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Permanent preservation areas and environmental fragility: a methodological proposal

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ABSTRACT

Permanent Preservation Areas (PPAs) are essential for protecting sensitive ecosystems. However, their functions are increasingly compromised by human activities. Incorporating PPAs into environmental fragility assessments is strategic for identifying conflicts between land use and legally protected areas. Using Geographic Information Systems (GIS), this study proposes a methodology that integrates land use and land cover (LULC) data with PPA boundaries to generate an environmental fragility layer, using the municipality of Lorena, State of São Paulo, Brazil, as a case study. The method applies spatial overlay techniques and assigns different fragility levels to LULC classes according to their occurrence inside or outside water-related PPAs. The application of the methodology in Lorena showed that more than 60% of water-related PPAs are occupied by pastures and mixed-use mosaics, resulting in high-fragility areas diffusely distributed across the municipality. PPAs associated with urban areas, rocky outcrops, and non-vegetated areas concentrated very high fragility levels (0.2% of the territory) mainly in the central region. These patterns are driven by soil impermeabilization and consolidated land occupation. The integrated analysis enabled a more refined fragility classification than assessments based solely on LULC data. The proposed methodology effectively identified overlaps between anthropogenic land uses and legally protected areas, providing an environmental fragility diagnosis consistent with ecological and regulatory frameworks. It represents a robust and replicable tool for environmental management, supporting territorial planning, identification of priority areas for ecological restoration, and natural resource conservation in different regional contexts.

Keywords: environmental planning, geographic information systems, land use and land cover.

Áreas de preservação permanente e fragilidade ambiental: uma proposta metodológica

RESUMO

Áreas de Preservação Permanente (APPs) são essenciais para a proteção dos ecossistemas. Contudo, suas funções estão sendo comprometidas pelas atividades humanas. A incorporação das APPs em avaliações de fragilidade ambiental é estratégica para identificar conflitos entre

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uso do solo e áreas legalmente protegidas. Utilizando Sistemas de Informação Geográfica (SIG), este estudo propõe uma metodologia que integra dados de cobertura e uso do solo com limites das APPs para gerar uma camada de fragilidade ambiental, utilizando o município de Lorena-SP como estudo de caso. O método aplica sobreposição e atribui diferentes níveis de fragilidade às classes de cobertura e uso do solo de acordo com sua ocorrência dentro ou fora das APPs hídricas. A aplicação da metodologia em Lorena mostrou que mais de 60% das APPs hídricas estão ocupadas por pastagens e mosaicos de uso, resultando em áreas de alta fragilidade distribuídas difusamente. APPs associadas a áreas urbanas, afloramentos rochosos e áreas não vegetadas concentraram a fragilidade muito alta (0,2% do território), principalmente na região central. Esses padrões são impulsionados pela impermeabilização do solo e ocupação consolidada. A análise integrada possibilitou uma classificação de fragilidade mais refinada que avaliações baseadas apenas em cobertura e uso do solo. A metodologia proposta identificou de forma eficaz as sobreposições entre usos antrópicos e áreas legalmente protegidas, fornecendo um diagnóstico de fragilidade ambiental consistente com referenciais ecológicos e regulatórios. Ela representa uma ferramenta robusta e replicável de gestão ambiental, apoiando planejamento territorial, identificação de áreas prioritárias e conservação dos recursos naturais em diferentes contextos.

Palavras-chave: cobertura e uso do solo, planejamento ambiental, sistemas de informação geográfica.

1. INTRODUCTION

Permanent Preservation Areas (PPAs) constitute one of the main instruments of Brazilian environmental policy aimed at protecting environmentally fragile ecosystems. Their roles include preservation of watercourses, geomorphological stability, and biodiversity (Ruas *et al.*, 2025). According to Brazilian legislation, a PPA is a protected area, whether covered or not by native vegetation, with the environmental function of preserving water resources, landscapes, geological stability, and biodiversity, facilitating gene flow for fauna and flora, protecting soil, and ensuring the well-being of human populations (Brasil, 2012). In this study, the focus is on PPAs associated with watercourses, springs, and seeps, hereafter referred to as water-related PPAs.

Despite their ecological relevance and legal protection established by Federal Law No. 12,651 of May 25, 2012 – the Native Vegetation Protection Law – PPAs have been subjected to continuous degradation processes driven by the intensification of anthropogenic pressures (Machado Júnior and Machado, 2025; Kraeski *et al.*, 2023). This degradation is evidenced by the disordered urban expansion that disregards watercourse boundaries, leading to native vegetation suppression and reduced environmental quality in water-related PPAs (Vasconcelos *et al.*, 2021). In addition, the expansion of agricultural activities and managed pastures over native vegetation between 2018 and 2020 has further intensified pressures on these areas (IBGE, 2021).

Within this context, incorporating PPAs into environmental fragility assessments is essential, as the conservation of riparian vegetation along watercourses and around springs plays a key role in reducing ecosystem vulnerability to human pressures (Jeong *et al.*, 2025; Martins *et al.*, 2021). Environmental fragility refers to the vulnerability of ecosystems to disturbances that alter their dynamic equilibrium, based on intrinsic and extrinsic characteristics (Anjinho *et al.*, 2021). Therefore, analyzing the spatial distribution of land use and land cover in conjunction with legally defined PPA boundaries constitutes a strategic management tool, as it enables the identification of priority areas for protection, restoration, and monitoring, contributing to preventive planning and impact mitigation (Moura *et al.*, 2017; Paula *et al.*, 2021).

To facilitate this process, advances in geotechnologies have significantly expanded the potential for integrating environmental data in spatial analyses. In this regard, Geographic Information Systems (GIS) have become prominent tools, enabling the overlay of multiple variables and supporting a systemic understanding of environmental components in complex decision-making scenarios (Ribeiro and Longaray, 2025). Integrated analyses of environmental variables allow diagnoses at different hierarchical scales, and several studies have demonstrated the effectiveness of data overlay techniques in developing environmental fragility maps (Lira *et al.*, 2022; Ferreira *et al.*, 2022; Djabri *et al.*, 2023).

Land use and land cover is among the most frequently applied variables in environmental fragility assessments, often combined with multicriteria decision-making methods such as Analytic Hierarchy Process (AHP) and fuzzy logic (Amorim *et al.*, 2021; Campos *et al.*, 2021; 2023; Anjinho *et al.*, 2022; Oliveira and Nunes, 2022; Shekar and Mathew, 2023). However, these approaches generally do not incorporate PPAs as a specific analytical variable, despite their ecological relevance and legal status. When included, PPAs are often represented only by their legally delimited extent, without accounting for their conservation or degradation condition, which limits the accurate representation of their environmental susceptibility.

The present study proposes a methodology that integrates land use and land cover data with PPA delimitation to generate a thematic layer for multicriteria-based environmental fragility mapping. The novelty of this approach lies in explicitly incorporating PPAs into environmental fragility analyses by assigning distinct fragility values to land use and land cover classes located inside and outside PPAs, acknowledging their greater ecological sensitivity and the importance of vegetation cover. By doing so, this study seeks to enhance diagnostic capacity and provide technical support for environmental and territorial planning, contributing to conservation strategies and the prevention of environmental impacts in areas subject to intense anthropogenic pressure.

2. MATERIAL AND METHODS

For the development of the methodological proposal integrating Permanent Preservation Areas (PPAs) and land use and land cover (LULC), the municipality of Lorena, located in the state of São Paulo, Brazil, was selected as the study area. This choice was motivated by the diversity of LULC patterns present in the municipality - including consolidated urban areas, productive rural zones, and natural remnants - as well as by the variety of hydrological contexts, such as watercourses of different orders and distinct riparian environments. In addition, the availability of geospatial data enables the testing and validation of the proposed methodology under real-world conditions.

Although applied to a specific study area, the methodological proposal has strong potential for replication across the Brazilian territory within the scope of Federal Law No. 12,651/2012, which regulates PPAs. Furthermore, it is adaptable to water resources protection contexts in other countries, as vegetation buffer width is widely used as a reference for conservation and regulatory policies worldwide (Brumberg *et al.*, 2021).

The following sections describe the study area and the procedures adopted for data acquisition and map production.

2.1. Study area

Lorena is located in the Metropolitan Region of the Paraíba Valley and North Coast, in southeastern São Paulo State (Figure 1). The municipality covers an area of 414.16 km² and had an estimated population of 87,468 inhabitants in 2025 (IBGE, 2025). From a physical perspective, Lorena has an average altitude of 524 m and is characterized by a highland tropical climate (Cwb), according to the Köppen classification (Lorena, 2022). The relief consists predominantly of alluvial plains associated with the Paraíba Valley, interspersed with hills and mounds, forming landscapes susceptible to erosion and flooding processes (IPT, 2015).

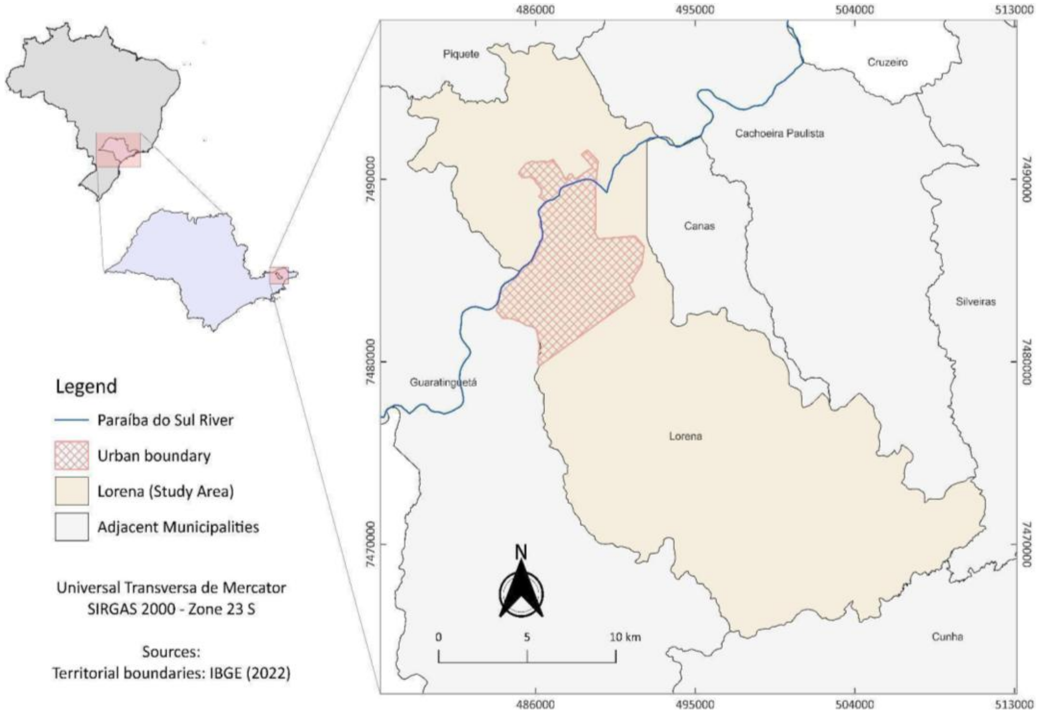


Figure 1. Location of the municipality of Lorena.

From a water resources management perspective, Lorena belongs to the Paraíba do Sul Water Resources Management Unit (UGRHI 2), one of the most strategic units in São Paulo State due to its role in urban water supply and the maintenance of large-scale economic activities (REGEA, 2025). UGRHI 2 has experienced significant LULC transformations driven by successive economic cycles, hydrological interventions, and anthropogenic expansion (Paiva *et al.*, 2020).

Economically, the service sector accounts for the largest share of the municipal Gross Domestic Product (GDP), followed by industry and livestock production (IBGE, 2021). This productive structure generates different pressures on the territory, primarily associated with urban expansion and intensive land use in rural areas (Devide *et al.*, 2014). Given that the municipality is situated in a physically susceptible environment with respect to erosive processes and recurrent hydrological events, these dynamics intensify environmental fragility (CPRM, 2018). Consequently, the area exhibits degradation of springs, irregular occupation of PPAs, and recurrent flooding and waterlogging events, characterizing a typical scenario of conflict between land use and environmental conservation (Bargos *et al.*, 2017; Coutinho *et al.*, 2018; IPT, 2015).

2.2. Data acquisition and base map preparation

Data acquisition was carried out using thematic information obtained from open-access and open-source databases. The datasets were organized into distinct information layers and processed in a GIS environment using QGIS software, version 3.34.11 (Prizren).

The LULC map was generated using MapBiomas data (Collection 7.1, 2024), derived from Sentinel-2 satellite imagery with a spatial resolution of 10 m, for the year 2022. This resolution enabled detailed identification of riparian vegetation along streams and springs, which is a key aspect for PPA analyses.

The delimitation of water-related PPAs was based on products provided by the Brazilian Foundation for Sustainable Development (Fundação Brasileira para o Desenvolvimento

Sustentável - FBDS), whose cartographic base was constructed through supervised classification and vectorization of high-resolution imagery, encompassing hydrography and associated PPAs (FBDS, 2024). In this study, PPAs associated with watercourses, springs, and seeps were considered in accordance with Article 4 of Federal Law No. 12,651/2012, disregarding specific rules for consolidated use in PPA areas, as established in the adopted database. Marginal buffer strips of perennial and intermittent watercourses, in both rural and urban areas, were defined based on regular riverbed width, with minimum widths of: (a) 30 m for watercourses up to 10 m wide; (b) 50 m for watercourses between 10 and 50 m wide; and (c) 100 m for watercourses between 50 and 200 m wide (Brasil, 2012).

To ensure spatial compatibility and cartographic consistency, all datasets were reprojected to the SIRGAS 2000 datum using the Universal Transverse Mercator (UTM) coordinate reference system, Zone 23 South.

2.3. Determination of fragility intensity levels and final map generation

Environmental fragility was represented using five intensity levels (very low, low, medium, high, and very high), distributed along a numerical scale ranging from 0 to 1. The adopted numerical scale was conceptually based on the environmental fragility framework proposed by Ross (1994) and on subsequent methodological adaptations by Anjinho *et al.* (2021) and Lira *et al.* (2021). Within this range, the fragility values assigned to each land use and land cover (LULC) class were defined by the authors according to the relative degree of anthropogenic disturbance and the expected capacity of each class to maintain key ecological functions, including soil protection, hydrological regulation, and biodiversity conservation. For instance, forest formations were assigned lower fragility values than urban areas because of their greater capacity to sustain ecological functions. Coupled with this interpretation, areas located within PPA (present) were assigned higher fragility values than those outside PPA (absent), reflecting their intrinsically greater environmental sensitivity and the legal protection established to ensure the conservation of their ecological functions. Consequently, values approaching 0 represent lower environmental susceptibility, whereas values approaching 1 indicate higher environmental fragility.

The environmental fragility map for the PPA theme was developed by integrating the LULC map with the spatial delimitation of water-related PPAs. Distinct fragility values were assigned to LULC classes depending on whether they were located inside or outside PPA boundaries. This differentiation was justified by the intrinsic ecological sensitivity of PPAs, which play a critical role in environmental regulation and water resource maintenance. Degradation within these areas tends to intensify local environmental imbalances, such as erosion, flooding, and droughts. Considering both their ecological function and the legal requirement that PPAs be preferably covered by native vegetation, as established by Federal Law No. 12,651/2012, higher fragility values were attributed to LULC classes located within PPAs compared to the same classes outside these areas (Table 1). Conversely, areas characterized by less anthropized land use and cover were assigned lower fragility values, reflecting their greater capacity to maintain ecosystem functions and environmental balance.

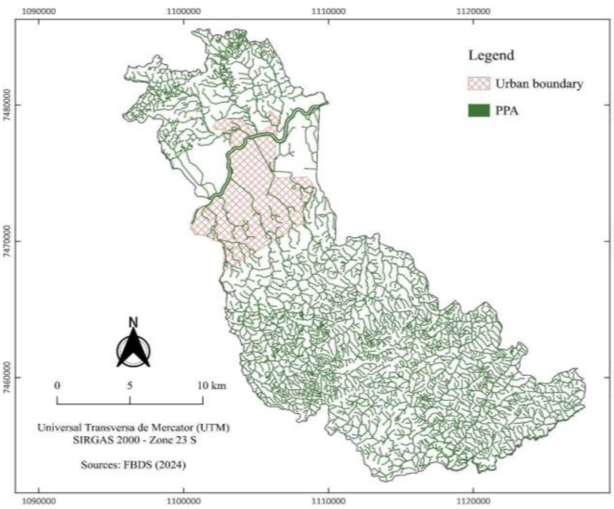
Table 1. Environmental fragility classes of the PPA theme.

PPA	LULC classes	Fragility degree	Values
Absent	Forest formation/ Forest plantation/ Wetlands	Very low	0.2
Absent	Pasture / Mosaic of uses	Low	0.4
Absent	Urban area / Rock outcrop / Other non-vegetated areas	Medium	0.6
Present	Forest formation/Forest plantation/ Wetlands	Medium	0.6
Present	Pasture / Mosaic of uses	High	0.8
Present	Urban area / Rock outcrop / Other non-vegetated areas	Very high	1.0

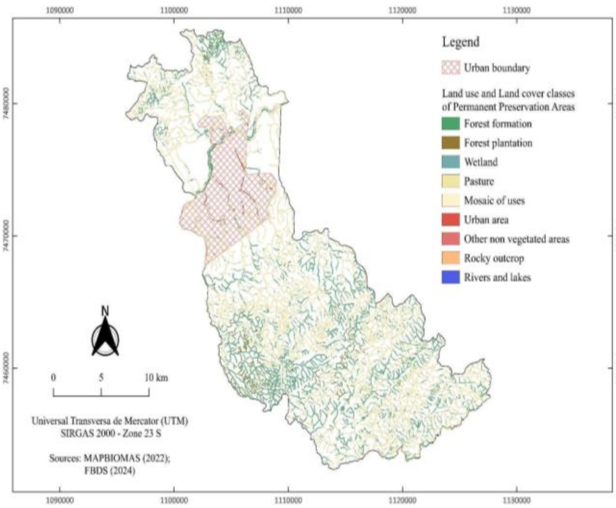
To operationalize the proposed method, the LULC map, originally in raster format, was converted to vector format to ensure compatibility with the PPA delimitation map. Fragility values were assigned by creating specific attribute fields according to the LULC classes (Table 2). In an initial stage, integer values were used to distinguish classes with identical fragility weights but located in different contexts. For example, “Urban area / Rock outcrop / Other non-vegetated areas” outside PPAs and “Forest formation/ Forest plantation/ Wetlands” inside PPAs, both assigned a value of 0.60. This procedure prevented the QGIS dissolve tool from merging heterogeneous categories. After spatial aggregation, the vector dataset was converted back to raster format and reclassified to restore the decimal fragility indices (Table 1) using the r.recode algorithm in QGIS.

3. RESULTS AND DISCUSSION

In the municipality of Lorena, water-related PPAs (Figure 2a) account for 23.3% of the total territory. The predominant category corresponds to 30 m buffer strips along watercourses, which represent 79.38% of the total PPA area. PPAs associated with springs, defined by a 50 m radius, represent 16.38% of the delimited area (Table 2).



(a)



(b)

Figure 2. Municipality of Lorena - (a) water-related PPAs and (b) land use and land cover classes within water-related PPAs.

Table 2. Comparison of areas corresponding to different water-related PPA widths in the study area.

Hydrography	PPA width (m)	PPA area (km²)	PPA area (%)
Springs	50 (radius)	15.778	16.38
Watercourses (0-10 m)	30	76.482	79.38
Watercourses (10-50 m)	50	1.158	1.20
Watercourses (50-100 m)	100	2.931	3.04
Total		96.349	100.00

Independently, the analysis of LULC within PPA boundaries (Figure 2b) revealed strong anthropogenic pressure, mainly from pastures (34.05% of the area) and mosaic of uses (28.75%). Together, these classes account for more than 60.00% of PPA areas occupied by land uses that conflict with environmental legislation, which requires preferential coverage by native vegetation, represented here by the forest formation class. Although forest formations still occupy 32.34% of the PPAs, this proportion alone does not ensure the ecological integrity of local ecosystems (Table 3).

Table 3. Areas of land use and land cover classes within water-related PPAs in the municipality of Lorena.

LULC classes of PPAs	Area (km²)	Area (%)
Pasture	32.822	34.05
Forest formation	31.176	32.34
Mosaic of uses*	27.714	28.75
Forest plantation	3.550	3.68
Urban areas	0.820	0.85
River and lakes	0.255	0.26
Rocky outcrop	0.032	0.03
Other non-vegetated areas	0.015	0.02
Wetlands	0.016	0.02

*Agricultural areas where it was not possible to distinguish between pasture and agriculture.

PPAs occupied by pastures and mosaic of uses were classified as high environmental fragility, resulting in 14.63% of the municipal territory falling into this category and being diffusely distributed throughout the municipality. In contrast, PPAs associated with urban areas, rocky outcrops, and other non-vegetated areas were concentrated in the central portion of the municipality. In these areas, intense soil sealing and consolidated occupation led to classification as very high fragility, corresponding to 0.21% of the municipal area (Figure 3 and Table 4).

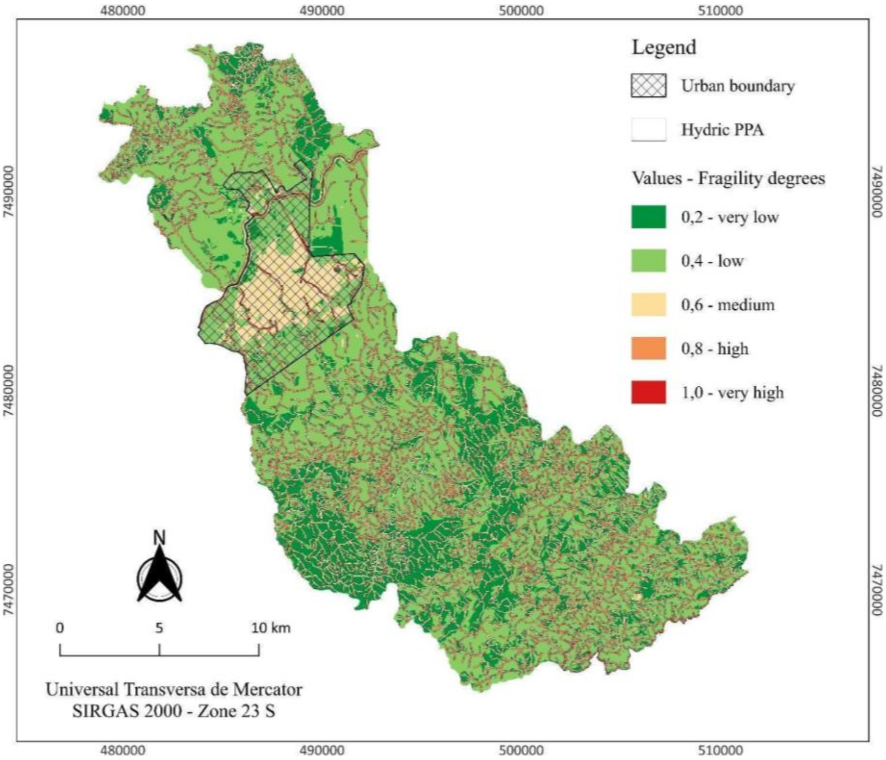


Figure 3. Environmental fragility map derived from the overlap between water-related PPA delimitations and land use and land cover.

Table 4. Areas of environmental fragility classes based on the presence or absence of PPAs and land use and land cover in the municipality of Lorena.

PPA	LULC classes	Area (km²)	Area (%)	Fragility degree	Fragility degree area (%)
Absent	Forest formation/Forest plantation/ Wetlands/Rivers	83.940	20.27	0.2 (Very low)	20.27
Absent	Pasture/Mosaic of uses*	216.420	52.25	0.4 (Low)	52.25
Absent	Urban area/Rocky outcrop/ Others non-vegetated areas	17.340	4.19	0.6 (Medium)	12.64
Present	Forest formation/Forest plantation/Wetlands/ Rivers	35.020	8.45		
Present	Pasture/Mosaic of uses*	60.580	14.63	0.8 (High)	14.63
Present	Urban area/Rocky outcrop/ Others non-vegetated areas	0.860	0.21	1.0 (Very high)	0.21
	Total	414.160	100.00	-	100.00

*Agricultural areas where it was not possible to distinguish between pasture and agriculture.

The pressure exerted by pastures and mosaic of uses within PPAs reflects patterns widely reported in different Brazilian river basins, where agricultural expansion advances over legally protected areas, reducing ecological connectivity and compromising ecosystem services such as water regulation and biodiversity conservation (Pereira *et al.*, 2023).

The literature consistently highlights the importance of continuous riparian vegetation corridors for maintaining hydrological dynamics, geomorphological stability, and biodiversity connectivity (Monteiro *et al.*, 2016; Prado *et al.*, 2022). In this context, the fragmentation observed in Lorena undermines these functions and intensifies degradation processes.

The results also reveal the coexistence of distinct dynamics associated with the highest fragility levels. In rural areas, high fragility is mainly related to soil degradation, intensified erosive processes, deterioration of river water quality due to diffuse agricultural pollution, and reduced water regulation capacity. In urban areas, very high fragility is predominantly associated with flood risk, socio-environmental disasters, and water quality degradation caused by point-source and urban diffuse pollution.

The integration of LULC data with PPA delimitation proved essential for environmental fragility assessment. An isolated analysis of LCLC would merely depict the spatial distribution of anthropogenic activities and vegetation cover. In contrast, the overlap with water-related PPA boundaries highlighted conflicts between land occupation and environmental legislation and enabled the reclassification of environmental fragility levels.

This approach not only allowed the identification of agricultural and urban land uses within legally protected areas but also enabled the attribution of differentiated fragility levels to identical LULC classes depending on whether they were located inside or outside PPAs. For example, pastures located outside PPAs were classified as low fragility, whereas those occurring within PPAs were assigned high fragility. This differentiation resulted in an environmental diagnosis more closely aligned with ecological and regulatory realities, reinforcing the proposed methodology as a valuable tool for supporting environmental management and planning.

Finally, the PPA-themed fragility map generated in this study can be incorporated as one layer within broader multicriteria analyses that integrate additional variables such as relief, soil characteristics, climatic factors, and water resources. In this sense, it provides a robust technical basis for environmental zoning, the definition of preservation and restricted-use areas, the identification of zones with restoration potential, and the support of preventive actions in regions that are more vulnerable to environmental degradation and water-related impacts.

4. CONCLUSION

The integration of a PPA-specific layer into environmental fragility mapping, combining LULC data with legally defined spatial boundaries, represents a robust technical instrument and a relevant methodological contribution to territorial management and planning. By assigning differentiated fragility levels to identical land-use classes according to their occurrence inside or outside protected areas, the proposed approach strengthens the analytical consistency of the assessment and clearly exposes conflicts between current occupation patterns and environmental protection requirements. The application of this method to the municipality of Lorena demonstrated its effectiveness in identifying priority areas for restoration, conservation, and monitoring. Moreover, its structure allows for straightforward replication in other regions, offering a strategic cartographic basis to support environmental planning and decision-making processes, particularly in landscapes subject to intense anthropogenic pressure.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

6. ACKNOWLEDGMENTS

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