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Effects of Restoration and Conservation of Riparian Vegetation on Sediment Retention in the Catchment Area of Corumbá IV Hydroelectric Power Plant, Brazil

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Abstract: Vegetation cover and land use are important factors related to the capacity of ecosystems to provide soil loss regulation and sediment retention services, which are highly relevant for sediment management in watersheds draining into reservoirs with multiple water uses. One way to ensure the protection and recovery of vegetation by landowners in Brazil is the implementation of the federal Native Vegetation Protection Law (NVPL), which designates environmentally sensitive areas as Areas of Permanent Preservation (APPs), aiming to conserve water resources and prevent soil erosion. The benefits of riparian vegetation in the catchment of Corumbá IV Hydroelectric Power Plant (HPP), located in the Brazilian Cerrado, were analyzed considering landscape reconfigurations from a baseline condition (year 2011) in order to account for the recovery of riparian vegetation by the agricultural sector, as foreseen in the NVPL. The Sediment Delivery Ratio (SDR) model from the InVEST (Integrated Valuation of Environmental Services and Tradeoffs) package was used to map and quantify variations in sediment export and sediment retention throughout the catchment. The reduction in annual sediment export in the drainage basin of the Corumbá IV reservoir reached −27% in the scenario where the total deficit of riparian APPs occupied by pasture or agriculture in the baseline map (41.000 ha) are recovered. While 14% of riparian APP are occupied by crops versus 86% occupied by pasture in the drainage basin of the Corumbá IV HPP, the recovery of riparian zones occupied by agricultural activities resulted in the greatest benefits in sediment retention for the reservoir. The methodology employed in this study can support the prioritization of sectoral efforts for the restoration and conservation of native vegetation, considering the highest returns in benefits perceived by water users affected by sediment input in reservoirs. The study's results reinforce the importance of conserving vegetation in riparian areas and their surroundings for sediment retention, highlighting the role of these areas as assets in providing water-related ecosystem services. For future developments, it is suggested to assess the interconnections among the energy, water, and food sectors to better understand the barriers and challenges to the maintenance and improvement of water-related ecosystem services in the catchment area of Corumbá IV HPP.

Keywords: water-related ecosystem services; sediment retention; riparian vegetation; Brazilian Native Vegetation Protection Law; water management; water–energy–food nexus

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1. Introduction

The concept of ecosystem services provides a valuable approach to communicate societies' dependence on natural ecosystems and serves as a support tool in implementing measures for environmental protection to minimize impacts on the capacity of ecosystems to provide social benefits [1,2].

The alteration of land use and land cover (LULC) is one of the main factors determining the degradation of ecosystem properties and their capacity to provide ecosystem services [3]. Studies have demonstrated the role of land use and land cover in the process of erosion in watersheds [4,5] and the importance of preserved vegetation and riparian zones in promoting water-related ecosystem services, such as soil loss regulation and sediment retention [6–10].

Soil loss regulation and sediment retention services are of great relevance to sediment management in watersheds where there is drainage to reservoirs with multiple water uses, as the reduction in sediment input brings benefits that can extend to different water-use sectors and beyond the reservoir boundaries [11]. Some of these benefits include flood control upstream of the reservoir, maintenance of water storage capacity in the reservoir, reduction of impacts on built structures (such as hydroelectric turbines and irrigation pumps), and improvement in water quality parameters [12,13].

The process of soil erosion is a common phenomenon in tropical watersheds [14], and the greater or lesser susceptibility of soil to erosion is driven by physical factors, like soil type, slope, and climate, and by LULC patterns [5,15]. A series of hydrological and environmental processes influence the transport of sediments into the drainage network and subsequently the sediment load at the outlet [16]. The magnitude of soil loss is related not only to natural factors but also to the degree of degradation and alteration of the natural vegetation in the watershed and the propensity for adopting soil conservation measures that reduce or mitigate erosion on rural properties [17]. In Brazil, soil degradation and reservoirs siltation are strongly related to deforestation, soil cover, and soil and water conservation practices adopted by landowners [18–20].

One way to ensure the protection and recovery of vegetation by landowners in Brazil is the implementation of the federal Native Vegetation Protection Law (NVPL) [21], which replaced the Forest Code from 1965. The NVPL, in addition to defining the proportion of a given rural property that can be used for agriculture, silviculture, or cattle ranching, as well as the area of native vegetation that must be maintained under protection or restricted use [22], also designates environmentally sensitive areas as Areas of Permanent Preservation (APPs), aiming to conserve water resources and prevent soil erosion. APPs include both riparian preservation areas that protect riverside forest buffers and hilltop preservation areas at hilltops, high elevations, and steep slopes [23].

After the revisions of the 1965 Forest Code, the width of APPs of rivers in the new NVPL, for conservation purposes, remained the same as in the previous CF, that is, it ranges from 30 to 500 m from each bank depending on the width of the river [24]. For recovery purposes, there was a reduction in the area of riparian APPs to be recomposed in relation to the 1965 Forestry Code, with the width of the APPs being determined by the deforestation history and the size of the rural property, ranging from 5 to 15 m—regardless of the river width, and from 20 to 100 m—depending on the width of the river [21,22,24].

The recovery and conservation of riparian vegetation in APPs promote important ecological functions for water regulation, such as buffering of matter and energy between terrestrial and aquatic systems [25,26]. Therefore, riparian vegetation acts as an effective filter that retains sediments and nutrients originating from upstream areas, especially in areas draining agricultural landscapes [26–29], contributing to the regulation of sediment and nutrient input into rivers and water reservoirs [10,11].

In this sense, public policies and mechanisms that ensure the integrity of vegetation in environmentally sensitive areas of watersheds ultimately promote ecosystem services that benefit multiple water uses [10,30]. Assessing the role of vegetation protection measures in promoting water-related ecosystem services in hydroelectric catchments is of great importance in the Brazilian context, considering the role of hydroelectric production in the national energy matrix [31], the soil-loss impact of the advancement of agricultural areas in basins with important HPP reservoirs [18,20,32], and the effects of the flexibility of the Federal Law for the Protection of Native Vegetation on the recovery of riparian vegetation [24,33].

In this work, we assess the role of riparian vegetation protection measures in promoting water-related ecosystem services that benefit multiple water uses in hydroelectric reservoirs, such as sediment retention. To analyze the benefits of conserved riparian vegetation areas and scenarios of riparian recovery, the Sediment Delivery Ratio (SDR) model from the InVEST 3.3.1 package was used to map and quantify variations in sediment export and sediment retention throughout the watershed upstream of Corumbá IV HPP, located in the Brazilian Cerrado.

Using scenarios of vegetation recovery in riparian APPs occupied by agriculture or pasture in the baseline LULC map and scenarios of vegetation degradation in conserved riparian APPs, we demonstrate that the relative variation in sediment export to the reservoir is dependent on the location, area extension, and original type of land use in which the riparian APP was recovered.

We invoke a simple but spatially explicit model capable of mapping and quantifying sediment retention ecosystem services to assess the effects of LULC changes on riparian APPs in the context of watershed landscapes. We expect this approach to be applicable to providing valuable insights into land management practices and riparian APPs recovery strategies in regions such as the Brazilian Cerrado, where significant losses of natural landscapes occur and challenges are faced by the water, energy, and agricultural sectors.

2. Materials and Methods

To analyze the landscape location (location of sub-watersheds draining into the reservoir) and which change in land use and land cover in riparian APP has the greatest impact on reducing the annual sediment load to the Corumbá IV HPP reservoir, we applied the InVEST sediment delivery ratio model [34]. The model allows estimating an integrated response of the watershed based on large-scale characteristics and processes (temporal and spatial). Sediment export was chosen as the variable of interest because it is a physical parameter that affects water quality and storage capacity in reservoirs, and it is directly influenced by conservation and riparian vegetation recovery policies.

The framework used for quantifying variations in sediment retention and for assessing the benefits of vegetation recovery and conservation in riparian APP mainly comprised (Figure 1): (1) Data preparation, using Digital Elevation Model (DEM) data, Land Use and Land Cover (LULC) data, climate data (rainfall erosivity), soil type data, relationship between riparian buffer width and stream size, and LULC biophysical data (factor C and P); (2) Sediment retention ES assessment, involving model selection, calibration, and assessment; and (3) Results and analysis, involving quantification and analysis of the benefits of the conservation of riparian APPs and benefits of restoration of riparian APPs under different LULC changes per sub-watershed.

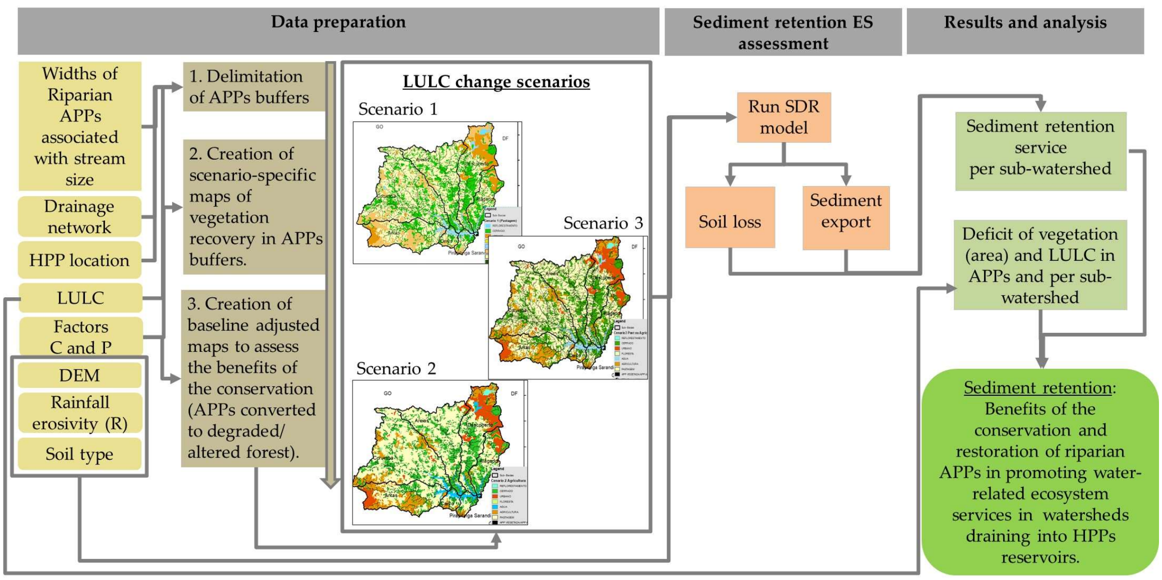


Figure 1. Analytical framework used to quantify and assess sediment retention by riparian vegetation in watersheds draining into HPP reservoirs.

2.1. Study Area

The study area was the watershed of the Corumbá IV HPP reservoir, which covers approximately 7010 km^2. The reservoir, with a surface area of 173 km^2, is located in the upper section of the Corumbá River in the state of Goiás (GO) and the Federal District (DF) of Brazil. The geographical coordinates of the reservoir are approximately 16°19′22″ S and 48°11′15″ W [35].

In addition to electricity generation (with an installed capacity of 129.6 MW), the project also aims to utilize the reservoir for multiple purposes, such as water supply, recreation, and tourism [36]. The main tributary sub-basins to the reservoir are Corumbá, Areias, Descoberto, Alagado, Antas, Cervo, and Pirapitinga-Sarandi (Figure 2).

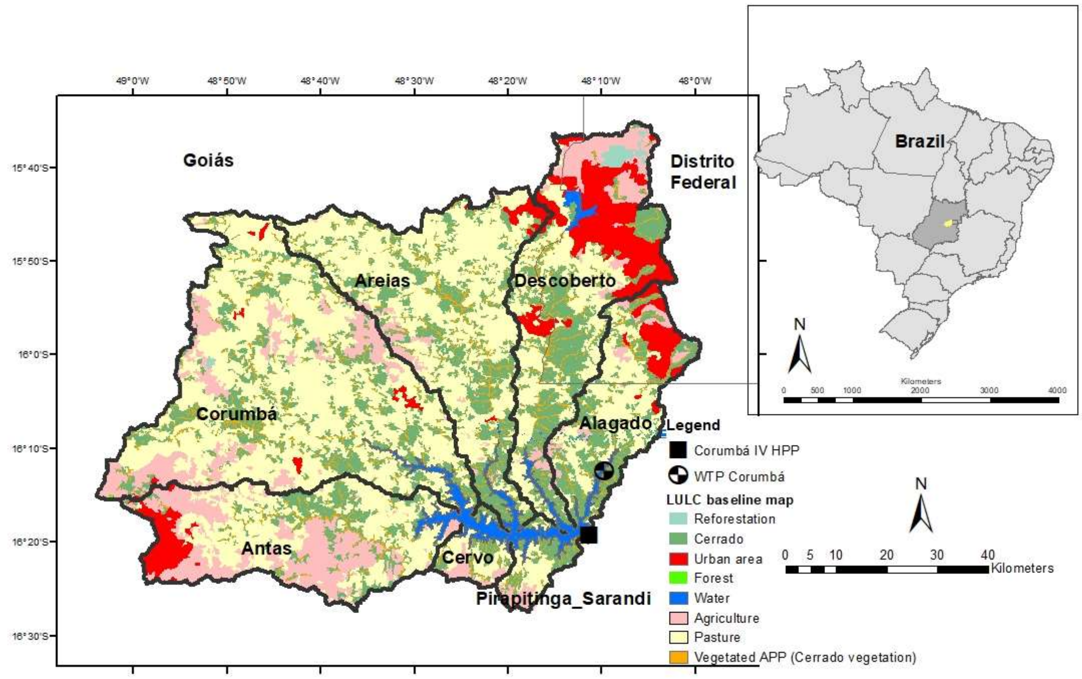


Figure 2. Land use and land cover map in the drainage basin of the Corumbá IV HPP. WTP_Corumbá: Water treatment plant of the Corumbá IV System (under construction).

The basin is located in a Köppen climate classification region, characterized as "Aw," which corresponds to a hot tropical climate with consistent temperatures throughout the year (monthly average temperature of 20 °C) and a dry winter season [35].

The average annual precipitation is 1650 mm, with marked seasonality between dry months (May to September) and wet months (October to April). The basin features slopes exceeding 10% in various sections, with the highest altitudes reaching around 1400 m in the headwaters region of the Corumbá River [35].

Regarding erosion potential, the natural susceptibility (soil and slope) is compounded by the reduced preservation of vegetation cover and intense agricultural activity (which covers about 60% of the basin area) [35]. The study area, located within the Cerrado biome, had experienced deforestation of over 70% of its natural vegetation by the year 2002, due to the expansion of large-scale agriculture and the emergence of major urban centers [35]. According to Soares-Filho et al. [24], the Cerrado biome has the largest deficit of riparian APPs (1.7 Mha), with the state of Goiás leading the deficit ranking for this biome (around 380 thousand hectares) [24], reflecting high deforestation rates caused by the expansion of the agricultural and energy sectors in the state [35,37].

2.2. Vegetation Recovery Scenarios in Riparian APPs

Based on the land use map from 2011 of the state of Goiás and Distrito Federal (baseline scenario) [38] (Figure 2) and the drainage network map [39], new maps were created incorporating the recovery of vegetation in riparian APPs occupied by agriculture or pasture, as required by NVPL. From the drainage network map of the basin [39], buffers of 30 m width were generated for river riparian areas. Additionally, based on the land use map of the baseline scenario, a 90 m buffer was generated for the riparian area surrounding the reservoir of the Corumbá IV HPP (according to the width specified in the environmental licensing of this project—100 m in rural basins) [36]. In this study, the widths of the riparian areas were adjusted based on the resolution of the DEM raster (30 m) [40,41]. The methodology used by Soares-Filho et al. [24] was adopted for delimiting the riparian APP, where, due to the lack of information on river widths, a hypothetical width was associated with the drainage order adopted by the National Water Agency (ANA) [39], the Brazilian regulatory body, in order to comply with the widths specified in the NVPL (Table 1).

Table 1. Widths of riparian APPs associated with ANA's drainage hierarchy (adapted from Ref. [24]).

Order	Width (m)
1	240
2	180
3	90
4	60
5	60
6	30
7	30
8	30
9	30
≥10	30

After using the Zonal Statistics Tool in ArcGIS to analyze the land use situation within the APPs buffers, three vegetation recovery scenarios were generated: scenario (1) vegetation recovery in APPs occupied by pasture; scenario (2) vegetation recovery in APPs occupied by agriculture; and scenario (3) vegetation recovery in APPs occupied by agriculture or pasture. Finally, the land uses within the APPs were reclassified, and new management and land cover parameters (C and P factors) were associated with them. The other land uses in the basin were not changed. Map generation and analysis were performed using ArcGIS 10.2 software.

2.3. Benefits of Conservation of Riparian APPs

Section 2.2 presents the methodology to assess the impacts of relative changes in the restoration of APPs deficits but does not consider the benefits gained from the conservation of APPs (environmental assets), which is an important consideration for determining the value of existing native vegetations and the benefits of avoiding degradation of these areas. To analyze the benefits of avoiding the degradation of the conserved APPs, a set of land use and land cover maps were created based on the methodology proposed by [42]. In these new maps, the deficits of vegetation in APPs are restored according to the recovery scenarios presented in Section 2.2, but the APPs designated as "conserved" in the baseline (APPs with native vegetation) are altered (converted into altered vegetation).

2.4. Modeling Sediment Retention Service

The Sediment Delivery Ratio model from InVEST [34] was used, which allows assessing ecosystem services provided by vegetated riparian zones, such as the service of regulating soil loss and the service of retaining sediments from sheet erosion.

The model uses georeferenced datasets, which allows mapping and quantifying soil loss from sheet erosion and the annual export of sediments at a point of interest. For each pixel, the model's algorithm calculates the potential soil loss using the Revised Universal Soil Loss Equation (RUSLE) [43] (Equation (1)).

The Equation (Equation (1)) is as follows:

$$\text{uslei} = (\text{R} \cdot \text{K} \cdot \text{LS} \cdot \text{C} \cdot \text{P})\text{i} \quad (1)$$

where:

- uslei is the potential soil loss (t/ha/year) at pixel i;
- R is the rainfall erosivity (MJ.mm/ha.hr);
- K is the soil erodibility factor (t.ha.hr/MJ.ha.mm);
- LS is the topographic factor, which is a function of the slope of pixel i;
- C and P (dimensionless) represent the land use and land cover factors, as well as any management factors applied.

This equation combines these factors to estimate the potential soil loss at a given pixel based on the erosivity of rainfall, the erodibility of the soil, the topographic characteristics, and the land use and management practices [34]. The vegetation cover and management factor (*C*) were assigned values between 0 and 0.25. For the soil and water conservation measures factor (*P*), the values ranged from 0 to 1. The values of factors C and P were based on the literature with values specific to the study region whenever possible. In this study, the LULC maps were used to assign the different C and P factors to create new maps incorporating each land use/land cover class according to APPs deficit restoration scenarios and for the assessment of the conservation benefits of APPs. The spatial variation in erosivity of rainfall, soil erodibility, and slope parameters for the Corumbá IV HPP catchment is presented in Figure 3.

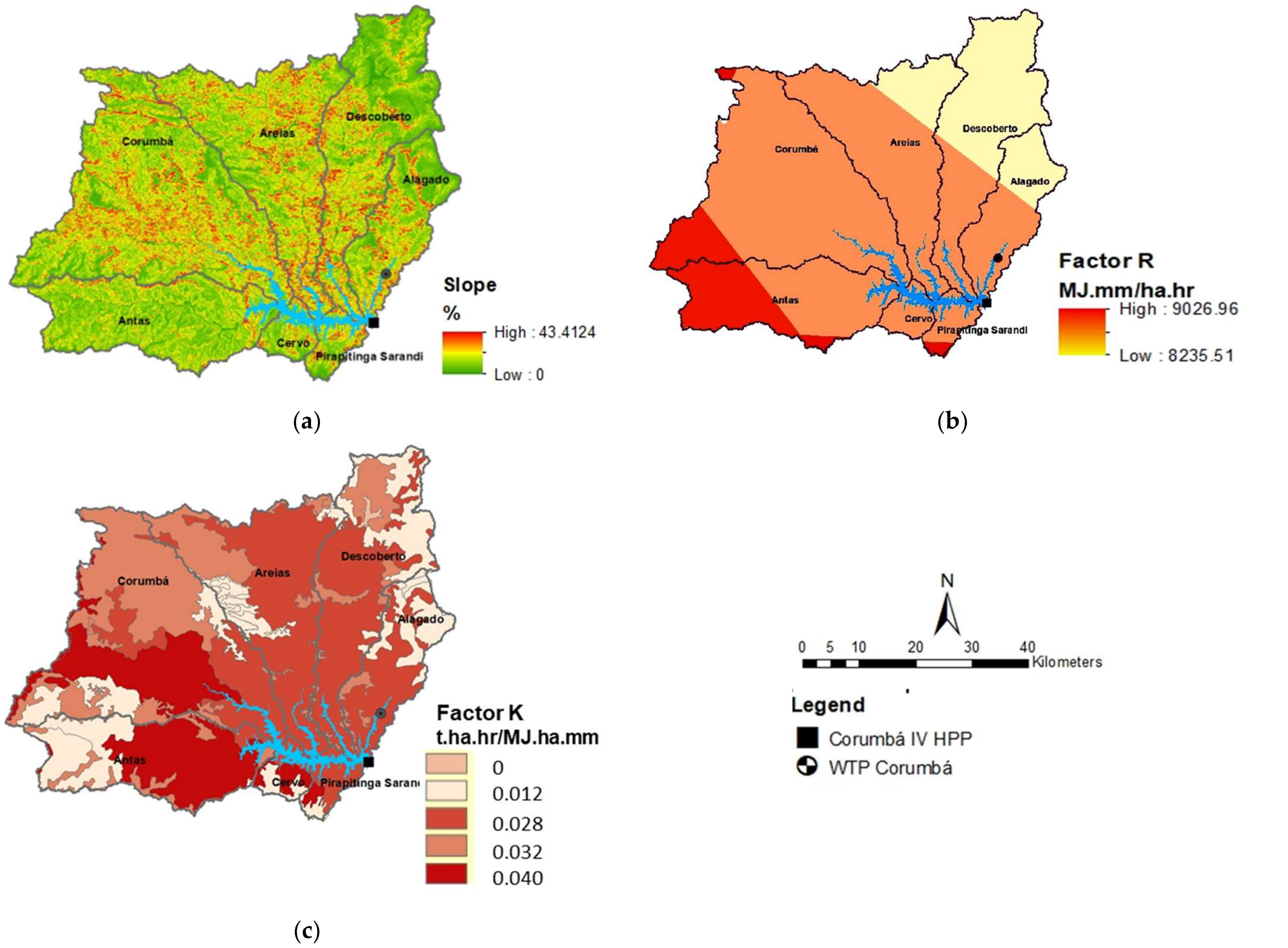


Figure 3. The slope (**a**), R-factor (**b**), and K-factor (**c**) maps of Corumbá IV HPP catchment.

The proportion of expected soil loss that actually reaches the watercourse is determined by the sediment delivery ratio (SDR), which is a function of the hydrological connectivity of the landscape [44]. Hydrological connectivity refers to the transfer of sediments from a source to a sink and is a key factor in determining how the spatial configuration of the landscape influences sediment retention. The model calculates the connectivity index (CI), which determines the degree of hydrological connectivity from a pixel to the watercourse based on its contributing area and the flow path to the drainage network, following the methodology proposed by [45]. The sediment delivery ratio is then derived from this index (Equation (2)):

$$SDRi = SDRmax/(1 + \exp(IC0 - Ici/kb)) \tag{2}$$

where:

- SDRmax represents the theoretical maximum value of the sediment delivery ratio (SDR), which is the maximum proportion of fine sediments that can reach the drainage network. In the absence of detailed soil information, a default value of 0.8 is commonly used [44];
- IC0 and kb are calibration parameters of the model used in the equation to calculate the sediment delivery ratio (SDR). IC0 is the initial value of the hydrological connectivity index (IC), and kb is an adjustment factor in the equation. These parameters are calibrated according to the specific characteristics of the studied landscape.

The sediment yield of a specific pixel i, sed_exporti (ton/ha.year), is a direct function of the soil loss and the SDR factor (Equation (3)):

$$Sed\_exporti = uslei \times SDRi \tag{3}$$

Finally, the total sediment yield in the drainage basin, originating from sheet erosion, is calculated as the sum of the sediment production of all pixels. Tables 2–4 present the data used as input for the model and their sources. The parameters used in this study were obtained from the literature with values specific to the study region, whenever possible (Tables 2–4).

Table 2. Input data for the model and associated sources.

Data	Base Year	Scale/Spatial Resolution	Goal	Source
Land use and land cover map	2011	1:250,000	To obtain land use and land cover classes	[38]
Soil Map	2005	1:500,000	To associate soil classes with Erodibility (K) data	[38]
Drainage Network	2014	1:50,000	To generate APP buffer from land use map	[39]
Digital Elevation Model	2000	30 m	To delineate the sub-basins area To delineate the HPP drainage area To calculate the topographic factor (calculated by the model)	[40,41]
Point of interest location	2011	-	To obtain the HPP Corumbá IV catchment outlet position	[35]
Erosivity Map	1980 to 2010	-	To obtain the R factor	[46]

Table 3. C and P factors associated with land use classes.

Land Use Class	Factor C	Factor P *	Source
Urban	0.1	1	[4]
Agriculture (annual basis)	0.25	0.5	[4,47]
Cerrado Biome	0.042	1	[48,49]
Water	0	0	By definition

Table 3. *Cont.*

Land Use Class	Factor C	Factor P *	Source
Atlantic Forest	0.005	1	[4]
Pasture	0.03	1	[50]
Reforestation	0.05	1	[4]
Recovered/vegetated APP	0.005	1	[4]
Altered APP (absence of vegetation or unnatural vegetation)	0.01	1	[4,51]

* Note: As most areas of intensive agriculture in this basin employ conservation practices such as no-tillage [35], a value of P = 0.5 was selected based in estimates made by [4] and recognized by [47]. For the other classes of use and vegetation cover, values of P = 1 were assigned, with the exception of the water class in which the value 0 was adopted, by definition. The P factor modulates the effect of the C (cover) factor, which is a measure of the sediment generation of each land-use type; a P factor closer to 1 means the land-use generates the full amount of sediment assigned by the C factor, while a P factor of 0.5 means the land-use only generates 50% of the sediment assigned by the C factor [4].

Table 4. K factor values associated with soil classes.

Class	k Factor (t·ha·hr/MJ·ha·mm)	Source
Water	0	By definition
Haplic Cambisol	0.028	[52]
Dystrophic Red Latosol	0.012	[52]
Dystrophic Red Yellow Latosol	0.032	[48]
Red Argisol	0.04	[48]
Litholic Neosols	0.04	[48]

The model was calibrated to minimize the difference between the sediment production estimated by the model in the baseline and the average presented by the studies of [53] (1.5 t/ha/year)—based on measurements at sediment monitoring stations in the region—and [36] (1.8 t/ha/year)—based on pre-filling measurement campaigns at the reservoir. The calibration resulted in the modification of the calibration parameter Kb (1.7), following the guidance of the SDR model guide [34]. The value of 1000 was adopted for the Threshold Flow Accumulation (TFA) parameter after verifying correspondence between the InVEST output raster of pixels that drain to a stream and the real stream network [39], following the guidance of the SDR model guide [34].

2.5. Estimating the Benefits of Sediment Retention by APPs

The variation in sediment export in the analyzed sub-basins was quantified as the change in sediment export after the restoration of APPs compared to the estimated sediment export in the baseline plus the benefits of conservations of APPs, relative to the baseline adjusted (conserved areas converted to degraded vegetation). The total benefit was then calculated as the benefit of restoration (Equation (4)) and the benefit of conservation (Equation (5)) of the APPs, for each sub-basin that contributes to the Corumbá IV HPP reservoir.

$$BR = ((Yc;j - Yb;j))/(Yb;j) \times 100 \quad (4)$$

$$BC = ((Yc;j - Ya;j))/(Yb;j) \times 100 \quad (5)$$

where:

- BR is the benefit of restoring the APPs;
- BC is the benefit of conserving the APPs with native vegetation in the baseline;
- Y is the estimated annual sediment export (t/year) for the sub-basin (j) in the following scenarios: restoration of APPs and maintenance of conserved APPs as baseline (c); restoration of APPs plus the conserved APPs in the baseline converted to altered vegetation (a); and the baseline (b).

The sub-basins draining into the reservoir were delineated using ArcGIS 10.2 software, considering level 6 for the Ottobacias of the ANA's coded hydrographic base. The estimated values for each sub-basin were derived from the modeling results using the Zonal Statistics Tool in ArcGIS. The deficit of vegetation in APPs (area) and the LULC in the basin in the APPs were also assessed using the Zonal Statistics Tool.

3. Results and Discussion

We split this section into subheadings to provide a concise and precise description of the experimental results, their interpretation and discussion, as well as the experimental conclusions that can be drawn.

3.1. Land Use in Sub-Basins and in APPs

Table 5 presents the land use and land cover classes in the sub-basins contributing to the Corumbá IV HPP and also in the buffers that delimit the APPs mapped in this study for the baseline scenario. Pasture is the predominant class in the Corumbá IV HPP drainage basin (49%), followed by Cerrado vegetation (27%) and annual agriculture (14%). The sub-basin with the highest proportion of preserved native vegetation is Alagado (39%), while the lowest is Antas (18%). This configuration is a reflection of the strong expansion of the agricultural sector in this region of Brazil in the 2000s [35], where the majority of the analyzed sub-basins have over 50% of their areas occupied by agriculture, reaching 72% and 74% in the Antas and Corumbá sub-basins, respectively. Regarding the riparian APPs mapped in this study, they occupy 74 thousand hectares of the total area of the Corumbá IV HPP basin, representing approximately 10% of the basin. About 40% (30 thousand ha) of the APPs in the Corumbá IV HPP basin are conserved (Cerrado vegetation class), and 55% (41 thousand ha) have a deficit of vegetation, meaning that instead of preserved native vegetation, these areas are occupied by agricultural crops (approximately 6 thousand ha) or pasture (approximately 35 thousand ha).

Table 5. Land use and land cover in the drainage sub-basins of Corumbá IV HPP and within the APPs, and vegetation deficit in APPs in the year 2011 (baseline scenario).

Ottobacia Code	Basin	Agriculture		Pasture		Cerrado		Other *		Total		APP Deficit **	
		%								Thousand Ha		Thousand Ha	%
		Basin	APP	Basin	APP	Basin	APP	Basin	APP	Basin	APP	APP	
869696	Alagado	7	3	38	36	39	56	15	5	64	6	2	39%
869698	Corumbá	13	6	61	61	24	34	2	0	225	27	18	66%
869697	Antas	33	27	39	36	18	32	10	6	109	10	6	62%
869695	Pirapitinga-Sarandi	14	7	34	44	34	48	18	0	17	2	1	52%
869699	Cervo	19	9	36	47	26	45	19	0	16	2	1	55%
869694	Descoberto	12	10	30	30	31	45	28	15	128	13	5	40%
869696	Areias	4	1	61	49	32	50	3	0	141	14	7	50%
Corumbá IV HPP Basin		14	8	49	47	27	41	10	4	701	74	41	55%

Note: * Other = Urban, Forest, Reforestation, Water (in the basin, corresponds to lakes and reservoirs). ** APP Deficit = areas occupied by pasture or Agriculture in the 2011 map (baseline).

The LULC pattern in riparian APP analyzed in this study is in line with the pattern identified in studies that considered the study region [24,35]. According to Soares-Filho et al. [24], under the NVPL, Brazil has a deficit vegetation in riparian APPs of 4.8 ± 1.8 million hectares (Mha), with an estimated 0.6 ± 0.35 Mha of this being potentially occupied by crops, representing less than 1% of national agriculture, and the remaining area occupied by pastureland. The Cerrado biome has the largest deficit of riparian APPs (1.7 Mha), with the state of Goiás leading the deficit ranking for this biome (around 380 thousand hectares) [24], reflecting high deforestation rates caused by the expansion of the agricultural and energy sectors in the state [35].

It is important to note that, to meet the objectives of this study, areas occupied by pasture and by agriculture were considered as a deficit of APP, while areas occupied by urban land use were not considered as a deficit of riparian APP since there is a limitation or impossibility in recovering the vegetation in these consolidated areas.

3.2. Benefits of APPs Recovery and Conservation

The results show that the conservation of riparian APP (extent of conserved riparian forest in baseline map) and the recovery of riparian APP (recovery of vegetation in areas occupied by pasture or agriculture in baseline map) in all scenarios have an impact on the sediment retention service that benefits the Corumbá IV reservoir by reducing the annual sediment export to the streams. The reduction in sediment export resulting from riparian vegetation recovery in the drainage basin of the Corumbá IV reservoir was −9%, −16%, and −27% in scenarios 1, 2, and 3, respectively (Figure 4). The contribution of conserved APPs to sediment export in the drainage basin of the Corumbá IV HPP remains relatively constant at around −3% across all scenarios (Figure 5), as the extent and location of protected APPs remain unchanged.

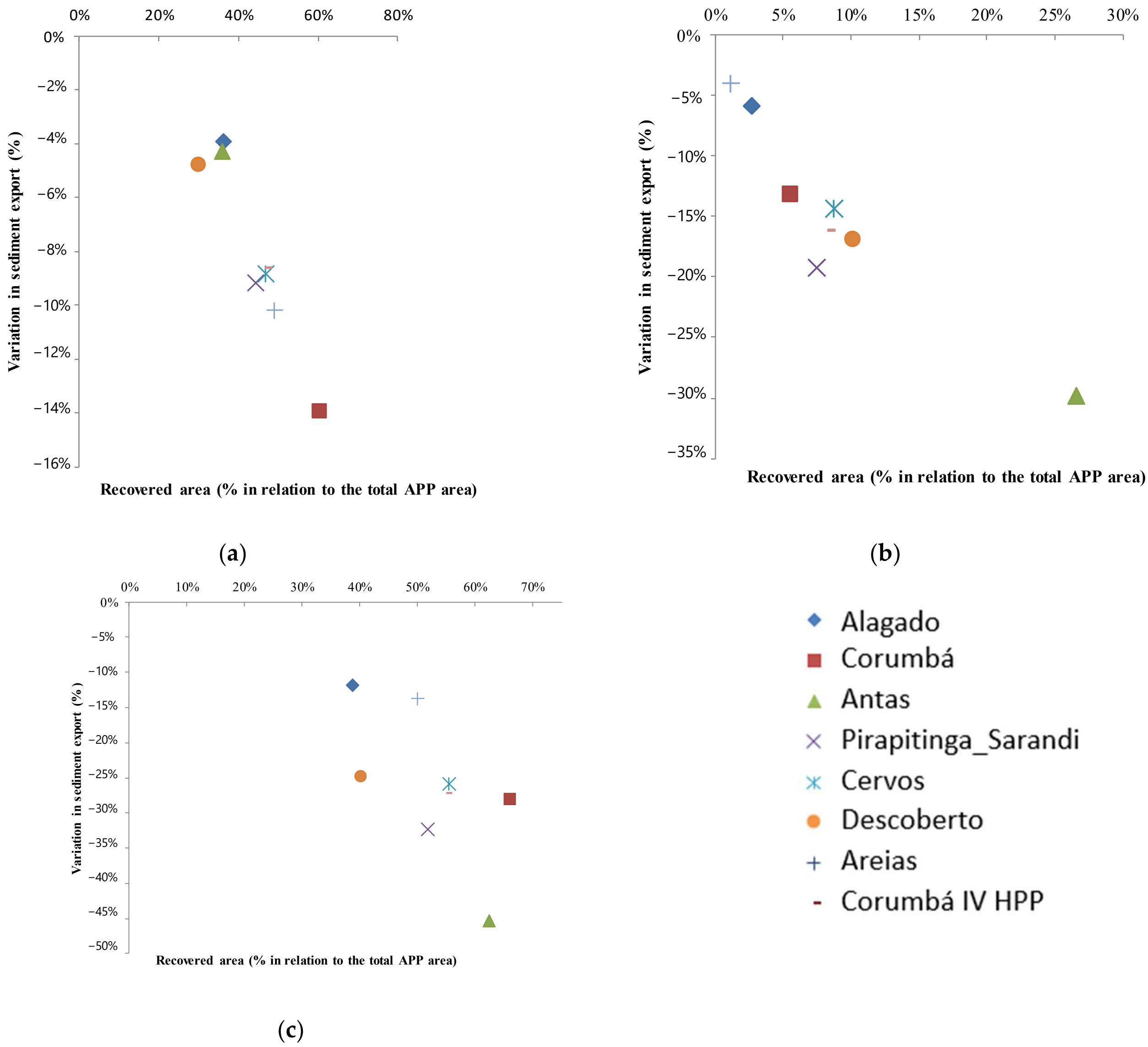


Figure 4. Percentage variation in average annual sediment export compared to the baseline, calculated by the SDR InVEST model, for each hydrographic sub-basin in scenario 1 (**a**), scenario 2 (**b**), and scenario 3 (**c**). These results represent the benefits (BR) of APP recovery, as calculated in Equation (4). Note that the x-axis values are different among the graphs.

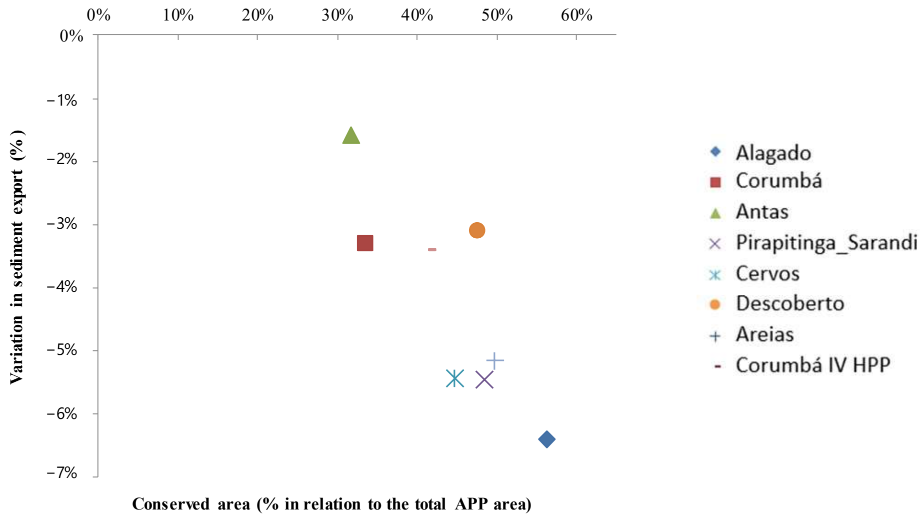


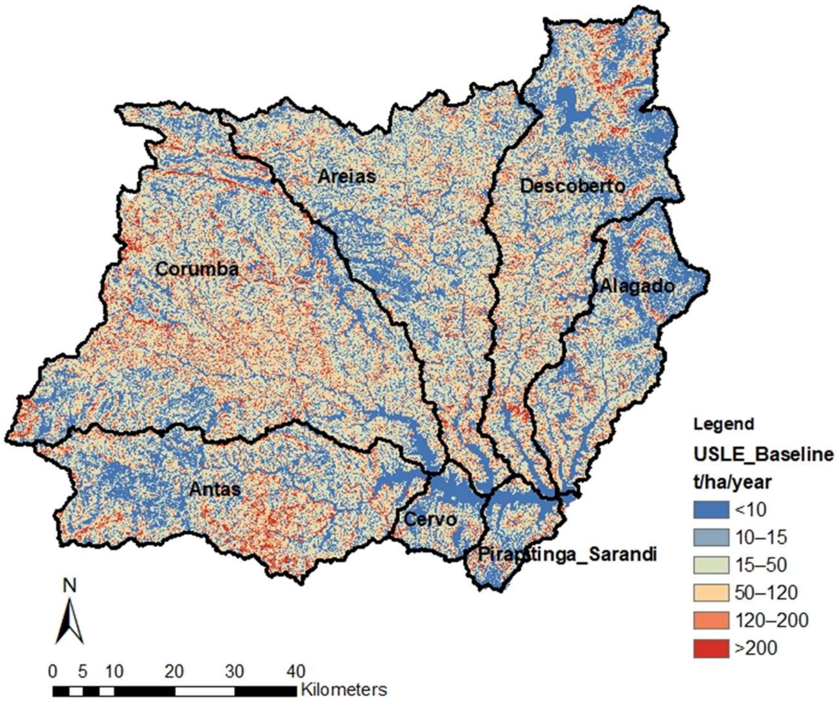
Figure 5. Percentage variation in average annual sediment export compared to the baseline, calculated by the SDR InVEST model, for each hydrographic sub-basin in conservation scenarios. These results represent the benefits (BC) of APP conservation, as calculated in Equation (5).

In terms of sediment retention at the sub-basin level, scenario 3 exhibits the largest variations for all sub-basins. This was expected since scenario 3 combines the APP recovery deficits from scenarios 1 and 2. When comparing scenarios 1 and 2, despite having smaller deficits of vegetation to recover (Table 5), the largest benefits are observed in the recovery of APPs occupied by agricultural crops in scenario 2, except for the Corumbá and Areias sub-basins. The recovery of riparian vegetation in areas draining agricultural landscapes can contribute to a reduction of approximately 30% (Antas sub-basin) in sediment input to the reservoir, considering the baseline sediment export from the respective sub-basin. The proportion of sediment retention benefits attributed to the conservation of native vegetation ranges from −2% to −6% across sub-basins, with the Antas and Alagado sub-basins having the lowest and highest percentages, respectively.

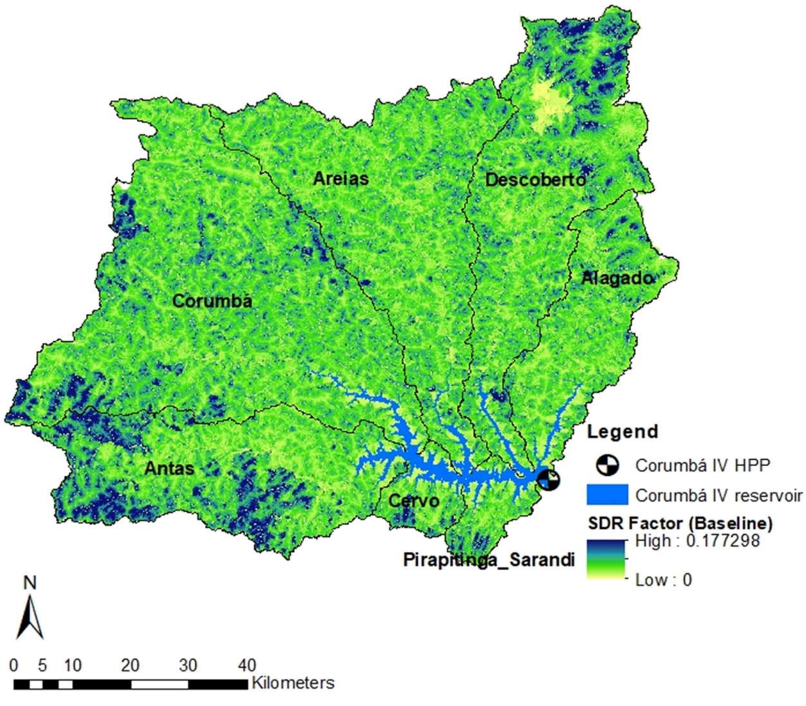
Since all other parameters remained constant (slope, soil properties, rainfall erosivity, C and P factors in areas not occupied by riparian APPs, and calibration parameters), the modeling results indicate that the variation in sediment retention service in a given sub-basin is related to the effect of the conversion of LULC in riparian APPs, which captures the difference in the C and P factors between the scenarios and the extent of the area converted. Variation in sediment export between sub-basins could be explained by the original characteristics (baseline) that may differ between them, such as potential soil loss (Figure 6), given by the product of erosivity (R), erodibility (K), slope length and steepness factor (LS), land use coefficients (C and P), and the sediment delivery ratio (SDR) (Figure 6), representing the proportion of sediment produced by the sub-basin that will travel to the stream, computed as a function of the hydrologic connectivity of the area [54].

The difference in the effects of APP conservation compared to recovery can be explained by the fact that the conserved areas identified in this study are predominantly located within remnants of Cerrado vegetation. This landscape configuration influences the hydrological connectivity simulated by the model, as the surrounding Cerrado vegetation plays a significant role in reducing soil erosion and retaining sediment loads from upstream areas.

In general, the results show that the greatest benefits of sediment retention in relation to the area to be recovered occur in riparian zones occupied by agricultural activities. Of the total deficit of vegetation in riparian areas in the drainage area of Corumbá IV HPP, 14% is occupied by crops and 86% by pasture.



(**a**)



(**b**)

Figure 6. Outcomes from the InVEST model, showing the potential soil loss (USLE) in t/ha/year (**a**), and the sediment delivery ratio (SDR) (**b**) across sub-basins in baseline conditions.

The recovery of vegetation in riparian areas has a proportionally greater effect in areas with a high hydrological connectivity, such as areas with a high sediment contribution upstream and where the sediment flow path to the drainage network has low sediment retention, such as agricultural areas [54]. The results reinforce the buffering function of riparian vegetation as an effective practice for managing sediment flows originating from sheet erosion in landscapes draining agricultural areas.

The differences between the conservation and recovery of riparian areas in providing the sediment retention service, quantified in this study, can be explained by the effect of remnants of Cerrado vegetation surrounding the conserved APPs. This will have an impact on reducing the hydrological connectivity computed by the model and, consequently, on the amount of sediment transported throughout this portion of the landscape.

The impact of APP recovery and conservation on sediment retention is driven by a multiplicity of biophysical factors captured by the SDR InVEST model. The SDR model is a widely used tool that estimates the ratio of sediment delivered to a river network from a given landscape unit [55]. By incorporating data on land use, soil characteristics, topography, and hydrological processes, the model can simulate the sediment delivery process and identify areas with higher or lower sediment yields. This is important for assessing the impact of different land management scenarios, including the protection and restoration of riparian areas, on sediment retention in watersheds that drain multipurpose water reservoirs.

The NVPL of Brazil is an important instrument to guarantee the potential of riparian buffers to supply watershed ecosystem services. However, there is still substantial uncertainty regarding how to ensure its implementation. [22,33,56]. The proposed methodology can support the implementation of management strategies and policies with the prioritization of areas to be recovered and conserved, considering the relative benefits of sediment retention in relation to the extent of the area to be recovered and in relation to the area conserved.

According to [55], the spatial prioritization of sediment retention services does not require precise absolute prediction but does rely upon the accurate relative representation of areas within a catchment that have greater or lesser importance in determining total sediment export for the entire catchment. Therefore, data that closely represent the local reality and align with the management goals of the watershed lead to better estimates of the provision of the water-related ES. In this study, whenever possible, data for the region obtained from the literature were used. Future developments could involve performing sensitivity analyses to detect the effect of the spatial variability of input parameters on sediment retention service across the sub-basins.

4. Conclusions

In this study, the benefits of riparian vegetation conservation and recovery were analyzed in terms of sediment retention in the drainage area of a multi-purpose water reservoir. The SDR InVEST model was calibrated to provide estimates of annual sediment loads to the reservoir under different land use and land cover scenarios in riparian buffer zones (APPs). The model captures the integrated response of the watershed to land use changes, considering the interaction among environmental factors that vary across the landscape. The variations in sediment input to the reservoir are greatly influenced by the land cover and land use in converted areas, as well as the availability of land for changes.

The results of the study demonstrate that the adoption of soil and water conservation measures, such as the NVPL, has the potential to have a positive impact on landscapes with high sediment exportation, especially in areas such as Brazilian Cerrado, where areas occupied by agriculture experience relatively greater soil loss than areas occupied by pasture [57]. In this sense, the adoption of conservation practices by the agricultural sector to minimize soil loss combined with practices to increase sediment retention services, like riparian APP recovery, have potential to reduce loads into rivers that benefit hydropower reservoirs, and another water uses.

The methodology adopted in this study allows for quantifying and mapping the effects of soil and water conservation measures on watersheds, enabling the prioritization of sectoral efforts for the recovery of native vegetation while considering higher returns of benefits perceived by water users affected by sediment input in reservoirs. Furthermore, the study's results reinforce the importance of conserving vegetation in APPs and their surroundings for providing sediment retention, highlighting the role of these areas as assets in the provision of water-related ecosystem services.

The adoption of an ecosystem approach in the analysis of measures and instruments to protect soil and water allows for the simultaneous consideration of biophysical and socioeconomic components, which is particularly relevant in the case of water resources that depend on the environmental characteristics of the landscape and the complex intersectoral interactions in the watershed [58,59]. For future developments, it is suggested to access the interconnections among the energy, water, and food sectors, which in Brazil are highly interrelated [60], to better understand the barriers and challenges to the maintenance and improvement of water -related ES in the catchment area of Corumbá IV HPP.

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