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MAPPING THE ENVIRONMENTAL VULNERABILITY OF A LAGOON USING FUZZY LOGIC AND THE AHP METHOD.

Dissertation presented to the Graduate Program in Forest Sciences of the Center for Agricultural Sciences and Engineering of the Federal University of Espírito Santo as part of the requirements for obtaining the Master's Degree in Forest Sciences in the Forest Sciences Concentration Area.
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MAPPING THE ENVIRONMENTAL VULNERABILITY OF A LAGOON USING FUZZY LOGIC AND AHP METHOD

Clebson Pautz

Dissertação apresentada ao Programa de Pós-Graduação em Ciências Florestais do Centro de Ciências Agrárias e Engenharias da Universidade Federal do Espírito Santo, como parte das exigências para obtenção do Título de Mestre em Ciências Florestais na Área de Concentração Ciências Florestais.

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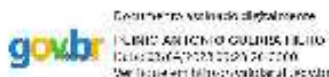
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ABSTRACT

PAUTZ, Clebson, Dissertation (Master's degree in Forest Sciences), Federal University of estate of Espírito Santo, March 2023. **Mapping the environmental vulnerability of a lagoon using fuzzy logic and the AHP method.** Adviser: Prof. Dr. Alexandre Rosa dos Santos.

Environmental vulnerability refers to the susceptibility of a region to damage when it is subjected to natural or anthropogenic actions. The assessment of environmental vulnerability in lakes is an important tool to assist managers in planning and intervening for sustainable production and environmental preservation. The combination of geotechnologies, fuzzy logic and the Analytic Hierarchy Process (AHP) has been applied by professionals and researchers to improve work and research in various areas and environments. In this context, the objective of this work was to map the environmental vulnerability of a lake and its surroundings through fuzzy logic and the AHP method. The study area comprises the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil. A survey of the physical characteristics of the watershed (drainage surface) that feeds the Juparanã lagoon was carried out and also of the use and land cover of this surface. To achieve the proposed objectives, the following methodological steps were implemented: a) delimitation of watersheds, b) spatialization of Permanent Preservation Areas (APP) based on the Brazilian Forestry Code (Law nº 12,651/2012), c) application of logic fuzzy and AHP to spatialize the environmental vulnerability, and d) apply the evaluation of environmental vulnerability to the Preservation Areas (APP). Environmental vulnerability was modeled using Euclidean distance analysis, fuzzy logic and the AHP method, as proposed by Saaty (1977). For the development of the work, geotechnologies were used, with special emphasis on the use of the free software QGIS. The analysis revealed that 31.20%, 32.86% and 20.93% of the JLDS have very high, high and medium vulnerability, respectively. The evaluation of environmental vulnerability of the APP showed that there is protection in the APP of the JLDS at rates of 47.35%, 34.05% and 14.5% for very high, high and medium vulnerability classes, respectively. The difficulties encountered were related to the lack of studies in the area of environmental vulnerability with a particular focus on lagoons. Here, for the first time, we perform a photointerpretation of the surroundings of Juparanã lagoon. An important improvement measure would be the application of a temporal analysis to assess the dynamics of environmental vulnerability over time, considering socioeconomic, climatic, and environmental changes. This would provide a more complete understanding of the distribution of environmental vulnerability in the study area. The methodology can be adapted to consider different scales of analysis, from local to regional, national and global scales, to assess environmental vulnerability at various levels of scope and complexity. It can also be adapted to include local communities and governments.

RESUMO

PAUTZ, Clebson. Dissertação (Mestrado em Ciências Florestais), Universidade Federal do Espírito Santo, março de 2023. **Mapeamento da Vulnerabilidade Ambiental de uma Lagoa usando Lógica Fuzzy e Método AHP.** Orientador: Prof. Dr. Alexandre Rosa dos Santos.

A vulnerabilidade ambiental refere-se à suscetibilidade de uma região a danos quando ela é submetida à ação natural ou antrópica. A avaliação da vulnerabilidade ambiental em lagos é uma importante ferramenta para auxiliar os gestores no planejamento e intervenção para produção sustentável e preservação ambiental. A combinação de geotecnologias, lógica fuzzy e *Analytic Hierarchy Process* (AHP) vem sendo aplicada por profissionais e pesquisadores, contribuindo para a realização trabalhos e pesquisas em diversas áreas e ambientes. Nesse contexto, o objetivo deste trabalho foi mapear a vulnerabilidade ambiental de uma lagoa e seu entorno por meio da lógica fuzzy e o método AHP. A área de estudo compreende a Superfície de Drenagem da Lagoa Juparanã (SDLJ), estado do Espírito Santo, Brasil. A pesquisa foi realizada com base nas características físicas da bacia hidrográfica (Superfície de Drenagem) que alimenta a lagoa Juparanã e no uso e cobertura da terra dessa superfície. Para atingir os objetivos propostos, foram implementadas as seguintes etapas metodológicas: a) Delimitação das bacias hidrográficas, b) Espacialização das Áreas de Preservação Permanente (APP) com base no Código Florestal Brasileiro (Lei nº 12.651/2012), c) Aplicação da lógica fuzzy e o método AHP para espacializar a vulnerabilidade ambiental e d) Confrontar as Áreas de Preservação Permanente (APP) com a vulnerabilidade ambiental. A vulnerabilidade ambiental foi modelada usando análise de distância euclidiana, lógica fuzzy e o método AHP, proposto por Saaty, em 1977. Para o desenvolvimento do trabalho foram utilizados geotecnologias, com especial destaque para a utilização do software livre QGIS. A análise revelou que 31,20%, 32,86% e 20,93% da SDLJ possui vulnerabilidade muito alta, alta e moderada, respectivamente. O confronto das APP com a vulnerabilidade ambiental evidenciou que há uma fragilidade na APP da SDLJ, com predomínio de 47,35%, 34,05% e 14,5% para classes de vulnerabilidade muito alta, alta e moderada, respectivamente. As dificuldades encontradas dizem respeito à ausência de trabalhos na área de vulnerabilidade ambiental, principalmente abordando lagoas. A fotointerpretação do entorno da lagoa Juparanã é inédita. Uma medida importante de melhoria seria a aplicação de uma análise temporal, para avaliar a dinâmica da vulnerabilidade ambiental ao longo do tempo, considerando as mudanças socioeconômicas, climáticas e ambientais, para uma compreensão mais completa da distribuição da

vulnerabilidade ambiental na área de estudo. A metodologia pode ser adaptada para considerar diferentes escalas de análise, desde escala local, regional, nacional ou global, para avaliar a vulnerabilidade ambiental em diferentes níveis de abrangência e complexidade, além da inclusão de comunidades locais e governos.

Palavras-chave: geotecnologias; área de preservação permanente; bacia hidrográfica; função de pertinência; ambientes lacustres; massa dágua.

LIST OF ILLUSTRATIONS

LIST OF TABLES

SUMMARY

1. INTRODUCTION

Lakes, ponds and lagoons are bodies of water of different sizes. The first two are continental, with lakes being larger than ponds. The third type, represented by lagoons, are depressions filled with brackish or salty water that are located on coastal edges and communicate with the sea through a channel. The three are extremely complex, both from the point of view of contamination and the composition and volume of their waters (GOMES *et al.*, 2011).

Over the decades, human activities in coastal lagoons have had a significant impact on their ecology and valuable ecosystem services. Basic biological and physiological needs, such as food and shelter, social status and occupation, financial self-sufficiency, and self-realization drive activities such as fishing, agriculture, expansion of settlements, mining, mangrove harvesting, and industries, among others. These activities have altered lagoon environments, contributing to the predation of fish and mangrove species, the introduction of heavy metals, organic materials, nutrients and pathogens, decreasing oxygen levels, increasing biochemical oxygen demand, and reducing biodiversity and lagoon areas (TAKYI *et al.*, 2022). Aquatic ecosystems are commonly used by populations to obtain food for their own survival or that of their dependents who live further away. This explains the occupation and use of their surroundings for a series of actions and activities essential to human life. These uses and occupations have their limits, notably due to the environmental vulnerability of such ecosystems (ASSIS *et al.*,2013).

The region of the lower Doce River (Espirito Santo state) has about 90 lakes, which correspond to a total area of 165 km², representing one of the most important coastal lake systems in Brazil (BARROSO, 2007). The lagoons of the Baixo Rio Doce (ES) originate from ancient estuarine sediments that are influenced by oceanic and fluvial processes and are often embedded in large valleys, such as Lake Juparana, or are remnants of large and ancient coastal lagoons (SUGUIO *et al.* 1982).

Juparanã Lagoon covers the municipalities of Rio Bananal, Sooretama and Linhares, the latter having legal jurisdiction over most of its territory. The lagoon has an approximate area of 68.58 km² and a perimeter of 89.50 km. It is 38 km long, 5 to 7 km wide and has an average depth of 13 m. Its main tributary is the São José River. It is the largest lagoon in Espírito Santo, the second largest in terms of land area, and the largest in terms of fresh water volume in Brazil (GONÇALVES, 2005).

In recent decades, the Juparanã lagoon has been subjected to a series of anthropic impacts, silting and disorderly occupation of its surroundings, both for real estate development (urbanization) and agricultural purposes (GONÇALVES, 2005; CAVATI, 2008). Anthropogenic activities such as industrial and urban discharges, agriculture, coastal landfills, heavy traffic, naval activity, and atmospheric accumulation directly contribute to the increase in toxic metals and sediment in the water column and cause pollution in marine ecosystems (EL OUATY *et al.*, 2022).

Agricultural activities, when practised in an intensive manner, can disrupt the dynamic balance of the physical environment, with the main consequence being deforestation that is related to the historical context and occupation of the Brazilian territory and the predatory exploitation of natural resources (RIBEIRO *et al.*, 2005).

With the intention of mitigating impacts and limiting anthropic action on natural resources, the Brazilian Forest Code, under Law 12,651 from 05/25/2012 (BRASIL, 2012), provides protection of native vegetation, while allowing forest exploitation and the supply of forest raw materials, with regulation of the origin of forest products. It also regulates the control and prevention of forest fires, and provides economic and financial instruments to achieve its objectives. It also establishes strips of vegetation around water bodies and springs as permanent reserves. Permanent Preservation Areas (APP) are protected areas, covered or uncovered by native vegetation, whose environmental function is to protect water resources, landscapes, geological stability, and biodiversity, promote gene flow in plants and, animals, protect soils and ensure the well-being of the population (BRASIL, 2012).

Despite being recognized as an APP, according to the Forest Code, many are vulnerable, in situations of disrespect for current legislation, being exploited for various purposes. Therefore, understanding the level of environmental vulnerability in a given area is a requirement to implement effective environmental planning and prevent environmental disasters (RIBEIRO *et al.*, 2016).

Understanding land use is very important in environmental research, as it directly affects its natural properties, physical, chemical, and biological aspects. Land use can be understood as a set of information related to the classification of land uses on the earth's surface that constantly changes under the influence of various factors. However, as the occupation and change of the earth's surface evolve, so do the means of recording and identifying these processes, especially through Remote Sensing tools and Geographic Information Systems (SIG) (IBGE, 2022).

In recent decades, technology has become popular and geotechnologies stand out in the implementation of research and monitoring activities in different types of environments and areas. Geotechnologies are a set of techniques to collect, process, analyze and disseminate georeferenced information through computational tools that accurately assess processes that cause environmental impacts (SANTOS, 2017). The geotechnologies stand out: geographic information systems, digital cartography, remote sensing, global positioning system, and topography (ROSA, 2005).

The use of geotechnologies has provided methodological support for technical and scientific production in several areas, with emphasis on environmental planning, and land cover and in the process of land cover identification (PELUZIO, 2010).

Geotechnologies make it possible to identify and establish control and direction of anthropic land use activities, and improve the production of various cartographic products, such as vulnerability maps, essential for the environmental diagnosis of an area (BIANCHINI, 2019). The vulnerability map results from a combination of different geographic information and includes a geographic inference process with multicriteria analysis. This type of analysis involves a set of decision alternatives based on different evaluation criteria (MALCZEWSKI, 2010).

Environmental vulnerability can be defined as the degree to which natural systems are vulnerable or unable to cope with the impact of external interactions which may come from natural or anthropogenic actions (AQUINO *et al.*, 2017). It is essential to establish methodologies to identify the occurrence of vulnerability, to understand how these changes and their consequences are attenuated or amplified by different human and environmental conditions, as well as to identify what can be applied to reduce environmental vulnerability to change and as a society is more resilient and adaptable can be built (TURNER et al., 2003).

Understanding the areas and the dynamics in which environmental vulnerability occurs in land use and land cover units is essential to support studies regarding the assessment of the ecosystem's environmental vulnerability. In this context, applying geotechnology tools associated with Fuzzy Logic and the Analytic Hierarchy Process (AHP) multicriteria analysis method becomes fundamental for developing work that addresses the theme of environmental vulnerability.

Fuzzy modeling, or fuzzy logic, has the ability to convert the qualitative variables of an object of study into quantitative variables, providing a more detailed and less subjective analysis of the results. Fuzzy logic was used in this study to describe environmental characteristics more comprehensively. This artificial intelligence technique has been used in

several studies and environmental documents that help in decision-making, due to the possibility of precise aggregation of data inherent to classic mathematical models and the inaccuracies of the real world. Fuzzy logic is used to standardize the criteria on a scale of 0 to 1, with values close to 0 considered the least fair and values close to 1 the most favorable (PELUZIO, 2017).

The Analytic Hierarchy Process (AHP) multicriteria analysis method developed by Thomas L. Saaty was used to support the study. AHP is a selection method based on pairwise comparisons and a predefined scale to express the importance of one criterion over another concerning to decision-making. Addresses the level of consistency in calculations and can be applied to quantitative or qualitative data(SAATY, 1987).

The combination of fuzzy logic, the AHP method, and geotechnologies can be a promising tool for analyzing the environmental vulnerability of a pond, considering its drainage surface (LIRA *et al*., 2022).

In the works of Parsian *et al*. (2021) it is Madhu *et al*. (2021) recent research involving fuzzy logic, the AHP method, and geographic data used to map flood risk and classify environmental fragility in a watershed. They work similarly to this research, as the environmental protector is related to environments at risk, and represents the environment's vulnerability when suffering complications, encompassing erosive processes, silting and flooding(SPÖRL, 2007). Lira *et al*. (2022), in surveys classify environmental fragility in watersheds, they also used fuzzy logic and the AHP method. As study methodologies, the authors found satisfactory results in their studies. Research on typical estuarine and coastal ports obtained significant results by analyzing the essential regularity and determining factors of their spatial expansion using remote sensing and geographic information system technology (*Li et al.,* 2022).

Environmental vulnerability mapping is a technique that consists of identifying and evaluating the factors that make a certain area or ecosystem susceptible to negative impacts resulting from human activities or natural events. It is an important management and territorial planning tool, allowing the protection of the environmental system to be measured and the development of mitigation measures to reduce negative impacts(LOPES, 2019).

In this context, the objective of this work is to describe and evaluate the effectiveness of a methodology based on fuzzy logic and the Analytic Hierarchy Process (AHP) method and the use of geotechnologies for mapping the environmental vulnerability of a lagoon and its surroundings.

2. MATERIALS AND METHODS

2.1. ESTUDY AREA

The study area comprises the Juparanã Lagoon, located in Espírito Santo state, Brazil, and its surroundings, named in this work as Juparanã Lagoon Drainage Surface (JLDS). It is located in the north of the state between parallels 19°13′44″and 19°23′16″S and meridians 40°13′09″and 40°04′16″ W (Figure 1). The area was defined from the selection of the 09 ottobasins of level 7, stretches of the drainage surface that faces the Juparanã lagoon, generated from the methodological steps presented in Figure 2. It has an area of 271.31 km², with approximately 35 km long and 08 km wide, covering the municipalities of Linhares, Rio Bananal, and Sooretama.

According to the Köppen climate classification, the study area of the Juparanã Lagoon Drainage Surface (JLDS) has an "Aw" climate, that is, a rainy tropical climate, with a dry season in winter. The average temperature of the coldest month is above 18 °C (SEKI et al., 2021).

The average annual rainfall is 1278.9 mm, seasonally divided into two periods. A rainy one, which comprises the months of October to April, with a total of 1019.9 mm, which corresponding to 79.8% of the accumulated annual total, and a less rainy period between the months of May to September, with a total of 258.3 mm, which corresponds to 20.2%. In addition, the average rainfall of the driest month is less than 60 mm (INCAPER, 2019). The predominant soil is an Oxisol, classified as a dystrophic red yellow Oxisol (LVd11 and LVd13), with a medium clayey texture, with a flat, gently undulating, and undulating relief (EMBRAPA, 1971).

The main economic activities in the JLDS are agriculture, and livestock, emphasizing on pasture, coffee production, eucalyptus and fish farming (INCAPER, 2019).
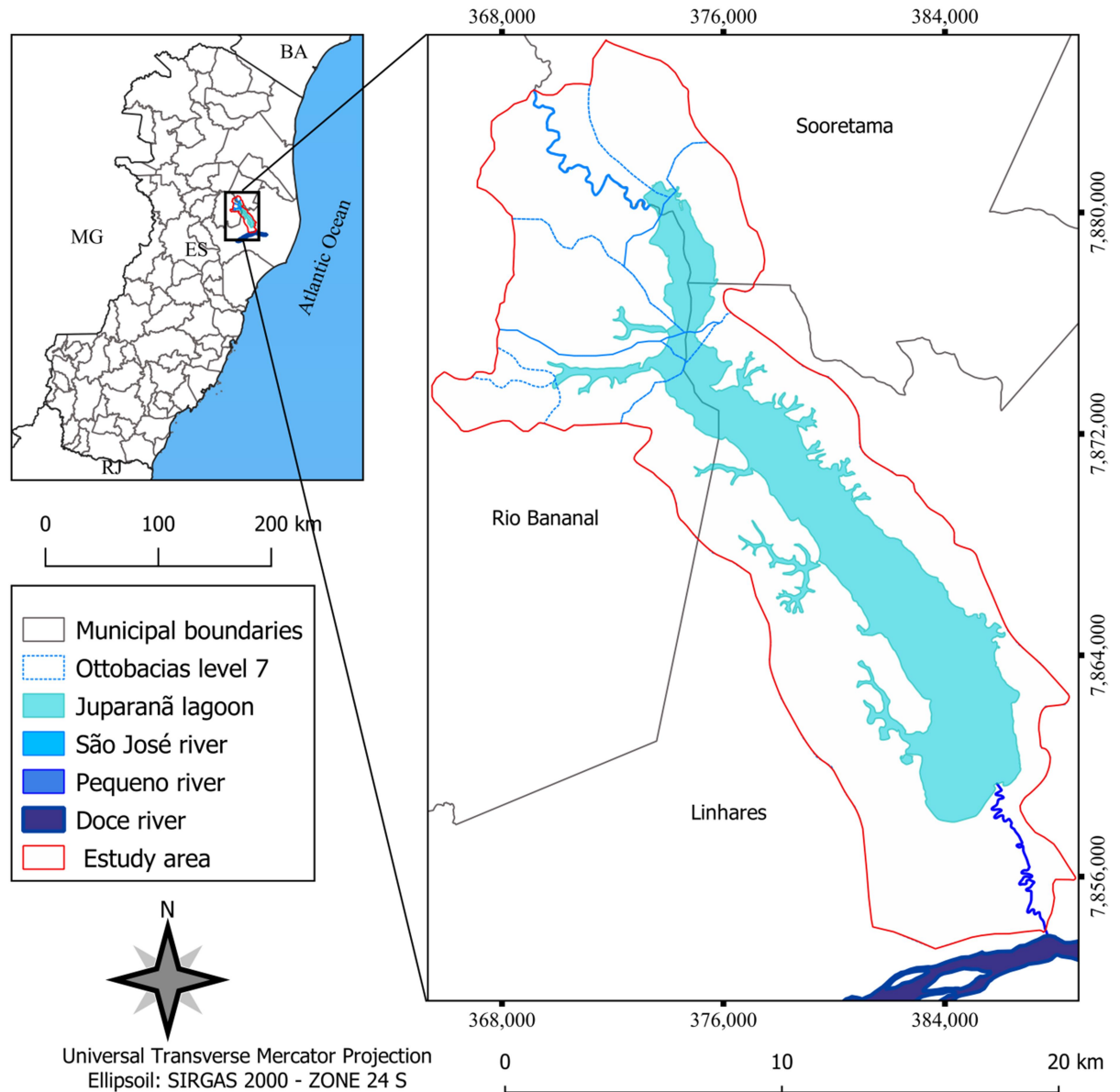
Figure 1. Geographical location of the Juparanã Lagoon Drainage Surface (JLDS), Espírito
Santo state, Brazil.

2.2. METHODOLOGICAL STEPS

The area was defined from the selection of the 09 ottobasins of level 7, stretches of the drainage surface that face the Juparanã lagoon, generated from the methodological steps developed in Figure 2.

2.2.1. Stage 01 – Delimitation of watersheds around Juparanã Lagoon, Espírito Santo state, Brazil

In order to apply the methodological steps adopted for the delimitation of watersheds for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil, the free software QGIS (version 3.22.10) was used, together with the complement SAGA-GIS (version 7.8.2) and other functions, as shown in Figure 2.

Initially, the acquisition of matrix images of the Digital Elevation Model (DEM) was carried out, with a spatial resolution of 30 m (1 arc-second), from the Shuttle Radar Topography Mission (SRTM) available on the United States Geological Survey website (https://earthexplorer.usgs.gov/ (accessed on 05 July 2021)) representative of the study area quadrant (SANTOS, 2020b).

Subsequently, the matrix images of the DEM were pre-processed for: the generation of the image mosaic, clipping of the images for the study area (JLDS), correction of negative values, filling of pixels without data, and removal of spurious depressions. After pre-processing the DEM, it was applied to the function "network of channels and drainage basins" to generate images of water flow direction (flow direction model D8), accumulated water flow water, hydrographic network, and delimitation of hydrographic basins.
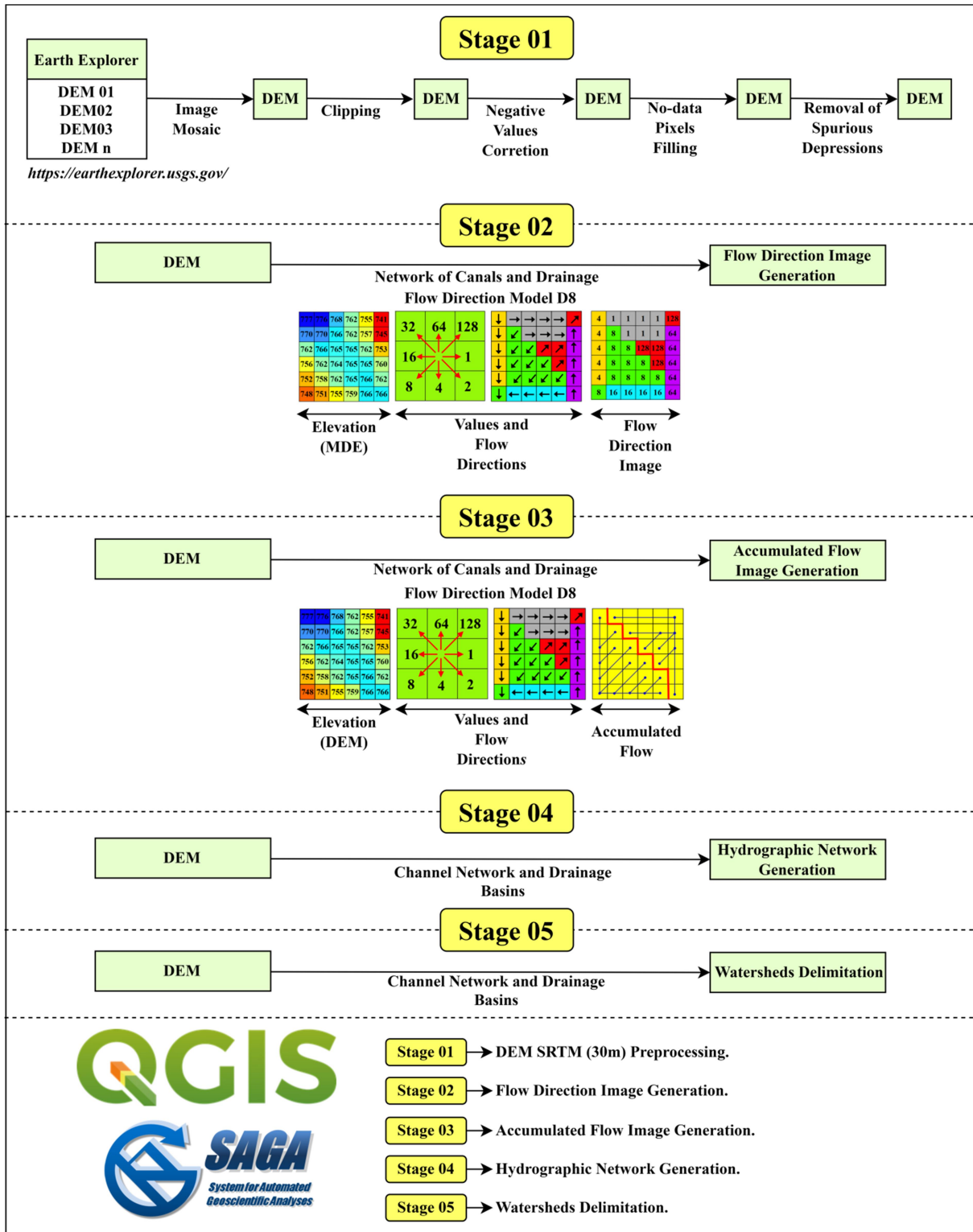
Figure 2. Methodological steps adopted for the delimitation of watersheds for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

2.2.2. Stage 02 – Spatialization of Permanent Preservation Areas (APP) based on the Brazilian Forest Code (Law nº. 12.651/2012) for the study area (JLDS)

The methodological steps for the spatialization of Permanent Preservation Areas (APP) based on the Brazilian Forest Code (Law nº. 12,651/2012) for the study area (JLDS) are shown in Figure 3.

All methodological steps were applied using the free QGIS application (version 3.22.10) and its complements and functions based on the methodology proposed by Peluzio *et al.* (2010), Peluzio *et al.* (2013), Santos *et al.* (2016), e Eugenio *et al.* (2017) .

2.2.3. Delimitation of the APP around the springs

At this stage, the vector file of points of springs, in shapefile format, of the study area (JLDS) was initially dissolved, using the "dissolution" function, with the objective of generating the point vector image of dissolved springs.

Subsequently, the "proximity analysis" function was applied, with a buffer of 50 m, having as input the point vector image of dissolved springs, with the final objective of generating the vector file of polygons representative of the APP of springs.

2.2.4. Delimitation of APPs along the marginal strip of watercourses

In this step, the vector file of hydrographic lines, in shapefile format, of the study area (JLDS) was initially dissolved, using the "dissolution" function, with the objective of generating the linear vector image of dissolved hydrography (PELUZIO *et al.*, 2010).

Subsequently, the "varied proximity analysis" function was applied, with buffers of 30 m (watercourses <10 m wide) and 50 m (watercourses between 10 and 50 m wide), having as input the linear vector image of dissolved hydrography, to generate the vector file of polygons representative of the APP along the marginal strip of watercourses (PELUZIO *et al.*, 2010).
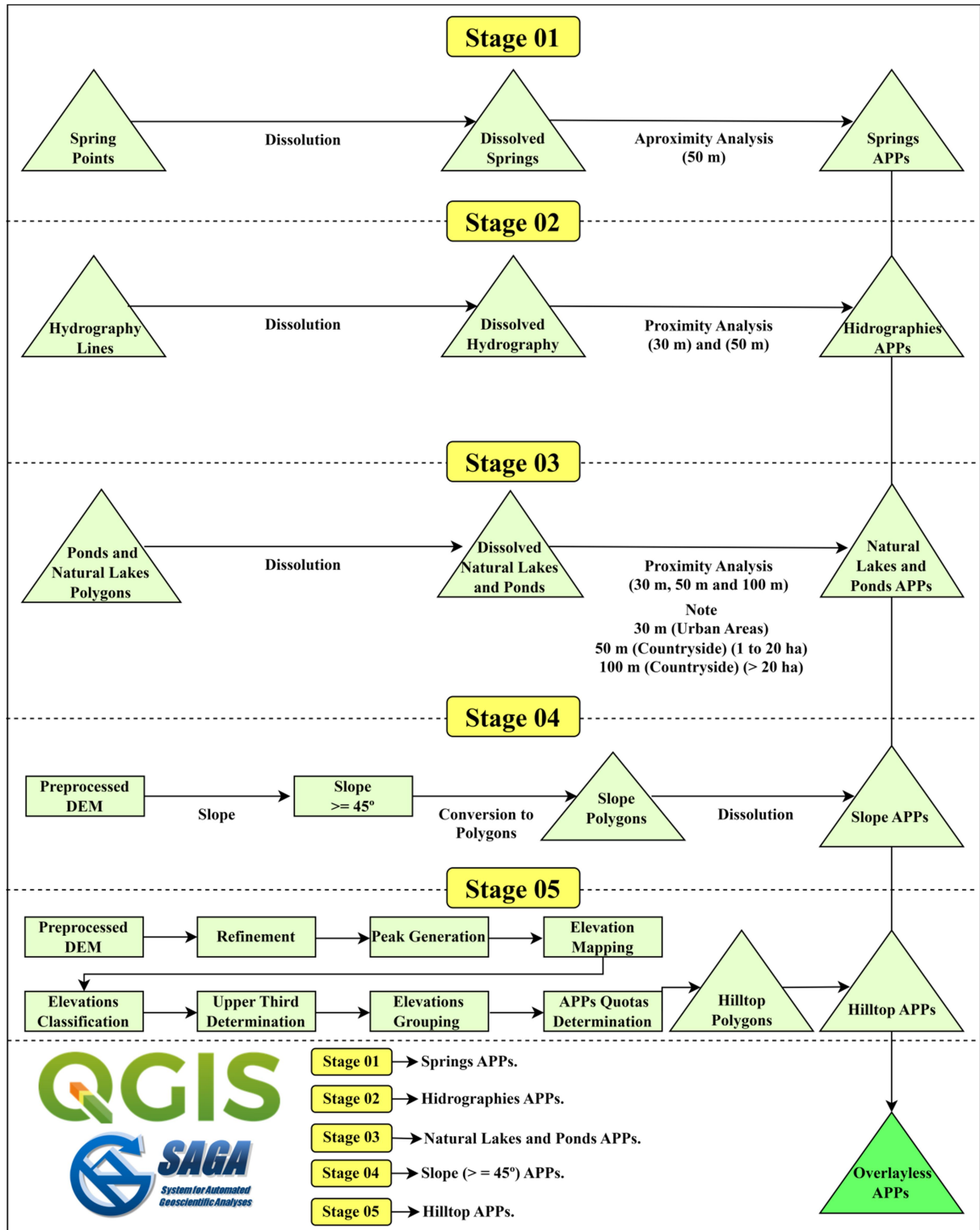
Figure 3. Methodological steps applied for the spatialization of Permanent Preservation Areas (APP) based on the Brazilian Forestry Code (Law nº 12.651/2012) for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

2.2.5. Delimitation of APP around natural lakes and ponds

At this stage, the vector file of polygons of natural lakes and ponds, in shapefile format, from the study area (JLDS) was initially dissolved using the "dissolution" function, with the objective of generating the dissolved polygonal vector image of lakes and ponds natural.

Finally, the "varied proximity analysis" function was applied, with buffers of 30 m (Urban Area), 50 m (Rural Area: 1 to 20 ha), and 100 m (Rural Area: >20 ha), having as input the dissolved polygonal vector image of natural lakes and ponds, with the final objective of generating the vector file of polygons representative of APPs around natural lakes and ponds.

2.2.6. Delimitation of the APP of slopes with a slope greater than 45°

In this stage, the "declivity" function was applied, having as input the he Digital Elevation Model (DEM) matrix image pre-processed in 05 steps, with the objective of generating the continuous matrix image of a slope.

Subsequently, the slope continuous matrix image was reclassified, using the "reclassify" function, with the objective of generating the reclassified slope discrete matrix image with slopes greater than 45°.

Then, the reclassified slope discrete matrix image with slopes greater than 45° was converted to polygons, using the "conversion to polygons" function, with the aim of generating the polygonal vector image with slopes greater than 45°.

Finally, the polygonal vector image with slopes more excellent than 45° was dissolved ("dissolution" function) with the final objective of generating the vector file of polygons of the slope APPs.

2.2.7. APP delimitation

The hilltop APPs, according to Law nº 12.651/2012 (BRASIL, 2012), are represented by areas on top of hills, hills, mountains, and mountains, with a minimum height of 100 m and an average slope more significant than 25°. These areas are delimited from the contour corresponding to 2/3 (two-thirds) of the minimum elevation height to the base of the hill or mountain with the lowest height in the set.

Having as input the matrix image of the DEM from SRTM, initially, its refinement was carried out, and, later, the matrix images of the summits of each hill, and mountain ranges

were generated. Once the summits of each hill were in possession, the elevations were mapped, which were reclassified with the aid of the "map calculator" function, where the parameters contained in the current legislation were inserted, resulting in the determination of the upper third.

2.2.8. Total APP delimitation without overlapping

In this last stage, all the APP processed in the previous stages (APP around the springs, APP along the marginal strip of watercourses, APP around natural lakes and ponds, APP on slopes with slopes greater than 45° and APP top de morro) were updated using the "update" function in order to generate the polygonal vector image of the APP without overlapping, making it possible to calculate the area (km²), perimeter (km) and percentage (%) of the APP classes for the study area (JLDS).

2.2.9. Stage 03 – Spatialization of environmental vulnerability for the study area (JLDS)

The methodological steps necessary for the spatialization of environmental vulnerability for the study area (JLDS) are shown in Figure 4. All methodological steps were applied using the free software QGIS (version 3.22.10), as well as its respective complements and functions.
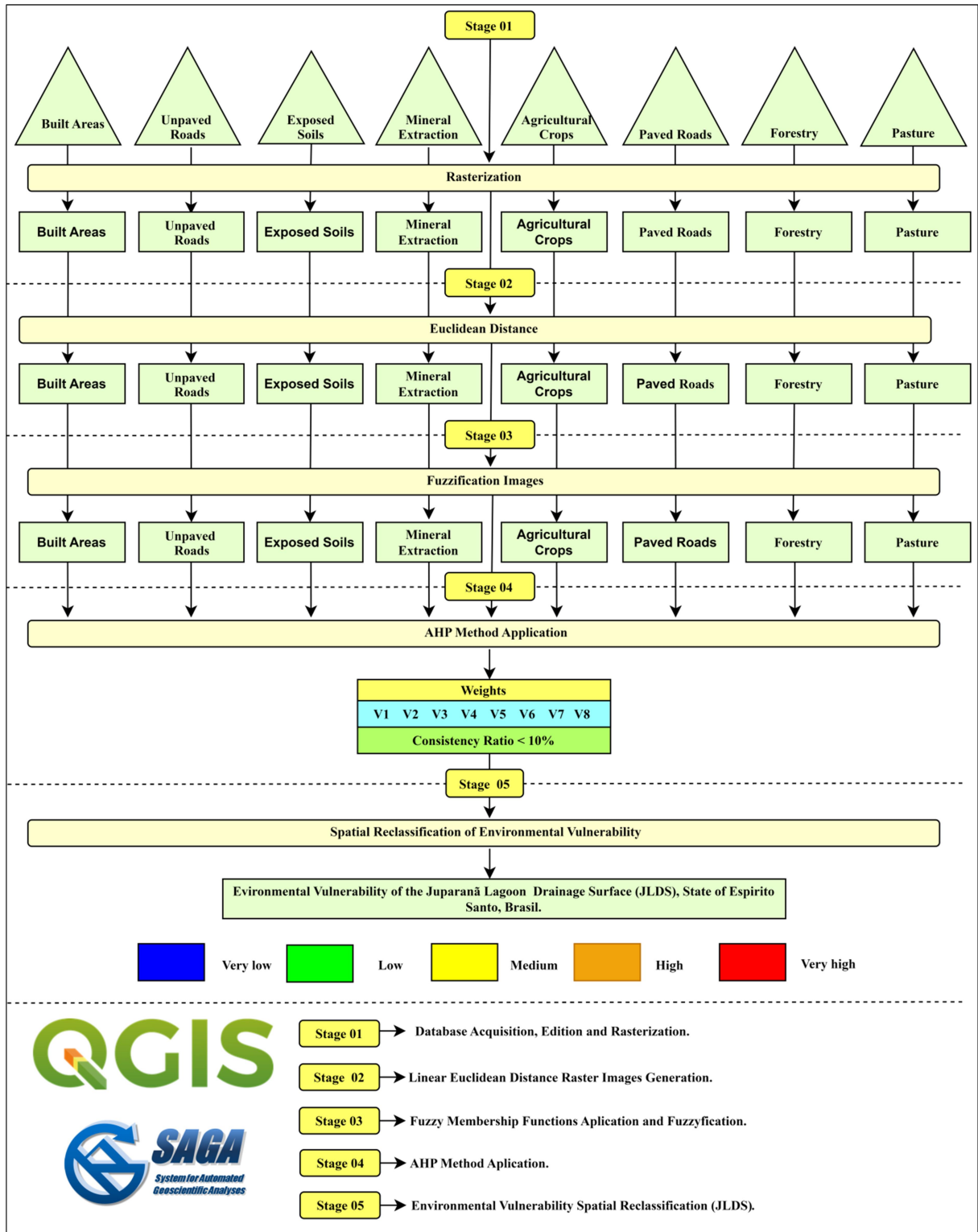
Figure 4. Methodological steps adopted for the spatialization of environmental vulnerability for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

2.2.10. Database acquisition, editing and rasterization of input variables

The land use and the land cover map was generated from the interpretative analysis at a scale of 1:2000 (photointerpretation) and the manual vectorization of the boundaries between classes of land use and land cover, about the images of the 3/3A sensors of the Kompsat satellites, of the ES—2019–2020 with a resolution of 0.5 m, aided by the orthophotomosaic ES—2007–2008 with a resolution of 1.0 m and the orthophotomosaic ES—2012–2015 with a resolution of 0.25 m, both obtained from the Integrated System of Geospatial Bases of the State of Espírito Santo (Geobases) website (https://geobases.es.gov.br/(accessed on 18 February 2022)).

After classifying land use, and land cover, the following vector input variables, in shapefile format, were pre-processed, edited and subsequently rasterized using the "rasterize" function: V1 - Built–up areas, V2 - Unpaved roads, V3 - Exposed soil, V4 - Mineral extraction, V5 - Agricultural crops, V6 - Paved roads, V7 - Forestry and V8 - Pasture..

2.2.11. Generation of linear euclidean distance matrix images

In this step, for each of the eight input variables rasterized in the previous step, the "proximity raster" function was applied, which uses the Euclidean metric, intending to generate eight continuous matrix images of Euclidean distance, in meters, for the area of study (JLDS) (SANTOS, *et al.*, 2017; TEIXEIRA *et al.*, 2018; SANTOS, 2020a.

2.2.12. Application of fuzzy membership functions and fuzzification of images

In this step, for each of the eight continuous matrix images of Euclidean distance of the input variables, the fuzzy membership function entitled "matrix fuzzification (decreasing linear association)" was applied, with the objective of generating eight fuzzified continuous matrix images for the area of study (JLDS), with values ranging from 0 to 1, in which the shortest distance, in meters, to the studied variable, received the value of 1 and the most significant distance, the value of 0 (SANTOS *et al.*, 2017; TEIXEIRA *et al.*, 2018).

2.2.13. Application of the Analytical Hierarchical Process (AHP) proposed by Saaty (1977)

To determine the weights, the AHP method proposed by Saaty (1977), through the decision of the problem in hierarchical levels. This method determines, through the synthesis of the values of the decision makers, a global measure for each alternative, prioritizing or classifying them at the end of the method (EUGENIO *et al.*, 2016; SANTOS, 2022).

The pairwise comparison matrix or decision matrix was used, using Saaty's fundamental scale (Table 1). The matrix elaboration method makes use of a comparison scale, in which the hierarchy of importance between the pre-defined factors can be linearly defined (V1 - Built–up areas, V2 - Unpaved roads, V3 - Exposed soil, V4 - Extraction mineral, V5 - Agricultural crops, V6 - Paved roads, V7 - Forestry and V8 - Pasture).

Table 1. Scale of comparators of the AHP method

Values	Mutual Importance
1/9	Extremely less important than
1/7	Much less important than
1/5	Strongly less important than
1/3	Moderately less important than
1	Equally important to
3	Moderately more important than
5	Strongly more important than
7	Much more important than
9	Extremely more important than

Adapted from Saaty (1977).

The phase of choosing the values, based on the scale of comparators, is considered one of the most important moments of the entire process for the spatialization of environmental vulnerability and the degree of importance of each factor was defined based on the bibliographical research, experience of the researchers and support from a multidisciplinary team.

An analysis of the consistency ratio of the weights chosen for each variable used in the model was performed using a tool available online (https://bpmsg.com/ahp/ahp-calc.php), in which an adequate consistency ratio (CR) was found for the weights used (SANTOS, 2022).

To evaluate the results of the calculated weights, it was necessary to calculate the consistency ratio (RC), which presented a value lower than 0,10.

Finally, in possession of the statistical weights of the eight variables, the "map calculator" function was used, in which Equation (1) was inserted:

$$VJLDS = P_1 \cdot Var_1 + \cdots + P_8 \cdot Var_8$$

Where $VJLDS$ is the Environmental Vulnerability for the Juparanã Lagoon Drainage Surface, Espírito Santo state, Brazil,, P_1 to P_8 são are the statistical weights of the input variables and Var_1 to Var_8 are the continuous raster images of the variables of fuzzified input

2.2.14. Spatial Reclassification of Environmental Vulnerability for the study area (JLDS)

At this stage, the continuous matrix image of the environmental vulnerability for the study area (JLDS) was reclassified in the free computational application SAGA-GIS (version 7.8.2) using the "reclassify" function, using the natural breaks method. Of Jenks to generate the discrete matrix image of environmental vulnerability represented by the very low, low, medium, high and very high environmental vulnerability.

2.2.15. Stage 04 - Confrontation and Statistical Analysis between Permanent Preservation Areas (APP) based on the Brazilian Forest Code (Law nº. 12.651/2012) and the Environmental Vulnerability for the study area (JLDS).

The methodological steps adopted for the confrontation and statistical analysis between the Permanent Preservation Areas (APP) based on the Brazilian Forest Code (Law nº 12.651/2012) and the environmental vulnerability for the study area (JLDS), Espírito Santo state, Brazil are shown in Figure 5.

All methodological steps were applied using the free QGIS applications (version 3.22.10), and the R-statistics complement (free software environment for statistical computing and graphics).

At this stage, a confrontation and statistical analysis were carried out between the representative classes of the Permanent Preservation Areas (APP) with the environmental vulnerability for the study area (JLDS), Espírito Santo, Brazil. In this context, the R-statistics complement present within the QGIS application (version 3.22.10) was used in order to justify that anthropogenic actions corroborate the presence of areas with high environmental vulnerability within Permanent Preservation Areas (APP) based on the Brazilian Forest Code (Law nº 12.651/2012) for the study area (JLDS).
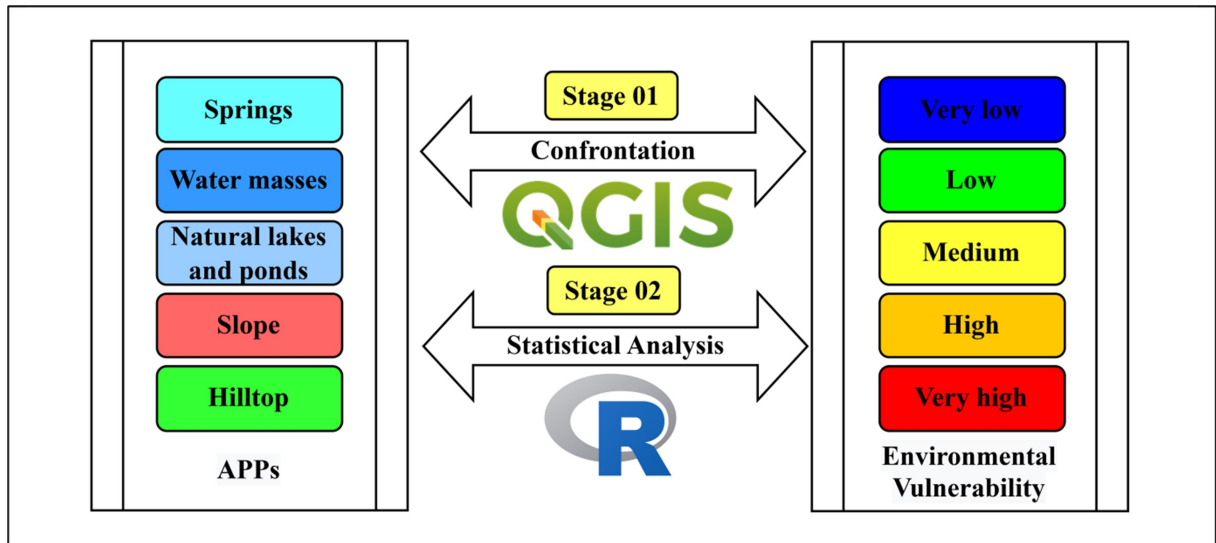
Figure 5. Methodological steps for the confrontation and statistical analysis between the Permanent Preservation Areas (APP) based on the Brazilian Forest Code (Law nº 12.651/2012) and the environmental vulnerability for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

3. RESULTS

3.1. LAND USE AND LAND COVER FOR THE JUPARANÃ LAGOON DRAINAGE SURFACE (JLDS), ESPÍRITO SANTO STATE, BRAZIL

In the study area (JLDS) there is a distribution of several classes of use and coverage, with emphasis on the water mass class that represents 25.68% (69.68 km²) of the total study area (Figure 6 and Table 2). In this context, the Juparanã lagoon represents 24.98% (67.80 km²) of the study area (JLDS).

Among productive activities for agricultural purposes, the classes represented by pastures and coffee stand out, occupying 68.34 km² (25.19%) and 50.58 km² (18.64%) of the total area, respectively. However, 28.20 km² (10.40%) of the total area is formed by native forest and 11.70 km² (4.31%) by native forest in an initial stage of regeneration (Table 2).
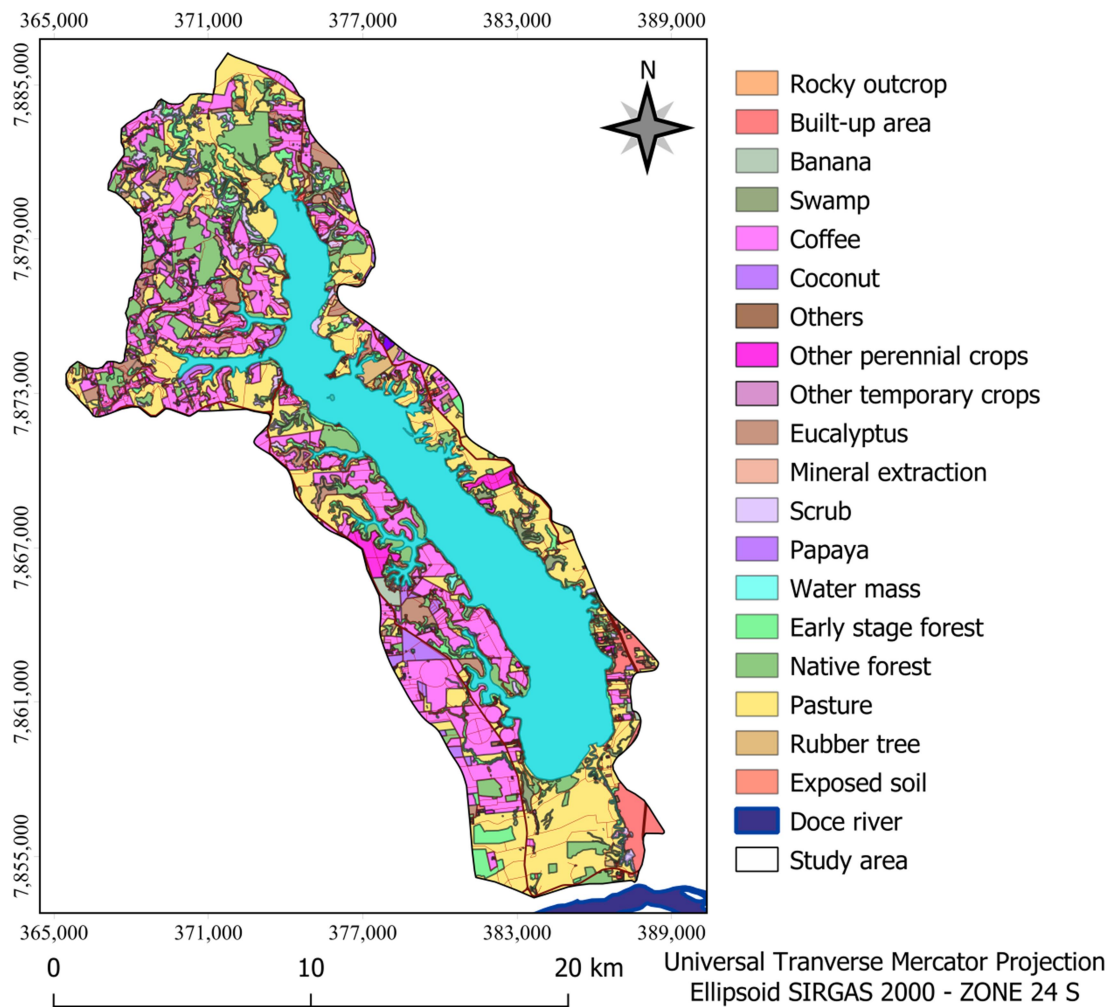
Figure 6. Land use and land cover for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

Table 2. Area and area percentage of land use and land cover classes for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

Land Use Classes	Area (km²)	Percentage (%)
Water Bodies	69.68	25.68
Pasture	68.34	25.19
Coffee	50.58	18.64
Native forest	28.20	10.40
Eucalyptus	12.19	4.49
Early stage forest	11.70	4.31
Scrub	6.66	2.46
Built-up area	5.83	2.15
Swamp	4.99	1.84
Coconut	3.51	1.29
Other perennial crops	3.13	1.15
Others	2.68	0.99
Exposed soil	1.39	0.51
Rubber tree	1.10	0.41
Banana	0.72	0.27
Other temporary crops	0.32	0.12
Papaya	0.15	0.05
Mineral extraction	0.09	0.03
Rocky outcrop	0.05	0.02
Total	271,31	100,00

The total identified APP area is 25.37 km² (Figure 7 and Table 3), equivalent to 9.35% of the total study area. The lagoon APP represents 53.58% of the total APP territory, while the watercourse and spring APP represents 42.24% and 4.17%, respectively. When compared with the study area (JLDS), the lagoon APP represents 5.01% while the APP of watercourses and springs represents 3.95% and 0.39%, respectively.
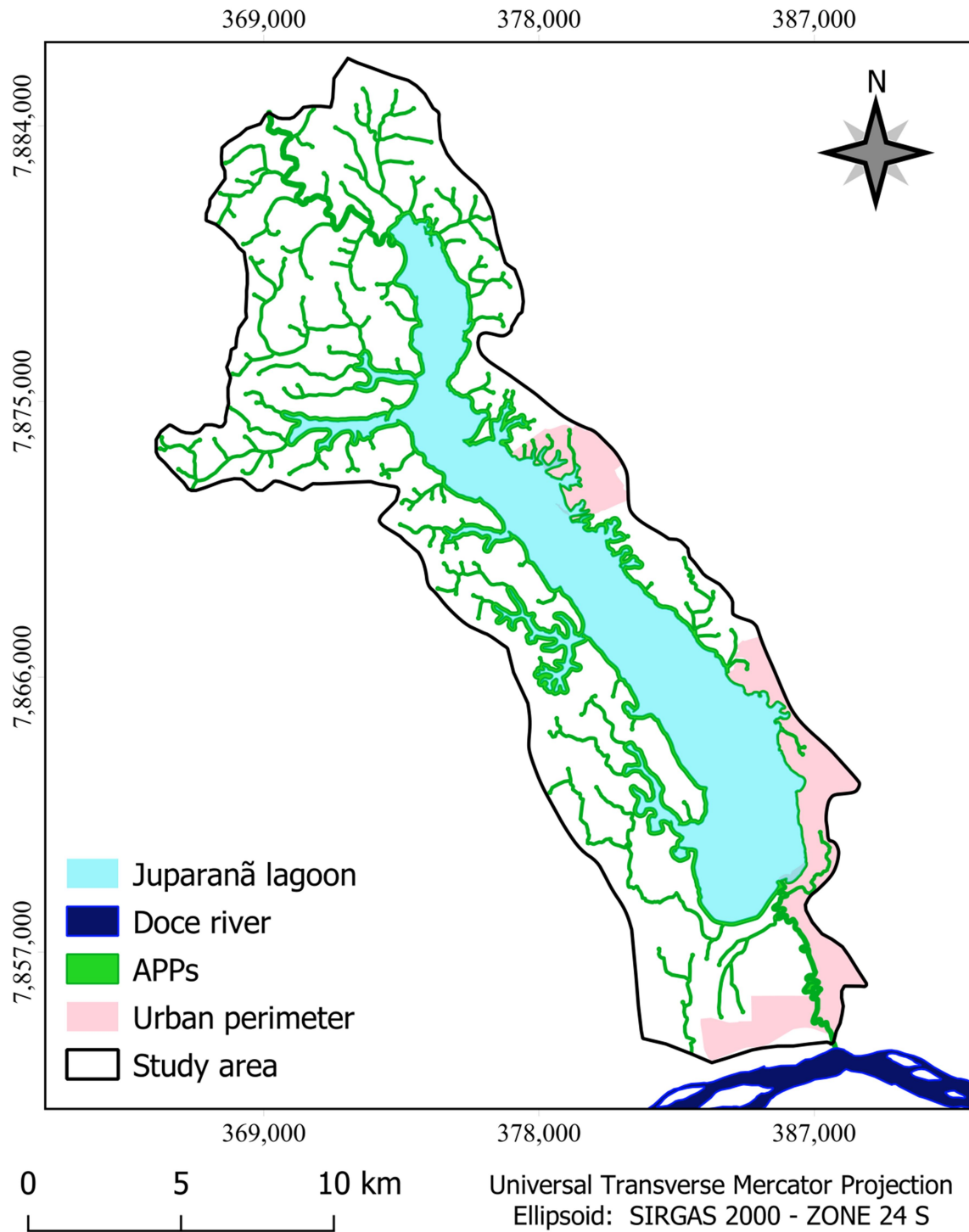
Figure 7. Permanent Preservation Areas (APP) for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

The total APP area identified in the study area is 25.37 km²; the lagoon APP represents 53.58% of the total APP territory, 42.24% of watercourses, and 4.17% of springs, according to Table 3.

Table 3. Area of the different types of APP related to the total study area for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

APP	Area (km²)	Total APP Area (%)	Study Area (%)
Lagoon	13.60	53.59	5.01
Watercourses	10.72	42.24	3.95
Springs	1.05	4.17	0.39
Total	25.37	100.00	9.35

Table 4 shows the current situation of land use and land cover exclusively for the environment characterized by the APP where 23.37%, 14.48%, and 13.19% of the area is occupied by native forest, native forest in the initial stage of regeneration and marsh, respectively, totaling 51.04% of the APP distributed to the study area. When analyzing the classes involving agricultural exploration, the predominance of pastures stands out with 24.96%, followed by eucalyptus with 4.72% and coffee with 3.84%.

Table 4. Land use and land cover in the APP for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

Land Use Classes	Area (km²)	Percentage (%)
Pasture	6.33	24.96
Native forest	5.93	23.37
Early stage forest	3.67	14.48
Swamp	3.35	13.19
Scrub	1.53	6.04
Eucalyptus	1.20	4.72
Coffee	0.97	3.84
Exposed soil	0.95	3.73
Others	0.59	2.32
Coconut	0.32	1.25
Built–up area	0.27	1.08
Rubber tree	0.16	0.63
Other perennial crops	0.07	0.26
Other temporary crops	0.02	0.09

Banana	0.004	0.02
Rocky outcrop	0.003	0.01
Mineral extraction	0.001	0.003
Total	25,37	100

3.2. GENERATION OF LINEAR EUCLIDEAN DISTANCE MATRIX IMAGES FOR THE JUPARANÃ LAGOON DRAINAGE SURFACE (JLDS), ESPÍRITO SANTO STATE, BRAZIL

The Euclidean distances are represented in the images through a color palette, where blue color represents the most significant distances, and the red color the smallest distances.

Among the generated images, mineral extraction (Figure 8d) and paved roads (Figure 8f) stand out with the highest linear distance values for the study area (JLDS), equivalent to 25,339 m and 11,979 m, respectively, according to Figure 8.

The variables that present smaller Euclidean distances are unpaved roads (Figure 8b), built-up areas (Figure 8a), pastures (Figure 8h), agricultural crops (Figure 8e), exposed soil (Figure 8c), and forestry (Figure 8g) with values of 1780 m, 1890 m, 2050 m, 4690 m, 4782 m and 4819 m, respectively.

Figure 8. Euclidean distance of anthropogenic variables for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil. (a) V1 - Built–up areas, (b) V2 - Unpaved roads, (c) V3 - Exposed soil, (d) V4 - Mineral extraction, (e) V5 - Agricultural crops, (f) V6 - Paved road, (g) V7 - Silviculture, (h) V8 - Pasture.

3.3. APPLICATION OF FUZZY MEMBERSHIP FUNCTIONS AND FUZZIFICATION OF IMAGES

The diagrams of the membership functions (decreasing linear fuzzy) representing the anthropogenic variables are shown in Figure 9. It is observed that where the areas considered

most considered are those that present absolute values of the fuzzy set close to 1, while the less relative areas values are close to 0.
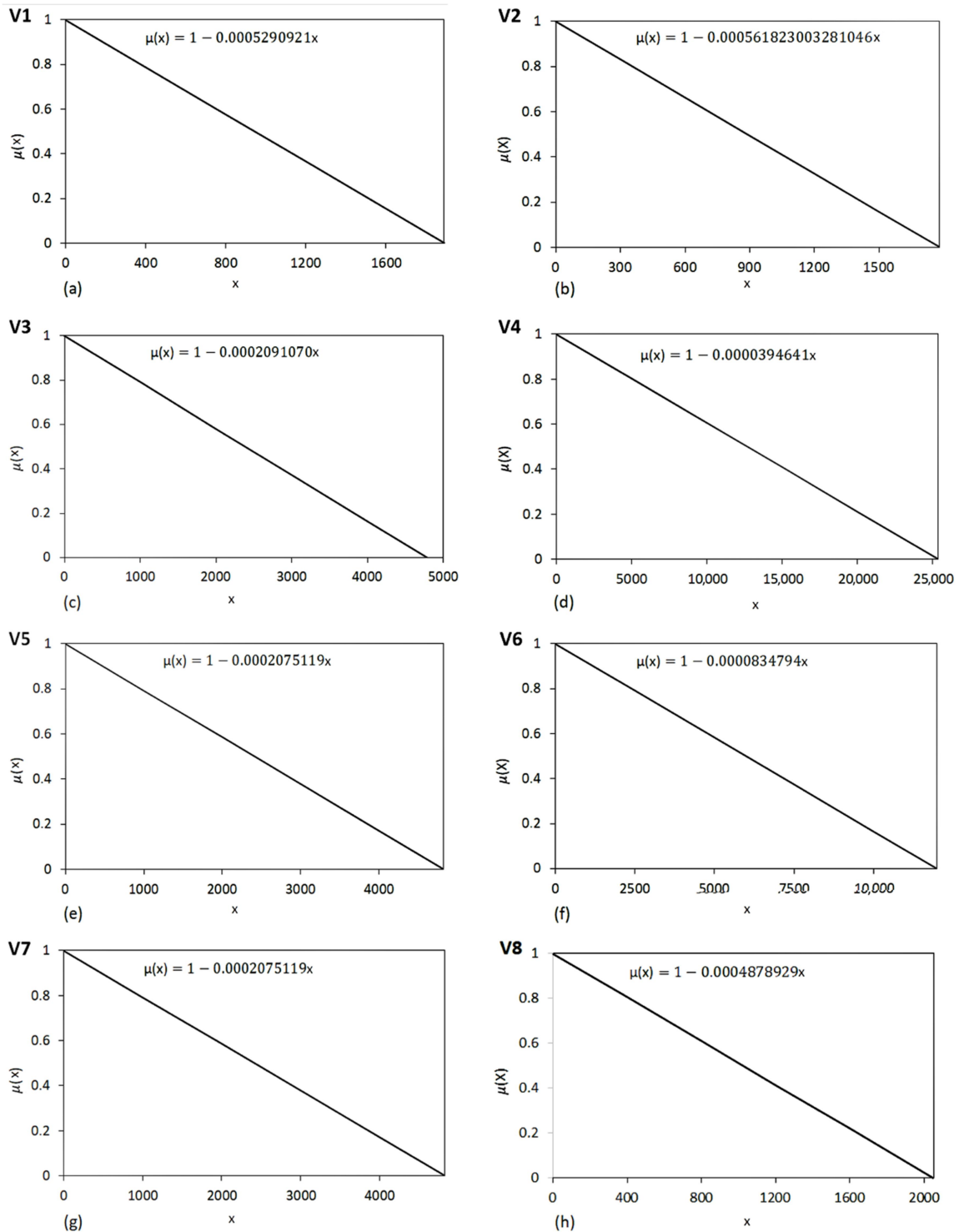
Figure 9. Diagrams of membership functions (decreasing linear fuzzy) representing the anthropogenic variables identified for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil. (a) V1 - Built–up areas, (b) V2 - Unpaved roads, (c) V3 - Exposed soil, (d) V4 - Mineral extraction, (e) V5 - Agricultural crops, (f) V6 - Paved road, (g) V7 - Silviculture, (h) V8 - Pasture.

Figure 10 shows the results of fuzzy logic spatialization for anthropogenic matrix variables. Of the variables used, those that are most harmful to the environment due to their lower Euclidean distance and values of the fuzzy set of intervals closer to 1 are unpaved roads (Figure 10b), built-up areas (Figure 10a), pasture (Figure 10h), agricultural crops (Figure 10e) and exposed soil (Figure 10c).
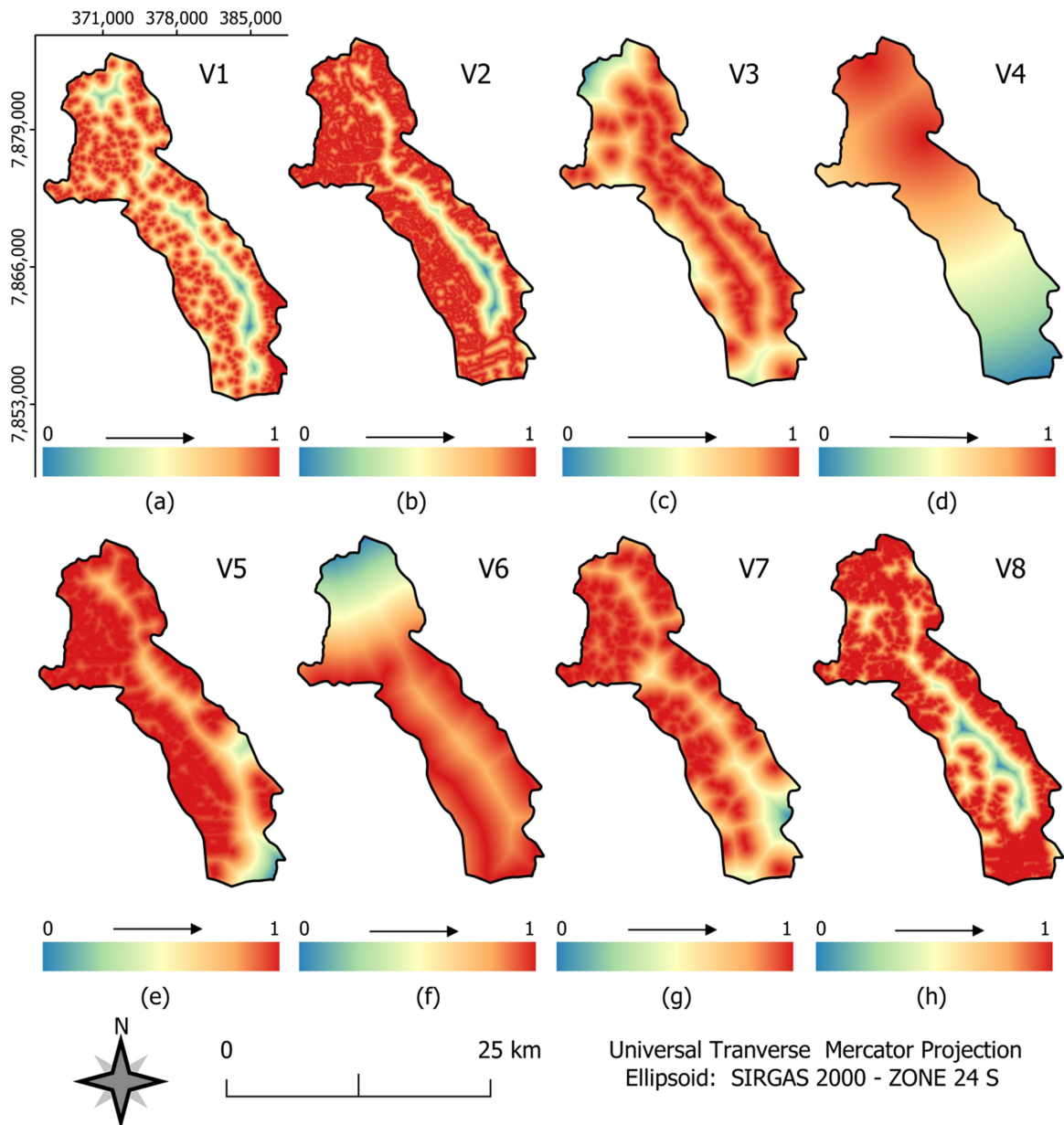
Figure 10. Spatialization of fuzzy logic for anthropogenic matrix variables for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil. (a) V1 - Built-up areas, (b) V2 - Unpaved roads, (c) V3 - Exposed soil, (d) V4 - Mineral extraction, (e) V5 - Agricultural crops, (f) V6 - Paved road, (g) V7 - Silviculture, (h) V8 - Pasture.

The representative histograms of the pixel frequency percentages for the range of the decreasing linear fuzzy set of the anthropogenic variables are presented in Figure 11. The results are fundamental when one wants to evaluate the behavior of a certain variable in the range most harmful to the environment (0.75 - 1) or the sum of the two main ranges (0.50 - 1).

This histogram is representative of the pixel frequency percentage and demonstrates how much, within a given interval, these pixels occurred for each vulnerability class..

In this context, of all anthropogenic variables, those that present the highest percentage values (values above 90.00%) of the fuzzy set interval between 0.50 and 1 are agricultural cultivation (95.11%), unpaved road (93.70%), forestry (93.68%), pasture (92.33%), exposed soil (92.19%) and paved road (90.20%). However, due to its small occurrence in the entire study area (JLDS), the anthropogenic variables, paved road, and mineral extraction presented, for the same range of the fuzzy set (0.50 - 1), the lowest percentage values equivalent to 84, 79 and 66.34%.
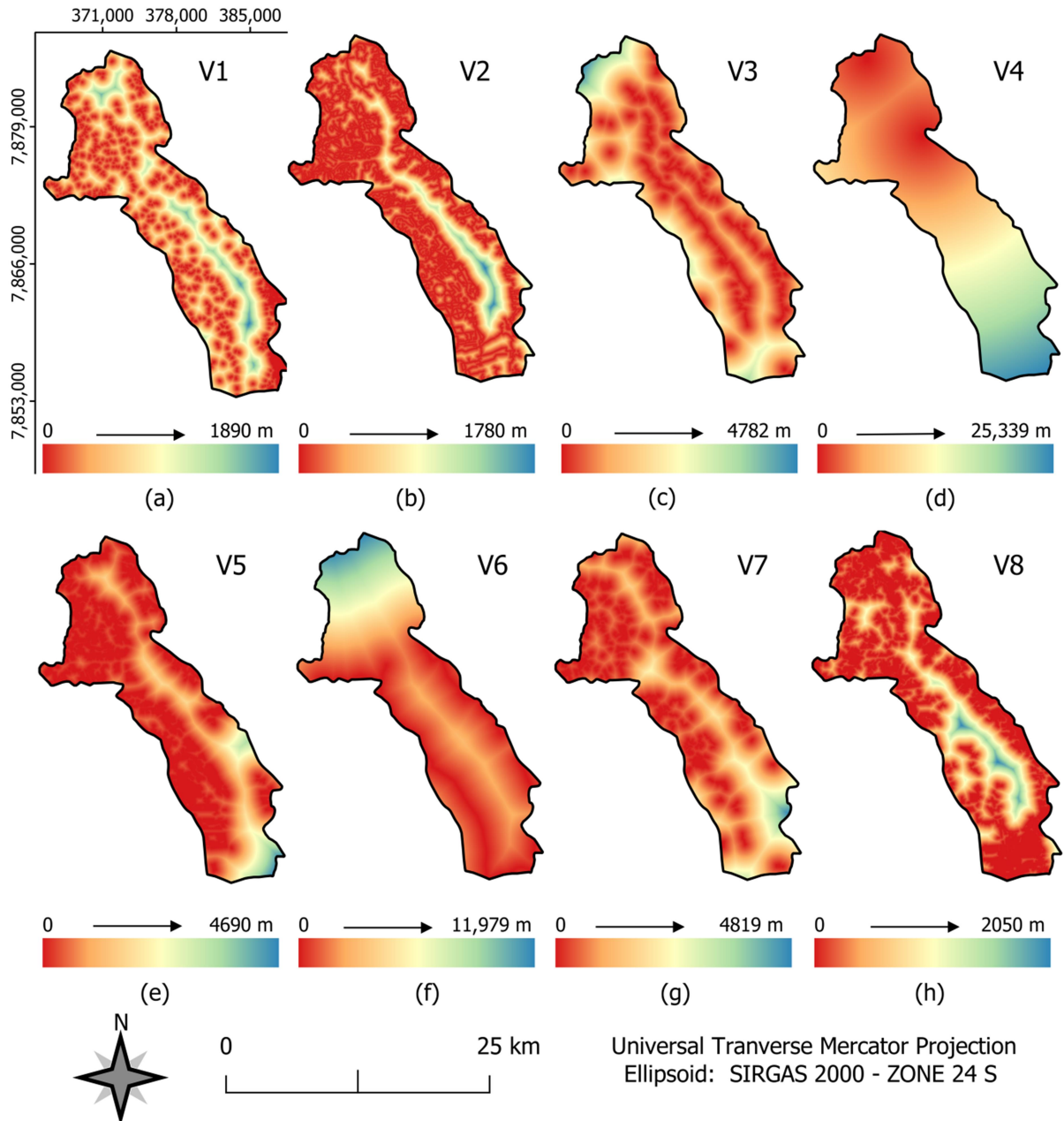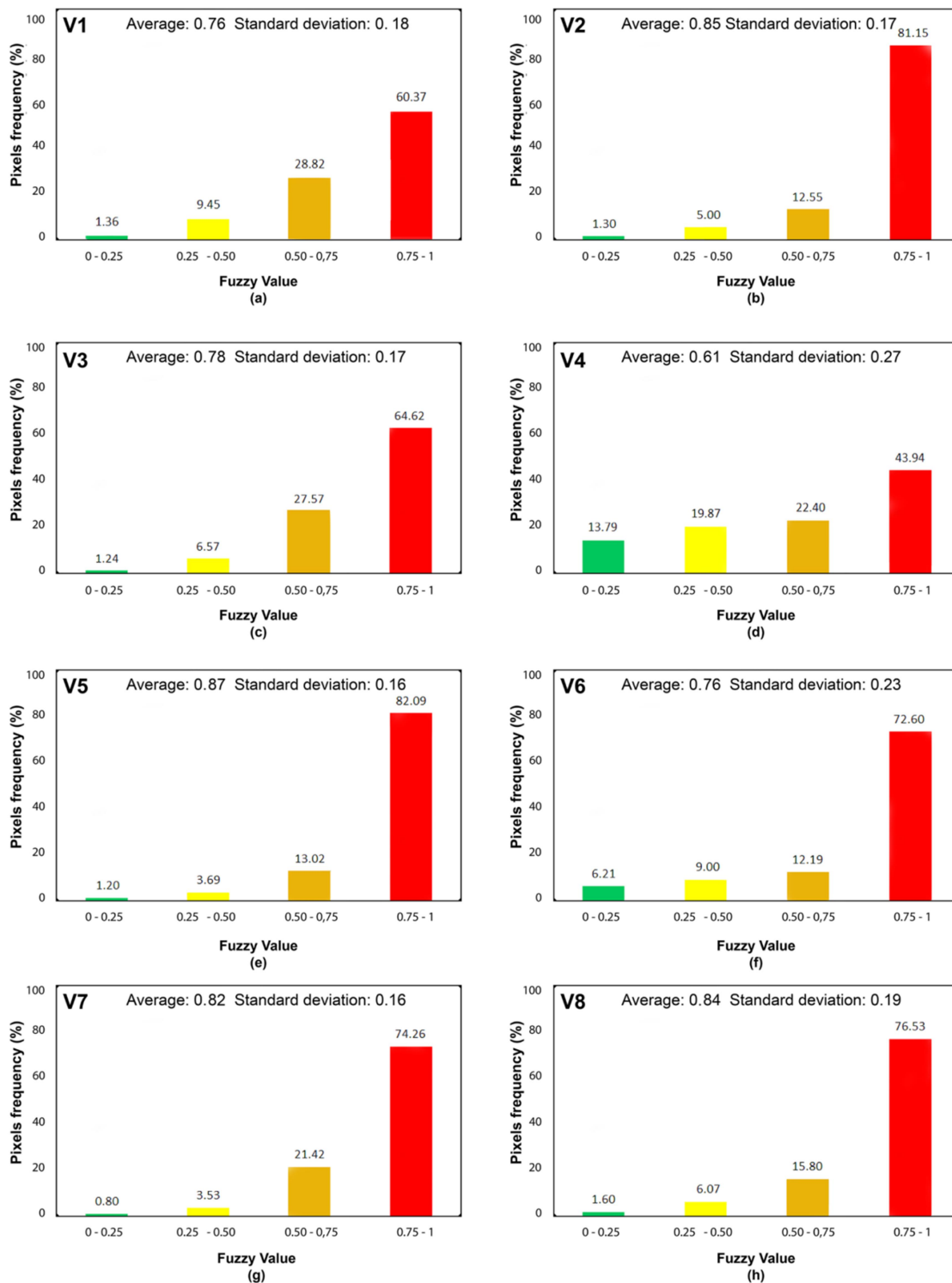
Figure 11. Pixel frequency percentage for the decreasing linear fuzzy set interval of anthropogenic variables for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil. (a) V1 - Built–up areas, (b) V2 - Unpaved roads, (c) V3 - Exposed soil, (d) V4 - Mineral extraction, (e) V5 - Agricultural crops, (f) V6 - Paved road, (g) V7 - Silviculture, (h) V8 - Pasture.

3.4. APPLICATION OF THE ANALYTICAL HIERARCHICAL PROCESS (AHP) PROPOSED BY SAATY (1977)

To determine the weights of the study variables, the AHP method was used, through Saaty's fundamental scale (Table 1). The hierarchy of importance (from 1 to 8) was linearly defined between the pre-defined factors (Pasture (P); Forestry (S); Paved roads (EP); Agricultural crops (CA); Mineral extraction (EM); Exposed soil (SE); Unpaved roads (ENP); Built-up areas (AE)), which resulted in the weight of each criterion, as shown in Table 5

Table 5. Paired comparison matrix with mutual importance values for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil. Pasture (P); Silviculture (S); Paved roads (EP); Agricultural Crops (CA); Mineral Extraction (EM); Exposed soil (SE); Unpaved roads (ENP); Built-up areas (AE).

	P	S	EP	CA	EM	SE	ENP	AE
P	1							
S	2	1						
EP	3	2	1					
CA	4	3	2	1				
EM	5	4	3	2	1			
SE	6	5	4	3	2	1		
ENP	7	6	5	4	3	2	1	
AE	8	7	6	5	4	3	2	1

Table 6 presents the statistical weights for the anthropogenic variables that were validated based on the consistency ratio (RC), which presented a value of 0.029 (acceptable consistency ratio)(SANTOS, 2022).

Table 6. Statistical weights were calculated by the AHP method for each variable for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

Anthropic Variable	Weight
Built–up areas	0.331322
Unpaved roads	0.230663
Exposed soil	0.157238
Mineral extraction	0.105905
Agricultural crops	0.070935
Paved roads	0.047680
Forestry	0.032696
Pasture	0.023561

3.5 SPATIAL RECLASSIFICATION OF ENVIRONMENTAL VULNERABILITY FOR THE JUPARANÃ LAGOON DRAINAGE SURFACE (JLDS), ESPÍRITO SANTO STATE, BRAZIL

The spatialization and reclassification of environmental vulnerability are represented in Figure 12. It is demonstrated that the study area (JLDS), has a great environmental vulnerability, evidenced by the values of the very high class (31.20%), high (32.86 %) and medium (20.93%). The areas in red are represent of the occurrence of greater vulnerability. They are geographically distributed on all sides, including in the vicinity of Juparanã Lagoon, which characterizes a stage of environmental disturbance, which justifies attention to these classes.
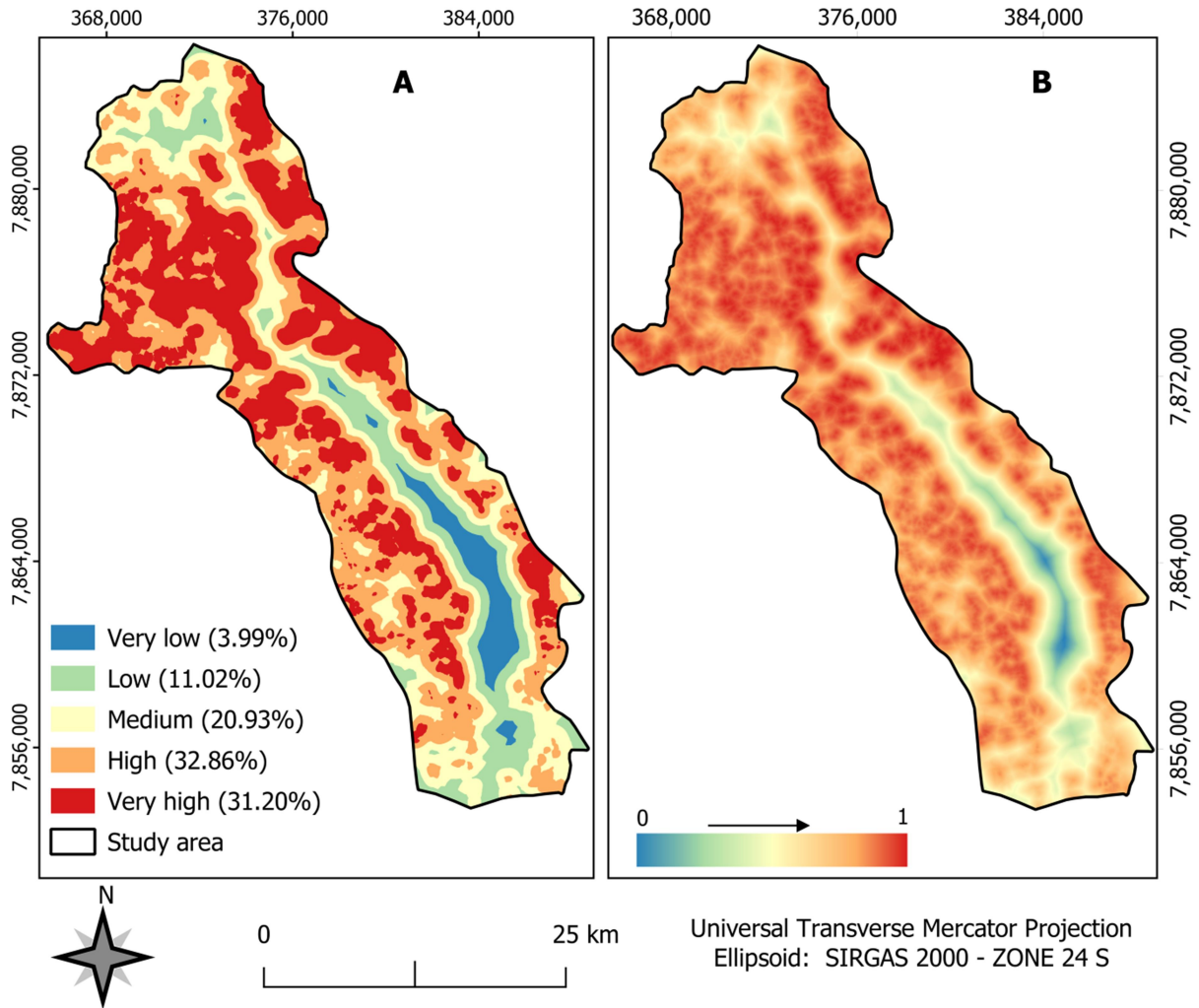
Figure 12. Spatialization of environmental vulnerability using fuzzy logic and AHP method for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil. (A) Vulnerability Classes with natural Jenks breaks, (B) Vulnerability ranging from 0 to 1.

The most vulnerable region is where there is a more significant presence of economic activities, especially agriculture. The class of agricultural crops, unpaved road, forestry, pasture, and exposed soil presented the highest percentage values, greater than 90% for the fuzzy set between 0.50 and 1, followed by the built area class, which presented a percentage value of 89.19%. All anthropogenic classes presented above are directly related to human presence and proximity to buildings, combined with economic actions.

The confrontation of land use and land cover with environmental vulnerability is represented in Table 7. The four variables that presented the most intense vulnerabilities (very high class) were: mineral extraction (85.14%), Silviculture (63.41%), unpaved roads (59.03%) and exposed soil (52.24%).

Table 7. Confrontation of land use and land cover with environmental vulnerability for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil. Pasture (P); Silviculture (S); Paved roads (EP); Agricultural Crops (CA); Mineral Extraction (EM); Exposed soil (SE); Unpaved roads (ENP); Built–up areas (AE).

Variables	Vulnerability									
	Very Low		Low		Medium		High		Very High	
	km²	(%)	km²	%	km²	%	km²	%	km²	%
AE	1,87	32,11	1,09	18,74	0,63	10,78	1,26	21,58	0,98	16,80
ENP	0,02	0,81	0,14	5,24	0,21	7,58	0,75	27,34	1,62	59,03
SE	0,03	1,94	0,02	1,51	0,09	6,46	0,53	37,85	0,73	52,24
EM	0,00	0,00	0,00	0,48	0,01	14,38	0,00	0,00	0,08	85,14
CA	0,27	0,46	1,42	2,44	7,01	12,01	21,48	36,80	28,18	48,29
EP	0,11	15,67	0,03	4,06	0,04	5,22	0,26	35,59	0,29	39,46
S	0,02	0,16	0,11	0,82	0,92	6,95	3,80	28,66	8,40	63,41
P	1,66	2,44	14,11	20,65	12,07	17,66	14,11	20,64	26,39	38,62

3.6. CONFRONTATION AND STATISTICAL ANALYSIS BETWEEN TOTAL APPS WITHOUT OVERLAPPING WITH ENVIRONMENTAL VULNERABILITY FOR THE JUPARANÃ LAGOON DRAINAGE SURFACE (JLDS), ESPÍRITO SANTO STATE, BRAZIL

The confrontation between the APP and the environmental vulnerability is represented in Table 8 and Figure 13, which demonstrated that the total APP without overlap present high environmental vulnerability represented by 47.35% (very high), 34.05% (high), 14.55% (medium), 4.02% (low) and 0.03% (very low). In this context, 81.40% of the APP areas are represented by the combination of very high and high vulnerability classes with good geographic distribution over the study area (JLDS). This occurrence is associated with the environmental nonconformities present in some of these APPs, which are not properly protected.

Table 8. Confrontation between total APPs without overlapping and environmental vulnerability for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

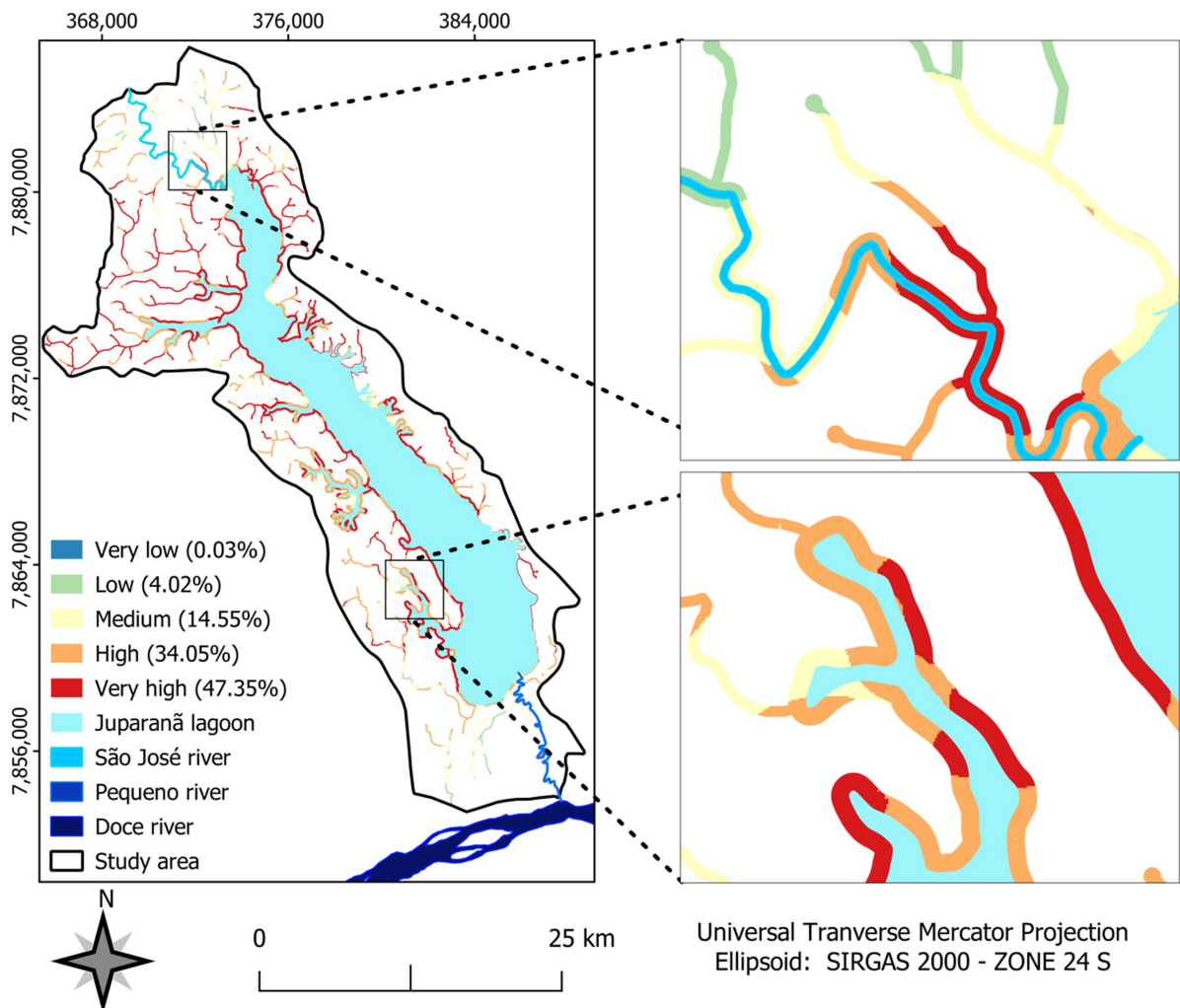| Vulnerability	Area (km²)	Percentage (%)
Very low	0.01	0.03
Low	1.02	4.02
Medium	3.69	14.55
High	8.64	34.05
Very high	12.01	47.35
Total	**25,37**	**100**

Figure 13. Spatialization of the confrontation between total APPs without overlapping with environmental vulnerability for the Juparanã Lagoon Drainage Surface (JLDS), Espírito Santo state, Brazil.

DISCUSSION

The delimitation of watersheds and the classification of land use and land cover were fundamental for the development of this research. The area of the ottobasins generated (Figure 2) through the methodology presented an area of 271.31 km² for the drainage surface of the study area, while the level 7 ottobasins made available by geobases (https://geobases.es.gov.br/) presented areas of 268.29 km². For similar works, the delimitation of watersheds is a step that can be disregarded for regions that have a reliable database. The delimitation of the polygon of the Juparanã Lagoon, through photointerpretation, identified an area of 67.80 km², diverging from the 2012–2015 mapping of the Environmental State Institute of Espírito Santo (IEMA) available on the website (https://geobases.es.gov.br/) and from Cavati e Fernandes (2008) who stated that the Juparanã Lagoon has approximate areas of 60.48 km² and 63.00 km², respectively.

The difference in the Juparanã lagoon area may be due to the characteristics of the database and procedures adopted for the delimitation and generation of the files. It may also be associated with the dam built at the mouth of the Pequeno River to prevent the entry of water from the Doce River, contaminated by tailings, from the rupture of a dam containing mining tailings owned by Samarco Mineração, located in Mariana/MG, in 5 November 2015 (SAMPAIO *et al.*, 2017).

The classification of land use and land cover was fundamental for the development of this research as well as for composing the scenario of environmental vulnerability of the area of this study, corroborating with the Brazilian Institute of Geography and Statistics (IBGE, 2006) e and Santos *et al.* (2016), when stating that land cover mapping is essential for planning, as they provide information on land use, preservation and conservation areas, specific use areas, environmental impact, in addition to describing and mapping the main existing occupations. The result identified explored areas, impacted by anthropic actions, in conflict with the Brazilian Forest Code (Law nº 12.651/2012) which provides for full protection of Permanent Preservation Areas (BRASIL, 2012).

Pastures and coffee cultivation are the productive activities of agriculture that stood out in the study area (JLDS), which corroborates the results found by Martins (2016), which highlights pasture and agriculture among the main elements in the predominance of land use in the Juparanã lagoon hydrographic basin and in the surrounding areas.

It is observed that there is a great vulnerability, being geographically distributed throughout the study area (JLDS) with different intensities, including in the APP. The class

representing very high vulnerability was more intense in the northwest part of the study area (JLDS). It is possible to observe that this result is linked to land use and land cover in these regions, where the highest concentration of unpaved roads, agricultural crops and pasture stands out. Ribeiro *et al.* (2005) point out that agricultural activities, when exploited in a predatory manner, can disrupt the dynamic balance of the physical environment.

The result of the research matches the information presented by Gonçalves, (2005) and Cavati e Fernardes (2008), in which in recent decades, the Juparanã Lagoon has been subjected to a series of anthropic impacts, silting up and disorderly occupation of its surroundings, both for real estate (urbanization) and agricultural purposes.

The confrontation between environmental vulnerability and the APP, contrary to what is foreseen in the Brazilian Forestry Code, pointed to a high level of vulnerability in the areas of permanent preservation, evidenced by the vulnerability in the very high and high classes that presented values of 47.35% and 34.05%, respectively. This occurs due to the environmental nonconformity present in the APPs (Permanent Preservation Areas), which are not adequately protected and are exploited by various activities, identified in the land use and land cover map, as shown in Table 4.

Environmental vulnerability can have a several of negative impacts on a region or community. It can increase the likelihood of natural disasters such as floods, landslides, and storms, which can damage infrastructure and endanger people's lives. Exposure to pollutants or lack of basic sanitation can lead to health problems such as respiratory illnesses, dermatitis, and gastrointestinal infections. Environmental vulnerability can lead to scarcity of natural resources such as water and food, which can increase poverty and hunger. Promote the forced displacement of people who are forced to leave their homes and communities because of natural disasters or environmental degradation. Environmental vulnerability can lead to the destruction of natural ecosystems, which can resulting in loss of biodiversity and species extinction. Environmental vulnerability can have negative economic impacts, such as job losses, damage to infrastructure and a drop in agricultural production(SOUZA *et al.*, 2019).

The delimitation of urban centers based on the creation of an urban perimeter by the municipality of Linhares had an impact on a reduction of 0.75 km² (5.13%) in the APP of Juparanã Lagoon due to the reduction in this section of the APP to a strip of just 30 m, where previously it was 100 m, and also a reduction of 0.35 km² (36.04%) in the APP on the Pequeno river, where its strip was reduced from 50 m to 15 m in width. This reduction in the APP range in the urban perimeter represents a loss of 4.12% of the APP in the study area

(JLDS).

The main environmental problems found in the study area (JLDS) refer to unpaved roads and built-up areas that are geographically distributed over the area, presenting the lowest Euclidean distance values among all other variables, contributing to the occurrence of environmental problems such as soil loss, silting up of water courses, running over wild animals, forest fires, forest fragmentation, and domestic effluent.

The recent implementation of models using Artificial Intelligence (AI) has yielded excellent results. In work developed by Sharafati *et al.*, (2021), neuro-fuzzy hybrid models were used to analyze the performance of sediment removal efficiency in irrigation channels, and the modeling results obtained demonstrated an optimistic finding. An improved method for predicting the thermal performance parameters of a cylindrical cavity receiver using a modified neuro-fuzzy inference system algorithm, a powerful optimization tool for predicting energy performance, has been proposed by Zayed *et al.*, (2021). The authors Jeon and Paek, (2021) also used fuzzy logic to verify the performance of a wind turbine, obtaining results that confirmed that the proposed control increases the power performance and structural stability of wind turbines compared to conventional controls.

The methodology of this work can be applied to assess environmental vulnerability at different scales (local, regional and global), and in relation to different factors (social, economic, political, and environmental). It is similar to that presented by other authors. Where the delimitation of watersheds coincides with the work developed by Lira *et al.*, (2022), developed with the objective of carrying out the classification of environmental fragility in watersheds. Application of fuzzy logic and the Analytic Hierarchy Process (AHP) method is one of the most important steps and follows the same criteria used by Parsian et al., (2021), for mapping flood risks.

Projects and actions can be established based on this study and directed towards areas with greater environmental vulnerability, through the implementation of mitigating measures by managers and owners, expanding the environmental stability of the Juparanã lagoon.

4. CONCLUSIONS

The combination of fuzzy logic and the AHP method with the aid of geotechnologies proved to be efficient, as they allowed spatializing the distribution of environmental vulnerability in the Juparanã Lagoon Drainage Surface (JLDS), being important for the implementation of projects, action plans, decision making and proper management of anthropic activities aimed at reducing environmental impacts in areas of interest.

The techniques made it possible to identify a high positive relationship between anthropic activities in the study area and its surroundings and environmental vulnerability. The analysis found a marked environmental vulnerability to JLDS that is concerning, indicating that the region requires proper planning of actions, as 84.99% of the vulnerability is occurring in the classes: very high class (31.20%), high (32.86%), and medium (20.93%). The relationship becomes even more severe when considering only the Permanent Preservation Areas (APP), with almost 95% of the APP areas classified as very high, high, and medium vulnerability. The high environmental vulnerability may be mainly associated with the extensive distribution of built-up areas, unpaved roads, agricultural crops, and pastures, as well as the low level of forest cover in the study area and the existing exploitation in the permanent preservation areas (APP).

The difficulties encountered are related to the need for more studies in environmental vulnerability, especially regarding lagoons. The photointerpretation of the Juparanã lagoon surroundings is unprecedented. A vital improvement measure would be applying a temporal analysis to assess the dynamics of environmental vulnerability over time, considering socioeconomic, climatic, and environmental changes for a more comprehensive understanding of the distribution of environmental vulnerability in the study area.

The methodology can be adapted to consider different scales of analysis, from local, regional, national, or global levels, to assess environmental vulnerability at various levels of scope and complexity, as well as the inclusion of local communities and governments.

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