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Article

Methodologies and Criteria for Defining Areas for Forest Restoration Aiming at Water Production and Security

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Abstract

This study presents a methodological framework for prioritizing areas for forest restoration with the primary objective of enhancing water provision. A multi-scale approach was employed, starting with macro-scale criteria at the river basin level, followed by more localized landscape and hydro-ecological assessments. This two-stage process facilitated strategic planning for interventions aimed at restoring forest cover in permanent preservation areas (PPAs) along watercourses and springs. The methodology was applied to the Joanes and Jacuípe Rivers Permanent Protection Areas Forest Rehabilitation Project in the Salvador Metropolitan Region, Bahia. The project's primary goal is to improve water security by restoring native vegetation across 100 springs and 100 hectares of riparian zones, which are critical to the water supply system for the Salvador Metropolitan Region. The prioritization process integrated hydrological, ecological, and socio-environmental criteria, ensuring that restoration efforts not only enhance water production but also provide long-term ecological and social benefits.

Keywords: ecological restoration; reforestation; water security; riparian zones; watershed management

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1. Introduction

Human actions have altered the global hydrological cycle more aggressively, or on a more immediate time scale, than natural environmental changes. This is primarily due to numerous interventions, such as changes in land use and the construction and operation of hundreds of thousands of dams [1,2]. These actions have significantly altered river processes, compromising river ecosystems' functions and their environmental services and leading to a reduction in biodiversity.

Areas with concentrated populations and agricultural and industrial activities place demands on water resources, depending on the water accumulated in upstream basins, which ultimately defines the quantity and quality available downstream [1,3,4]. Specific locations and their upstream and downstream basins are part of an interconnected system that must be understood in its entirety when considering water production. In this context, the conditions for water infiltration into soils, percolation, and the consequent recharge

of aquifers—processes that occur primarily in the higher regions of river basins—are significantly influenced by the presence of forests [5].

Tambosi et al. [6] analyze the ecohydrological functions of forests in different landscape elements, including hilltops, slopes, riparian areas, and intervals. Forests on hilltops intercept rainwater, while canopy cover and the presence of undergrowth protect the soil from the direct impact of rain, preventing erosion, leaching, and soil compaction [3,5,7,8]. Additionally, forests regulate runoff along slopes, providing greater stability and reducing the risk of landslides or mass slides [9]. Forest development and condition are critical for better interception of rainfall and more effective water infiltration into the soil [10]. Dense canopies, undergrowth, and high organic matter concentrations in the soil are characteristics of forests with a higher capacity for water infiltration [5,9]. In contrast, degraded forests have lost or reduced this potential, leading to increased runoff and higher erosive potential.

The presence of native forests is therefore associated with water regulation, quality, and production, performing additional ecohydrological functions such as erosion control and sediment filtering, which strongly influence the physical and chemical parameters of watercourses [4,5,11,12]. The role of forests in these functions is closely linked to their position within the landscape. Forests located in the higher areas of river basins contribute to the formation of springs and regulate water availability in downstream regions, ensuring the quantity and quality of water at points of use and abstraction [1,4,13].

The Brazilian Forest Code (Federal Law N°. 12.651, of 25 May 2012) defines two main conservation areas: permanent preservation areas (PPAs) and Legal Reserves (ARLs). PPAs protect forests on hilltops, steep slopes, springs, and along watercourses, while ARLs focus on protecting forests inside the properties that could be managed. The protected area around springs, a circle of 50 m radius, and along watercourses, a 30 m (or more, depending on the river size) strip on each margin, are the principal protection mechanism of water sources and their vegetation in Brazilian policy. This Code has been controversial and recently modified, reducing the extent of native vegetation to be conserved on private properties and amnestying deforestation carried out before 2008. Some argue that these changes weaken the Code's role in protecting forests, with consequences for water resource protection [14,15].

Despite these legal protections, springs and watercourses depleted of their vegetation are common, and efforts to restore forests in the Joanes and Jacuípe river basins—key water sources for the Salvador Metropolitan Region—have been incorporated into ongoing restoration projects. These efforts aim to mitigate the negative impacts of land degradation while ensuring the sustainable management of water resources in the region.

About the "Project for the Forest Rehabilitation of Permanent Protection Areas of Rio Joanes and Rio Jacuípe—Metropolitan Region of Salvador—BA

This paper presents methodological elements used in the development phase of the "Project for the Forest Rehabilitation of Permanent Protection Areas of the Joanes and Jacuípe Rivers—Metropolitan Region of Salvador—BA", which aims at the rehabilitation of native vegetation around 100 springs and 100 hectares of marginal areas of these rivers. These are direct contributors to the reservoirs of the Joanes I and II dams and Santa Helena, which today are responsible for 38% of the water supply of the Metropolitan Region of Salvador (MRS).

Three targets have been established to achieve the project's main objective of improving MRS water supply and quality: TARGET 1—mobilization for the selection of small rural owners from the ten municipalities, which should result in the registration of 300 rural properties in CAR/CEFIR; TARGET 2—elaboration and implementation of 10 projects for the recovery of permanent preservation areas of the rural properties benefited and

monitoring of the recovery process of the areas; TARGET 3—elaboration of a regional payment plan for environmental services (PSA).

The project's work was carried out in two stages: in the first, a multi-scale spatial prioritization of the entire basin was performed; in the second, priority areas, as defined, were visited in loco for socio-environmental assessments at the microbasin and rural property level. This second stage resulted in specific diagnoses, as well as critical environmental education projects and proposals for environmental recovery actions with regard to revegetation.

The prioritization stage, described in this article, was carried out to identify the most important regions for water production and to present the best scenarios for forest recovery and the best responses mainly regarding the "production" of water. From the prioritization at this broader scale, and within the priority regions, areas containing rural communities with a profile of family agriculture that would accept the project and commit to its long-term maintenance of the natural areas to be recovered were considered at the local scale. This stage of prospecting for acceptance and commitment was carried out both through contacts with community leaders and representatives and during site visits, as well as at Project Management Unit (PMU) meetings, where these representatives participate together with the project's partner institutions and representatives from the seven municipal governments.

During the visits, with the objective of evaluations for producing critical environmental education and forest recovery projects, the university's field teams met with the communities to gather socio-environmental and economic information, to describe the project's possible actions on a local scale, and to clarify doubts. The main environmental issues were raised, assessing the current situations of permanent preservation areas (PPAs), of springs and riverbanks, both in relation to the quality and soil cover of the area as a whole, and the hydroecological conditions of various stretches of rivers and springs. In the field, the geographical coordinates of points and areas surveyed with the potential to receive environmental recovery actions were recorded. From this material, maps were constructed containing the location of the areas to be recovered, as well as a diagnosis of the local conditions and a recovery plan containing the necessary actions for the desired purpose.

This article presents the bases designed and considered for spatial prioritization at the basin scale, aiming at identifying the regions that would have preference and respond better to the development of the project, based on small family farms.

2. Materials and Methods

2.1. Description of the Study Area

2.1.1. Geographic Characteristics

The study area encompasses the Joanes and Jacuípe River Basins, which are located in the state of Bahia, Brazil. The total area covered by these two river basins is approximately 6.975 km^2, spanning across 18 municipalities. The basins are situated in a region characterized by a mix of urbanized areas and rural zones. Several cities, including Camaçari, Dias D'Ávila, Simões Filho, and Mata de São João, are located within the river basins, exerting significant pressure on the natural resources.

The Joanes and Jacuípe River are the main watercourses in this region. The rivers have different lengths, with the Joanes River being the main contributor to water flow into the Joanes I and II dams and other reservoirs that supply water to the Salvador Metropolitan Region.

2.1.2. Hydrological Characteristics

In terms of hydrology, the river basins have several important features:

River Flow: Both rivers have seasonal fluctuations in flow, with higher water flow during the rainy season and lower flow during dry periods. These fluctuations affect water quality and availability.

Streamflow Gage Stations: There are measurement sites located along key points in the rivers, including near the Joanes I and II dams. These gage stations measure river stages and flow, providing real-time data on discharge and water quality.

Standing Water: There are significant areas of standing water within the river basins, including reservoirs and wetlands. These are important for water storage and flood regulation, especially during the rainy season. The area around Camaçari and Simões Filho includes wetlands and floodplain regions that are crucial for the region's hydrology and biodiversity.

Artificial and Natural Retention: Natural retention is provided by riparian forests, while artificial retention occurs in dams and reservoirs (Joanes I and II). The combination of these natural and artificial features ensures a stable supply of water to the metropolitan region, particularly during dry periods.

2.1.3. Climatic Characteristics

The study area experiences a tropical climate, characterized by

Temperature: The average temperature varies from 24 °C to 32 °C, with the warmest months being from October to March. There is a marked difference between the daytime and nighttime temperatures, especially in the higher altitudes of the basins.

Precipitation: The region has a distinct wet season from April to August, with the wettest months typically being May and June. Precipitation ranges from 1.000 mm to 1.800 mm per year, with some areas in the higher elevations receiving more rain due to orographic effects. The rainfall is concentrated in these months, while the dry season can last from September to March.

Measurement Posts for Climate: The National Institute of Meteorology (INMET) has climate measurement posts scattered throughout the region. These posts collect data on temperature, humidity, and precipitation, which are essential for hydrological modeling and understanding water availability throughout the year.

2.1.4. Economic and Agricultural Use

The region has a predominantly agricultural economy, with some areas also focusing on industrial activities. Key agricultural activities include

Cattle Ranching and Agriculture: The lower areas of the river basins are used for extensive cattle grazing and crop cultivation, particularly sugarcane, cassava, and banana. These activities are concentrated in the lower, flatter regions of the basins.

Urbanization: The growth of Camaçari, an industrial hub, as well as nearby cities like Dias D'Ávila and Simões Filho, has led to significant urbanization and industrialization within the river basins. This has put pressure on natural resources, especially water quality in the rivers due to industrial effluents and untreated domestic sewage discharge.

Environmental Impact: Agricultural practices, particularly those that involve deforestation, as well as urban expansion, have resulted in soil erosion and water pollution, significantly impacting the natural habitats and ecosystems of the region.

2.2. Development of Estimated Criteria and Measurement Units

The upgrade was developed to quantify and prioritize areas with the greatest potential for water production, considering factors such as the density of springs (which directly reflects the recharge of aquifers) and forest cover (important for maintaining water quality and regulating the hydrological cycle). This breakdown was formulated based on collabora-

tion between several public environmental agencies and university researchers, in addition to field data obtained throughout the project.

The adoption of this planning aimed to prioritize areas that contribute significantly to the basin's water resources, especially considering the increased demand for water and the manipulation of natural ecosystems. The emphasis on the density of springs and vegetation cover aims to identify regions with the greatest capacity to recharge aquifers, improve water quality, and mitigate erosion.

This objective was inspired by scientific studies and national environmental policies, such as the Brazilian Forest Code, which highlights the importance of forest conservation in protecting water resources.

The units of the variables used in the prioritization are

Spring Density (springs per square mile): Expresses the number of springs per unit area (km^2), calculated by dividing the total number of springs in a specific area by the total area in km^2.

Percentage of Forest Cover: Expresses the percentage (%) of the area covered by native forests in relation to the total area of the analysis unit (hexagon).

These two parameters are combined in a weighted algorithm, with spring density given greater weight due to its direct relationship with water production. Forest cover and property density are also considered, based on their relevance to the success of forest recovery. Finally, the weights of the variables used in the prioritization algorithm were established through a participatory process, during which all the researchers and technicians from environmental and social public agencies discussed the importance of each variable related to water production and resilience capacity.

2.3. Methodological Procedures Developed

This item presents the methodological procedures, criteria adopted, and other information regarding approaches at the broad scale, or river basin level, and at the local scale, where the elements and information considered were of greater detail. For the construction of the methods, some rounds of suggested criteria were carried out, including the various project participants: Bahian Water and Sanitation Company (EMBASA), Institute of Environment and Water Resources (INEMA), National Institute of Colonization and Agrarian Reform (INCRA), Federal University of Bahia (UFBA). During the meetings, several elements of the participants' expertise were brought in, in addition to the information obtained during the field visits by the project teams. As mentioned at the beginning of this item, different criteria were adopted at different spatial scales:

- **Macro-scale criteria**, directly related to the production and maintenance of water quantity and quality;
- **Meso-scale criteria**, involving a landscape analysis aimed at assessing the quality and quantity of vegetation present, which is related to facilitating recovery processes, effectiveness, and lower cost;
- **Criteria at the local scale**, for the selection of the areas where the planning and recovery actions will be effectively executed, involving the possibilities of perennialization of the actions, which depends on the acceptance of the project by the owners and the local organizational potential, besides the quality of the area to be restored and its insertion in the microbasin.

2.3.1. Macro- and Meso-Scale Analysis—Identification of Areas with Potential for Forest Recovery and Water Production

The large extension of the river basins considered in this project and the impacts of the main environmental problems that are currently occurring in the Joanes and Jacuípe

Rivers, as well as the heterogeneity of the basins areas for water production, the high cost of restoration of degraded areas, the size of the Joanes and Jacuípe River basins, and the limited time to travel through them, have led to the need to prioritize the areas to receive environmental recovery actions. For this, it was necessary to carry out a regional diagnosis and later, in a participatory process, select the criteria for the prioritization of actions.

The Joanes and Jacuípe river basins occupy a large territorial extension, overlapping with 18 municipalities distributed in about 6.975 km^2, close to large urban centers and a petrochemical industrial complex. Among the environmental problems found in the basins of interest are (a) the wide and diffuse occurrence of erosive processes and silting of river gutters and water reservoirs used in the supply; (b) the discharge of untreated industrial and domestic effluents into these bodies of water, which has generated exaggerated flowering of cyanobacteria and too much growth of macrophytes, negatively impacting water quality; and (c) agricultural activities, irregular occupations, and deforestation of permanent preservation areas (PPAs).

Given the high cost of restoring degraded areas, especially on riverbanks, there is a need to prioritize the areas to receive the actions, and in this way, to list exclusively technical criteria for the selection of natural areas. In this way, it was sought to ensure that the areas chosen had greater adherence to the objectives and targets of the project and the established criteria.

The criteria and methods used to prioritize the areas to be recovered are presented below, along with the product synthesis of this analysis in the form of a priority map. Based on this prioritization, the 10 most relevant areas were selected for more detailed analysis, to receive the actions of forest restoration of springs and PPAs.

To produce the map of priority areas, we initially sought to evaluate some criteria on a broader scale (macro scale) that are directly related to the production and maintenance of water quantity and quality. These criteria were used for the selection of regions within the total area of the project, which includes the Joanes and Jacuípe river basins. Within these selected regions, prioritization included a landscape analysis (meso scale), assessing the quality and quantity of vegetation present. These factors are related to the facilitation of the recovery processes and ecological stability of the forest implemented in the medium and long term.

The following are the development stages of macro- and meso-scale analyses:

2.3.2. General Diagnosis of the Vegetation Coverage of the Joanes and Jacuípe River Basins

The diagnosis was made through field visits, aerial image analysis, and land use and occupation mapping of the regions covered by the project. With this material, it was possible to assess the types of vegetation found in the Joanes and Jacuípe river basins and to detect some of the main vectors of degradation and threat to the remaining forest cover. It was also possible to diagnose part of the flora and identify situations that may favor regeneration processes and the recovery of degraded areas.

The Joanes and Jacuípe river basins are inserted in the Atlantic Forest domain, currently occupied by the urban meshes of several municipalities in the metropolitan region of Salvador (Figure 1). Most of the area is occupied by agriculture or cattle raising, and there are also some areas of eucalyptus plantations.

Forests at different stages of regeneration, associated with humid areas and coastal formations, make up the set of native vegetation (Figure 1). Most of the forests are in an initial and medium stage of regeneration, indicating the intense level of impact on the remnants. They are found in small fragments, usually isolated in the landscapes and in the highest portions of the land. There are few riparian forests currently occupying riverbanks. Currently, there is also the expansion of the urban network as a factor of pressure on the

remaining forest fragments, especially near the urban centers of Camaçari, Dias D'Ávila, and Simões Filho and some localities in the municipality of Mata de São João. Besides the pressure close to the urban centers, consolidated agricultural activities occupy a large part of the area, including the PPAs of riparian forests and springs. Close to the pasture and sugarcane areas, especially, the remaining forests suffer pressure from fire and irregular deforestation, in addition to pressure from wood and firewood removal.

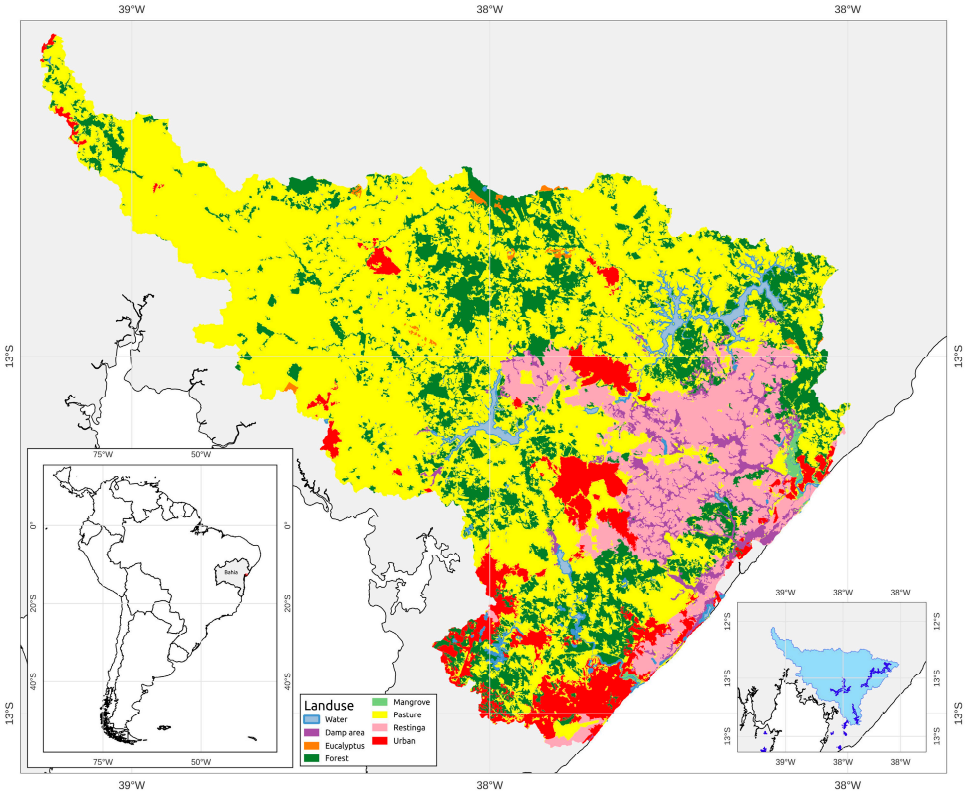

Figure 1. Map of the study area showing land use and land cover, as well as the hydrographic basins under study in the Joanes and Jacuípe River Basins, Bahia, Brazil.

The regions closest to the coast present a set of wetlands, associated with flat reliefs, near the drains. Most of these areas are now quite anthropized, occupied by livestock and generally lacking any riparian forest. Because they are located in the river deposit areas, they receive the enormous load of sediments coming from the region. This process is intensified by the advanced upstream occupation, especially with pastures that have little or no soil conservation technique. Due to the strong siltation, these areas are covered by aquatic vegetation dominated by taboos (*Tipha* sp.) besides grasses, cyperaceae, and reedbeds, which are indicators of anthropized areas.

A large number of springs are found within the basins of both rivers, associated with different types of land use and occupation (Figure 1). Greater densification is found in the central portion of the basin, associated with a set of small mountains in the municipalities of Camaçari and Dias D'Ávila. The distributions of the springs, as well as the hydrographic network, give differentiated importance to some regions of the basins of the two rivers, especially in relation to the production of water for the basin. The density of springs was used in the project to prioritize environmental education and restoration actions. This density here is understood as simply the "number of springs per area, number of springs/km^2" (Figure 2)

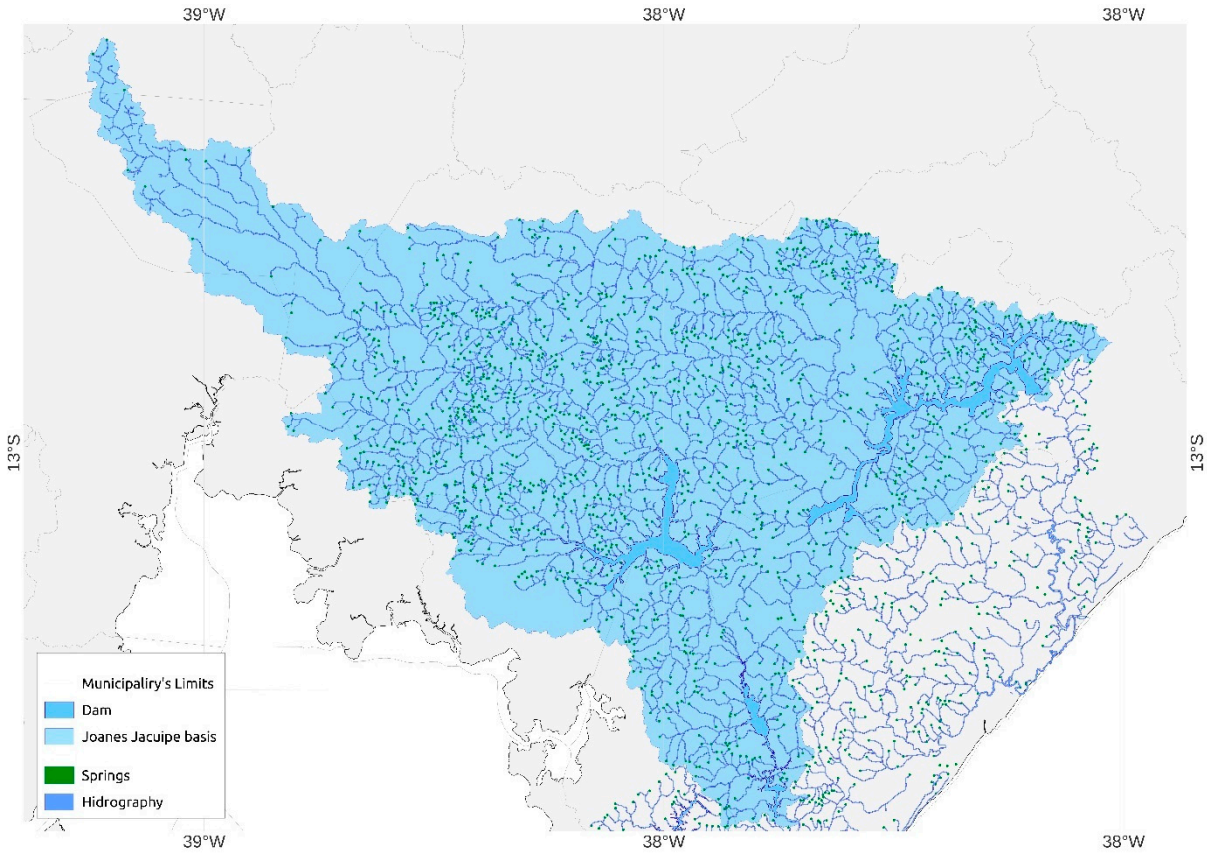

Figure 2. Hydrography in blue and riverbanks covered with green riparian forests in the Joanes and Jacuípe river basins, Bahia.

In contrast to the hydrographic network with the current coverage, it is possible to evaluate the total (to avoid confusion with the term upstream/downstream) of areas of permanent preservation of river margins that, currently, still have coverage with riparian forests (Figure 1). It is also possible to evaluate which regions present the deficit of forested PPAs.

2.3.3. Description of the Environmental Criteria Adopted

The physical characteristics of precipitation, hydrogeomorphology, and number of springs per area, associated with a diagnosis of the basin occupation, including rural communities and the state of vegetation cover, were used to develop the criteria and methods for prioritization.

The environmental criteria are described below:

(I) Criteria for selecting areas on a macro scale

In the present study, the macro-scale landscape was understood at the level of river basins, namely the Joanes and Jacuípe river basins. The process of prioritization at the macro scale comprised the following steps:

i. Definition of the total area to be analyzed;
ii. Definition of the size of smaller work units that will be effectively classified;
iii. Selection of the characteristics to be used in the classification and the levels that these variables may assume;
iv. What weight each variable will have in the process of evaluating the total area.

This process causes each smaller unit to receive a score based on the level of each characteristic considered and its weight, through a simple algorithm. The units with the highest grades are then selected and highlighted in red on the map. It is worth noting that

these units are then analyzed using meso-scale variables, the scale of a microbasin, and later the local scale (rural property), i.e., at the level of the rural property, to define where forest recovery actions will be executed.

The region was divided into hexagons, each with a side length of 1 km and an area of 25.980 km^2. This unit size allowed the use of the different available spatial data, including the physical variables of soil, rainfall, hydrology, relief, and density of buildings. Among the criteria involved in water production selected by the team, several are autocorrelated (redundant) in space, and all are correlated with the density of springs themselves. This variable, then, synthesizes this set of characteristics with little loss of information, besides being a direct reflection of the importance of the site for the "production" of water. As this variable brings together hydrology, relief, and precipitation information and is directly related to the "production" of water, the focus of the project, it has received the greatest weight from the prioritization process, and this methodology is best described in the items that follow. Three categories of densities of springs/km^2 were established, according to Table 1.

Table 1. Categories of the "Spring Density" criterion.

Number of Springs/km^2	Spring Density
0	Low
1 to 5	Average
>5	High

The existence of vegetation cover in the vicinity was listed as a macro-scale criterion for the selection of areas. The percentage of forest cover in the landscape is a variable strongly related to the natural resilience of vegetation and its capacity for self-regeneration. Therefore, this vegetation variable was also included in the classification process. Since part of the river basins lies within consolidated urban areas, which even meets the established criteria that natural areas should be located exclusively in rural zones, it was decided that one of the criteria would be the presence of a low density of properties, with a higher score given to areas with lower property density and fewer constructions.

The macro-scale selection criteria were used to generate the prioritization of each hexagon using the following expression:

$$\text{Priority} = (\text{density of springs}) \times (5) + (\text{percentage of forests}) \times (3) + (\text{number of properties}) \times (-1)$$

Thus, the areas with more springs have greater weight, followed by the existence of forest in the surroundings and the areas with greater densities of real estate (urban) with lower values in prioritization.

Criteria for Selecting Meso-Scale Areas

The meso scale means the landscape contained in a microbasin and in the immediate surroundings of a rural property that has the potential to receive the actions. Some variables were defined regarding the maintenance of structural connectivity of vegetation (possibility of physical continuity or proximity to forest nuclei with good ecological conditions). The connectivity of forest fragments is related to the dispersion of seeds and animals and, thus, to the gene flow between species of flora and fauna. This connection of fragments also facilitates the recovery process of degraded areas and increases the possibilities for water production. The categories indicated in Table 2 were defined as classes for the connectivity potential.

Table 2. Categories of the "Connectivity Potential" criterion.

Distance Between Forest Fragments	Potential for Connectivity
>1000 m	Low
500 to 1000 m	Average
<500 m	High

In addition to connectivity, the size of the forest fragment close to the areas was also considered in the selection criteria. Based on the reality of the existing fragments in the project region, Table 3 presents the corresponding categories.

Table 3. Categories of the "Size of Forest Fragment" criterion.

Size of the Forest Fragment	Environmental Quality
<50 hectares	Low
50 to 100 hectares	Average
>100 hectares	High

The quality of the fragment has to do with its history of use and disturbances. One aspect is the stage of vegetation regeneration. For the present project, the classification of the successional stages by the National Environmental Council (CONAMA) is being considered (CONAMA RESOLUTION n° 33, of 12 July 1994). Other aspects are related to the integrity and existence of ecological groups of plants (most apparent beings), such as large trees, belonging to the climatic species and producing fruits that attract fauna, epiphytes, and underwood herbs. This quality of the area is also associated with its resilience conditions, which means that it is able to contribute again in a shorter term, with the functioning of biotic communities and the maintenance of the water quality of the system (water cycle). The higher the quality, the greater the potential for its regeneration and the fewer anthropic interventions for recovery will be necessary. The categories adopted here for the quality of the area are indicated in Table 4.

Table 4. Criteria categories based on soil coverage, erosive processes, degree of surface runoff, soil loss, and presence of fauna.

Environmental Criteria	Environmental Quality
Absence of land coverage Erosive criticism High surface runoff rate High soil loss Absence of fauna	Low
Presence of land coverage (pasture) Medium erosive processes (presence of ravines) Average runoff rate Starting soil loss Low presence of fauna	Average
Presence of land coverage (secondary forests) Absence of erosive processes No soil loss Presence of fauna	High

The size of the area to be restored is the continuous area on the property or rural properties that needs the restoration actions foreseen in this project. The larger this restored

area, the greater the chances of functional communities recovering, so the potentials vary from low to high for the criteria indicated in Table 5.

Table 5. Categories of the criterion "Size of Fragment to be Forested".

Size of Fragment to be Forested	Potential
<1 hectare	Low
1 to 10 hectares	Average
>10 hectares	High

2.4. Selection of Assigned Weights to Individual Variables

The weights assigned to the individual variables in the prioritization algorithm were determined based on their relative importance for achieving the goals of water production and forest restoration in the study area. The selection of weights was performed through consultation with experts from various environmental public bodies, as well as through analysis of field data and the scientific literature on hydrology and ecological restoration. The variables were assigned the following weights:

Density of Springs: Weight = 5

The density of springs is the most important variable, as springs directly contribute to groundwater recharge and surface water flow, which are crucial for water production. The higher the density of springs in a given area, the greater its potential for replenishing water resources. This variable received the highest weight (5) because of its direct and significant impact on water availability.

Percentage of Forest Cover: Weight = 3

Forest cover is the second most important variable, as it plays a key role in regulating water quality and maintaining the hydrological cycle. Forests, particularly riparian forests, help prevent erosion, increase water infiltration, and contribute to water storage in the landscape. This variable was assigned a weight of 3, reflecting its strong but secondary role in the restoration process.

Property Density: Weight = -1

Property density was assigned a negative weight of -1, indicating that areas with higher densities of properties and urbanization are less favorable for restoration. High property density can reduce the feasibility of implementing forest restoration actions due to competing land uses and the challenges of engaging local communities. This negative weight reflects the challenge of working in highly developed or densely populated areas.

These weights were applied to each variable in the prioritization algorithm, and areas with higher scores for these weighted variables were prioritized for forest restoration activities aimed at improving water production.

In Figure 3 we can observe the flowchart of the multi-scale methodological framework for identifying and prioritizing forest restoration areas aimed at enhancing water production in the Joanes and Jacuípe River Basins, Bahia, Brazil. The process is structured across three main analytical scales: the macro scale, where priority zones are identified based on hydrological and ecological indicators such as spring density, forest cover, and property density; the meso scale, which deepens the ecological assessment by considering forest fragment connectivity, patch size, and environmental factors including soil erosion,

land cover, surface runoff, and fauna presence; and the local scale, where the practical feasibility of restoration is evaluated based on landowner engagement, local governance capacity, and site-specific conditions. The outcome is a priority map highlighting viable areas for restoration, with methodological flexibility that allows parameter adjustments for application in other regions.

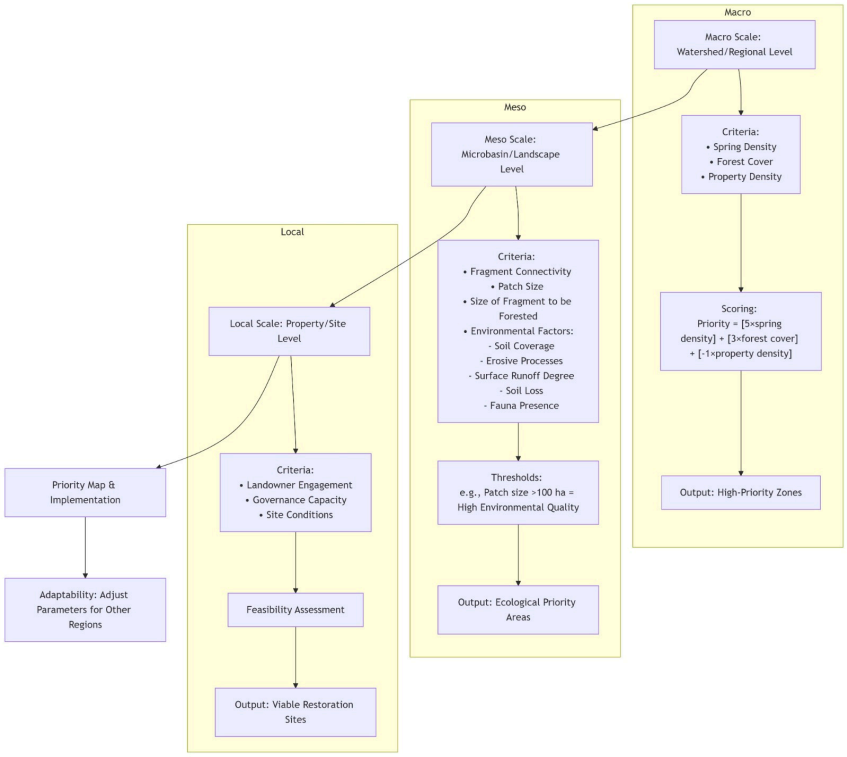

Figure 3. Flowchart of the multi-scale methodology for prioritizing forest restoration in the Joanes and Jacuípe River Basins, Bahia, Brazil. It integrates macro (regional), meso (landscape), and local (site) analyses based on ecological, hydrological, and social criteria to identify viable areas for water-oriented restoration.

2.5. Methodology Adopted for Map Elaboration

As previously mentioned, the selection of technical criteria was the result of discussion between several public institutions managing the region together with the university and its researchers. The application of the prioritization and production algorithm of the map itself was supervised by the Geoprocessing sector of the state environmental agency, being reviewed by researchers. The study area was determined between the Joanes and Jacuípe Basins, in the north of the State of Bahia, to define the areas with the greatest potential for restoration, and four stages were followed, namely

1ª—Division of the study area into smaller reference units with a hexagonal format, each with a side length of 1 km and an area of 25,980 km^2;

2ª—Obtaining information on native vegetation, rural properties, springs, and soil within each hexagon, standardized for the entire region;

3ª—Weighting the relative importance of this information for the composition of the final map;

4ª—Generation of the layout for viewing.

For each hexagon, the percentage of native vegetation, the density of springs, the average of the density of the buildings, and the average of the weights for the soil classes were calculated. The percentage of native vegetation was calculated by the ratio of the forest area to the total area of the hexagon. The identification of the forests in the region was

made from the diagnosis of the use and vegetation cover in the area, mapping the classes by visual interpretation of the Sentinel-2A satellite matrix input from 8 September 2016. The scale of the vector product was 1:40,000, and the legend applied for the mapping contemplated forest (Dense Ombrophylous Forest), urbanized areas, pasture and water.

The density of each hexagon's springs was calculated from a map of the probable springs in the region, produced based on the starting points of drainage under the hydrography map of the Superintendence of Economic and Social Studies of Bahia (SEI-BA), on a scale of 1:100,000. The average property density was obtained from IBGE 2010 Census data, by census sector. The soil classes were obtained from IBGE soil mapping on the scale of 1.1.000.000, which were weighted by specialist considering the potential for water production and percolation. In order to ponder the relative importance of these inputs, the attribute values of the variables were standardized, maintaining a scale of variation from 0 to 1, in order to avoid bias from the magnitude of values existing in each data.

The relative weight among the variables was attributed by a specialist: the percentage of vegetation had a weight of 3, density of springs had a weight of 5, density of buildings had a negative weight of 1, and soil type had a weight of 3. The higher the value, the greater its importance in the composition of the final map. Positive values reflect aspects that promoted the restoration, while negative values reflect variables that were unfavorable to the restoration. After weighting, a map was generated indicating a gradient of values assigned to each hexagon, representing the priority for restoration, ranging from 0 to 1. The final result (Figure 4) was presented in a cartogram format, where larger values were represented in warmer colors (shades of red), indicating the areas with the greatest potential for forest restoration, and smaller values were represented in colder colors (shades of yellow), representing areas with less propensity for forest restoration.

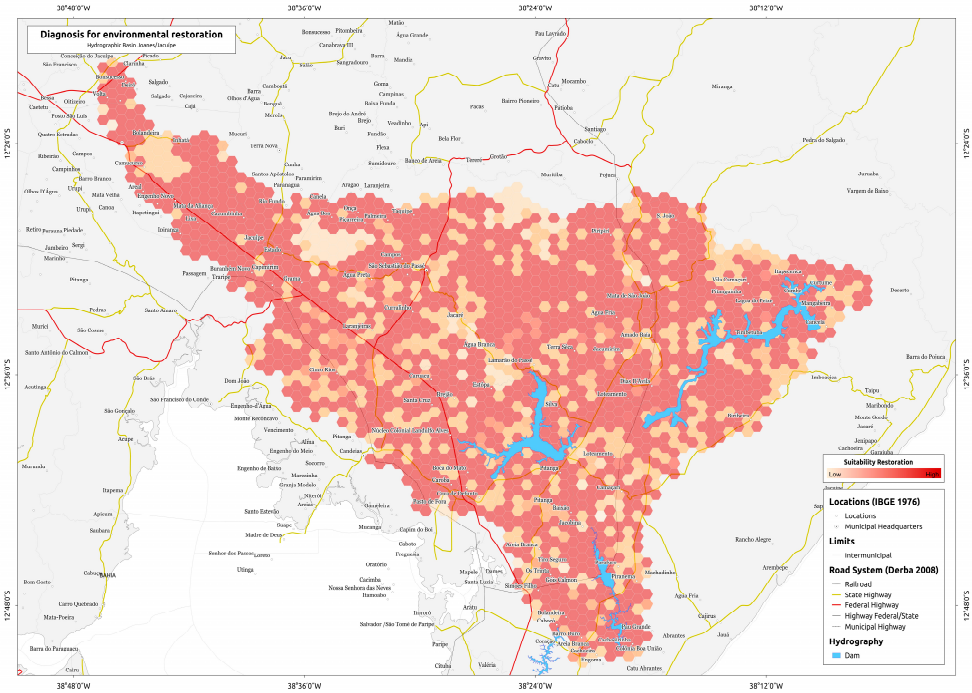

Figure 4. Prioritization map of areas for the selection of communities that participated in the project in the Joanes and Jacuípe river basins. Note: The areas in dark red are the most relevant in the prioritization for the project aiming at water production, while the lighter areas with the lowest values have less relevance.

2.6. Local-Scale Analysis—Identification and Delimitation of Areas for Forest Restoration

Starting from a macro-scale assessment aimed at identifying areas with greater potential for water production, associated with forest degradation conditions and requiring their recovery, a second stage of work was carried out associating socio-environmental assessments in the field with an analysis of satellite images with a greater level of detail.

Two approaches are presented in this process: first, the socioeconomic and organizational criteria of the communities considered, and then, the method designed for the local physical evaluation of the forest conditions and the potential of water production, characterized as hydroecological condition in this work.

2.6.1. Socioeconomic and Organizational Aspects of Communities

On a local scale, the possibilities of installing the restoration project were evaluated, regarding the existing organizational structure and the possibilities of accepting the project and perpetuating the recovered areas. This information was obtained during the preliminary visits to the communities and also obtained after the property registration phase at CEFIR (State Register of Rural Property Forestry). In addition to these characteristics, the quality of the areas to be recovered, in relation to the history of disturbances, and the effort or cost required for recovery were also used as criteria. Finally, the size of the area that can be recovered was also used as a criterion for prioritization. In this micro-scale context, it should be noted that these organizational issues are difficult to measure and map spatially. Thus, for the final definition of the criteria and of the information to be considered, the support of the representatives of the municipalities and communities in the Project Management Unit was essential, given that they hold or obtain more precise local information. For these social and organizational variables, the following was basically considered:

Presence of Organizational Structure: Organizational structure is related to the presence of organizations representing the beneficiary public of the project (associations, cooperatives, leadership groups, etc.), where in these organizations there is a minimum understanding of the issues of preservation and environmental education, as well as practices and experiences with preservation and environmental education. The areas will be classified as

Low Organizational Potential: Absence of organizations (associations, cooperatives, leadership groups, etc.) + little or low knowledge in relation to environmental preservation and education + absence of experience and practice with preservation and environmental education.

Medium Organizational Potential: Presence of organizations + little or low knowledge in relation to environmental preservation and education + presence of limited experience and practice with preservation and environmental education.

High Organizational Potential: Presence of organizations + high knowledge in relation to preservation and environmental education + develops day-to-day experience and practice with preservation and environmental education.

2.6.2. Physical Aspects—Forest State Index (FSI) and Hydroecological Condition

The health and functional condition of riparian ecosystems and associated water bodies should be assessed for their preservation or recovery. Standardized assessment protocols are useful and necessary in order to effectively measure their functional and health condition, as well as to serve as a guide for future recovery and/or monitoring programs. In Brazil, more specific guidelines for this purpose are not yet systematically practiced, nor are they formalized in the legal and normative framework of environmental and water resources management systems. Also, protocols usual in other countries are obviously developed for their local conditions. Thus, it was necessary to think about the specific local conditions in order to propose a protocol valid in our reality, besides considering the

resources available for its application. The so-called "Rapid Assessment Protocols (RAPs)", quite well established in the USA [16,17]) and Europe [18], and also already employed in Brazil [9,19], constituted the basis for the development of the protocol applicable in this project. This allowed an evaluation synthesis in the form of an index called the Forest State Index (FSI), and from it, recovery actions were defined for each location.

In order to converge with the proposed actions for forest recovery, the hydroecological condition of the degraded micro areas was diagnosed through the use of the FSI. The aforementioned "micro areas" refer to permanent preservation areas (PPAs), in the surroundings of springs and on the banks of streams and rivers. The location of the communities in which they are located was oriented in the map of priorities for water production and forest recovery, shown in Figure 4.

Springs and watercourses were evaluated according to the FSI, which consists of two sections:

(i) Assessment of riparian vegetation;
(ii) Quality of the system and of the drainage or fluvial channel.

This information was taken at the springs and in stretches of 100 m along some drains and rivers assessed during field visits. The two sections include ecological aspects (riparian and corridor vegetation) and hydrological, engineering, and morphological aspects (channel system and quality) and topography, in addition to soil and water quality.

Each component is divided into subcomponents, where the attributes to be evaluated are described. In turn, each subcomponent is made up of elements, which are the variables to be analyzed, in the field or in a cabinet according to the spatial scale of the assessment.

Index Sections:

i. Section 1—assessment of riparian vegetation

The first section is composed of five metrics:

- Integrity of arboreal vegetation;
- Longitudinal continuity;
- Transverse connectivity and coverage of arboreal vegetation;
- Quality and structure of vegetation;
- Regeneration of vegetation.

This section was structured to allow assessing the degree of disturbance in the vegetation and riparian corridor, due to its great importance for rivers. Within this component, the abundance and diversity of riparian vegetation is assessed. This component is evaluated at a meso-scale level and can be evaluated in the field or in the office using satellite images. In the cabinet study, estimates of the coverage and structure were made by photointerpretation, which were confirmed and calibrated in the field.

In the study of the riparian corridor, the degree of fragmentation of the corridor with its surrounding ecosystems was assessed, as well as whether its width (in relation to the banks of the watercourse) is sufficient to perform the typical functions of a riparian area. In this item, we also evaluated the longitudinal connectivity, transversal connectivity, and extension of the riparian corridor.

ii. Section 2—quality of the system and of the drainage or fluvial channel

Section 2 has three metrics:

- Vertical connectivity;
- Bank conditions and naturalness of the canal;
- Substrate and soil conditions.

This section assesses whether the system maintains a certain naturalness that allows it to maintain a certain degree of macro-scale functionality, such as annual flood events

where hydrograms (if available) can be used, whether the system allows and facilitates the exchange of energy and mass between the riparian area and the river, and whether the system maintains river sediment transport dynamics for the maintenance of the margins and the regeneration of native riparian vegetation. Within this component, the existence of a floodplain where the dissipation of energy from natural floods can take place is also considered. This section also evaluates the naturalness of the river, changes in the channel, and the presence of anthropic structures such as dams, dikes, and canalizations, among others. These structures can cause great interference in the aquatic and terrestrial flora and fauna due to the retention of sedimentation, causing erosion of the margins and consequential silting, breaking the horizontal and transversal connectivity, besides nutrient and pollutant accumulation [18,20].

Synthesis and elements concerning the above sections are presented in painting 2. Once the elements of analysis are parameterized and converted to the FSI (Appendix A, Tables 6 and 7), the hydroecological condition of the areas is categorized, as shown in painting 3.

Table 6. Metrics used in the elaboration of the FSI index and parameters analyzed to characterize the areas.

Metrics Assessed	Description	Parameters Analyzed
Integrity of arboreal vegetation	Evaluation of arboreal quality and composition.	Percentage, composition, and vegetation structure.
Longitudinal continuity	Analysis of the effects of anthropic activities on the continuity of riparian vegetation.	Effects of linear, perpendicular, or diagonal works on the canal.
Transverse connectivity and arboreal vegetation cover	Assessment of riparian corridor connectivity and degree of habitat fragmentation.	Effects of various anthropic activities.
Quality and vegetation structure	Effect of riparian vegetation on the quality of the river canal.	Percentage of exotic and native species and their influence on bank stabilization.
Regeneration of vegetation	Analysis of human activities that impede vegetation regeneration.	Effects of pesticides and farming activities.
Vertical connectivity	Vertical connectivity between the canal and riparian zone in a way that allows the mobility of sediments and nutrients.	Evaluation of vertical connectivity in sediment and nutrient mobility.
Bank conditions (lateral connectivity)	Evaluation of the physical and supporting conditions of the banks.	Effects of bank stability on canal and vegetation.
Naturality of canal and substrate	Evaluation of the degree of naturalness of the canal.	Evaluation of the effects of transversal infrastructure and other anthropic actions.
Soil conditions	Assessment of soil conditions according to the geology of the region.	Analysis of the effects of intensive land use or degradation conditions.

Table 7. Interpretation of the total score of the FSI and basin management options (adapted from Munné et al., 2002; González et al., 2010) [18,20].

Score	Condition	State of the Attributes. Type of Management Required.
P > 325	**Excellent**	Riparian attributes under natural conditions, with specific threats to their functioning. Great interest in conservation and protection to maintain the current status and avoid future changes in the riverine and river ecosystem. Measures that favor the regeneration of native species, filling, fencing, and protection may be necessary.
199 < P < 325	**Good**	Most attributes are in good or very good condition; one or two parameters may be altered. Riparian systems need protective measures to prevent potential new impacts and restoration measures to achieve full integrity of ecological functions. Eliminate pressures and impacts as much as possible. Measures to favor the regeneration of native species, fencing, and protection may be necessary.
112 < P < 199	**Regular**	Several attributes are moderately altered. The river ecosystem and especially the riparian vegetation require restoration measures to ensure adequate hydrological and ecological functioning. Eliminating or reducing pressures and impacts as much as possible is necessary. Measures that favor the regeneration of native species, fencing, and protection are necessary.
P < 112	**Poor**	Several attributes have been altered. The hydrological condition and ecological functions are reduced. The river and riverine ecosystem requires rehabilitation or restoration measures to gradually reintroduce or improve ecohydrological functions. It requires reducing possible pressures and impacts yet restoring the social perception of river degradation. Measures that favor the regeneration of native species, fencing, and protection are essential for recovery.

2.6.3. Analysis of Land Use and Occupation and Forest Cover of the Areas

Land Use, Occupation, and Forest Cover Assessment

The assessment of land use, occupation, and forest cover in the study area was conducted using an integrated approach that combined remote sensing, geospatial analysis, and field validation. High-resolution satellite imagery (Sentinel-2A, Google Earth, and Bing Maps) and official cartographic datasets from INEMA were processed to classify land cover types and detect anthropogenic impacts on permanent preservation areas (PPAs), riverbanks, and springs. Additionally, spatial data on properties, settlements, and quilombola communities were provided by INEMA.

A preliminary phase of the project involved environmental regularization efforts, including the registration of 319 rural properties in a proprietary system provided by the competent public bodies, which provided georeferenced boundaries for land tenure assessments. The spatial analysis focused on identifying the presence or absence of native vegetation within these properties, particularly in PPAs, and mapping forest patches that could serve as propagule sources for natural regeneration. The classification process employed supervised image analysis techniques, integrating machine learning algorithms to differentiate between native forest remnants, pasturelands, croplands, urban settlements,

and degraded areas. The accuracy of this classification was enhanced through ground-truthing field surveys conducted across multiple sampling sites.

Once the remote sensing analysis was completed, field visits were conducted to validate geographic data, assess vegetation conditions, and identify restrictive factors impacting forest recovery. During these visits, the executing team, guided by local community members, mapped springs and riverbanks, classified vegetation according to successional stages [1], and identified species composition. The survey categorized tree species into functional groups, including fast-growing pioneers, long-lived hardwoods, fruit-bearing species that attract fauna, emergent canopy species, understory palms, flood-adapted species, and economically valuable species. Additionally, exotic species with high colonization potential and those inhibiting forest regeneration were documented to guide targeted restoration actions.

Beyond vegetation assessments, faunal indicators were surveyed to evaluate ecosystem resilience, particularly the presence of seed dispersers and pollinators such as native bees, birds, and terrestrial and arboreal mammals. This biological assessment informed the prioritization of restoration areas, ensuring ecological connectivity and long-term sustainability.

The spatial arrangement of land use elements, hydroecological diagnoses, and floristic composition data were synthesized to develop site-specific forest recovery plans. These plans, structured within the broader landscape prioritization framework, ensured that restoration strategies aligned with both hydrological and ecological objectives. An example of the final detail of an area designated for forest restoration is illustrated in Figures 5 and 6, referring to the Nova Panema Settlement.

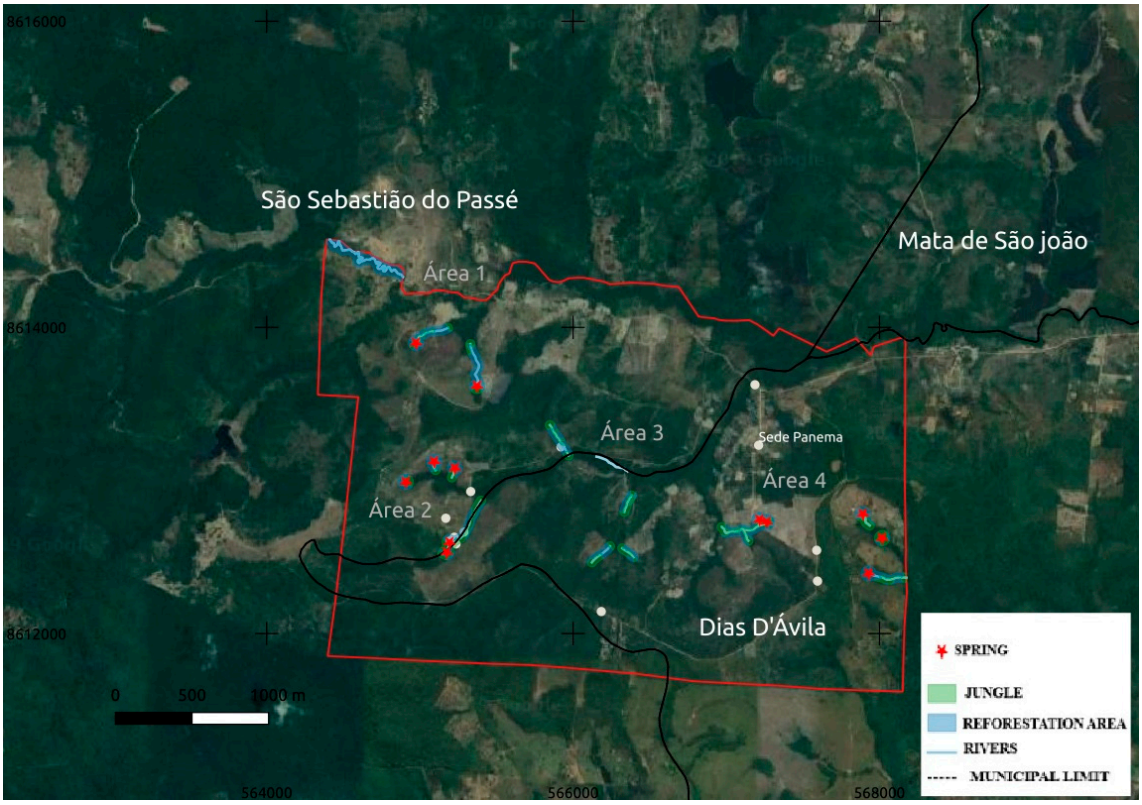

Figure 5. General appearance of the areas to be restored at the Nova Panema Settlement (municipalities of Dias D'Ávila, S. Sebastião do Passé, and Mata de São João, Bahia): location of the settlement's perimeter and the sites for PPA and spring recovery.

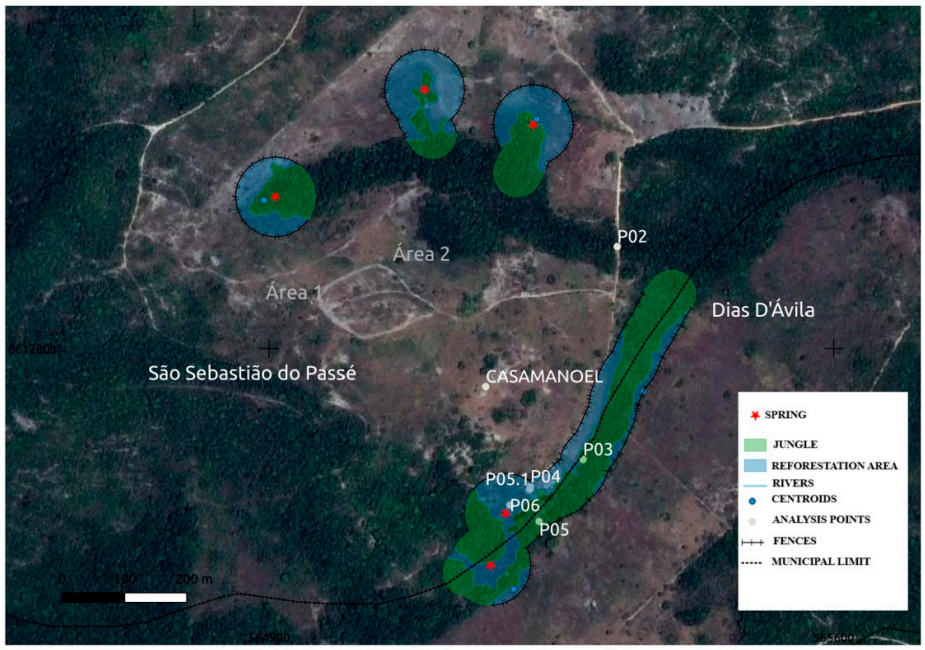

Figure 6. Detail of the proposed recovery actions—example, Area 2, Nova Panema Settlement.

3. Conclusions

This study demonstrates the importance of prioritizing areas for forest restoration to enhance water production and quality. By integrating multi-scale hydrological, ecological, and socio-environmental criteria, the proposed methodology effectively guides restoration efforts in the Joanes and Jacuípe river basins, which are essential for the Salvador Metropolitan Region's water supply. The restoration of riparian zones and springs, through strategic planning and collaboration, will not only improve water security but also contribute to the long-term ecological sustainability of the region. Despite legal challenges, these restoration initiatives are crucial for mitigating environmental degradation and ensuring a reliable water source for both urban and rural communities.

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Appendix A. Index Created for Verifying GIS Data During Fieldwork

The protocol for the field assessment of forests and riparian ecosystems is presented below.

Forest Condition Index—FCI

Municipality:	Location:	Site:
Date:	GPS coordinates:	
Researcher name:	Number of photos:	

Forest area ( ) Riparian area ( ) Degraded area ( ) Other _____
Soil sampling ( ) # of samples: _____ Water sampling ( ) # of samples: _____
IF FOREST AREA:
Section 1: Assessment of riparian vegetation and corridors

1. Integrity of Tree Vegetation					
1.1 Percentage of continuous canopy cover.	0–20%	20–40%	40–60%	60–80%	80–100%
1.2 There is connectivity between the assessed vegetation and the remaining forest/woodland.	0	3	6	9	15
1.3 Level of human activities in the area under assessment (urban area, agriculture, construction, roads, others).	15	9	6	3	0
1.4 What is the level of confinement of the vegetation? (Existence of limitations such as roads, paths, neighbors' land, other structures.)	15	9	6	3	0
1.5 Percentage of area occupied by agriculture.	15	9	6	3	0

Integrity of tree vegetation	

1—Condition	Excellent	Good	Regular	Poor
Score	60–37	36–25	24–13	12–0

2. Longitudinal Continuity	0–20%	20–40%	40–60%	60–80%	80–100%
2.1 The tree community is continuous along the river, covering at least 75% of the natural area?	0	3	6	9	15
2.2 Linear, perpendicular or diagonal works in the area such as dams, dikes, bridges, paths and others.	15	9	6	3	0
2.3 Existence of human activities that interrupt the longitudinal continuity of the corridor.	15	9	6	3	0

Longitudinal continuity	

2—Condition	Excellent	Good	Regular	Poor
Score	45–28	27–10	9	8–0

3. Transverse Connectivity and Tree Cover.	0–20%	20–40%	40–60%	60–80%	80–100%
3.1 What is the level of cross-connectivity of the corridor?	0	3	6	9	15
3.2 Level of anthropogenic activities that break the transversal connectivity of the corridor	15	9	6	3	0
3.3 Degree of habitat fragmentation.	15	9	6	3	0
3.4 Level of occupation of the area by urban areas or agricultural activities, among others	15	9	6	3	0

Transverse connectivity and tree cover

3—Condition	Excellent	Good	Regular	Poor
Score	60–37	36–25	24–13	12–0

4. Vegetation Quality and Structure	0–20%	20–40%	40–60%	60–80%	80–100%
4.1 Tree cover level	0	3	6	9	15
4.2 Presence of native tree species	0	3	6	9	15
4.3 Exotic species of trees, shrubs and herbaceous plants.	15	9	6	3	0
4.4 Existence of anthropogenic constructions and activities.	15	9	6	3	0
4.5 Is there garbage on the banks or in the riverbed?	15	9	6	3	0
4.6 Are there any changes in water quality in the riverbed, for example due to sewage?	15	9	6	3	0

Quality and structure of tree vegetation

4—Condition	Excellent	Good	Regular	Poor
Score	90–55	54–37	36–19	18–0

5. Vegetation Regeneration	0–20%	20–40%	40–60%	60–80%	80–100%
There are human activities that prevent the regeneration of vegetation (urban areas, agriculture, construction, roads, herbicides, flow regulation and others.)	15	9	6	3	0
What is the intensity of agricultural activities and passages along the banks?	15	9	6	3	0
Degree of forest stratification (presence of young, emerging and mature individuals)	0	3	6	9	15

Vegetation regeneration

5—Condition	Excellent	Good	Regular	Poor
Score	45–28	27–10	9	8–0

PROCEED IF RIPARIAN AREA
Section 2: System and channel quality

6. Vertical Connectivity	0–20%	20–40%	40–60%	60–80%	80–100%
What is the level of vertical connectivity between the channel and the riparian zone in order to allow the mobility of sediments and nutrients, among others?	0	3	6	9	15
Level of area affected by structures and solid waste.	15	9	6	3	0

Vertical Connectivity

6—Condition	Excellent	Good	Regular	Poor
Score	30–19	18–13	12–10	9–0

7. Riverbank Condition (Lateral Connectivity)	0–20%	20–40%	40–60%	60–80%	80–100%
What is the level of vegetation coverage on the banks?	0	3	6	9	15
What is the level of stability of the banks? (Stable, with points of instability, totally unstable).	0	3	6	9	15
What percentage of the margin is affected by hydraulic action?	15	9	6	3	0
Are there any buildings or human activities on the banks?	15	9	6	3	0
Do the banks have artificial or elevated lateral dikes?	15	9	6	3	0

Riverbank condition

7—Condition	Excellent	Good	Regular	Poor
Score	75–46	45–31	30–16	15–0

8. Naturalness of the Channel and Substrate	0–20%	20–40%	40–60%	60–80%	80–100%
Does the river channel have any changes in its layout?	0	3	6	9	15
Are there any solid structures within the riverbed or intermittent rigid structures and channeling in the river section?	15	9	6	3	0
Are there dams, small dams or other transversal infrastructure in the studied section, downstream or upstream?	15	9	6	3	0
Are there areas affected by excavations, earthmoving or mining?	15	9	6	3	0
What is the intensity of agricultural activities and passages in the riverbed?	15	9	6	3	0

Naturalness of the channel and substrate				
8—Condition	Excellent	Good	Regular	Poor
Score	75–46	45–31	30–16	15–0

9. Soil Condition Texture: Texture More Sandy ( ) Texture More Clayey ( )	0–20%	20–40%	40–60%	60–80%	80–100%
Intact soils, but covered with grass.	0	3	6	9	15
Intact soils, but covered with grass and shrubs.	0	3	6	9	15
Soils with traces of erosion.	15	9	6	3	0
Eroded soils. Presence of ravines and gullies.	15	9	6	3	0

Soil condition				
9—Condition	Excellent	Good	Regular	Poor
Score	60–37	36–25	24–13	12–0

General Condition	Excellent	Good	Regular	Poor
Total score	540 $\geq$ P > 325	325 > P > 199	199 > P > 112	P < 112

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