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Enhancing Water Ecosystem Services Using Environmental Zoning in Land Use Planning

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Abstract: Land use and land cover (LULC) changes alter the structure and functioning of natural ecosystems, impacting the potential and flow of ecosystem services. Ecological restoration projects aiming to enhance native vegetation have proven effective in mitigating the impacts of LULC changes on ecosystem services. A key element in implementing these projects has been identifying priority areas for restoration, considering that resources allocated to such projects are often limited. This study proposes a novel methodological framework to identify priority areas for restoration and guide LULC planning to increase the provision of water ecosystem services (WESs) in a watershed in southeastern Brazil. To do so, we combined biophysical models and multicriteria analysis to identify priority areas for ecological restoration, propose environmental zoning for the study area, and quantify the effects of LULC changes and of a planned LULC scenario (implemented environmental zoning) on WES indicators. Previous LULC changes, from 1985 to 2019, have resulted in a nearly 20% increase in annual surface runoff, a 50% increase in sediment export, a 22% increase in total nitrogen (TN) export, and a 53% increase in total phosphorus (TP) export. Simultaneously, they reduced the provision of WESs (baseflow −27%, TN retention −10%, and TP retention −16%), except for sediment retention, which increased by 35% during the analyzed period. The planned LULC scenario successfully increased the provision of WESs while reducing surface runoff and nutrient and sediment exports. The methodology employed in this study proved to be effective in guiding LULC planning for improving WES. The obtained results provide a scientific foundation for guiding the implementation of WES conservation policies in the studied watershed. This method is perceived to be applicable to other watersheds.

Keywords: water management; ecological restoration; land use and land cover; modelling; InVEST model

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1. Introduction

LULC changes impact the ecohydrological processes responsible for maintaining Earth's major biogeochemical cycles, thereby affecting water ecosystem services (WESs) [1,2]. Vegetation influences water and energy flows due to the capacity of different plant species to capture and redistribute energy and water in the environment [1]. Therefore, nutrient and sediment cycles are also affected as they are inherently connected to hydrological cycles and energy cycles [3,4]. In addition to the direct impacts on habitats and biodiversity [5], studies have shown that LULC changes can affect WESs [6], including water yield [7–10], water purification, erosion control, and flood regulation [11–14]. Although LULC may enhance the supply of some ecosystem services, such as food and timber, the degradation of these WESs may impact human well-being and public health in the long term, causing a scarcity of water for human consumption, irrigation losses, and energy-generation-related issues [15,16]. These issues are strategic factors related to water and energy security. Thus, understanding the effects of different LULCs on WESs is crucial for developing watershed planning and management policies.

Ecological restoration projects are being developed and implemented worldwide to increase ecosystem resilience, provide ecosystem services, and promote biodiversity conservation [17–21]. Initiatives such as the Bonn Challenge [22] and 1t.org (https://www.1t.org/ accessed on 10 September 2023) aim to restore millions of hectares of land by 2030. Ecological restoration is a practice that seeks to recover degraded or destroyed ecosystems, restoring their structure and ecosystem processes [23]. Evidence shows that ecological restoration using native vegetation can have significant benefits in regulating water flows, reducing floods, and stabilizing water flow during dry periods [24–26]. Furthermore, ecological restoration improves soil and water quality, reduces erosion processes, and retains sediments and nutrients flowing from the upstream areas of watersheds [7,18,27,28].

Although essential for environmental conservation, ecological restoration to improve WESs must be properly planned and executed. Resources for projects of this nature are often scarce, thus requiring the identification of priority areas for restoration and efficient allocation of resources [29–31]. One way to identify priority areas for restoration is through effective environmental zoning methods that consider the characteristics and potential of the territory [32]. Environmental zoning is a LULC planning tool that aims to promote sustainable territorial management, taking into account environmental and socioeconomic criteria [33]. It can be applied at various territorial scales, including countries, states, municipalities, and watersheds. The adoption of guidelines for territorial management is crucial for the conservation of WESs.

Many studies have been conducted to identify priority areas for the conservation and restoration of ecosystem services [29,34–36]. In the context of WESs, part of the literature highlights the potential for multicriteria analysis to identify priority areas for forest restoration, aiming to increase the provision of these services. Valente et al. [30] developed a decision support model based on multicriteria analysis to identify priority zones for forest restoration in the context of WESs, adopting five criteria that experts analyzed through participatory techniques. Anjinho et al. [33] used multicriteria analysis and on-site assessment to develop an environmental zoning methodology to increase the provision of WESs. Other studies have used biophysical models of ecosystem services, coupled with spatial analysis tools, to identify priority areas for ecological conservation and restoration [31,37–39]. The use of biophysical models, such as those available in the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), is crucial for environmental zoning analyses as they allow for the quantification of the biophysical value of WESs, as well as the identification of areas with higher service provisions and with higher potential for degradation [40]. Moreover, biophysical models enable the simulation of future scenarios and the identification of those that provide benefits to ecosystems and their associated services.

Despite the global relevance of ecological restoration practices in mitigating the impacts of human activities and climate change [41,42], it is frequently unclear which ecological restoration strategy provides the greatest benefits for ecosystem services and habitats for biodiversity. This can be justified due to variations in the ecohydrological functions of native vegetation according to their composition and configuration in the landscape [43–45]; the optimal strategy may vary depending on the specificities of each region and the pressures felt therein. Some studies have used biophysical models to select priority areas for restoration [31,37–39]. The outcomes may allow the development of tailored policy recommendations and enable efficient spatial development.

This work aims to develop a methodology that overpasses the beforementioned limitations of the applied methodologies found in the literature and, therefore, is able to enhance the provision of WESs, providing evidence-based knowledge for the implementation of optimal ecological restoration strategies. We hypothesize that increasing green areas in strategic locations within the watershed can enhance the provision of WESs and reduce surface runoff and nutrient and sediment exports. To test our hypothesis, we developed a novel methodological framework that combines multicriteria analysis and biophysical models to conduct environmental zoning and LULC scenario building and applied it to a watershed located in southeastern Brazil. The methodological framework was designed based on the following objectives: (i) to quantify the LULC changes between 1985 and 2019; (ii) to quantify the effects of LULC changes on eight indicators associated with WESs: surface runoff, sediment export, nutrient export, sediment retention (erosion control services), nutrient retention (water purification), and baseflow (water supply); (iii) to map the potential levels of WES degradation; (iv) to propose environmental zoning that promotes an increase in WESs; and (v) to evaluate the effects of a planned LULC scenario on indicators of WESs.

2. Methodology

To meet the objectives of this study, a robust methodological framework that couples biophysical models and multicriteria analysis was developed (Figure 1). The LULC changes were analyzed within a Geographic Information System (GIS), using data from the *Brazilian Annual Land Use and Coverage Mapping Project* (5th collection) [46] for the years between 1985 and 2019.

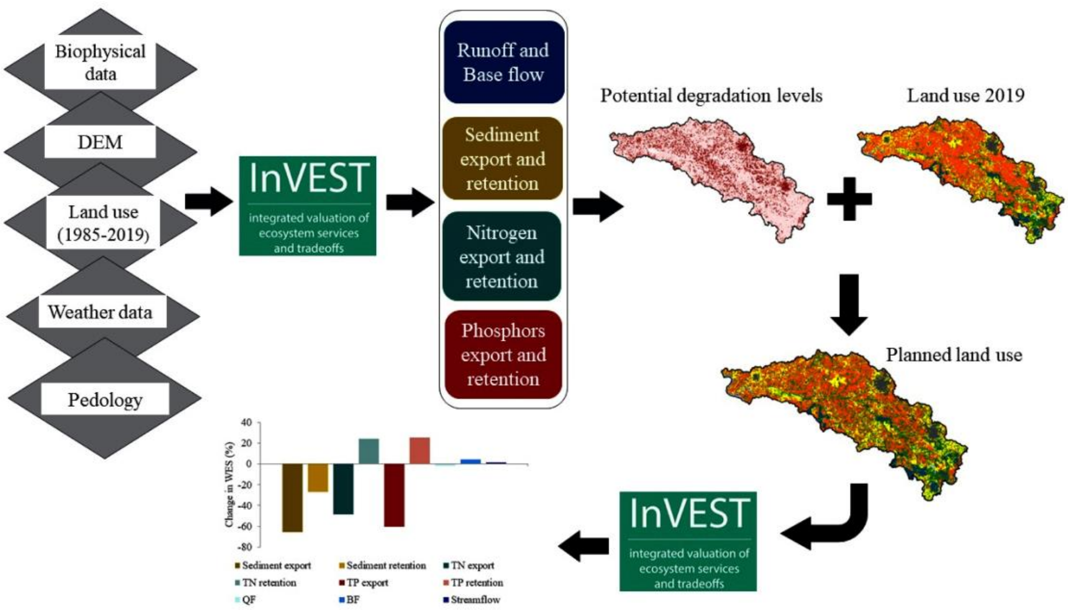

Figure 1. Methodological diagram of the proposed method.

Biophysical models from the InVEST 3.12.0 package [47] were used to quantify the indicators of surface runoff, sediment export, TN export, TP export, baseflow, sediment retention, TN retention, and TP retention, with the last four indicators representing the services of erosion control, water purification, and water supply. Therefore, this study considers only the last four as indicators of WESs. As one of the objectives of this study was to quantify the effects of previous LULC changes on WESs, LULC data from 1985 to 2019 were used as inputs in the biophysical models. For inputs that utilize meteorological data, such as precipitation, evapotranspiration, rain events, erosivity, and nutrient runoff proxy, long-term average values (1981 to 2019) were used for both years.

Multicriteria analysis was used to map the potential levels of WES degradation using the outputs of InVEST's biophysical models. Then, environmental zoning was proposed for the study area, based on integrating maps of the potential levels of WES degradation and of the LULC of 2019. The last step was to build a planned LULC scenario for the study area based on the proposed environmental zoning and evaluate its effects on the eight indicators used in this study, using the LULC configuration scenario as an input of the biophysical models from InVEST. A detailed description of each methodological step is presented in the following subsections.

2.1. Study Area

The Jacaré-Guaçu River Basin (JGRB) is located in the central–eastern region of the state of São Paulo, southeastern Brazil. It is part of Water Resources Management Unit number 13 (UGRHI 13), known as the Tietê Jacaré Basin (Figure 2). With a drainage area of approximately 4172.12 km^2, the JGRB is composed of watercourses of different orders that contribute to the formation of the Jacaré-Guaçu River, which is the main watercourse of the JGRB and one of the surface water supply sources of UGRHI 13 [48]. The region is characterized by a flat relief, composed of smoothly undulating hills (around 80%), resulting from the weathering of the Botucatu and Pirambóia formations, with low drainage density [49]. The altitude of the watershed ranges from 372.0 m to 1024.0 m above sea level. The soils in the region are predominantly sandy, emphasizing the Latosols that cover 60% of the area [50]. The region's climate falls within the CWA and CWB climatic zones, characterized by dry winters and wet summers [51]. The JGRB is located in a transitional area between the Cerrado and Atlantic Forest biomes, mainly featuring Seasonal Semideciduous Forest and savanna vegetation types [48].

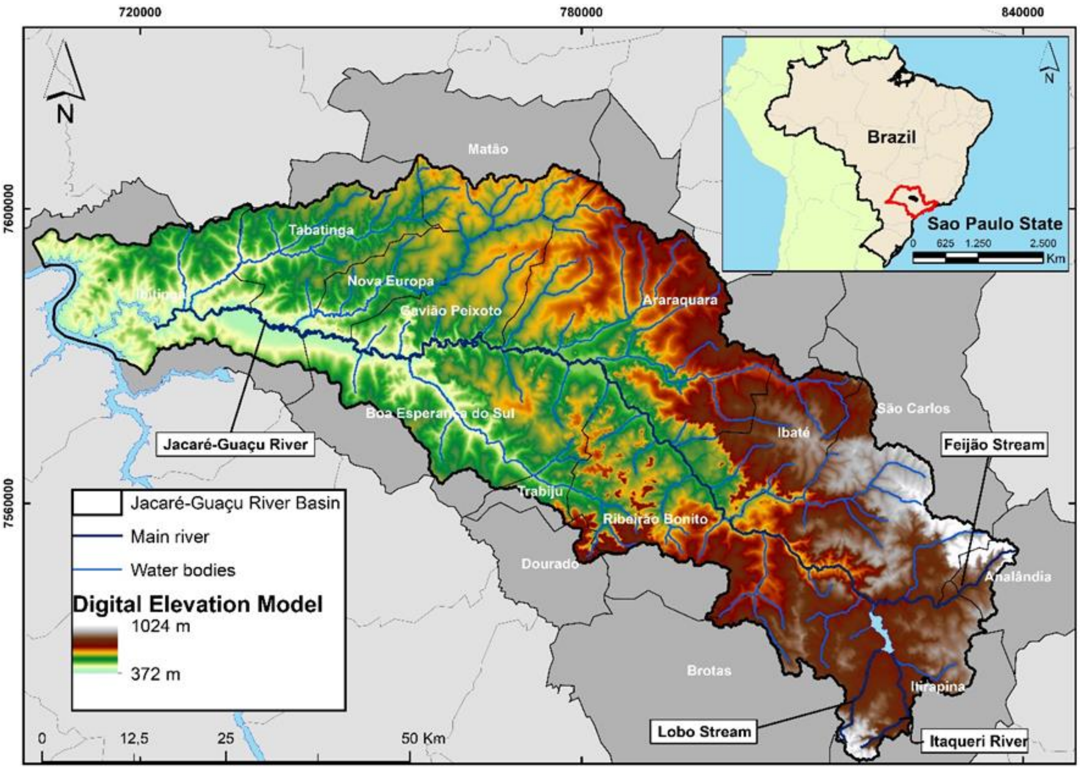

Figure 2. Location of Jacaré-Guaçu River Basin using the Digital Elevation Model.

The JGRB represents an adequate case study since its water resources, such as rivers, streams, reservoirs, and groundwater, are essential for serving multiple water uses that are important for regional socioeconomic development [48]. Additionally, the area is environmentally significant due to the presence of important ecosystems for biodiversity conservation, such as remnants of the Cerrado and Atlantic Forest [52,53]. Over the years, there has been an intense transformation of LULC in the watershed, resulting in a decline in natural ecosystems and the expansion of agricultural areas [54]. These LULC changes have affected the hydrosedimentology of the watershed, altering the flows of water, nutrients, and sediments [55–57] while increasing the risk of degradation of water resources, including underground aquifers [58].

2.2. Analysis of Land Use and Land Cover Changes

Data from the MAPBIOMAS project were used to characterize the LULC of the JGRB. In total, thirteen LULC classes were identified: (i) sugarcane, (ii) planted forest, (iii) grassland, (iv) forest, (v) savanna, (vi) urban infrastructure, (vii) perennial crops, (viii) agriculture–pasture mosaic, (ix) other non-forest natural formations, (x) other temporary crops, (xi) pasture, (xii) river, lake, and ocean, and (xiii) soybean. However, for result visualization, the thirteen LULC classes were regrouped into six categories: (i) agriculture (sugarcane, perennial crops, other temporary crops, and soybean), (ii) water (river, lake, and ocean), (iii) urban area (urban infrastructure), (iv) planted forest (planted forest), (v) pasture (pasture and agriculture–pasture mosaic), and (vi) natural vegetation (grassland, forest, savanna, and other non-forest natural formations).

The LULC transition matrix was used to quantify the changes between 1985 and 2019. This method allows for determining the quantity and direction of LULC changes, highlighting both the modified areas and the classes that remained unchanged during the analyzed period.

2.3. Biophysical Modelling and Quantification of the Effects of Land Use and Land Cover

The InVEST biophysical models were run for the years 1985 to 2019, using previously calibrated parameters from the study conducted by Anjinho et al. [49]. The parameters of the models were calibrated and validated on an annual scale using data on streamflow (39 years), the concentration of TN and TP (29 years), and total suspended solids (19 years) obtained from the Water and Sanitation Agency, Department of Water and Energy of the State of São Paulo and the Environmental Company of the State of São Paulo. A technical description of the models and the input data used can be found in Anjinho et al. [49].

The Seasonal Water Yield (SWY) model was used to quantify the annual surface runoff (QF) and baseflow (BF) of the JGRB. QF was calculated using a modified curve number method from the Natural Resources Conservation Service (NRCS) (NRCS, 1996), while BF was estimated based on local recharge values, which were determined from the local water balance between precipitation, QF, and evapotranspiration. The JGRB’s annual precipitation was generated based on data from rainfall monitoring stations. Evapotranspiration was calculated using meteorological data from a climatological station at the Center for Water Resources and Environmental Studies, University of São Paulo, using the method described by Camargo et al. [59]. QF was calculated using the adapted SCS method [47]. More information about the models can be found in Anjinho et al. [49].

The Sediment Delivery Ratio (SDR) model was used to quantify the export and retention of sediment in the JGRB. The model is based on the Revised Universal Soil Loss Equation (RUSLE) and the SDR parameter to quantify the export and retention of sediment in each pixel of the watershed. Sediment export represents the amount of sediment eroded in the pixels that effectively reaches the watercourse, calculated by summing the product of production (RUSLE) and SDR. As suggested in the user manual [47], the “Avoided export” model output was used as a proxy to quantify the sediment retention service in the watershed.

The Nutrient Delivery Ratio (NDR) model was used to quantify the export and retention of total nitrogen (TN) and total phosphorus (TP) in the study area. This model uses a simplified mass balance to map nutrient loads without considering the nutrient cycle in detail, as more complex models do. Similar to the SDR model, nutrient export in the NDR model was quantified by summing the product of nutrient loads in each pixel and their respective Nutrient Delivery Ratio (NDR) values. The loads were quantified using average TN and TP export coefficients that varied according to the LULC in the watershed. The nutrient retention service was estimated by comparing nutrient exports from a hypothetical scenario (where all LULCs in the watershed were converted to agriculture) with the actual

LULC conditions between 1985 and 2019, as suggested in the model manual [47]. The agricultural scenario used in this study was selected because it represents the LULC class with the highest TN and TP export coefficient values [60]. The difference in nutrient exports between the agricultural scenario and the years 1985 to 2019 reflects the amount of nutrients that is theoretically not exported due to the analyzed LULC configuration.

The effects of LULC types on QF, sediment export, nutrient export, and WESs were analyzed using the average values of these indicators for each LULC class, after being normalized on a scale from 0 to 1 using linear fuzzy logic [61]. The main objective of this analysis is to quantify the influence of each LULC type on these indicators.

2.4. Multicriteria and Spatial Analysis for the Proposition of Environmental Zoning

Environmental zoning aiming to increase the provision of WESs was developed through spatial analysis between potential levels of WES degradation and LULC in 2019, following a similar approach to the study by Anjinho et al. [33]. To determine the potential levels of WES degradation, annual data for QF, annual exports of TN and TP, and sediments simulated for the year 2019 were considered. Areas with high degradation potential under anthropic influence (agriculture, planted forests, and pastures) were classified as priority areas for ecological restoration (Table 1). The restoration of these areas aims to reduce surface runoff, nutrient, and sediment export and increase the provision of WESs. Low- and medium-potential areas under anthropic influence were designated as anthropic use zones (Table 1). These areas generally contribute little to surface runoff and nutrient/sediment export, making them suitable for human development. Urban areas were classified as consolidated use zones, considering the challenges of managing urban environments at a landscape scale (Table 1). The natural areas within the JGRB, including riparian forests, wetlands, the Brazilian Cerrado, and the Atlantic Forest, are crucial for conserving biodiversity and ecosystem services in the region [52,53]. Therefore, in environmental zoning, all-natural areas, regardless of their potential level, have been categorized as conservation priorities (Table 1).

Table 1. Criteria used for the development of environmental zoning.

Potential Degradation Levels	Land Use and Land Cover	Environmental Zoning
High	Anthropic use	Priority areas for restoration
Low and medium	Anthropic use	Anthropic use zone
Any potential degradation levels	Urban areas	Consolidated zone
Any potential degradation levels	Natural vegetation	Environmental conservation zone

The study assumes that areas with higher runoff and export of sediments and nutrients tend to degrade aquatic ecosystems. Nutrient enrichment leads to the eutrophication of aquatic ecosystems [62,63], and increased erosion and sediment transport in the watershed can alter the natural characteristics of water bodies, pollute the waters due to the presence of pollutants adsorbed to the sediment, and contribute to the sedimentation of hydroelectric reservoirs [64–66]. Runoff was also included in this analysis because areas with higher runoff generation have the potential to increase soil erosion and, consequently, sediment and nutrient transport, as well as increase the risk of downstream flooding [40,67,68].

The annual values of these three indicators were standardized on a scale of 0 to 1 using linear fuzzy logic [61], and then a weighted linear combination was performed in a GIS to aggregate the three indicators, resulting in the mapping of potential WES degradation levels. An equal weight of 1 was assigned to the three indicators in the weighted linear combination. Subsequently, the values were reclassified into three classes: low, medium, and high. For the reclassification, we analyzed the distribution of the data that were re-scaled using fuzzy logic (0 to 1) and divided them into three classes with equal numbers of pixels (low = 0–0.125, medium = 0.125–0.25, and high = 0.25–1). The assumption is that the closer the value is to 1, the higher its potential for degradation.

2.5. LULC Scenario Building and Quantification of Its Effects on Biophysical Indicators

The biophysical models from the InVEST 3.12.0 package [47] were run again to assess the effects of the planned LULC scenario on QF, sediment and nutrient exports, and WESs of the JGRB. This scenario was developed based on the assumption that areas identified as priorities for ecological restoration were effectively restored. To achieve this, the 2019 LULC data and the proposed environmental zoning were spatially integrated on a GIS. LULCs that coincided with priority areas for restoration were changed to equivalent natural vegetation, which includes Brazilian Cerrado and Atlantic Forest vegetation. The results were compared to the 2019 LULC values to quantify the effect of the changes.

3. Results

3.1. Land Use and Land Cover Changes between 1985 and 2019

The analysis of LULC dynamics revealed a change in landscape pattern between 1985 and 2019 (Figure 3). Agriculture was the main driver of change in the JGRB, experiencing a growth of nearly 120% during this period (changes in terms of area (km^2) can be viewed in Table S1 in the Supplementary Material). This expansion occurred mainly in areas that were previously designated as pastureland and, to a lesser extent, natural vegetation (Table S2). Agriculture became the dominant LULC in the JGRB in 2019, covering over 50% of its area. Large percentage increases in urban areas and planted forests were also observed, although smaller in comparison to agriculture when analyzed in terms of area (km^2). Urban expansion occurred primarily over pastureland, while planted forests occupied a larger proportion of areas that were previously covered by natural vegetation (Table S2). Despite their low representation in the JGRB, it is important to highlight that urban areas and planted forests were the LULC types that exhibited the highest percentage growth during the analyzed period, with increases of 285% and 147%, respectively.

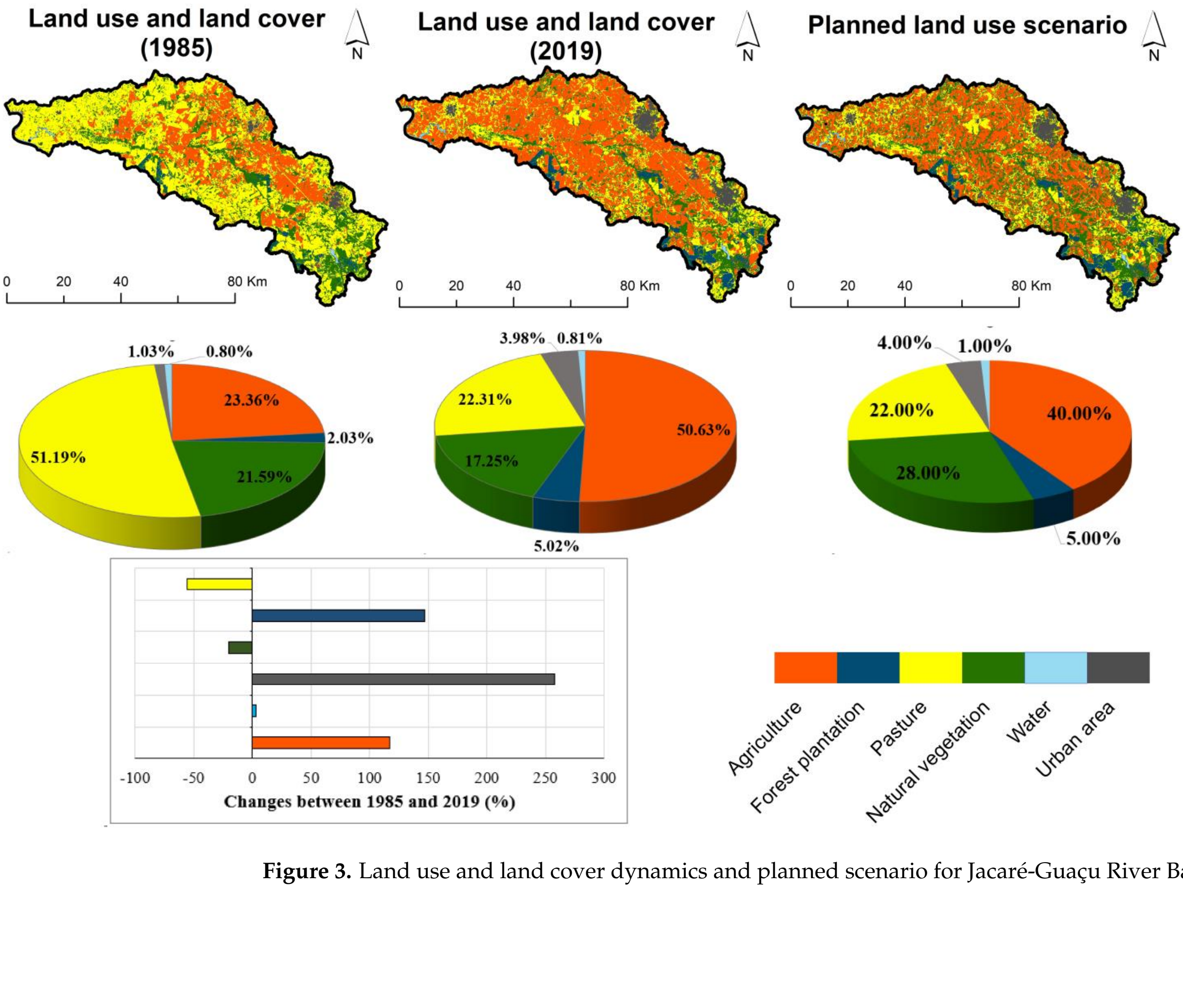

Figure 3. Land use and land cover dynamics and planned scenario for Jacaré-Guaçu River Basin.

In 1985, pastureland was the predominant LULC in the JGRB and it was distributed throughout its extent (Figure 3). Natural areas, represented by Atlantic Forest formations, Brazilian Cerrado grasslands, and savannas, were located near the headwaters of the Jacaré-Guaçú River and along the riverine regions, as well as in the form of small fragments within the JGRB. Crops were situated along the right bank of the Jacaré-Guaçu River, occupying nearly a quarter of the watershed. In 2019, the LULC configuration changed. Pastureland is now fragmented in the landscape, while agriculture has the largest continuous area in the JGRB. Natural vegetation is restricted to the riverine regions, planted forests have expanded upstream in the watershed, and urban areas have developed during the analyzed period, increasing in their respective areas.

3.2. Changes in Surface Runoff and Exports of Sediments and Nutrients

The spatial patterns of the QF in the studied watershed did not show significant changes between the analyzed years (Figure 4 and S1). Still, its average annual value increased by approximately 20% (Table 2). The highest percentage increases occurred in pasture and natural vegetation areas, while surface runoff values decreased in agricultural and urban areas. Regarding absolute values, surface runoff was more pronounced in urban areas, particularly where the cities of São Carlos, Araraquara, and Ibitinga are located. Urban areas and water were the LULC types that had the greatest influence on the QF of the watershed (Figure S2).

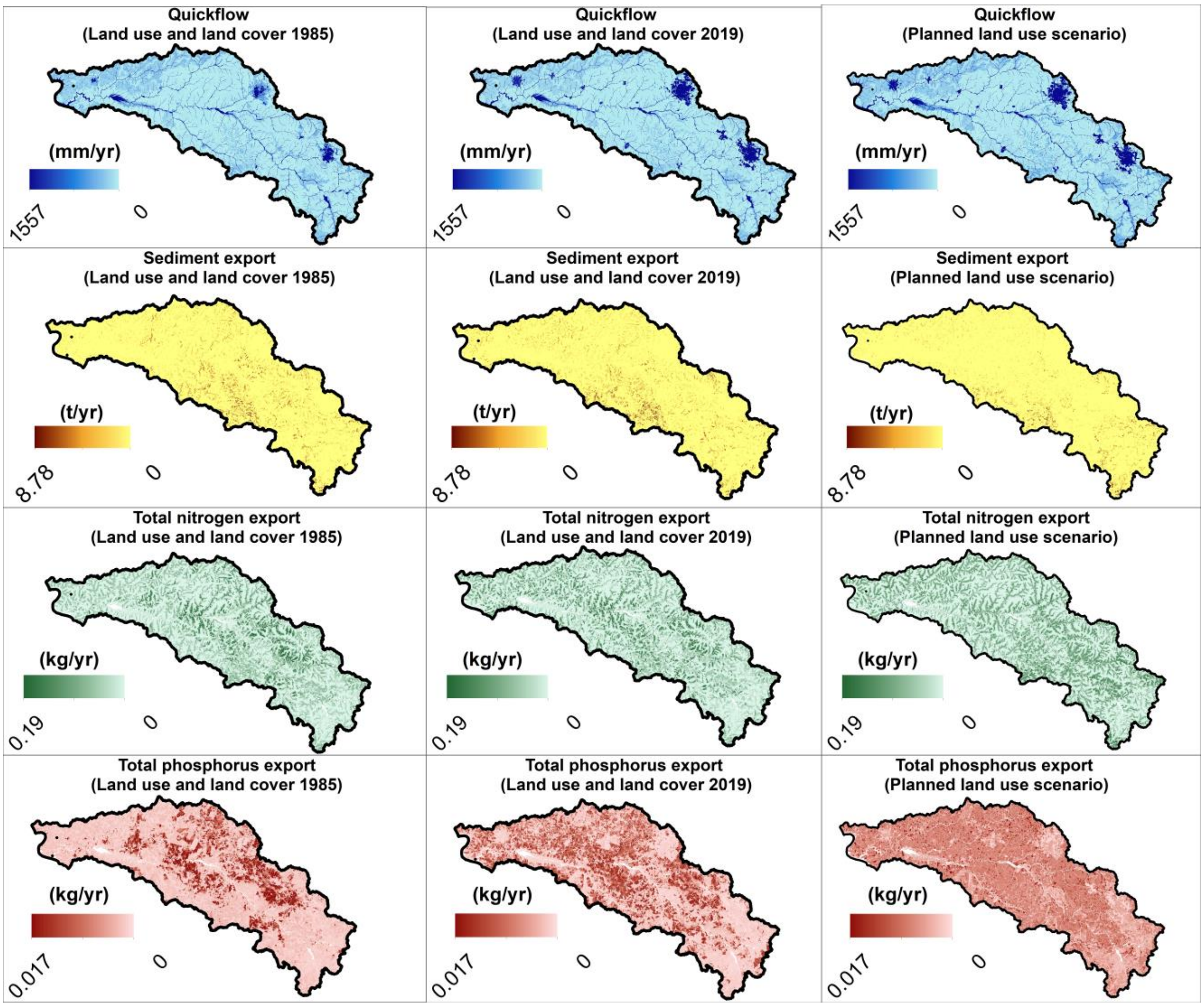

Figure 4. Spatial distribution of surface runoff and exports of sediments and nutrients in the Jacaré-Guaçu River Basin.

Table 2. Simulated values of surface runoff, sediment exports, nutrient exports, baseflow, sediment retention, and nutrient retention for land use and land cover from 1985 to 2019.

Land Use and Land Cover	Quickflow (mm/yr)			Sediment Export (t/yr)			Total Nitrogen Export (kg/yr)			Total Phosphorus Export (kg/yr)		
	1985	2019	Changes (%)	1985	2019	Changes (%)	1985	2019	Changes (%)	1985	2019	Changes (%)
Agriculture	64	54	−16	10,768	27,524	156	225,573	399,446	77	36,811	73,270	99
Water	1154	1155	0	0	1	45	63	76	19	4	4	5
Urban area	1011	1004	−1	3	66	2114	2899	12,525	332	134	535	300
Natural vegetation	169	218	29	575	627	9	62,030	62,815	1.26	4683	4019	−14
Forest Plantation	26	28	7	353	1586	349	2615	7505	187	350	1023	192
Pasture	110	172	56	14,220	9284	−35	178,233	89,523	−50	13,257	5839	−56
JGRB	128	154	20	25,920	39,087	51	471,413	571,889	21	55,239	84,690	53
Land use and land cover	**Baseflow (mm/yr)**			**Sediment retention (t/yr)**			**Total nitrogen retention (kg/yr)**			**Total phosphorus retention (kg/yr)**		
	1985	**2019**	**Changes (%)**	**1985**	**2019**	**Changes (%)**	**1985**	**2019**	**Changes (%)**	**1985**	**2019**	**Changes (%)**
Agriculture	141	138	−3	1,805,134	4,519,504	150	166,773	361,429	117	34,290	77,523	126
Water	12	13	3	28,185	57,884	105	204	285	40	27	37	40
Urban area	195	192	−1	590	53,915	9038	1732	6799	292	156	533	241
Natural vegetation	219	199	−9	1,893,772	3,004,434	59	354,960	350,281	−1	58,633	47,882	−18
Forest Plantation	253	252	−0	123,829	503,007	306	20,259	51,429	154	5616	13,840	146
Pasture	373	345	−7	5,174,698	4,031,867	−22	745,857	389,850	−48	140,843	61,892	−56
JGRB	279	202	−27	9,026,207	12,170,611	35	1,289,786	1,160,074	−10	239,565	201,707	−16

The exported sediment in the JGRB increased by approximately 50% between 1985 and 2019 (Table 2). The areas that experienced the greatest increases are located near the watercourses of the watershed, with more pronounced effects observed in the municipalities of Boa Esperança do Sul and Ribeirão Bonito, in the central part of the study area. (Figure 4). For both years, crops and pastures were the LULC classes that exhibited the highest exported sediment loads and also had the most significant effects (Table 2 and Figure S2). In 2019, the sediment loads exported by these two LULC classes accounted for nearly 95% of the total sediment load exported in the JGRB. In terms of percentage, the highest increases during the period were observed in urban areas (2113.76%) and planted forests (348.75%). However, it is important to note that urban areas exported the lowest sediment loads in both 1985 and 2019.

LULC changes also affected nutrient exports in the JGRB. The areas with increased nutrient exports are scattered throughout the watershed, although TN exports are more concentrated near the watercourses than TP (Figure 4). Despite the significant increase, a decrease in TN exports is observed on the right bank of the Jacaré-Guaçu River, particularly in the northeast region in the municipalities of Araraquara and Ibaté. Urban areas and planted forests showed the highest percentage changes in nutrient exports. In 2019, agricultural areas were responsible for exporting 70% of TN and 87% of TP, significantly influencing nutrient exports (Table 2 and Figure S2).

3.3. Changes in Baseflow and Retentions of Sediments and Nutrients

The spatial pattern of BF in the JGRB has changed over the years (Figure 5 and S1). In 1985, high values, represented by dark blue, were observed in many parts of the watershed. However, in 2019, areas with higher BF values were restricted primarily to near the sources of the Jacaré-Guaçu River, where the tributaries Ribeirão do Lobo, Ribeirão da Onça, and Ribeirão Feijão and the Itaqueri River are located, as well as scattered along the floodplain. The BF of the watershed decreased by approximately 30% during the study period, with the most significant decreases observed in the natural vegetation and pasture classes (Table 2). Despite the decrease in BF value, pasture was the LULC type with the greatest effect on BF, followed by planted forests (Figure S3).

The spatial pattern of sediment retention service was similar for the analyzed years (Figure 5). Decreased values were observed in small, scattered fragments in the JGRB (Figure S1). Sediment retention increased by 35% between 1985 and 2019 (Table 2). The most significant percentages of change occurred in urban areas and planted forests. However, in absolute terms, the highest amounts of retained sediments in 2019 were found in agricultural areas (37%), pastures (33%), and natural vegetation (25%), which together accounted for 95% of the total sediment retention in the JGRB. Natural vegetation and pasture greatly affected the sediment retention service (Figure S3).

The nutrient retention service decreased between 1985 and 2019 (Table 2). The areas where reductions in TN and TP retention occurred are scattered in small fragments throughout the JGRB, although more significantly for TP (Figure 5 and S1). Similar to the sediment retention service, the largest changes were found in urban areas and planted forests. Agriculture, pasture, and natural vegetation are the LULC classes that presented the highest retained loads in 2019. Agriculture retained 31% of TN and 38% of TP, pasture retained 34% of TN and 31% of TP, and natural vegetation retained 30% of TN and 24% of TP. Natural vegetation and pasture had a greater effect on nutrient retention in the watershed. Planted forests also significantly influenced TP retention (Figure S3).

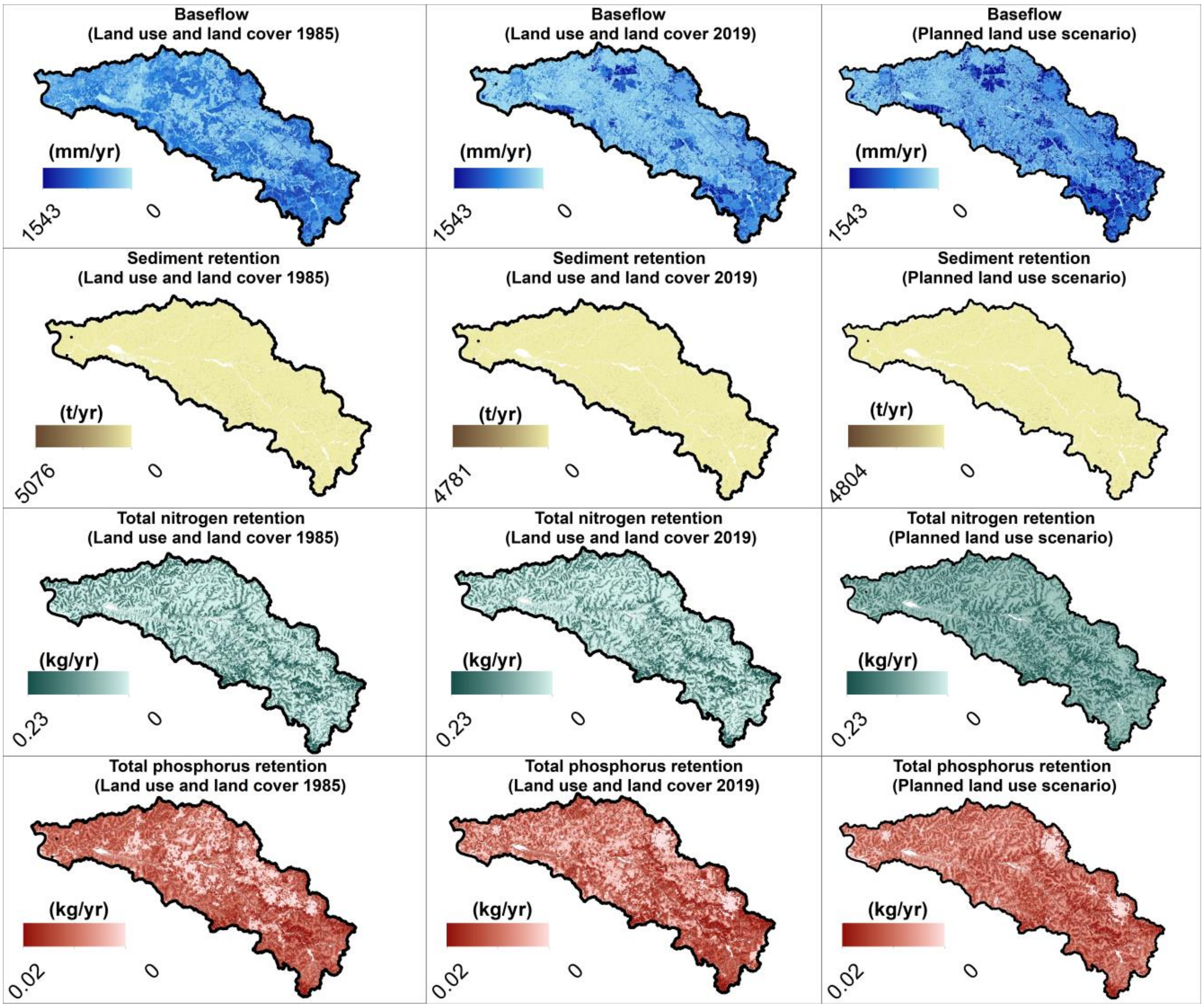

Figure 5. Spatial distribution of baseflow and sediment and nutrient retention in the Jacaré-Guaçú River Basin.

3.4. Proposal for Environmental Zoning Aiming to Increase the Provision of Water Ecosystem Services

The potential WES degradation levels and the proposed environmental zoning are presented in Figure 6, and the planned LULC scenario, generated based on the proposed environmental zoning, is depicted in Figure 3. The areas with the highest potential for WES degradation encompass 13% of the JGRB and are fragmented across the landscape, where areas with high surface runoff and export of sediments and nutrients are located. The lowest potential degradation levels are observed upstream of the JGRB and in many stretches along the Jacaré-Guaçu River, often associated with riparian forests and wetland areas.

The spatial analysis of potential WES degradation levels and LULC in 2019 resulted in the identification of five use zones, as illustrated in Figure 6. The anthropic use zone is the largest, occupying 67% of the area. The second largest zone corresponds to areas designated for environmental conservation, which refers to existing natural vegetation in the JGRB. The zone designated for ecological restoration occupies 11% of the area and is concentrated in steeper areas near the watercourses of the watershed. The consolidated use zone refers to urbanized areas where it is not possible to relocate LULC.

Based on the analysis of the environmental zoning, a planned LULC scenario was proposed for the JGRB (Figure 3). Agriculture and natural vegetation are the two LULC classes that changed this new landscape configuration compared to the 2019 data. Agriculture remains the dominant class in the watershed, occupying 40% of the area. Natural vegetation is the second most representative class (28%) and is mainly located upstream of the watershed and near the Jacaré-Guaçu River and its tributaries. The remaining LULC classes did not show changes in their respective areas.

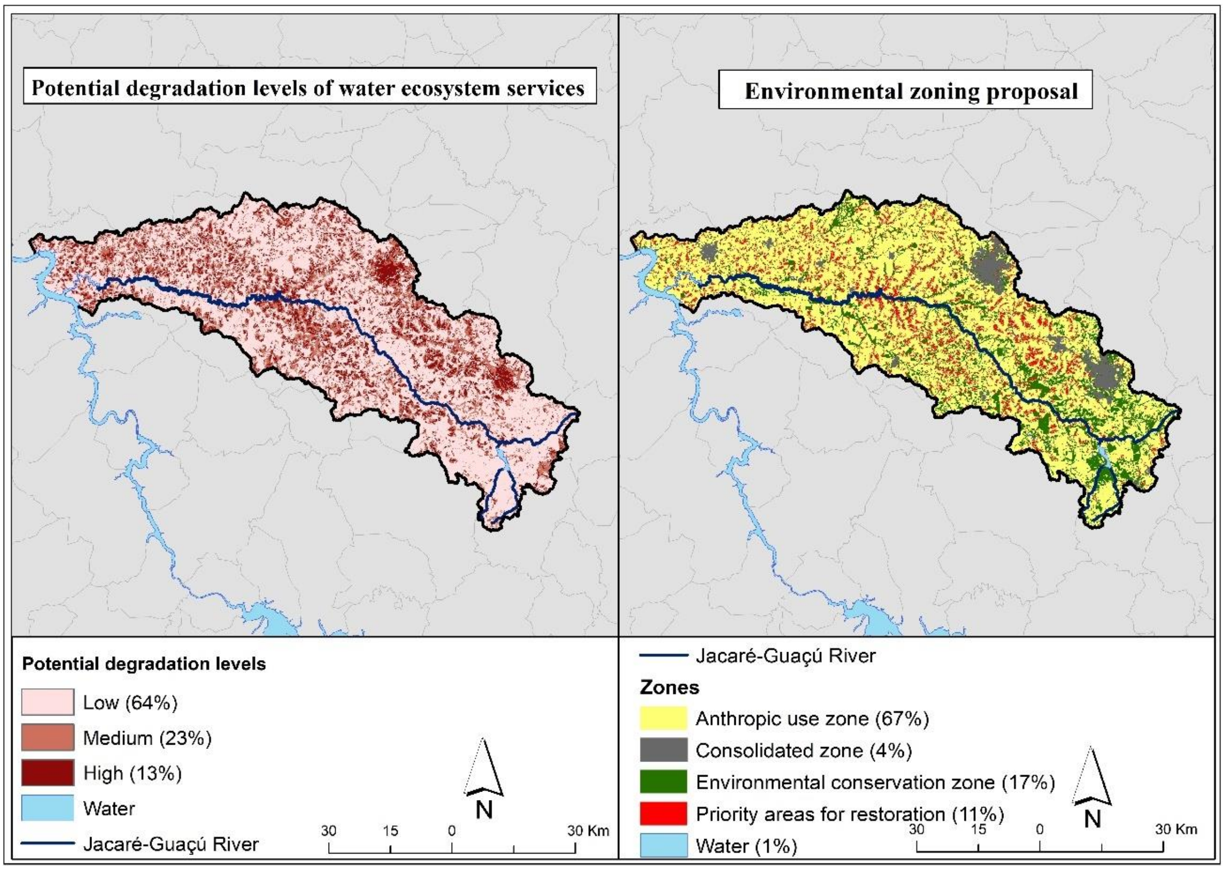

Figure 6. Potential degradation levels of water ecosystem services and proposed environmental zoning for the Jacaré-Guaçu River Basin.

3.5. *Effects of the Planned LULC Scenario on Surface Runoff, Sediment Exports, Nutrient Exports, and Water Ecosystem Services*

The spatial distribution of QF, sediment exports, nutrient exports, and WESs for the planned LULC scenario is presented in Figures 4 and 5, and Table S3 shows the simulated values. Overall, when compared to the 2019 LULC, it is observed that the planned LULC scenario resulted in a reduction in QF and sediment and nutrient exports while also providing increases in BF and nutrient retention services (Figure 7). The QF showed a slight reduction of 2% with the changes in LULC. The largest reduction was observed for sediment exports (65%), followed by phosphorus (60%) and nitrogen (49%) exports. On the other hand, BF increased by around 4%, and nutrient retention services increased by approximately 25%. The sediment retention service decreased by 27% in the new LULC configuration.

Just like in the years 1985 and 2019, water and urban areas were the LULC classes that most affected the QF of the JGRB (Figure S2). Pasture and planted forests had a greater effect on sediment exports, with the former also affecting nutrient exports along with natural vegetation. Agriculture had a more pronounced effect on phosphorus exports in the watershed. Regarding the BF, the LULC classes with the greatest influence were pasture and planted forests, while natural vegetation played a more significant role in sediment and nutrient retention (Figure S3). Pasture also had a strong influence on sediment and nutrient retention and planted forests played a relevant role in phosphorus retention (Figure S3).

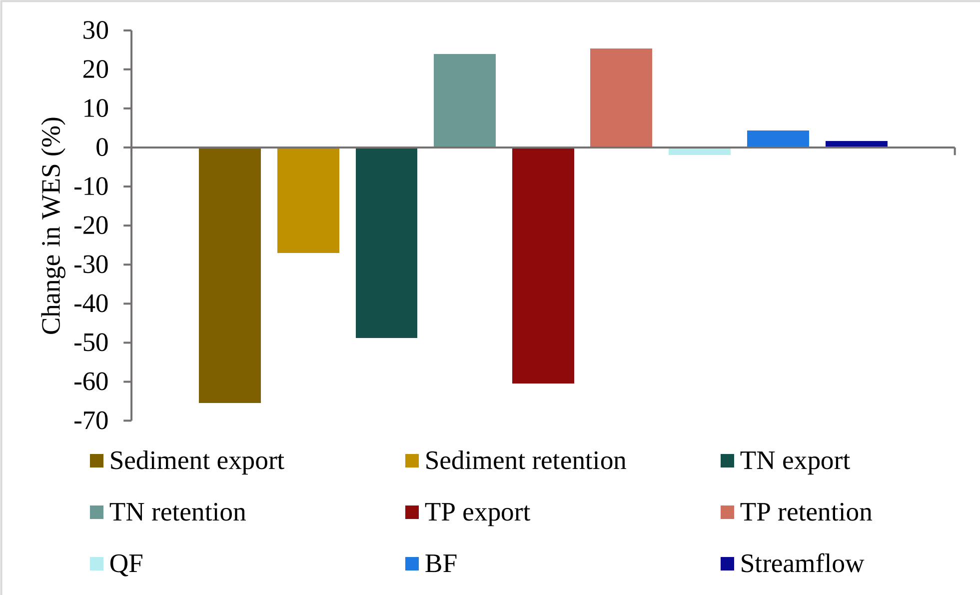

Figure 7. Percentage changes in surface runoff, sediment export, nutrient export, baseflow, sediment retention, and nutrient retention between the planned scenario and the 2019 land use and land cover.

4. Discussion

4.1. Analysis of the Effects of LULC Changes on Surface Runoff and the Exports of Sediments and Nutrients

The study results revealed that the LULC pattern in the JGRB has changed over the years. The main driver of change has been crops, which have significantly increased in the study area. This growth is associated with the economic model of the state of São Paulo, which has been largely dominated by the sugarcane industry in the past three decades, becoming one of the main agro-industrial centers in Brazil [69]. These findings are consistent with other studies that have already indicated the expansion of this crop in the state of São Paulo, particularly over pasture areas [70–72]. The area of natural vegetation also decreased during the analyzed period due to agricultural and planted forest expansion over the Atlantic Forest and Brazilian Cerrado areas, notably affecting the biodiversity and functions of these ecosystems [73–76].

LULC changes in the JGRB seem to be associated with higher sediment and nutrient exports in the year 2019. Previous studies conducted in the state of São Paulo also found similar results when forests and pastures were replaced by agriculture [75,77,78]. In the Lobo stream watershed, which is one of the tributaries of the Jacaré Guaçu River (the main watercourse of the JGRB), Anjinho et al. [57] observed a greater influence of agriculture on annual nitrogen and phosphorus exports. The hydrosedimentological model established by Santos [55] indicated higher sediment production during the wet months in a scenario that predicts an increase in urban and agricultural areas upstream of the JGRB. Sediment and nutrient exports were higher in areas with high hydrological connectivity, naturally predisposed to material transport, as predicted by InVEST's SDR models [47].

Surface runoff proved to be less sensitive to LULC changes, which corroborates the previous model conducted by Santos [55], which indicated a slight change in average monthly flow with LULC changes in the JGRB. The spatial pattern of the QF barely changed between 1985 and 2019, with small increases observed in urban areas due to soil sealing. Pasture and natural vegetation areas showed increases in average QF values during the analyzed period. With the expansion of sugarcane and other crops until 2019, natural vegetation and pasture became generally limited to regions of high hydrological connectivity, typically associated with steep slopes where human occupation is limited. This condition resulted in higher average QF values in these areas, which naturally tend to have high QF due to their physical characteristics, regardless of LULC type. Therefore, although this study found that pasture and natural vegetation had the highest QF values, excluding urban areas, it should be noted that QF would likely be even higher if these areas were occupied by sugarcane, especially during the first year of planting, as demonstrated by Youlton et al. [79].

The low sensitivity of the QF to LULC changes may have contributed to mitigating the export of sediments and nutrients. Even though sediment and nutrient exports increased between 1985 and 2019, this increase could have been more significant if the physiographic characteristics of the watershed favored QF and, consequently, sediment and nutrient production and transport. The limited impact of landscape changes on QF may be related to the physiographic characteristics of the JGRB. Overall, the JGRB is flat and composed of smoothly undulating hills resulting from weathering of the Botucatu and Pirambóia formations, with low drainage density [49]. Additionally, the soils in the region are predominantly sandy, with Latosols covering 60% of the area [50]. These characteristics reduce the intensity of surface runoff and the export of nutrients and sediments. These observations have been noted in other studies conducted in the region [71,80].

4.2. Analysis of the Effects of LULC Changes on Baseflow and the Retentions of Sediments and Nutrients

The conversion of pasture and natural vegetation to agriculture in the JGRB resulted in a decrease in all WESs, except for sediment retention. Changes in the region's vegetation type may be associated with a decrease in the JGRB's baseflow. The JGRB's natural ecosystems, including wetlands, grasslands, savannas, and forests [48,52,53], facilitate water infiltration and the recharging of aquifers due to their deep-rooted vegetation that creates fissures in the soil and allows greater penetration of water [81], preserving the soil's hydraulic characteristics [73]. The reduction of pasture areas may have also affected the BF of the watershed. While Anache et al. [56] observed higher impacts on soil hydrological patterns in pastures at the hillslope scale, compared to sugarcane and Cerrado vegetation, the results of this study suggest a different effect in the JGRB. Pastures in the JGRB primarily feature herbaceous species associated with extensive small-scale livestock production located in low-slope areas, which naturally generate less surface runoff. These pastures may not be as impacted by grazing, allowing for better water infiltration. Additionally, the low-lying vegetation reduces evapotranspiration, increasing water availability and promoting vertical water movement in the soil [56].

The reduction in nutrient retention is directly related to the decrease in natural vegetation and pasture. Due to the specifics of the approach taken in this study, the results for this service were already expected, as the export coefficients used in this study assume higher nutrient export in agricultural areas compared to other LULCs. Thus, the greater the difference in exported loads, the greater the contribution of the nutrient retention service. Other studies that used the NDR model also observed negative effects on water purification services with the reduction of natural areas [82–85].

A noteworthy finding of this study was the result for the sediment retention service, which increased with LULC changes. This increase may be associated with the higher sediment export resulting from the expansion of sugarcane in the JGRB. The "avoided export" output of the SDR model indicates vegetation's role in reducing erosion and retaining sediment from upstream areas. Consequently, the greater the sediment export upstream of a pixel, the greater its retention. Additionally, the physical characteristics of the JGRB also contribute to the increase in sediment retention. Although there may be sediment production due to the presence of erosion-prone soils, their transport in the watershed becomes limited due to the topography of the study area. In other words, the higher the production, the greater the retention.

4.3. Effects of Environmental Zoning on Biophysical Indicators

The results of this study indicate that land use planning can be an effective strategy to increase the provision of water ecosystem services. Our methodological approach complements classical techniques based on multicriteria analysis [30,32,33], allowing for the zoning of the watershed and the quantification of the effects of alternative land use scenarios.

The environmental zoning proposed in this study indicates that 67% of the JGRB consists of areas designated for anthropic use, which can be used for sugarcane production, the main economic activity in the region, or urban expansion. Another 4% represents consolidated areas where LULC changes are limited due to existing urban infrastructure. The conservation zone covers 17% of the area and includes fragments of the Cerrado, riparian forests, gallery forests, and wetlands, which provide multiple ecosystem services [86,87]. Priority restoration areas are concentrated near watercourses and occupy 11% of the watershed. Our analysis linked the potential WES degradation levels with the socioeconomic characteristics of the watershed, which is represented in this study by LULC. Our goal was to identify a sustainable LULC scenario capable of increasing the provision of WESs while promoting socioeconomic development. The results obtained were robust and feasible for implementation in the study area.

The study indicated that increasing natural vegetation by just 11% in strategic locations in the JGRB can enhance the provision of WESs and reduce surface runoff and the export of nutrients and sediments. These findings align with other studies in the literature that demonstrate the effects of ecological restoration on the provision of ecosystem services [12,17,88]. In the JGRB, the areas identified as priority restoration sites are associated with riparian zones, as they were deemed critical in terms of generating runoff and exporting sediments and nutrients. As discussed in previous studies, riparian zones play a crucial role in enhancing multiple ecosystem services, including nutrient removal, flow regulation, climate regulation, erosion control, water purification, and providing habitats for biodiversity [86,89]. Additionally, they also play an important role in promoting landscape connectivity, acting as ecological corridors that offer refuge and facilitate gene flow among scattered patches of natural vegetation in the landscape [90,91].

In addition to ecological restoration, actions aimed at conserving existing fragments are also important, as the provision of ecosystem services can vary depending on the age of the vegetation, suggesting that public policies should promote the conservation of primary forest fragments, in addition to efforts focused on increasing forest cover [43].

4.4. Methodological Potentials, Limitations, and Uncertainties

The methodology employed in this study allowed for the spatial mapping of WESs, identification of priority areas for conservation and ecological restoration, and evaluation of the effects of an alternative land use scenario generated based on the proposed environmental zoning. The method is based on the use of free and simplified models, making it applicable in unmonitored watersheds or those with limited available data, where the use of complex models is not feasible. Furthermore, the methodology is flexible and can be replicated in any rural region, allowing for landscape composition and configuration adjustments. The advantage of this approach lies in its ability to quantify the impacts of planned land use scenarios, in contrast to methods solely based on multicriteria analysis, as demonstrated by Valente et al. [30] and Anjinho et al. [33].

Although the methodology proved to be effective for land use planning aiming to increase the provision of WESs, it is important to acknowledge its limitations and interpret the results with caution. The limitations discussed in this study focus on the results generated from the proposed methodology. Operational limitations of the InVEST models can be found in Anjinho et al. [49].

One of the uncertainties related to the results of this study is associated with the outputs of the models used. The three hydrological models in InVEST operate at an annual scale, which prevents capturing the seasonal hydrological variability of the watershed. Surface runoff, sediment exports, and nutrient exports exhibit significant variations throughout the year, with peaks occurring mainly during the rainy season, which, in this study area, takes place between October and March [49]. Annual values mask and smooth out the seasonal effects of land use changes on watershed hydrology, which can lead to misinterpretations when using them for decision-making. For example, studies in the literature demonstrate the effects of forests on water production, indicating that this type of vegetation can reduce the water yield of the watershed [92], impacting local water availability. However, when considering seasonal effects, it is observed that forests and other natural areas regulate water flow throughout the year [93], maintaining the minimum flow necessary to ensure water during dry periods. Additionally, the models do not capture seasonal exports of nutrients and sediments. In the JGRB, precipitation during the rainy months represents 80% of the total annual precipitation volume [49]. Intense precipitation during this period promotes higher sediment and nutrient exports due to surface runoff and leaching from agricultural areas [94]. Therefore, additional studies at finer scales may be necessary to complement our findings and quantify the seasonal effects of land use changes on WESs in the studied watershed.

The criteria adopted for environmental zoning (outputs from the InVEST WESs models) may restrict more comprehensive land use strategies aimed at providing multiple ecosystem services and promoting biodiversity. Although the areas proposed for restoration in this study may contribute to the provision of other ecosystem services, it is recommended to include in the analysis other services such as climate regulation, habitat provision, pollination, and recreation [95] for broader land use planning. When it comes to biodiversity conservation, we know that many other characteristics are important and should be taken into consideration in identifying priority areas for conservation and ecological restoration, such as the quality, configuration, and connectivity of natural vegetation fragments in the landscape [43]. Although our results demonstrate the effectiveness of this approach for the four quantified WESs in this study, we cannot assert whether additional ecological benefits will be effectively achieved with increased natural vegetation [96], as they were not quantified in this paper.

5. Conclusions

The methodology of this study allowed us to quantify the effects of land use changes on surface runoff, nutrient exports, sedimentation, and WESs, highlighting the importance of ecological restoration in mitigating these effects. The approach is straightforward and recommended for unmonitored watersheds or those with limited data availability. The method is flexible and can be replicated in rural regions that still allow land use composition and configuration modifications.

The results highlight the negative impacts of agricultural expansion in the study area, particularly sugarcane cultivation, which had the greatest effect on annual sediment and nutrient exports. Due to the physical characteristics of the JGRB, land use changes had a smaller impact on surface runoff. However, the average annual value still increased by approximately 20% during the analyzed period. The conversion of pastures and natural vegetation to agriculture decreased the provision of WESs, except for the sediment retention service.

Through the proposed environmental zoning, it was possible to identify priority areas for ecological restoration, which are associated with riparian zones in this study. Restoring these areas has the potential to increase the provision of WESs and reduce surface runoff, as well as nutrient and sediment exports in the JGRB. These findings provide valuable insights for decision-making and sustainable land use planning. Our results offer a scientific basis for the implementation of legal instruments aimed at conserving and restoring natural ecosystems, such as the legally protected areas established in the *Brazilian Forest Code* and payments for environmental services programs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16114803/s1, Figure S1: Changes in water ecosystem services indicators between the period of 1985 and 2019, and 2019 and planned land use scenario; Figure S2: Effects of land use and land cover types on surface runoff and exports of sediments and nutrients in Jacaré-Guaçu River Basin; Figure S3: Effects of land use and land cover types on water ecosystem services in Jacaré-Guaçu River Basin; Table S1: Area of each land use class for the years 1985, 2019, and planned land use scenario; Table S2: Land use and land cover conversion matrix from 1985 to 2019 (km^2); Table S3: Simulated runoff, sediment export, nutrient export, baseflow, sediment retention and nutrient retention values for the planned land use and land cover scenario.

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