), Silva; Ferreira (2022), Marinho Filho (2013), and Pedro; Lorandi (2004).

R Factor (Erosivity)

The mean monthly and annual precipitation values for the Ivaí River watershed were obtained from NASA raster data (2022). After data processing, an equation by Rufino *et al.* (1993) was applied, which presents eight linear formulas to estimate rainfall erosivity in different regions of Paraná. This equation was adapted in this work based on Terassi *et al.* (2018) and used to calculate the erosivity of the Ivaí River watershed:

$$R = 19{,}55 + 4{,}20 \, . \left(\frac{p^2}{P}\right) * 9{,}80665 \qquad (1)$$

Where:

p= mean monthly precipitation (mm).

K Factor (Soil Erodibility)

The vector layer of soils from Empresa Brasileira de Pesquisa Agropecuária - Embrapa (Brazilian Agricultural Research Corporation) (2008), at a scale of 1:250,000, was used. Erodibility relates to the capacity of soils, according to their physical properties, to resist erosion (Bertoni; Lombardi Neto, 2005). Thus, erodibility values were assigned to the 1st-order soil classes present in the Ivaí River watershed, based on Melo (2017). The values range from 0.14 to 0.47 for the following classes: Latosol (clay texture), Nitisol, Latosol (medium texture), Cambisol, Argisol, Gleysol, Organosol, and Neosol.

LS Factor (Topographic)

To calculate the LS factor, the SAGA software with the LS factor (one step) function was used, applying the methodology by Desmet; Govers (1996). The choice was based on Zanin *et al.* (2017), who, when comparing the methods of Desmet; Govers (1996) and Moore *et al.* (1991), indicated the former as more appropriate due to offering better relief detailing and lower standard deviation. Other authors, such as Farinasso *et al.* (2006), Mata *et al.* (2007), and Graça *et al.* (2015), also adopted this methodology, either directly or indirectly. For execution, the raster layer of hypsometry for the Ivaí River watershed was used (SRTM data, Topodata Project – INPE, 2011), with the application of the “SinkRemoval” option for depression correction.

Map Algebra - Natural Erosion Potential (NEP)

For the NEP, the resampling (mean) of pixels in the R and LS factor rasters was performed. Subsequently, the raster calculator was used to apply equation (2), adapted from Sampaio (2019), which directly standardized the R, LS, and K factors to the range of 0 to 1. Finally, the factors were multiplied.

$$Vp = V - \frac{Vmin}{Vmax} - Vmin \qquad (2)$$

Where:

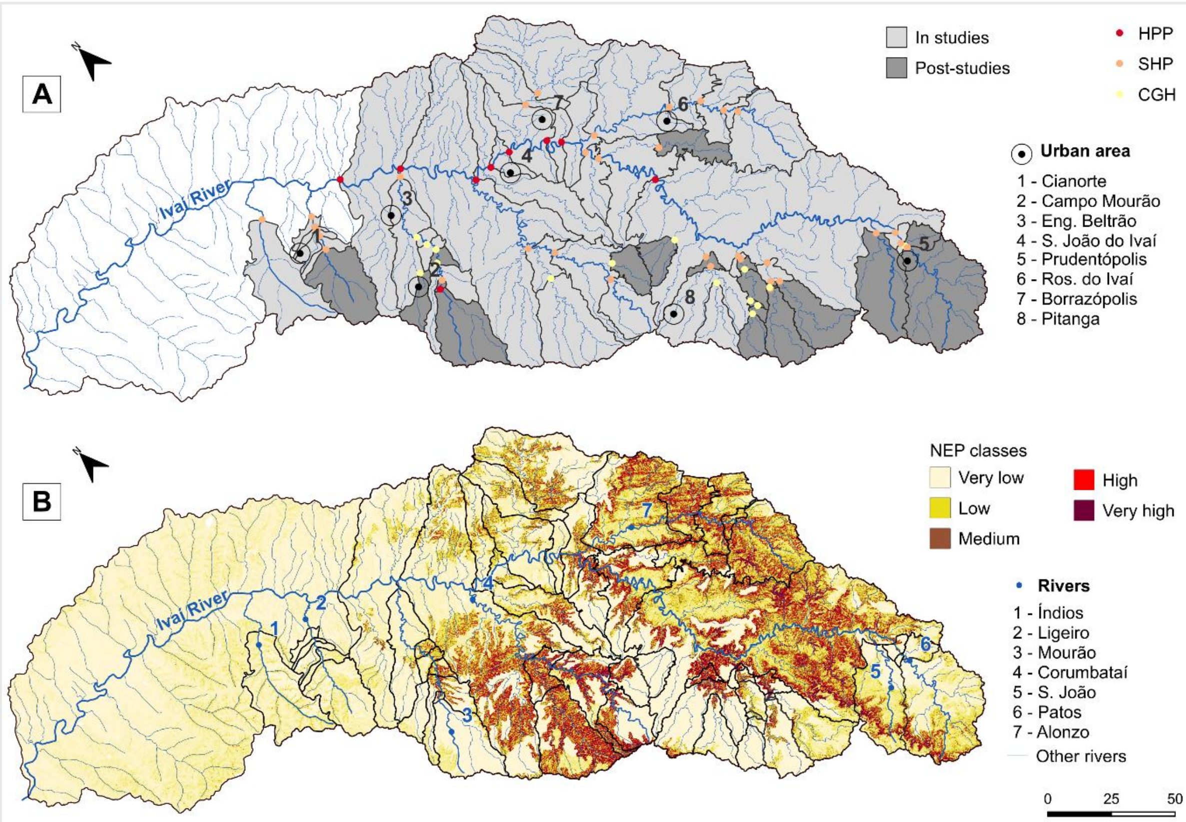
V_p = Variable to be standardized
V = Value to be standardized
V_{min} and V_{max} = minimum and maximum values of the data series

To define the number of classes, the method adapted from Sturges (1926), exemplified by Sampaio (2019), was used, resulting in five classes: very low, low, medium, high, and very high.

RESULTS

The Ivaí River watershed currently has 16 dams in the operation phase, specifically: ten CGHs, five SHPs, and one HPP. The drainage areas of these dams represent 12.6% (4,626 km²) of the watershed area. In addition to these projects, there are five others that are in the post-studies phase, meaning they are ready for construction. Therefore, considering the addition of those already approved, the influence of dams will soon reach 13.7% of the Ivaí River watershed (Figure 2-A). These projects, both built and planned, are located in the Upper Ivaí River hydrographic unit, with the exception of one SHP that will be located in the lower course of the watershed in the future. Considering a potential scenario based on licensing requests—thus, hypothetical—the 36 projects in the studies phase represent an increase of 56.8% in the area of the Ivaí River watershed (Figure 2-A). With the addition of these requests to the current scenario, the drainage area within the watershed influenced by dams would reach 70.5%. Evaluating the spatial distribution of the potential scenario reveals an advancement of dam licensing requests towards the lower course of the Ivaí River. Figure 2 - B demonstrates the NEP classes for the Ivaí River watershed, conditioned mainly by the relief morphology, where areas with greater slope exhibit the highest erosion potential. The majority of current dams and those still under construction or licensing are concentrated in the upper course. This region features plateau relief and Paleozoic sedimentary rocks, such as the Rio do Rasto and Teresina Formations. According to the precipitation isohyets from Serviço Geológico do Brasil – SBG (Geological Survey of Brazil) (2011), the period 1977-2006, the highest averages (1600–1800 mm) occur in this region. The pedological classes present are Argisol, Latosol, Nitisol, Neosol, and Cambisol, with the areas of highest NEP values mainly associated with Neosols (EMBRAPA, 2008). Land use in this upper course region is predominantly dedicated to temporary crops (soybeans), forest formation, silviculture, pasture, among others (MAPBIOMA, 2024).

Figure 2 – Results: A) Scenario with dams in the studies and post-studies phases B) Distribution of NEP and drainage areas of existing and planned dams



Source: ANEEL (2022; 2023). Prepared by the authors (2024).

The right bank of the Upper Ivaí River watershed, with special attention to the Alonzo River sub-watershed, exhibits the highest occurrences of the high and very high NEP classes, a location where there are hydroelectric projects in the studies phase. On the left bank, the NEP values are quite relevant near the Corumbataí, Patos, and São João Rivers. The Mourão River, a left-bank tributary, still in the upper course, presents high NEP classes near its mouth and has dams in operation, as well as others that are in the studies phase.

DISCUSSION

The Ivaí River watershed has dams destined for electricity generation that influence a significant portion of its area (12.6%). According to Kliemann; Delariva (2015), the Ivaí River watershed contains 28.13% of the built and inventoried SHPs in the state of Paraná, which, along with the Paraná River watershed, are the ones with the largest number of small hydropower plants built in Brazil.

The dams in operation on the Ivaí River are located in the upper course of the watershed. However, the projects under licensing or not yet constructed are advancing toward the lower course. For example, the Ligeiro River, an important tributary of the lower course, has one SHP approved for construction and five others that are in the studies phase. As for the main channel of the Ivaí River, which receives this name from the junction of the Patos and São João Rivers, it is known that there are no dams on the main course. However, there is a geomorphological study that indicates the Ivaí River headwaters are associated with the longest tributary, which in this case is the Patos River (Fujita, 2009). From this perspective, the Ivaí River has two dams on its main course due to the presence of one SHP and one CGH on the Patos River.

Regarding the Natural Erosion Potential (NEP) in the watershed, the sub-watersheds of the Corumbataí and Alonzo Rivers, located in areas with the presence of high and very high classes for sediment production, stand out among the largest contributors to the Ivaí River. Considering these main tributaries, even though the Alonzo River currently has no dam, several projects are in the studies phase. Furthermore, according to Leli *et al.* (2017), the Corumbataí, Mourão, Marrecas, Cachoeira, and Patos Rivers are important to the Ivaí River watershed due to their contribution of water discharge and suspended load, with the Corumbataí River watershed being responsible for the largest water discharges. Although the Corumbataí River has no dams, there is a CGH dam on the Bocó River, which is one of its tributaries. The Mourão River, one of the main tributaries, has one HPP, one SHP, and one CGH, in addition to one CGH on its tributary, the Campo River, and others that are in the studies phase.

The largest suspended sediment load in the Ivaí River comes from the Corumbataí, Mourão, Ligeiro, Patos, and Antas Rivers watersheds, which are the main left-bank tributaries (Leli etol., 2017), and are influenced by dams. According to Souza *et al.* (2013), the left bank of the Ivaí River forms a high block, according to the profiles and drainage patterns, and Leli *et al.* (2017) consider that these characteristics condition the greater erosion of this bank. Thus, the Ivaí River transports five times more sediment than the Paraná River (Barros, 2006), which maintains its turbid waters, conferring the maintenance of physical integrity and ecological preservation. In contrast, the Paraná River has already lost part of its natural characteristics due to the large sequence of dams that retain its sediments.

For Leli *et al.* (2017), the largest specific flow discharges correspond to the Marrecas River (Ivaí's left bank) and the Cachoeira River, a tributary of the Marrecas, both having dams—one SHP and one CGH, respectively. There is ample evidence that the construction of dams on mainstem rivers or even on their tributaries, without foreseeing cumulative consequences, leads to large-scale degradation (Latrubesse *et al.,* 2017). There is a perception among developers that small dams generate small environmental damage to the system; that is, it is a small-scale construction, so the impacts will also be small-scale. However, due to the strong generalization of this perspective and the increasing dispersion of small dams, it is found that the related environmental problems would not be less numerous or serious than those of larger projects (Abbasi; Abbasi, 2011). Therefore, even dams outside the main course of a watershed can cause severe degradation.

The Ligeiro and Antas Rivers, in the upper course of the Ivaí River, stand out for their contribution of suspended load (Leli *et al.*, 2017), and are located in regions of very low and low NEP. In contrast, Melo (2017) indicates that some areas of the lower course present considerable sediment production values. For example, near the municipality of Cianorte, there are dams authorized for construction and others also in the studies phase. Noteworthy is the advancement of projects toward the Caiuá Sandstone region, where the highest rates of surface runoff occur, due to the strong erosive processes on the soils derived from these rocks (Santos *et al.*, 2013).

In addition to geomorphological impacts, the installation of dams also generates social, cultural, and economic impacts. The Ivaí River watershed encompasses more than one hundred municipalities, some of which are populous, such as Maringá, Guarapuava, and Campo Mourão. Furthermore, there are traditional communities (Faxinalenses and Quilombolas), indigenous peoples (Kaingang, Guarani, and Xetá), who directly depend on the Ivaí River and its tributaries. As much of its flow is still free of dams, families displaced by reservoirs built on the Paraná, Paranapanema, or Iguaçu Rivers still live in the region (Azevedo *et al.*, 2016). Among the directly affected social groups are artisanal fishermen and families settled by the agrarian reform, with particular conceptions of territory (Albuquerque; Sauer, 2021). In this context, intense discussions arise, such as those of the "Movimento Pró Ivaí/Piquiri" (Pro Ivaí/Piquiri Movement), an interdisciplinary team that acts against the implementation of new dams on the river, aiming for environmental and social preservation (Schirmer *et al.*, 2018).

CONCLUSIONS

The analysis of existing and planned dams in the Ivaí River watershed contributes to the knowledge of the spatial distribution of these interventions and the respective geographic characteristics of the drainage areas where hydrological and sediment flow are limited or altered. The application of the Natural Erosion Potential (NEP) helped to identify areas of the watershed most vulnerable to anthropic intervention, which in this case are concentrated in the upper course.

The study demonstrates that there are existing dams, and others under analysis, on rivers that are strategic for the hydro-sedimentological balance of the watershed. Considering that dams, even those of smaller dimensions (SHPs and CGHs), limit the transport of sediments and alter flow variability, resulting in severe geomorphological and ecological implications, the need for management strategies that consider the cumulative effects of these structures on the physical and ecological integrity of the rivers is reinforced. In this context, the study reiterates that, in watersheds still partially free of dams, containing the expansion of new projects can be a relevant strategy to mitigate alterations to sediment flow and discharge dynamics, which can be critical to ecosystem services.

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AUTHORS CONTRIBUTION

Mariana Manrique Tondati: Conceptualization, Data curation, Formal analysis, Visualization and Writing – review & editing; Eduardo Souza de Morais: Conceptualization, Supervision and Writing – review & editing.

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DATA AVAILABILITY: The data that support the findings of this study can be made available, upon reasonable request, from the corresponding author [Mariana Manrique Tondati].