Land Use Policy 100 (2021) 104946

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Environmental fragility analysis in reservoir drainage basin land use planning: A Brazilian basin case study

Phelipe da Silva Anjinho[a,*], Mariana Abibi Guimarães Araujo Barbosa[a], Carlos Wilmer Costa[b], Frederico Fábio Mauad[a]

[a] University of São Paulo, Center of Water Resources and Environmental Studies, São Carlos, SP, Brazil
[b] Federal University of Rio Grande do Norte, Civil Engineering Department, Natal, RN, Brazil

ARTICLE INFO

Keywords:
Environmental fragility
Erosion
Sedimentation
Land use planning
Lobo Reservoir

ABSTRACT

Reservoirs constructed for multiple water and land use changes alter the hydro-sedimentological dynamics of drainage basins, intensifying erosion and silting of water bodies. To ensure water and soil conservation, environmental fragility analysis is a notable tool in land use planning. Potential environmental fragility (PEF) is the dynamic equilibrium of the environment, understood as the natural susceptibility of physical parameters to erosion. In conjunction with the socioeconomic parameter of land use, it generates emergent environmental fragility (EEF). This study analyzes PEF and EEF of the Lobo Reservoir Drainage Basin, a small basin in southeastern Brazil, and recommends environmental zoning derived from its assessment. Physical parameters, on a 1:50,000 scale, and land use spatial data were used to create PEF and EEF maps, followed by recommendations for suitable use for the basin's sectors, taking into account their environmental fragility and current land use. The results indicate that the basin is primarily classified as medium EEF, which is related to its medium PEF and to the region's agricultural activities. The proposed environmental zoning designates nearly half the basin as suitable for anthropic use, while 28.5 % is considered a priority for environmental conservation. Areas identified as a priority for conservation/restoration represent some 16 % of the basin. Limitations and potential enhancements to the study's methodology were encountered, but none impaired the EEF analysis, which identified areas that could favor erosion. The land use planning proposed by the study based on its environmental fragility analysis provides a low cost, flexible, and easy to use method, facilitating its adoption by public managers and use by government technicians. Moreover, the study's methodology can be widely replicated in other regions and fine tuned in accord with their specific characteristics and morphodynamic patterns.

1. Introduction

The rapid increase in and broad diversity of human activities promoting socioeconomic development adversely impact natural systems and can lead to irreversible environmental changes that compromise the planet's resilience capacity (Rockström et al., 2009). This could prove catastrophic as a result of the loss of natural resources and the ecosystem services they provide (Pascual et al., 2017; Wood et al., 2018).

A significant source of environmental change is the construction of artificial reservoirs. Reservoirs are crucial strategic ecosystems for economic and social development as they reserve water for multiple uses, including human consumption, electricity generation, agriculture, tourism, and recreation (Padedda et al., 2017). Although deemed a source of renewable energy, the construction and anthropogenic use of reservoirs modify the environment, impacting social and environmental spheres (Reid et al., 2018; Cheng et al., 2019; Kelly, 2019; Liu et al., 2019; Souza-Cruz-Buenaga et al., 2019).

The construction of reservoirs significantly affects the dynamics of the hydro-sedimentological cycle in hydrographic basins (Huang et al., 2018a; Gao et al., 2018); and, through feedback effect, this imbalance impacts their environment. Reservoirs intensify evaporation and sediment deposition from surface runoff, which, in turn, impact their water storage. At the same time, anthropogenic changes in land use for social and economic development, such as the conversion of natural areas to agricultural, urban, and other uses, adversely impact surface runoff and

---

* Corresponding author.
E-mail addresses: phelipe.anjinho@usp.br (P.d.S. Anjinho), mariana.abibi@usp.br (M.A.G.A. Barbosa), carloswilmercosta@gmail.com (C.W. Costa), mauadffm@sc.usp.br (F.F. Mauad).

https://doi.org/10.1016/j.landusepol.2020.104946
Received 14 November 2018; Received in revised form 17 July 2020; Accepted 19 July 2020
0264-8377/

sediment production and transport in the basin (Gao et al., 2015; Briak et al., 2019). The quantity and quality of water in reservoirs are directly affected by sediment originating in the drainage basin due to erosion. Silting on the reservoir bed compromises its useful volume and, consequently, its availability for diverse uses (Estigoni et al., 2014; Yousaf et al., 2018). Moreover, sediment transportation can compromise water quality, since affects parameters as sediment concentration and others that can be carried out while adsorbed to the sediment particles (Zorzal-Almeida et al., 2018; Hahn et al., 2019).

The control of sediment production and its transport is a practice that combines soil and water conservation. Silting remediation in reservoirs can be attained directly by removing settled sediment or indirectly by preventing its settling (Annandale et al., 2016). Land use planning that takes into account the natural characteristics of the basin in respect to the production and transport of sediment can enhance socioeconomic development and environmental conservation. To this end, environmental fragility analysis can be applied to conserve water in reservoir drainage basins for multiple uses.

Environmental fragility is the susceptibility of the ecosystem to changes in its dynamic equilibrium according to their intrinsic and extrinsic characteristics. Recent studies use the concept to assess the susceptibility of natural ecosystems under diverse conditions, including ecological habitat vulnerability (Caniani et al., 2016), aquifer pollution (Caniani et al., 2015; Jesiya and Gopinath, 2019), flooding events (Nasiri et al., 2018; Santos et al., 2019), and environmental degradation (Macedo et al., 2018; Arriagada et al., 2019).

In this study, environmental fragility is related to the susceptibility of bodies of water to soil erosion and sedimentations. An environmental fragility index, based on the theory of the Ecodynamic Units recommended by Tricart (1977), was proposed by Ross (1994, 2012) and is widely used in Brazil, particularly in the state of São Paulo. The theory assumes that natural ecosystems are in a dynamic equilibrium with respect to the exchange of energy and matter and can be altered by human interventions, generating temporary or permanent imbalances. To apply such definitions to land use planning, Ross (1994) proposed a new configuration that takes into account morphodynamic instability.

Ross (1994) presents potential environmental fragility (PEF), based on stable units, areas in natural balance where morphodynamic processes are not evident (Tricart, 1977). Its classification runs from very high instability, indicating areas that are a priority for environmental conservation, to very low instability, where the natural characteristics of the soil hold high potential for various anthropic uses. The instable units are conceptualized as emergent environmental fragility (EEF), which refers to the interaction of the natural characteristics of potential fragility and current land use (Ross, 1994). Higher EEF classifications designate areas where land use intensifies the natural instability of the environment, while lower classifications indicate that current land use mitigates potential instability. In sum, environmental fragility analysis consists of an integrated study of the natural environment and socioeconomic activities to identify areas susceptible to erosion.

The criteria used to determine fragility considered conditions of the relief, soil type, and degree of soil protection (Ross, 1994). A subsequent study expanded the analysis to include parameters relevant to morphodynamic behavior and pedogenesis, such as slope shape and rainfall (Ross, 2012). Change in any of these components may compromise ecosystem functionality, disrupt its dynamic equilibrium (Spröl and Ross, 2004), and affect erosion and sedimentation (Dorici et al., 2016; Uddin et al., 2016; Guerra et al., 2017).

As a result of its capacity to analyze the functioning of the natural environment in relation to human activities, Ross's environmental fragility index has been used in many Brazilian studies on land use planning and management (Donha et al., 2006; Gonçalves et al., 2011; Adami et al., 2012; Bahr and Carvalho, 2012; Junior and Rohm, 2014; Costa et al., 2015; Valle et al., 2016). Classification of environmental fragility informs environmental zoning in assessing current land use and whether it should be maintained or modified to minimize erosion processes and protect water resources (Manfré et al., 2013; Cruz et al., 2017).

Given the critical need for land use planning that incorporates a comprehensive understanding of ecosystems, this study uses Ross's index as it enables an evaluation that integrates environmental fragility and socioeconomic activities. Its ease of execution is another asset as the variables used in its classification are readily found in Brazilian databases, which facilitates its use in establishing public policies and other decision-making actions.

This study analyzes the environmental fragility of the Lobo Reservoir Drainage Basin (LRDB), in Itirapina, São Paulo State, Brazil. Based on its analysis, environmental zoning is proposed to guide land use planning and conserve water resources. It contributes as well to national research scenario since the basin is classified in the Long-Term Ecological Research Program of the National Council for Scientific and Technological Development (Tundisi and Matsumura-Tundisi, 2014) and to international research by disseminating a methodology that enhances land use planning.

Following this introduction, Section 2 characterizes the basin's geopolitical and physical aspects. In Section 3, the methodology applied to assess its environmental fragility and determine its environmental zoning is detailed. Sections 4 and 5 respectively present and discuss the study's findings. Finally, Section 6, summarizes the study's results and makes recommendations for further research.

2. Area of study

The Lobo Reservoir Drainage Basin is located in the central region of the state of São Paulo, Brazil, between the municipalities of Brotas and Itirapina, and between the geographical coordinates 22° 9′ 30″ S and 22° 20′ 0″ S and 47° 57′ 0″ W and 47° 45′ 0″ W. Its drainage area is close to 220 km^2 (Fig. 1). The principal watercourses that comprise the region's hydrography are the Itaqueri River and the Lobo Stream, which represent 85 % of the volume of water that feeds the Lobo Reservoir (Tundisi et al., 2003).

Constructed in 1936 to generate electricity, the Lobo Reservoir is 6.2 km long, with an average and maximum depth of 5.8 m and 14 m, respectively, a surface area of 5.6 km^2, and a volume of 24.3 hm^3. By the 1970s, it had become a regional tourist and recreational attraction, which requires the maintenance of a level upstream (Estigoni et al., 2014).

The region's climate, as classified by Köppen, is warm with a dry winter, designated as tropical high-altitude climate (CEPAGRI, 2018). The average annual rainfall is 1500 mm, and temperatures range from 15° to 17 °C in winter and 21° to 23 °C in summer (Tundisi and Matsumura-Tundisi, 2014).

The geology of the basin is composed of rocks of the São Bento and Bauru lithologic units, represented by their Pirambóia, Botucatu, Serra Geral and Itaqueri formations, and by colluvial-residual and alluvial deposits (Perrota et al., 2005).

In terms of geomorphology, the region is in the basaltic cuestas, situated between plateaus and depressions (Almeida, 2018). These formations appear as abrupt forms that constitute frontal escarpments, consequence of basaltic spills, and the reverse, characterized by smooth relief (Corvalán, 2009). The relief, in short, is low active with average unevenness of 50, and maximum of 300 m near the district of Itaqueri da Serra (Guerra and Cunha, 1996).

The region's soil comprises eight types: purple, red, and red-yellow latosol, red-yellow argisol, gleysol, litholic and quartzarenic neosol, and nitosol. The most representative, red-yellow latosol, originated from the sandstones of the Pirambóia, Botucatu, and Itaqueri formations, while quartzarenic neosol, originated from the sandy rocks of the Pirambóia and Botucatu formations, mainly in the floodplains of the Itaqueri River and Lobo Stream (IAC, 1981; EMBRAPA, 2006).

The vegetation consists of Brazilian Cerrado fragments, riparian forests, and reforestation with species of *Pinus sp* and *Eucalyptus sp*

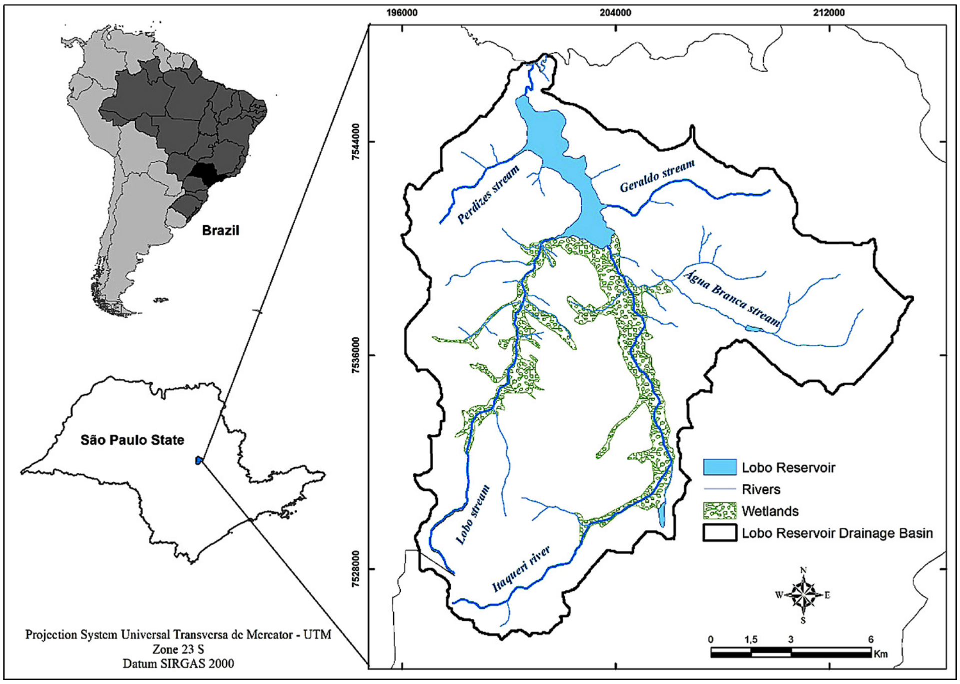

Fig. 1. Location of Lobo Reservoir Drainage Basin.

(Tundisi et al., 2003). Most of the basin's natural areas are environmentally protected. The basin is located within the Corumbataí-Botucatu-Tejupá Environmental Protection Area and includes the Itirapina Ecological Station, which preserves the phytophysiognomies and genetic heritage of the fauna and flora of the Cerrado biome in the state of São Paulo.

3. Materials and methods

3.1. Environmental and spatial data

The study evaluates LRDB’s environmental fragility according to the method in Ross (2012), which requires a set of data to assess the environment in an integrated manner. Its data is derived from public databases as detailed in Table 1.

Cartographic information was processed and analyzed in geographic information systems (GIS), using ArcGIS 10.3 software. The study’s geodesic system of reference was SIRGAS 2000, using the Universal Transverse Mercator projection system for zone 23 south. The spatial data in Table 1 was used to generate the maps in Fig. 2, as detailed herein.

The map characterizing soil types was created by converting the pedological chart (IAC, 1981) from analogical to digital format, with reference to LRDB boundaries.

The slope map is based on interpolation of planialtimetric contour lines and elevation points drawn from IBGE topographic charts (1969, 1971), using ArcMap 10.3 Slope tool. The slope shape, in reference to its concave, convex, or rectangular terrain profile and concentration or dispersion of runoff fluxes, was obtained from the TOPODATA project’s geomorphometric database (INPE, 2018).

Images used to create land use maps came from the Operational Land Imager (OLI) and Thermal Infrared Sensor of the Landsat 8 satellite, which provide 10 spectrum bands of 30 m spatial resolution and 1 spectrum band of 15 m spatial resolution (OLI panchromatic band 8). The images, dated July 15, 2017, were selected from the U.S. Geological Survey database (USGS, 2017). The land use characterization was made through the satellite image scanning, using the multilevel classification system proposed by the IBGE Technical Manual of Land Use (IBGE, 2013).

The precipitation chart was generated based on hydrological data from eight rainfall stations in the National Water Agency Hydrological Information System (HidroWeb) for 1975 and 2017 (ANA, 2018). The rainfall spatial data was generated from interpolation of the annual mean precipitation of the rainfall stations points within the drainage area, by means of the Inverse Distance Weighting (IDW) interpolator.

3.2. Environmental fragility analysis

The basic procedures for determining the basin’s environmental fragility are presented in in Fig. 3. Creating PEF and EEF maps in a GIS environment involves overlaying maps in a range of scales. Accordingly, the maps were rescaled from zero to one based on fuzzy logic, linear type [y = f(x)] (Marro et al., 2010), using ArcMap 10.3 Fuzzy Membership tool.

Table 1
Information plan map databases.

Spatial data	Source	Description	Scale
Topographic charts of Itirapina (SF-23-M-1-3) and São Carlos (SF-23-Y-A-1) municipalities	IBGE (1969; 1971)	Drainage system, contour lines and slope	1: 50000
Geomorphology	Geomorphometric database (INPE, 2018)	Slope shape	
Pedology	Semi-detailed pedological survey of São Paulo State (IAC, 1981). São Carlos grid.	Soil types	
Land use - 2017	Image LandSat 8, USGS.	Land use groups	–
Climate	HidroWeb ANA	Rain	–

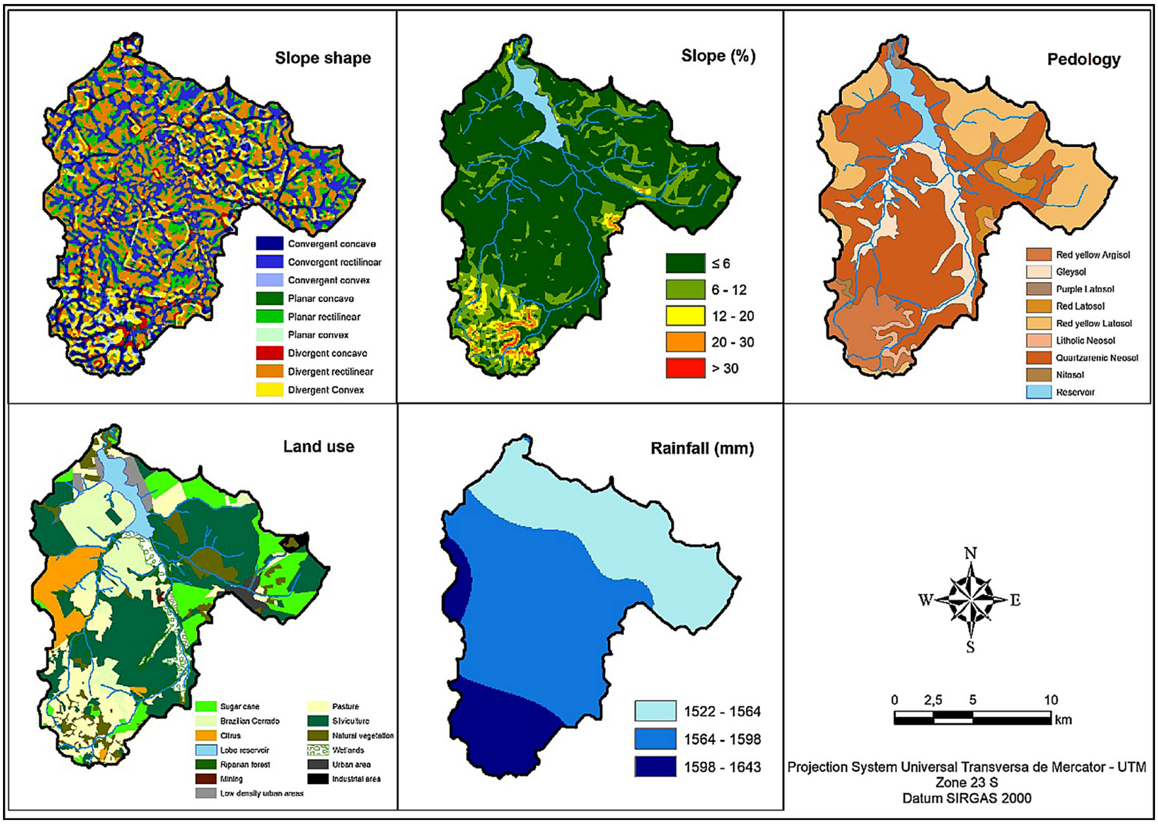

Fig. 2. Environmental fragility analysis maps.

The elaboration of the PEF map for the area of study was determined by the weighted sum of the physical parameters, using the ArcGIS 10.3 Weighted Sum tool. Subsequently, the PEF and land use maps were integrated, by means of the same tool to create the EEF map. In both steps, the attributes maps were weighted by 1, inferring equal relevance for each.

To categorize the PEF and EEF maps in five classes, from very low to very high fragility, their physical attributes and land use spatial data were first classified. The weighting of the fragility level for each map is related to resistance to erosive processes, taking into account intrinsic soil characteristics of the soil and interactive external parameters. The slope, soil type, rainfall, and land use maps (Tables 2–5, respectively) were classified from very low to very high fragility, as detailed in Ross (2012), and the the slope shape map (Table 6) was classified according to the definitions in Costa et al. (2015).

Table 2
Slope environmental fragility classes.

Slope (%)	Area (km^2)	Percentage (%)	Fragility class	Weight
≤ 6 %	173.69	78.47	Very low	1
6 – 12 %	36.66	16.56	Low	2
12 – 20 %	7.45	3.37	Medium	3
20 – 30 %	3.05	1.38	High	4
> 30 %	0.50	0.23	Very high	5

3.3. Environmental zoning

Environmental zoning was proposed based on methods in Manfré et al. (2013) and Cruz et al. (2017), which analyze land use and EEF maps. As presented in Table 7, the zoning considers the basin's

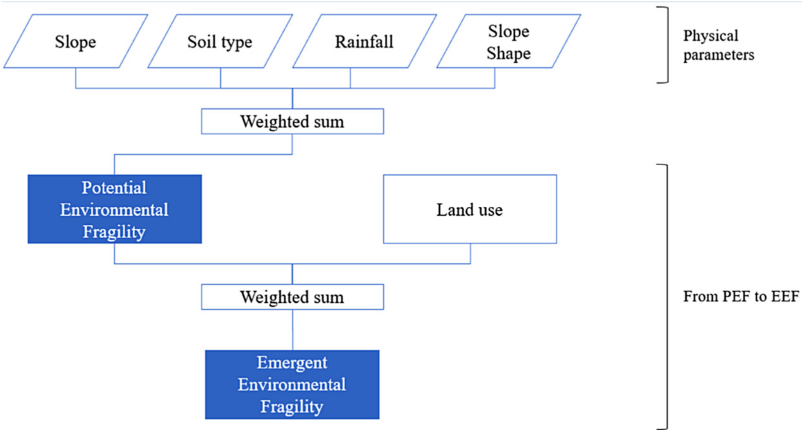

Fig. 3. Environmental fragility analysis methodology.

Table 3
Pedology environmental fragility classes.

Soil type	Area (km^2)	Percentage (%)	Fragility class	Weight
Purple latosol	1.06	0.48	Very low	1
Red latosol (clayey texture)	3.14	1.42	Very low	1
Red latosol (medium texture);	1.73	0.78	Medium	3
Red-yellow argisol (medium/clayey texture)	17.30	7.81	Medium	3
Nitosol	0.87	0.39	Medium	3
Red-yellow Latosol (medium texture)	54.66	24.68	High	4
Quartzarenic neosol (sandy texture)	109.65	49.51	Very high	5
Gleysol	22.93	10.35	Very high	5
Litholic neosol	3.76	1.70	Very high	5

Table 4
Rainfall environmental fragility class.

Mean precipitation (mm/year)	Fragility class	Weight
Irregular annual precipitation – 2–3 dry months during winter and intense rain volume during summer, from December to March – 1300–1600 mm/year	Medium	3

Table 5
Land use environmental fragility classes.

Land use	Area (km^2)	Percentage (%)	Fragility class	Weight
Riparian forest	9.95	4.49	Very low	1
Natural vegetation	17.61	7.95	Very low	1
Brazilian Cerrado	27.84	12.57	Low	2
Wetlands	7.57	3.42	Low	2
Citrus	13.33	6.02	Medium	3
Pasture	32.14	14.51	Medium	3
Silviculture	73.34	33.11	Medium	3
Sugar cane	25.36	11.45	High	4
Urban area	6.93	3.13	Very high	5
Industrial area	1.13	0.51	Very high	5
Mining	0.29	0.13	Very high	5
Lobo Reservoir	6.35	2.70	–	–

Table 6
Slope shape environmental fragility classes.

Slope shape	Area (km^2)	Percentage (%)	Fragility class	Weight
Convergent concave	20.04	9.05	Very low	1
Planar concave	6.60	2.98	Low	2
Divergent concave	7.23	3.27	Low	2
Planar rectilinear	35.91	16.22	Medium	3
Convergent rectilinear	55.45	25.04	Medium	3
Divergent rectilinear	68.59	30.97	Medium	3
Convergent convex	3.99	1.80	High	4
Planar convex	4.51	2.04	High	4
Divergent convex	19.14	8.64	Very high	5

Table 7
Proposed environmental zoning.

EEF	Land use	Environmental zoning
High and very high	Anthropic use	Conservation/restoration
Very low, low and medium	Anthropic use	Anthropic use
Any class of fragility	Urban area	Consolidated
Any class of fragility	Natural vegetation	Conservation

environmental fragility and most suitable land use to ensure environmental conservation and socioeconomic progress. The development of anthropic uses in areas of high fragility could intensify the process of soil degradation and thus affect the quality of water resources. Accordingly, these areas are a priority for implementing conservation practices, to ensure the adequation of the current anthropic use, or restoration of natural conditions. Anthropic use is suitable for areas of medium to low fragility. Natural vegetation areas, at any level of fragility, were considered conservation zones, and, given the difficulty of managing consolidated urban environments, such areas were classified as consolidated zones.

4. Results

4.1. Potential environmental fragility

The distribution of the five PEF classes in LRDB is presented in Fig. 4. The study found that areas with medium PEF are the most representative, accounting for 175.85 km^2 or 79.39 % of the basin (Table 8), which is directly associated with the region's natural characteristics. The preponderance (86.25 %) of the basin's soil types is highly susceptible to erosion, including quartzarenic neosol (49.51 %), red-yellow latosol (24.68 %), gleysol (10.35 %), and litholic neosol (1.70 %). However, these types of soil occur in areas with low slope (0–12 %), of which 95 % are classified as low to very low PEF, and 72 % as medium PEF of slope shape, influencing the final result of PEF.

Small areas with low and very low PEF occupy 11 % of the basin's total area (Table 8) and are distributed throughout, mainly in its southern region, where the springs of the Itaqueri River and Lobo Stream are located, and in its eastern region, near the Água Branca Stream, a tributary of the Itaqueri River. These low fragility areas are located on concave convergent slopes, which are less vulnerable to soil loss and on rectilinear slopes, which may favor erosion more or less intensely (divergent or convergent, respectively). The slope of these areas is in the 0–12% range and the soil types are red-yellow argisol (medium to clayey texture) and red latosol (clayey texture), which are characterized by low to medium vulnerability to environmental weathering.

Areas with high and very high PEF are distributed in small fragments in the basin and occupy 6.74 % of the basin. They occur, mostly in higher lands, close to the springs of the Itaqueri River and Lobo Stream. The physical characteristic most impacting PEF in this region is slope since the basin's steepest are located there, as well as litholic neosol, with small development degree with lithic contact within 50 cm. Other fragments are scattered in areas with great instability, characterized by convex slopes.

4.2. Emergent environmental fragility

EEF analysis, conducted by overlaying PEF and land use maps, provides a better understanding of the environmental impact of human activity. Fig. 5 depicts spatial distribution, and Table 9 quantifies the basin's EEF areas. The medium EEF class is predominant, occupying 149.51 km^2 or 67.51 % of the basin. This class occurs mainly in areas with medium PEF and a medium to high degree of soil protection, such as floodplains, Cerrado vegetation, silviculture, and pasture.

The next most prevalent class is the high EEF class, which occupies 19.69 % of the basin and is found in areas of high natural susceptibility

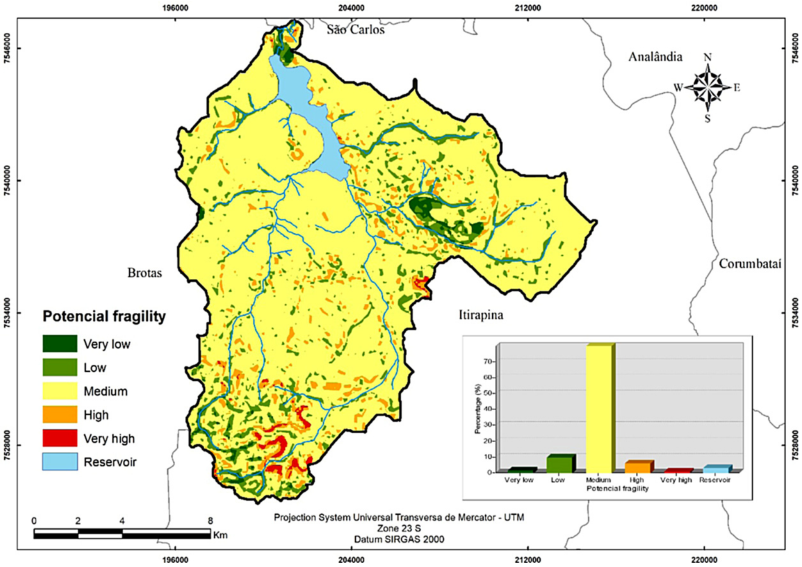

Fig. 4. Lobo Reservoir Drainage Basin's potential environmental fragility.

Table 8
Area/percentage of potential environmental fragility classes.

Potential environmental fragility classes	Area (km^2)	Percentage (%)
Very low	3.36	1.52
Low	21.00	9.48
Medium	175.85	79.39
High	12.98	5.86
Very high	1.95	0.88
Lobo reservoir	6.35	2.87

Table 9
Area/percentage of emergent environmental fragility classes.

Emergent environmental fragility classes	Area (km^2)	Percentage (%)
Very low	2.01	0.91
Low	18.39	8.31
Medium	149.51	67.51
High	43.60	19.69
Very high	1.60	0.72
Lobo Reservoir	6.35	2.87

to erosion associated with sugarcane plantations, urbanization, citrus, silviculture, and pasture. Areas of very high EEF cover 0.72 % of the basin and are associated with urban agglomerations.

Areas of low and very low and low EEF occupy an area of 20.40 km^2 or 9.21 % of the basin, occurring mainly in sites of medium and low PEF, such as riparian forests located adjacent to rivers and other fragments of natural vegetation.

4.3. Environmental zoning

The study's environmental fragility analysis was used to recommend environmental zoning for LRDB region by identifying priority areas for conservation or restoration and propitious areas for economic and social development (Fig. 6). The analysis indicates that 49.17 % of the basin is suitable for anthropic use (Table 10). These areas are characterized by very low to medium EEF and by agricultural activities.

Conservation areas occupy 28.37 % of the basin and are related to

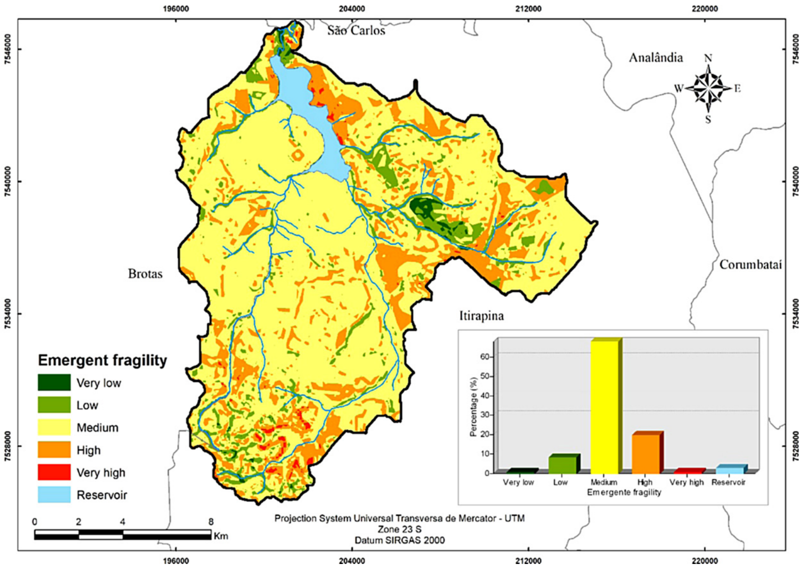

Fig. 5. Lobo Reservoir Drainage Basin's emergent environmental fragility.

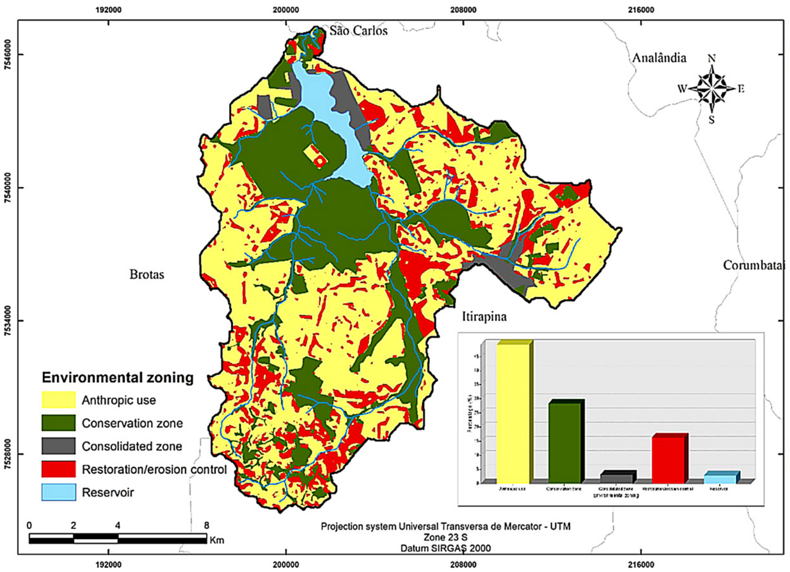

Fig. 6. Lobo Reservoir Drainage Basin's environmental zoning.

Table 10
Area/percentage of environmental zoning classes.

Environmental zoning	Area (km^2)	Percentage (%)
Anthropic uses	108.73	49.17
Conservation	62.74	28.37
Conservation practices/restoration	36.05	16.30
Consolidated	7.27	3.29
Lobo Reservoir	6.35	2.87

natural vegetation, regardless of the degree of environmental fragility to which they are subject. Zones with priority for conservation/restoration occupy 16.30 % of the basin and are mainly concentrated in southern and eastern sectors with agricultural activities developed in areas with high and very high EEF.

Finally, the consolidated zone occupies only 3.29 % of the basin and represents urban areas, which comprise part of the municipality of Itirapina, in the basin's eastern sector, and urban agglomerations, near the Lobo Reservoir.

5. Discussion

5.1. Potential and emergent environmental fragility

The study's PEF analysis indicates that LRDB has medium susceptibility to soil erosion as the result of high pedological fragility attenuated by other natural aspects of lower fragility. This indicates that it is suitable for the development of anthropic activities that apply appropriate techniques for soil conservation.

Soil's susceptibility to erosion is related to its physical and mechanical characteristics (Bünemann et al., 2018). Soils with higher sand or silt content are more fragile than those with higher clay content, and about 86 % of the basin is composed of such soils. The presence of medium texture soil, such as quartzarenic neosol, gleysol and red-yellow latosol, which permeates almost the entire basin, indicates it is more susceptible to erosion and increases its PEF.

The basin's slope, slope shape, and precipitation attenuate PEF. In general, the basin presents smooth relief with a low slope degree, which reduces erosion susceptibility. Precipitation is basically constant and is set within the PEF medium class according to the method in Ross (2012). Fragments where slope shapes are divergent or convex and slopes are steeper have the greatest soil instability and thus are classified as high to very high PEF.

EEF analysis enhances understanding of anthropic environmental impact. The study finds that 67.61 % and 19.69 % of the basin are areas of medium and high EEF, respectively. This result highlights the impact that land use changes can have on the environment and consequently on water. The basin's PEF was primarily characterized as medium in terms of natural susceptibility to erosion, but land use analysis found an increase of approximately 12 % in high EEF, corresponding to the loss of medium PEF areas.

Despite this negative impact, compared with other regions in the state of São Paulo, the basin provides a satisfactory rate of natural vegetation, which protects soil and conserves water, which occupies 28.43 % of its area, and maintains its quality. As previously noted, the basin lies within the limits of the Environmental Protection Area of Corumbataí-Botucatu-Tejupá, and two other protected areas, the most important of which is the Ecological Station of Itirapina, an area of 2300 ha designated to preserve natural resources and support scientific research vital to the maintenance of the Cerrado biome (IF, 2006). Several studies have showed the importance of the riparian forests and wetlands in mitigating the impact of human activity on water quality since they block entry of sediments and pollutants into water bodies (De Souza et al., 2013; Tanaka et al., 2015; Taniwaki et al., 2017), and these ecosystems also have positive effect in LRDB. These characteristics reduce EEF in the basin since, even in high PEF areas, the high degree of soil protection reduces erosion potential and, consequently, sedimentation of water bodies (Cruz et al., 2017; Fernandez et al., 2018; Macedo et al., 2018).

As a result of the expansion of agricultural activities, the Cerrado biome is one of the most threatened in Brazil (Strassburg et al., 2017). Several studies have examined the impact of sugarcane expansion in the state of São Paulo, particularly on the Cerrado and pasture areas (Rudorff et al., 2010; Adami et al., 2012; Moraes et al., 2017). Accordingly, although the basin is in a favorable situation regarding the conservation of natural vegetation (Tundisi and Matsumura-Tundisi, 2014), human activities such as expanded sugarcane cultivation could trigger erosive processes that can compromise water quality in the Lobo Reservoir.

This study found that agricultural activities are the basin's most representative land use, occurring in 65 % of its area. Brazil is one of the world's leading producers of such agricultural products as maize, sugar cane, meat, coffee and soybean (Nogueira et al., 2018), and the state of São Paulo is one Brazil's most important agroindustrial centers, producing sugarcane for sugar and biofuel uses, as well as oranges, pines, and eucalyptus (IEA, 2018). Agricultural areas in the basin encompass silviculture (33.11 %), sugarcane and oranges (17.4 %), and pasture (14.5 %).

Sugarcane cultivation associated with intensive mechanization and inadequate soil management practices can accelerate erosion, favoring the development of furrows and ravines. Cherubin et al. (2016) found that converting native vegetation to sugarcane reduces soil quality, rendering it more susceptible to erosion. It is estimated that the average rate of soil loss in the state of São Paulo is equal to 30 t ha^{-1} $year^{-1}$, which is directly related to sugarcane cultivation and pasture use (Medeiros et al., 2016). Costa et al. (2018) presented results analogous to this study's. Their study, which evaluated susceptibility to accelerated erosion in the Feijão River Basin, located near LRDB, concluded that sugarcane cultivation and pasture use are the principal contributors to erosion in the region. Dorici et al. (2016) examined the effects of sugarcane cultivation on erosion in the Araras River Basin in São Paulo state and reported results similar to this study's.

In addition to agricultural activities, urban agglomerations around the Lobo Reservoir and mining operations in the riparian forest along the Itaqueri River are associated with high to very high EEF. Deemed highly impermeable, urban areas nevertheless present a risk to soil erosion as they constitute dynamic environments that are constantly changing and expanding, leading to greater mass movement (Hu et al., 2001). Moreover, urban policies and practices in regard to soil protection are not uniform, but vary widely for residential, industrial, park, landfills, allotments and other urban uses. In addition, the removal of the riparian vegetation causes instability that could lead to erosion and sedimentation, and Pope and Odhiambo (2014) found that urbanization can lead to soil erosion and sedimentation of reservoirs.

Mining areas are highly susceptible to environmental degradation due to the direct exposure of rock and soil to weathering, and several studies have demonstrated the effects of mining on erosion and water contamination with heavy metals (Jarsjö et al., 2017; Slingerland et al., 2018).

Anthropic activities have the greatest impact on water quality in reservoirs, as they can introduce adsorbed pollutants. Land use changes may cause several effects on sedimentation and water quality. One of the most recurrent is the enrichment of nutrient concentration, which may lead to eutrophication and thus alteration of ecological status (Smith and Schindler, 2009; Yang et al., 2016; Chang et al., 2017). Such degradation can incur considerable costs for recovery and compromise multiple uses. In the Lobo Reservoir, these could include power generation, tourism, recreation, and fishing (Tundisi and Matsumura-Tundis, 2014). Periotto and Tundisi (2013) examined some 20 ecosystem services of the basin and estimated their value at \$120,445,657.87 $year^{-1}$.

It is estimated that half the storage capacity of the world's reservoirs will be lost in approximately 40 years (WCD, 2000). Changes in land use are one of the principal causes of the sedimentation in reservoirs, reducing their useful life and the generation of electricity (Annandale et al., 2016). Their management is a critical challenge in Brazil, where 65.2 % of electricity is generated by hydroelectric production (EPE, 2018).

The Lobo Reservoir Drainage Basin presents a favorable situation to the development of anthropic activities, but socioeconomic considerations indicate the need to reinforce conservation practices in soil management, particularly in areas with high PEF, to ensure and enhance water availability and quality. In addition to effecting erosion, the conversion of natural areas to anthropic activities may trigger other environmental impacts, such as changes in riparian ecosystems (Valle Junior et al., 2015), water availability and quality (Pacheco and Fernandes, 2016; Huang et al., 2018b; Hutchins et al., 2018) and ecosystem services (MEA, 2005; Liu et al., 2017; Song, Deng, 2017; Li et al., 2018).

5.2. Environmental zoning for environmental management

The environmental zoning analysis revealed that 49.17 % of the basin is suitable for anthropic use. The basin's medium PEF is propitious to such development and current agriculture use; however, soil conservation techniques should not be neglected.

The study deemed all natural LRDB areas (28 %) conservation priorities. This sector is basically comprised of the Ecological Station of Itirapina, wetlands and areas of riparian vegetation, which are critical to preserving the reservoir's water quality (Tundisi and Matsumura-Tundisi, 2014). Their maintenance also contributes to the preservation of the Cerrado fragments of São Paulo State composed of open physiognomies such as shrub (*campo sujo*) and wet savanna (*campo úmido*), savanna woodland (*campo cerrado*), and grassland (*campo limpo*), as well as fragments of woodland (*cerrado stricto sensu*), tall woodland (*cerradão*), and riverine forests (IF, 2006).

The study indicated that 16.30 % of the basin constitutes priority areas for conservation/restoration. This sector, areas of high to very high EEF, entails agricultural and forestry (pine and eucalyptus) uses. Although it is highly susceptible to erosion, a realistic approach consistent with its socioeconomic characteristics indicates its restoration to natural vegetation is impracticable. Accordingly, other approaches to soil and water conservation, such as management techniques for tillage and intensification of soil cover (Tang et al., 2015; Demirel et al., 2018; Poesen, 2018), and construction of areas for retention of surface runoff, such as bioengineering techniques (Evette et al., 2009; Vymazal and Březinová, 2015; Sun et al., 2018) are in order.

Areas of consolidated use constitute 3.14 % of the basin. For these areas, especially those around the reservoir, where the Santo Antônio bathing resort is located, environmental management strategies should be developed to reduce potential impact on reservoir water since such areas are difficult to redirect given their social uses.

A significant legal instrument enabling the zoning proposed recommended herein is Federal Law Nº12.651 of 2012, which instituted Brazil's forest code and regulates permanent preservation areas and legal reserves. The latter are focused on biodiversity conservation and sustainable use of natural resources, while the former prevent erosion in rivers, ensure the quality of water resources, provide gene flow and provide environmental services (Brazil, 2012). While their ecosystem functions differ, these areas are complimentary in terms of ecosystem maintenance and biodiversity conservation (Metzger, 2010; Tambosi et al., 2015). The cited Federal law could facilitate adoption of conservation and restoration measures in LRDB since it establishes a legal obligation for rural landowners to maintain a percentage of permanent preservation areas and legal reserves within their properties, which constitute a significant portion of the basin (IBGE, 2010).

Economic means can also be used to promote conservation and restoration measures in the basin. One such instrument is Brazil's Payment for Environmental Services, which is an incentive through compensation for rural property owners who own natural vegetation areas that can provide ecosystem services (Engel et al., 2008). Brazil's environmental service programs could also be used to fund conservation and restoration projects. Created by the National Water Agency, the Water Producer Program's objective is to enhance water quantity and quality through soil and forest conservation (Ruggiero et al., 2019). The program encourages farmers to adopt soil management practices that prevent erosion of soil and silting of springs in rural environments (ANA, 2012).

The Brazilian legal apparatus offers numerous instruments to facilitate land use planning and management. In theory, this requires integrated studies of environmental systems, but in practice, plans are often developed without regard to pertinent technical criteria. The zoning proposed herein, however, is based on a dynamic, systemic analysis of diverse environmental data yielding scientific results that can inform such management tools as ecological-economic zoning (Brazil, 1981), municipal (Brazil, 2001) and water resource management plans (Brazil, 1997), as well as plans to conserve the environments of artificial reservoirs (Brazil, 2002), the latter directly related to the purpose of this study.

5.3. Method evaluation

The study adopts an empirical ecodynamic approach that takes into account physical parameters and current land use to assess environmental fragility and identify priority areas for conservation in LRDB. This method offers a number of advantages.

First, it is efficient in determining areas for environmental zoning since it assesses multiple spatial data. Its approach can be used in land use planning and management in diverse contexts and a broad spectrum of applications (Junior and Rohm, 2014; Costa et al., 2015; Valle et al., 2016; and Cruz et al., 2017) as a practical and flexible tool in land use planning.

Second, it provides the simplicity of operation of the method proposed in Ross (2012). A principal challenge in analysis involving multiple variables is the attribution of weight based on specific technical knowledge. The study's method uses criteria in Ross (2012), which have been weighed by specialists, facilitating is adoption by public managers and use by technicians.

Third, it can be readily replicated elsewhere as it enables the use and the classification of criteria specific to the environment and morphodynamic patterns of each region to which it applied. Such fine tuning does not alter the method´s fundamental concept but provides more representative analyses from diverse sites.

Although the method in Ross (2012) proved satisfactory for the purpose of the study, limitations were observed. While the study used its criteria in determining LRDB's environmental fragility, it was deemed necessary to incorporate an additional parameter related to erosion. As previously noted, urban environments differ in regard to soil protection, and yet they significantly influence management of fine sediments in reservoirs (Macedo et al., 2018). Accordingly, urban areas were included in the study's EEF analysis.

It is also worth noting that Ross (2012) did not include a geology parameter since it is an attribute outside the interaction among the atmosphere, hydrosphere, and pedosphere known as geographic stratum. Although geological data is relevant to pedogenesis (Costa et al., 2015), it was not deemed a significant parameter to this study's PEF analysis as the basin is characterized by a thick layer of soil above the bedrock. In areas where there is rocky outcrop, this parameter could be evaluated as part of the physical attributes that affects PEF.

Additional parameters could be incorporated such as riparian vegetation (Arriagada et al., 2019) and distance to water resources of sources of sediment production (Macedo et al., 2018). In general, factors that prevent erosion and runoff, such as conservation practices, soil thickness and hydraulic conductivity, could be considered. The addition of such parameters in assessing the basin's fragility could attenuate erosion potential, decreasing medium and high fragility designations. A point to be considered, however, is that such data is not easily found since their quantification occurs in local scale studies, and one convenience of Ross method is the use of spatial data.

The Lobo Reservoir Drainage Basin is a recharge area of the Guarani Aquifer System, where deep soil layers with high hydraulic conductivity favor infiltration and reduce runoff (Anache et al., 2018; Costa et al., 2019). The basin's predominance of medium fragility could be qualitatively related to the occurrence of some erosion features. In this sense, Michette (2015) demonstrates the low density of erosion features in the basin, reflecting its low erosion susceptibility. Moreover, agricultural activities in the basin generally apply soil conservation practices, such as contour farming, as verified through satellite images, that attenuate erosion.

Scale is another characteristic that must be taken into account. The resolution of GIS data provided by government agencies in Brazil is large scale (≥ 1:250,000), varying according to region (Macedo et al., 2018). Thus, the dearth of data with better spatial resolution could prove an obstacle to the use of the study's methodology in small basins, due to the consequent low spatial representativeness of the available data. This study attempted to work only with standardized maps in 1:50,000 scale, but this scale proved inadequate since the homogeneous result evidenced that the spatial detailing did not represent the variability of potential erosion. The application of Ross (2012) methodology in large areas increases the variability of the result, since the attributes of the analysis cover a broader spectrum of data.

The method proposed by Ross (2012) to identify the environmental fragilities was developed based on theoretical concepts of morphodynamics. Many studies analyze environmental fragility, but few incorporate a validation method. Manfré et al. (2013), however, evaluated the correlation between soil physical attributes, such as porosity, and EEF, parameters used in this study, and found a satisfactory correlation with those proposed in Ross (2012). It was noted, however, that flexibility in determining which parameters to use in fragility analysis is characteristic of non-standardization of results and could compromise comparative studies.

6. Conclusions

Artificial Artificial reservoirs are complex systems that continuously interact with the environment, changing river systems, hydrological cycles, and the dynamics of river basins. The quantity and quality of their water for multiple uses are related to the socioeconomic activities.

Models of environmental fragility that enhance understanding of the soil's vulnerabilities, with or without human intervention, can inform planning and management of land use by enabling identification of areas suitable for anthropic use and those that are a priority for conservation or restoration.

The results of this study show that its methodology efficiently determines environmental fragility and appropriate environmental zoning. In sum, the natural susceptibility to erosion, represented by the basin's predominate medium PEF and the land use effect on this equilibrium, represented by its EEF increases to some degree its fragility. Accordingly, the environmental zoning finds the Lobo Reservoir Drainage Basin affords conditions suitable for anthropic use provided appropriate conservation practices in soil management are maintained to ensure water availability and quality of Lobo Reservoir. In fact, in small areas such as the basin, more detailed information is needed than the methodology provides to take into account physical characteristics affecting erosion, and in areas where runoff represents a small part of the water balance, the environmental fragility result must be critically analyzed.

In conclusion, the study's analytic method is low-cost, flexible, and easy to use and could be replicated in other regions according to their specific characteristics and morphodynamic patterns.

CRediT authorship contribution statement

Phelipe da Silva Anjinho: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **Mariana Abibi Guimarães Araujo Barbosa:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Carlos Wilmer Costa:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Frederico Fábio Mauad:** Supervision.

Acknowledgements

We would like to thank the National Council of Scientific and Technological Development (CNPq) and Coordination for the Improvement of Higher Education Personne (CAPES) for granting scholarships to the first and second author, and the Center of Water Resources and Environmental Studies (CRHEA), University of São

Paulo, for the structure offered.

References

Adami, M., Rudorff, B.F.T., Freitas, R.M., Aguiar, D.A., Sugawara, L.M., Mello, M.P., 2012. Remote sensing time series to evaluate direct land use change of recent expanded sugarcane crop in Brazil. Sustainability 4, 574–585. https://doi.org/10.3390/su4040574.

Almeida, F.F.M., 2018. Fundamentos geológicos do relevo paulista. Rev. Do Inst. Geológico. 39, 9–75. https://doi.org/10.33958/revig.v39i3.600.

ANA, 2012. Water National Agency. Manual Operativo do Programa Produtor de Água. ANA, Brasília 84 p.

ANA, 2018. Water National Agency. Sistema de Informações Hidrológicas. HidroWeb. . (Accessed 18 August 2018). http://www.snirh.gov.br/hidroweb/.

Anache, J.A., Flanagan, D.C., Srivastava, A., Wendland, E.C., 2018. Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado. Sci. Total Environ. 622, 140–151. https://doi.org/10.1016/j.scitotenv.2017.11.257.

Annandale, G.W., Morris, G.L., Karki, P., 2016. Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-river Hydropower. The World Bankhttps://doi.org/10.1596/978-1-4648-0838-8.

Arriagada, L., Rojas, O., Arumí, J.L., Munizaga, J., Rojas, C., Farias, L., Vega, C., 2019. A new method to evaluate the vulnerability of watersheds facing several stressors: a case study in mediterranean Chile. Sci. Total Environ. 651, 1517–1533. https://doi.org/10.1016/j.scitotenv.2018.09.237.

Bahr, G.C., Carvalho, S.M., 2012. Identificação da fragilidade ambiental da bacia hidrográfica do Arroio Uvaranal, como subsídio ao projeto de expansão urbana de Telêmaco Borba–PR. RAEGA 26, 157–181. https://doi.org/10.5380/raega.v26i0.30155.

Brazil, 1981. Federal Law Nº 6.938, August 31, 1981. Dispõe sobre a Política Nacional do Meio Ambiente, seus fins e mecanismos de formulação e aplicação, e dá outras providências. . http://www.planalto.gov.br/ccivil_03/Leis/L6938.htm.

Brazil, 1997. Federal Law Nº 9.433, January 08, 1997. Institui a Política Nacional de Recursos Hídricos, regulamenta o inciso XIX do art. 21 da Constituição Federal, e altera o art 1º da Lei Nº 8.001, de 13 de março de 1990, que modificou a Lei Nº 7.990, de 28 de dezembro de 1989. . http://www.planalto.gov.br/ccivil_03/leis/l9433.htm.

Brazil, 2001. Federal Law Nº 10.257, July 10, 2001. Regulamenta os artigos 182 e 183 da Constituição Federal, estabelece diretrizes gerais da política urbana e dá outras providências, Brasília, DF. . http://www.planalto.gov.br/ccivil_03/leis/leis_2001/l10257.htm.

Brazil, 2002. National Environmental Council Resolution 302. Dispõe sobre os parâmetros, definições e limites de Áreas de Preservação Permanente de reservatórios artificiais e o regime de uso do entorno. Ministério do Meio Ambiente. Conselho Nacional do Meio Ambiente. http://www2.mma.gov.br/port/conama/res/res02/res30202.html.

Brazil, 2012. Federal Law Nº 12.651, may 25, 2012. Institui o Código Florestal Brasileiro, Brasília, DF. . http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12651.htm.

Briak, H., Mrabet, R., Moussadek, R., Aboumaria, K., 2019. Use of a calibrated SWAT model to evaluate the effects of agricultural BMPs on sediments of the Kalaya river basin (North of Morocco). Int. Soil Water Conserv. Res. 7, 176–183. https://doi.org/10.1016/j.iswcr.2019.02.002.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., De Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., Van Groenigen, J.W., Brussaard, L., 2018. Soil quality – a critical review. Soil Biol. Biochem. 120, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030.

Caniani, D., Lioi, D., Mancini, I., Masi, S., 2015. Hierarchical classification of groundwater pollution risk of contaminated sites using fuzzy logic: a case study in the Basilicata Region (Italy). Water 7, 2013–2036. https://doi.org/10.3390/w7052013.

Caniani, D., Labella, A., Lioi, D.S., Mancini, I.M., Masi, S., 2016. Habitat ecological integrity and environmental impact assessment of anthropic activities: a GIS-based fuzzy logic model for sites of high biodiversity conservation interest. Ecol. Indic. 67, 238–249. https://doi.org/10.1016/j.ecolind.2016.02.038.

CEPAGRI, 2018. Center for Meteorological and Climatic Research Applied to Agriculture. Universidade Estadual de Campinas. Disponível em: http://www.cepagri.unicamp.br/. Acesso em: 06 mar. 2018.

Chang, C., Sun, D., Feng, P., Zhang, M., Ge, N., 2017. Impacts of nonpoint source pollution on water quality in the Yuqiao reservoir. Environ. Eng. Sci. 34, 418–432. https://doi.org/10.1089/ees.2016.0124.

Cheng, F., Zhang, H.M., Zhang, G.L., Liu, S.M., Song, G.D., Du, G.X., 2019. Distribution and emission of N2O in the largest river-reservoir system along the Yellow River. Sci. Total Environ. 666, 1209–1219. https://doi.org/10.1016/j.scitotenv.2019.02.277.

Cherubin, M.R., Karlen, D.L., Franco, A.L., Tormena, C.A., Cerri, C.E., Davies, C.A., Cerri, C.C., 2016. Soil physical quality response to sugarcane expansion in Brazil. Geoderma 267, 156–168. https://doi.org/10.1016/j.geoderma.2016.01.004.

Corvalán, S.B., 2009. Zoneamento ambietal da APA Corumbataí (SP) de acordo com critérios de vulnerabilidade ambiental. Thesis (Doctoral). Instituto de Geociências e Ciências Exatas. Universidade Estadual Paulista, Rio Claro 170 p.

Costa, C.W., Piga, F.G., Moraes, M.C.P., Dorici, M., Sanguinetto, E.C., Lollo, J.A., Moschini, L.E., Lorandi, R., Oliveira, L.J., 2015. Fragilidade ambiental e escassez hídrica em bacias hidrográficas: Manancial do Rio das Araras–Araras, SP. Revista Brasileira de Recursos Hídricos 20, 946–958. https://doi.org/10.21168/rbrh.v20n4.p946-958.

Costa, C.W., Lorandi, R., de Lollo, J.A., Imani, M., Dupas, F.A., 2018. Surface runoff and accelerated erosion in a peri-urban wellhead area in southeastern Brazil. Environ. Earth Sci. 77, 160. https://doi.org/10.1007/s12665-018-7366-x.

Costa, C.W., Lorandi, R., Lollo, J.A., Santos, V.S., 2019. Potential for aquifer contamination of anthropogenic activity in the recharge area of the Guarani Aquifer System, southeast of Brazil. Groundw. Sustain. Dev. 8, 10–23. https://doi.org/10.1016/j.gsd.2018.08.007.

Cruz, B.B., Manfré, L.A., Ricci, D.S., Brunoro, D., Appolinario Jr, L., Quintanilha, J.A., 2017. Environmental fragility framework for water supply systems: a case study in the Paulista Macro Metropolis area (SE Brazil). Environ. Earth Sci. 76, 441. https://doi.org/10.1007/s12665-017-6778-3.

De Souza, A.L., Fonseca, D.G., Liborio, R.A., Tanaka, M.O., 2013. Influence of riparian vegetation and forest structure on the water quality of rural low-order streams in SE Brazil. For. Ecology. Manag. 298, 12–18. https://doi.org/10.1016/j.foreco.2013.02.022.

Demirel, T., Öner, S.C., Tüzün, S., Deveci, M., Öner, M., Demirel, N.Ç., 2018. Choquet integral-based hesitant fuzzy decision-making to prevent soil erosion. Geoderma 313, 276–289. https://doi.org/10.1016/j.geoderma.2017.10.054.

Donha, A.G., Souza, L.D.P., Sugamosto, M.L., 2006. Determinação da fragilidade ambiental utilizando técnicas de suporte à decisão e SIG. R. Bras. Eng. Agríc. Ambiental. 10, 175–181. http://www.scielo.br/pdf/%0D/rbeaa/v10n1/v10n1a26.pdf.

Dorici, M., Costa, C.W., de Moraes, M.C.P., Piga, F.G., Lorandi, R., de Lollo, J.A., Moschini, L.E., 2016. Accelerated erosion in a watershed in the southeastern region of Brazil. Environ. Earth Sci. 75, 1301. https://doi.org/10.1007/s12665-016-6102-7.

EMBRAPA, 2006. National Soil Research Center. Sistema Brasileiro de Classificação de Solos, 2 ed. Embrapa Solos, Rio de Janeiro.

Engel, S., Pagiola, S., Wunder, S., 2008. Designing payments for environmental services in theory and practice: an overview of the issues. Ecol. Econ. 65, 663–674. https://doi.org/10.1016/j.ecolecon.2008.03.011.

EPE. Empresa de Pesquisa Energética, 2018. Brazilian Energy Balance 2018 Year 2017. EPE, Rio de Janeiro.

Estigoni, M.V., Matos, A.J.S., Mauad, F.F., 2014. Assessment of the accuracy of different standard methods for determining reservoir capacity and sedimentation. J. Soils Sediments 14, 1224–1234. https://doi.org/10.1007/s11368-013-0816-x.

Evette, A., Labonne, S., Rey, F., Liebault, F., Jancke, O., Girel, J., 2009. History of bioengineering techniques for erosion control in rivers in Western Europe. Environ. Manag. 43, 972. https://doi.org/10.1007/s00267-009-9275-y.

Fernandez, P., Delgado, E., Lopez-Alonso, M., Poyatos, J.M., 2018. GIS environmental information analysis of the Darro River basin as the key for the management and hydrological forest restoration. Sci. Total Environ. 613, 1154–1164. https://doi.org/10.1016/j.scitotenv.2017.09.190.

Gao, P., Jiang, G., Wei, Y., Mu, X., Wang, F., Zhao, G., Sun, W., 2015. Streamflow regimes of the Yanhe River under climate and land use change, Loess Plateau. China. Hydrol. Process. 29, 2402–2413. https://doi.org/10.1002/hyp.10309.

Gao, J.H., Jia, J., Kettner, A.J., Xing, F., Wang, Y.P., Li, J., Bai, F., Zou, X., Gao, S., 2018. Reservoir-induced changes to fluvial fluxes and their downstream impacts on sedimentary processes: the Changjiang (Yangtze) River, China. Quat. Int. 493, 187–197. https://doi.org/10.1016/j.quaint.2015.03.015.

Gonçalves, G.G.G., Daniel, O., Comunello, É., Vitorino, A.C.T., Arai, F.K., 2011. Determinação da fragilidade ambiental de bacias hidrográficas. Floresta. 41, 797–808. https://doi.org/10.5380/rf.v41i4.25344.

Guerra, A.J.T., Cunha, S.B., 1996. Geomorfologia e meio ambiente. Bertrand Brasil, Rio de Janeiro.

Guerra, A.J.T., Fullen, M.A., Jorge, M.D.C.O., Bezerra, J.F.R., Shokr, M.S., 2017. Slope processes, mass movement and soil erosion: a review. Pedosphere 27, 27–41. https://doi.org/10.1016/S1002-0160(17)60294-7.

Hahn, J., Opp, C., Ganzenmüller, R., Ewert, A., Schneider, B., Zitzer, N., Laufenberg, G., 2019. Catchment soils as a factor of trace metal accumulation in sediments of the reservoir Klingenberg (eastern Ore Mountains, Germany). J. Environ. Sci. 86, 1–14. https://doi.org/10.1016/j.jes.2019.05.002.

Hu, S., Zhi-mao, G., Jun-ping, Y., 2001. The impacts of urbanization on soil erosion in the Loess Plateau region. J. Geogr. Sci. 11, 282–290 ID: 1009-637X(2001)03-0282-09.

Huang, X.R., Gao, L.Y., Yang, P.P., Xi, Y.Y., 2018a. Cumulative impact of dam constructions on streamflow and sediment regime in lower reaches of the Jinsha River, China. J. Mt. Sci. 15, 2752–2765. https://doi.org/10.1007/s11629-018-4924-3.

Huang, Y., Chang, Q., Li, Z., 2018b. Land use change impacts on the amount and quality of recharge water in the loess tablelands of China. Sci. Total Environ. 628, 443–452. https://doi.org/10.1016/j.scitotenv.2018.02.076.

Hutchins, M.G., Abesser, C., Prudhomme, C., Elliott, J.A., Bloomfield, J.P., Mansour, M.M., Hitt, O.E., 2018. Combined impacts of future land-use and climate stressors on water resources and quality in groundwater and surface waterbodies of the upper Thames river basin, UK. Sci. Total Environ. 631, 962–986. https://doi.org/10.1016/j.scitotenv.2018.03.052.

IAC. Instituto Agronômico De Campinas, 1981. Carta pedológica da quadrícula de São Carlos (SF-23-Y-A-1). , 100000 1.

IBGE. Brazilian Institute of Geography and Statistics, 1969. Folha Topográfca de Itirapina (SF-23-M-1-3). Escala 1, 50000.

IBGE. Brazilian Institute of Geography and Statistics, 1971. Folha Topográfca de São Carlos (SF-23-Y-A-I-1). Escala 1, 50000.

IBGE. Brazilian Institute of Geography and Statistics, 2010. Censo demográfico de 2010. https://ww2.ibge.gov.br/home/estatistica/populacao/censo2010/default.shtm.

IBGE. Brazilian Institute of Geography and Statistics, 2013. Manual Técnico de Uso da Terra, 3ª edição. .

IEA. Instituto de Economia Agrícola, 2018. Valor da produção agropecuária do estado de São Paulo: resultado preliminar de 2018. 13, 6 p.. http://www.iea.sp.gov.br/out/TerTexto.php?codTexto=14543.

IF. Instituto Florestal do Estado de São Paulo, 2006. Plano de Manejo Integrado das Estações Ecológica e Experimetnal de Itirapina/SP.

INPE. Instituto Nacional De Pesquisas Espaciais, 2018. Projeto TOPODATA: banco de dados geomorfométricos do Brasil. (Accessed 8 July 2018). http://www.dsr.inpe.br/topodata/index.php.

Jarsjö, J., Chalov, S.R., Pietroń, J., Alekseenko, A.V., Thorslund, J., 2017. Patterns of soil contamination, erosion and river loading of metals in a gold mining region of northern Mongolia. Reg. Environ. Change 17, 1991–2005. https://doi.org/10.1007/s10113-017-1169-6.

Jesiya, N.P., Gopinath, G., 2019. A customized fuzzyAHP-GIS based DRASTIC-L model for intrinsic groundwater vulnerability assessment of urban and peri urban phreatic aquifer clusters. Groundw. Sustain. Dev. 8, 654–666. https://doi.org/10.1016/j.gsd.2019.03.005.

Junior, A.C., Rohm, S.A., 2014. Analysis of environmental fragility using multi-criteria analysis (MCE) for integrated landscape assessment. J. Urban. Environ Eng. 8, 28–37. https://doi.org/10.4090/juee.2014.v8n1.028037.

Kelly, S., 2019. Megawatts mask impacts: small hydropower and knowledge politics in the Puelwillimapu, Southern Chile. Energy Res. Social Sci. 54, 224–235. https://doi.org/10.1016/j.erss.2019.04.014.

Li, Y., Zhan, J., Liu, Y., Zhang, F., Zhang, M., 2018. Response of ecosystem services to land use and cover change: a case study in Chengdu City. Resour. Conserv. Recycling. 132, 291–300. https://doi.org/10.1016/j.resconrec.2017.03.009.

Liu, J., Li, J., Qin, K., Zhou, Z., Yang, X., Li, T., 2017. Changes in land-uses and ecosystem services under multi-scenarios simulation. Sci. Total Environ. 586, 522–526. https://doi.org/10.1016/j.scitotenv.2017.02.005.

Liu, X., Yang, M., Meng, X., Wen, F., Sun, G., 2019. Assessing the impact of reservoir parameters on runoff in the Yalong River Basin using the SWAT model. Water 11, 643. https://doi.org/10.3390/w11040643.

Macedo, D.R., Hughes, R.M., Kaufmann, P.R., Callisto, M., 2018. Development and validation of an environmental fragility index (EFI) for the neotropical savannah biome. Sci. Total Environ. 635, 1267–1279. https://doi.org/10.1016/j.scitotenv.2018.04.216.

Manfré, L.A., Da Silva, A.M., Urban, R.C., Rodgers, J., 2013. Environmental fragility evaluation and guidelines for environmental zoning: a study case on Ibiuna (the Southeastern Brazilian region). Environ. Earth Sci. 69, 947–957. https://doi.org/10.1007/s12665-012-1979-2.

Marro, A.A., Souza, A.D.C., Cavalcante, E.D.S., Bezerra, G.S., NUNES, R.O., 2010. Lógica fuzzy: conceitos e aplicações. Universidade Federal do Rio Grande do Norte (UFRN), Natal.

MEA. Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC.

Medeiros, G.D.O.R., Giarolla, A., Sampaio, G., Marinho, M.D.A., 2016. Estimates of annual soil loss rates in the state of São Paulo, Brazil. Rev. Bras. Cienc. Solo 40, 1–18. https://doi.org/10.1590/18069657rbcs20150497.

Metzger, J.P., 2010. O Código Florestal tem base científica. Nat. Conserv. 8, 1–5.

Michette, J.F., 2015. Modelos de previsão de erosão pluvial utilizando SIG: estudo na bacia hidrográfica da Represa do Lobo (Broa), SP. Thesis (Master). Escola de Engenharia de São Carlos. Universidade de São Paulo, São Carlos 275 p.

Moraes, M.C.P., de Mello, K., Toppa, R.H., 2017. Protected areas and agricultural expansion: biodiversity conservation versus economic growth in the Southeast of Brazil. J. Environ. Manag. 188, 73–84. https://doi.org/10.1016/j.jenvman.2016.11.075.

Nasiri, H., Yusof, M.J.M., Ali, T.A.M., Hussein, M.K.B., 2018. District flood vulnerability index: urban decision-making tool. Int. J. Environ. Sci. Technol. (Tehran) 6, 2249–2258. https://doi.org/10.1007/s13762-018-1797-5.

Nogueira, T.A.R., Abreu-Junior, C.H., Alleoni, L.R.F., He, Z., Soares, M.R., dos Santos Vieira, C., Lessa, L.G.F., Capra, G.F., 2018. Background concentrations and quality reference values for some potentially toxic elements in soils of São Paulo State, Brazil. J. Environ. Manag. 221, 10–19. https://doi.org/10.1016/j.jenvman.2018.05.048.

Pacheco, F.A.L., Fernandes, L.F.S., 2016. Environmental land use conflicts in catchments: a major cause of amplified nitrate in river water. Sci. Total Environ. 548, 173–188. https://doi.org/10.1016/j.scitotenv.2015.12.155.

Padedda, B.M., Sechi, N., Lai, G.G., Mariani, M.A., Pulina, S., Sarria, M., Satta, C.T., Virdis, T., Buscarinu, P., Lugliè, A., 2017. Consequences of eutrophication in the management of water resources in Mediterranean reservoirs: a case study of Lake Cedrino (Sardinia, Italy). Glob. Ecol. Conserv. 12, 21–35. https://doi.org/10.1016/j.gecco.2017.08.004.

Pascual, U., Palomo, I., Adams, W.M., Chan, K.M., Daw, T.M., Garmendia, E., Gómez-Baggethun, E., de Groot, R.S., Mace, G.M., Martín-López, B., Phelps, J., 2017. Off-stage ecosystem service burdens: a blind spot for global sustainability. Environ. Res. Lett. 12, 075001. https://doi.org/10.1088/1748-9326/aa7392.

Periotto, N.A., Tundisi, J.G., 2013. Ecosystem Services of UHE Carlos Botelho (Lobo/Broa): a new approach for management and planning of dams multiple-uses. Braz. J. Biol. 73, 471–482. https://doi.org/10.1590/S1519-69842013000300003.

Perrota, M.M., Salvador, E.D., Lopes, R.C., D'Agostino, L.Z., Peruffo, N., Gomes, S.D., Sachs, L.L.B., Moreira, V.T., Garcia, M.G.M., Lacerda Filho, J.V., 2005. Mapa geológico do Estado de São Paulo. Escala 1 750.000. Programa Geologia do Brasil – PGB, CPRM, São Paulo.

Poesen, J., 2018. Soil erosion in the Anthropocene: research needs. Earth Surf. Process. Landf. 43, 64–84. https://doi.org/10.1002/esp.4250.

Pope, I.C., Odhiambo, B.K., 2014. Soil erosion and sediment fluxes analysis: a watershed study of the Ni Reservoir, Spotsylvania County, VA, USA. Environ. Monit. Assess. 186, 1719–1733. https://doi.org/10.1007/s10661-013-3488-5.

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T., Kidd, K.A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., Cooke, S.J., 2018. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94, 849–873. https://doi.org/10.1111/brv.12480.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.

Ross, J.L.S., 1994. Análise Empírica da fragilidade dos ambientes naturais e antropizados. Revista do Departamento de Geografia 8, 63–74. https://doi.org/10.7154/RDG.1994.0008.0006.

Ross, J.L.S., 2012. Landforms and environmental planning: potentialities and fragilities. Revista do Departamento de Geografia 38–51. https://doi.org/10.7154/RDG.2012.0112.0003. Volume Especial 30 Anos.

Rudorff, B.F.T., Aguiar, D.A., Silva, W.F., Sugawara, L.M., Adami, M., Moreira, M.A., 2010. Studies on the rapid expansion of sugarcane for ethanol production in São Paulo State (Brazil) using Landsat data. Remote Sens. (Basel) 2, 1057–1076. https://doi.org/10.3390/rs2041057.

Ruggiero, P.G., Metzger, J.P., Tambosi, L.R., 2019. Payment for ecosystem services programs in the Brazilian Atlantic Forest: Effective but not enough. Land use policy 82, 283–291. https://doi.org/10.1016/j.landusepol.2018.11.054.

Santos, Reis, E., Pereira, S., Santos, M., 2019. A flood susceptibility model at the national scale based on multicriteria analysis. Sci. Total Environ. 667, 325–337. https://doi.org/10.1016/j.scitotenv.2019.02.328.

Slingerland, N., Sommerville, A., O'Leary, D., Beier, N.A., 2018. Identification and quantification of erosion on a sand tailings dam. Geosystem Eng. 1–15. https://doi.org/10.1080/12269328.2018.1538823.

Smith, V.H., Schindler, D.W., 2009. Eutrophication science: where do we go from here? Trends Ecol. Evol. (Amst.) 24, 201–207. https://doi.org/10.1016/j.tree.2008.11.009.

Song, W., Deng, X., 2017. 2017. Land-use/land-cover change and ecosystem service provision in China. Sci. Total Environ. 576, 705–719. https://doi.org/10.1016/j.scitotenv.2016.07.078.

Souza-Cruz-Buenaga, F.V.A., Espig, S.A., Castro, T.L.C., Santos, M.A., 2019. Environmental impacts of a reduced flow stretch on hydropower plants. Braz. J. Biol. 79, 470–487. https://doi.org/10.1590/1519-6984.183883.

Spröl, C., Ross, J.L.S., 2004. Análise comparativa da fragilidade ambiental com aplicação de três modelos. GEOUSP Espaço e Tempo 15, 39–49. https://doi.org/10.11606/issn.2179-0892.geousp.2004.123868.

Strassburg, B.B.N., Brooks, T., Feltran-Barbieri, R., Iribarrem, A., Crouzeilles, R., Loyola, R., Latawiec, A.E., Oliveira Filho, F.J.B., Scaramuzza, C.Ade M., Scarano, F.R., Soares-Filho, B., Balmford, A., 2017. Moment of truth for the Cerrado hotspot. Nat. Ecol. Evol. 1, 99. https://doi.org/10.1038/s41559-017-0099.

Sun, L., Wu, S., Hill, R.L., Guo, H., Feng, H., 2018. The effects of three micro-catchment practices on erosion and runoff dynamics for a typical soil slope on the Loess Plateau of China. Can. J. Soil Sci. 99, 46–59. https://doi.org/10.1139/cjss-2018-0089.

Tambosi, L.R., Vidal, M.M., Ferraz, S.F.D.B., Metzger, J.P., 2015. Funções eco-hidrológicas das florestas nativas e o Código Florestal. Estudos avançados 29, 151–162. https://doi.org/10.1590/S0103-40142015000200010.

Tanaka, M.O., De Fátima Fernandes, J., Suga, C.M., Hanai, F.Y., De Souza, A.L.T., 2015. Abrupt change of a stream ecosystem function along a sugarcane-forest transition: integrating riparian and in-stream characteristics. Agric. Ecosyst. Environ. 207, 171–177. https://doi.org/10.1016/j.agee.2015.04.014.

Tang, J.L., Cheng, X.Q., Zhu, B., Gao, M.R., Wang, T., Zhang, X.F., Zhao, P., You, X., 2015. Rainfall and tillage impacts on soil erosion of sloping cropland with subtropical monsoon climate - a case study in hilly purple soil area. China. J. Mt. Sci. 12, 134–144. https://doi.org/10.1007/s11629-014-3241-8.

Taniwaki, R.H., Cassiano, C.C., Filoso, S., de Barros Ferraz, S.F., de Camargo, P.B., Martinelli, L.A., 2017. Impacts of converting low-intensity pastureland to high-intensity bioenergy cropland on the water quality of tropical streams in Brazil. Sci. Total Environ. 584, 339–347. https://doi.org/10.1016/j.scitotenv.2016.12.150.

Tricart, J., 1977. Ecodinâmica. Recursos naturais e meio ambiente. IBGE, Diretoria Técnica, SUPREN, Rio de Janeiro 91 p.

Tundisi, J.G., Matsumura-Tundisi, T., 2014. The ecology of UHE Carlos Botelho (Lobo-Broa Reservoir) and its watershed, São Paulo, Brazil. Freshw. Rev. 6, 75–91. https://doi.org/10.1608/FRJ-6.2.727.

Tundisi, J., Matsumura-Tundisi, T., Rodrigues, S., 2003. Gerenciamento e Recuperação das Bacias Hidrográficas dos Rios Itaqueri e do Lobo e da UHE Carlos Botelho (Lobo-Broa) -Municípios de Itirapina e de Brotas. Rima Artes e Textos, São Carlos.

Uddin, K., Murthy, M.S.R., Wahid, S.M., Matin, M.A., 2016. Estimation of soil erosion dynamics in the Koshi basin using GIS and remote sensing to assess priority areas for conservation. PLoS One 11, e0150494. https://doi.org/10.1371/journal.pone.0150494.

USGS. United States Geological Survey, 2017. Imagens LANDSAT 8. Accessed: 15 July 2017. http://earthexplorer.usgs.gov/.

Valle, I.C., Francelino, M.R., Pinheiro, H.S.K., 2016. Mapeamento da Fragilidade Ambiental na Bacia do Rio Aldeia Velha, RJ. Floram-Revista Floresta e Ambiente 23, 295–308. https://doi.org/10.1590/2179-8087.107714.

Valle Junior, R.F., Varandas, S.G., Pacheco, F.A., Pereira, V.R., Santos, C.F., Cortes, R.M., Fernandes, L.F.S., 2015. Impacts of land use conflicts on riverine ecosystems. Land Use Policy 43, 48–62. https://doi.org/10.1016/j.landusepol.2014.10.015.

Vymazal, J., Březinová, T., 2015. The use of constructed wetlands for removal of pesticides from agricultural runoff and drainage: a review. Environ. Int. 75, 11–20. https://doi.org/10.1016/j.envint.2014.10.026.

WCD. World Commission on Dams, 2000. Dams and Development - a New Framework for Decision-making. Earthscan Publications Ltd, London.

Wood, S.L., Jones, S.K., Johnson, J.A., Brauman, K.A., Chaplin-Kramer, R., Fremier, A., Girvetz, E., Gordon, L.J., Kappel, C.V., Mandle, L., Mulligan, M., 2018. Distilling the role of ecosystem services in the sustainable development goals. Ecosyst. Serv. 29, 70–82. https://doi.org/10.1016/j.ecoser.2017.10.010.

Yang, H., Wang, G., Wang, L., Zheng, B., 2016. Impact of land use changes on water quality in headwaters of the Three Gorges Reservoir. Environ. Sci. Pollut. Res. 23, 11448–11460. https://doi.org/10.1007/s11356-015-5922-4.

Yousaf, W., Mohayud-Din-Hashmi, S.G., Akram, U., Saeed, U., Ahmad, S.R., Umar, M., Mubashir, A., 2018. Erosion potential assessment of watersheds through GIS-based hypsometric analysis: a case study of Kurram Tangi Dam. Arab. J. Geosci. 11, 711. https://doi.org/10.1007/s12517-018-4059-4.

Zorzal-Almeida, S., Salim, A., Andrade, M.R.M., de Novaes Nascimento, M., Bini, L.M., Bicudo, D.C., 2018. Effects of land use and spatial processes in water and surface sediment of tropical reservoirs at local and regional scales. Sci. Total Environ. 644, 237–246. https://doi.org/10.1016/j.scitotenv.2018.06.361.