Economic Value of Environmental Services Regulating Flow and Maintaining Water Quality in the Piracicaba River Basin, Brazil

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Abstract: From distributed or semidistributed hydrological models, it is possible to identify where land use decisions can bring greater economic benefits in relation to water use. This study aimed to integrate simulations of a hydrological model varying the land use in four reforestation scenarios that influence the economic benefits of provision environmental services, including the user's alternatives as a key parameter and finally estimating the economic value of such benefits. The "avoided costs" method was used for economic valuation of flow regularization service and adequacy of water quality in the Piracicaba River basin, aiming to generate various economic instruments to support decision makers. The cost for water storage was estimated from the rising rain volume infiltrating the soil from the change in the dynamics of land use, whereas the cost of maintaining water quality was obtained from the variation between the effects of scenarios in nitrogen, phosphorus, and sediment loads. The valuation methodology allowed us to estimate the avoided costs, which will mainly contribute to application of economic instruments to manage water resources, directing land use decisions in hydrographic basins, guiding environmental impact assessment studies, and the definition of mitigation measures. **DOI: 10.1061/JWRMD5.WRENG-5771.**

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Introduction

The southeast region of Brazil, more specifically the state of São Paulo, is highly impacted by extreme hydrological events because it is a densely populated area, has only 6% of the country's available water resources, and has a high demand for industry, agriculture, irrigation, hydroelectric power generation, and public supply (Marengo and Alvez 2015; Custódio 2015; Neto 2015).

The relationship between the availability and demand of water resources for urban and economic uses in the Piracicaba River basin, located in this region, is worrying. The problem is further aggravated by the absence of structures to regulate water in rivers, which makes the supply systems excessively vulnerable; this problem is amplified by phenomena of severe and prolonged drought, as occurred in the years 2012–2016 (Ritcher and Jacobi 2018). In addition, most cities do not have sewage treatment and release the effluents in natura into the rainwater sewage network, which flows through urban rivers, causing deterioration in the quality of water downstream and creating potential risks to the population's supply (Tucci 2008).

Between 2012 and 2016, the region of São Paulo faced one of its worst droughts ever recorded in the last 60 years as a result of the lack of rain. Along with poor planning in the supply and distribution of water, as well as irregular or disorderly urban occupation of the land, the lack of rain resulted in a serious water crisis and the severe reduction of the main water supply systems in cities (Soriano et al. 2016).

The Piracicaba River basin has the Cantareira System, which is a water capture and transposition system for the Metropolitan Region of São Paulo (MRSP). This system is considered one of the largest water-producing systems in the world (Soriano et al. 2016), covering 12 municipalities and producing about 33,000 L of water per second in order to supply approximately 9.9 million people (ANA/DAEE 2017). However, most of the water produced in the Cantareira System comes from the headwaters of the Piracicaba River basin and has better quality than the water that flows downstream from the basin and receives a large organic load. This water is transferred to Alto Tietê basin, where the MRSP is located. In times of drought (water crisis), the use of the Cantareira System's technical reserve, known as "dead volume," is allowed, which adds about 480 billion liters of water to the reservoirs (ANA 2019b), but only 2 $m^3\ s^{-1}$ are kept in the Piracicaba basin; that is, most of it is transported to the MRSP.

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Precipitation in the Cantareira System drainage area had a systematic reduction in 2012, 2013, and 2014, representing respectively 92%, 69%, and 61% of the historical average (ANA 2019b). According to Nobre et al. (2015), in these years, the annual inflow into the Cantareira System reservoirs also decreased. In the months of December 2013 to February 2014 (recharge season), the average flow was 16.1 $m^3 s^{-1}$, and in the same months of 2014 and 2015, it was 22.7 $m^3 s^{-1}$, which represents, respectively, 24.5% and 35.6% of the average flow of the affluent long period from December to February (historical series from 1930 to 2013).

In addition, there was also a decrease in water infiltration capacity due to the reduction in the permeable area (Du et al. 2012; Guan et al. 2015), which caused negative effects on the environment, affecting the landscape, local climate, and quality of life (Hung et al. 2020). Waterproofing causes the water that previously infiltrated to flow freely on the surface and in superficial drains, increasing flow velocity and consequently reducing its concentration time, increasing the probability of urban flooding (Ogden et al. 2011) and also affecting the regulation of water availability and quality.

The presence of forests, in turn, promotes increased infiltration of rainwater into the soil, increases the recharge of underground aquifers, and contributes to regulating the flow throughout the year, mainly by ensuring the flow of rivers during the dry months, providing the ecosystem services dependent on this water (Honda and Durigan 2017). In addition, native forests can also play the role of controlling erosion and sediment input and, consequently, influence physicochemical parameters of watercourses (Tambosi et al. 2015). Thus, flow regulation and water quality adequacy can be considered environmental services that generate economic benefits due to the conservationist use of the land and, therefore, these regulation services have economic value for society.

Given the critical relationship between water supply and demand in the Piracicaba River basin, in 2005, the first Brazilian Payments for Ecosystem Services (PSE) project was created, known as the Water Conservation Project, which aims to maintain the quality of water sources in the headwaters region of the basin (downstream of the reservoirs), promoting the environmental suitability of rural properties (Richards et al. 2015) with the aim of providing hydrological services and reducing erosion and sedimentation (Taffarello et al. 2017). Also implemented in the basin is the Water Producer Project (PCJ), which aims to restore the "ecosystem health" of hydrographic microbasins. It was developed in two cities located within the Piracicaba River basin (ANA 2019a), aiming to benefit rural producers who, through conservationist practices and improvement of vegetation cover, contribute to the effective reduction of erosion and sedimentation and increase of water infiltration (Taffarello et al. 2016, 2017). However, these projects are developed in specific regions of the basin, which could have strategic locations where Ecosystem Services Payments projects, if applied, could provide greater hydrological and economic benefits.

Knowledge of the environmental service value of flow regulation and water quality improvement contributes to the application of economic instruments to manage water resources (tariffs or payment for environmental services) and direct land use decisions in watersheds and guides environmental impact assessment studies and the definition of mitigation measures (Marques et al. 2017).

From hydrological modeling, it is possible to identify where land use decisions should favor a more or less intense occupation, as well as the consequences of the decisions. Therefore, in this work, simulations were integrated to the Soil and Water Assessment Tool (SWAT) hydrological model, varying the use of land that weighs economic benefits against losses of environmental services, using user preferences as a key parameter. From this, the objective of the work was to estimate the economic benefits from the cost avoided by underground water storage and the maintenance of water quality in the Piracicaba River basin, aiming to generate economic instruments to support managers and decision makers.

Material and Methods

Study Area

The Piracicaba River basin has an area of 12,587.21 km^2, located mainly in the state of São Paulo, in the range 22°00′ and 23°30′ of south latitude and 46°00′ and 48°30′ of west longitude, southeast region of Brazil (Fig. 1). Its main subbasins are the Corumbataí, Jaguari, Camanducaia, Atibaia, and Piracicaba rivers. In total, the basin of the River Piracicaba entirely or partially covers the area of 71 municipalities in the state of São Paulo and 5 municipalities in the state of Minas Gerais; it contains a contingent of approximately 5.8 million inhabitants and is responsible for 7% of the gross domestic product of Brazil (PCJ 2020).

In addition, the Piracicaba River basin has an area called the Cantareira System (Fig. 1), which is the largest water-producing complex for the MRSP. This system is formed by five reservoirs (Jaguari, Jacareí, Cachoeira, Atibainha, and Paiva Castro), which are used to supply approximately 46% of the population of the MRSP. To produce this amount of water, the system alternates between two hydrographic basins, diverting water from the Piracicaba River basin to the Alto Tietê basin (ANA 2019b).

The east of the Piracicaba River basin is mountainous, covered by large areas of forest, agriculture, and pasture. The central region has moderate elevation; the western part is mainly plains. These last two regions have extensive areas with sugarcane and annual crops, high population and industrial density in large urban centers, and also some pasture areas (MAPBIOMAS 2018; Filoso et al. 2003).

Environmental Economic Valuation

The environmental economic literature has shown that there is no single classification for valuation methods and that different approaches can be found, such as the methodologies proposed by Hufschmidt et al. (1983), Pearce and Pretty (1993), Hanley and Spash (1993), and Bateman and Tuner (1993).

A classification of valuation methods is also described by Motta (1997) (Fig. 2), in which these are classified into demand function methods: complementary goods market methods (hedonic price and travel costs) and valuation methods of contingent; production function methods: marginal productivity and substitute goods market methods (replacement, defensive expenditures, or avoided and control costs).

Between the two methods explored by Motta (1997), the market production function methods of substitute goods are the most used because their applicability lies in the fact that the environmental resource is observed for how much it can contribute as an input or factor of production of another product. The valuation of natural resources can be carried out by direct and indirect methods. The direct methods (travel cost, hedonic prices, and contingent valuation) consist of obtaining consumer preference through the individual's willingness to pay for environmental goods and services; that is, it is necessary to verify how much the individual is willing to pay for a good or environmental service. Therefore, in a watershed with thousands of individuals, it is difficult to apply valuation by direct methods. Indirect methods, on the other hand, recover the value of the environmental good or service through changes in market product prices resulting from environmental changes. The substitute

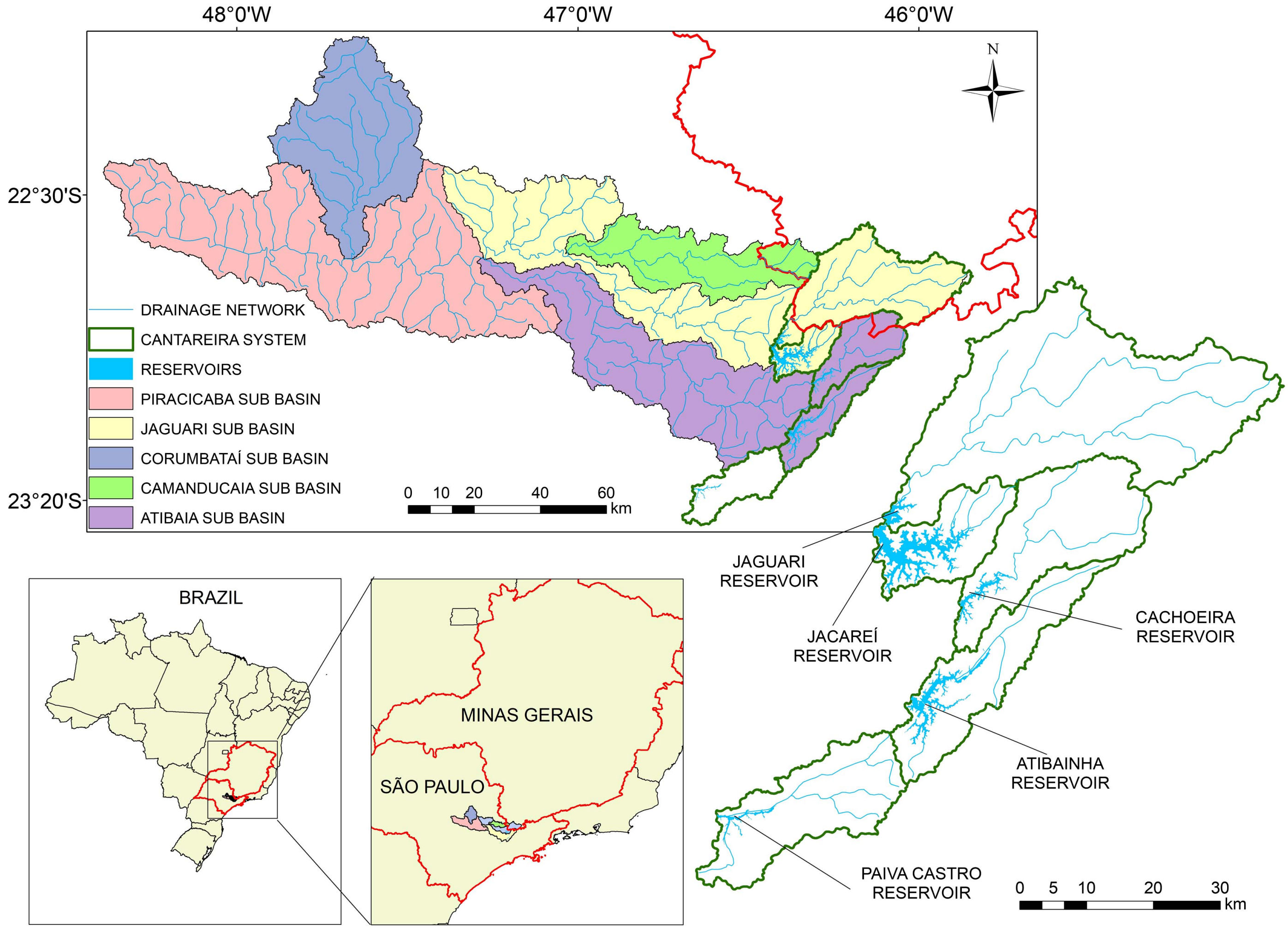

Fig. 1. Location of the hydrographic subbasins of the Piracicaba River basin and Cantareira system.

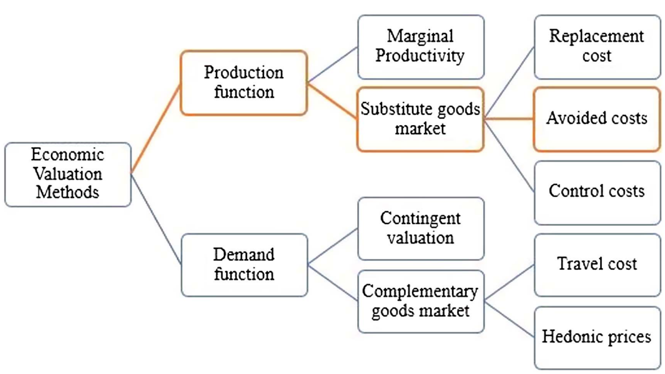

Fig. 2. Environmental economic valuation methods.

goods market methodology consists of the following principle: that the loss of quality or scarcity of the environmental good or service will increase the demand for substitutes in an attempt to maintain the same level of social well-being (Cavalcanti 1995); that is, replacing a resource in nature can generate benefits to maintain or improve social well-being. Therefore, this method is more viable for indirectly checking the value of a natural resource.

Thus, economic valuation presents some methods that can help to quantify an environmental service. In this study, the method of avoided costs was used (Fig. 2), which is also known as defensive or preventive spending. The avoided cost method estimates values related to the prevention of losses in quantity or quality of ecosystem services (Mota and Bursztyn 2013).

In order to value the environmental services for regulating the availability and quality of water, four scenarios of land use and occupation were used, which present an area with larger forest formation than the current scenario. These scenarios were inserted into the SWAT model calibrated and validated by Lopes et al. (2020) for the Piracicaba River basin. The outputs of sediments, phosphorus, nitrogen, and infiltrated water volume were verified, analyzing the relative variation of the variables in comparison with the current scenario. With the exception of the scenarios, the entire physical and climatological database included in the SWAT model was the same as that used in the study by Lopes et al. (2020).

Definition of Scenarios

To represent the current scenario (C0), the land use and land cover map prepared by the MapBiomas project (MAPBIOMAS 2018) was used, which separates the main land cover in the Piracicaba basin into agriculture/pasture (AGRL), annual crops (AGRR), planted forest (EUCA), forest formation (FRSE), savanna formation (FRST), pasture (PAST), grassland (RNGE), sugarcane (SURG), mining (URBN), urban area (URBN), nonvegetated area (URBN), and water (WATR) (Fig. 3).

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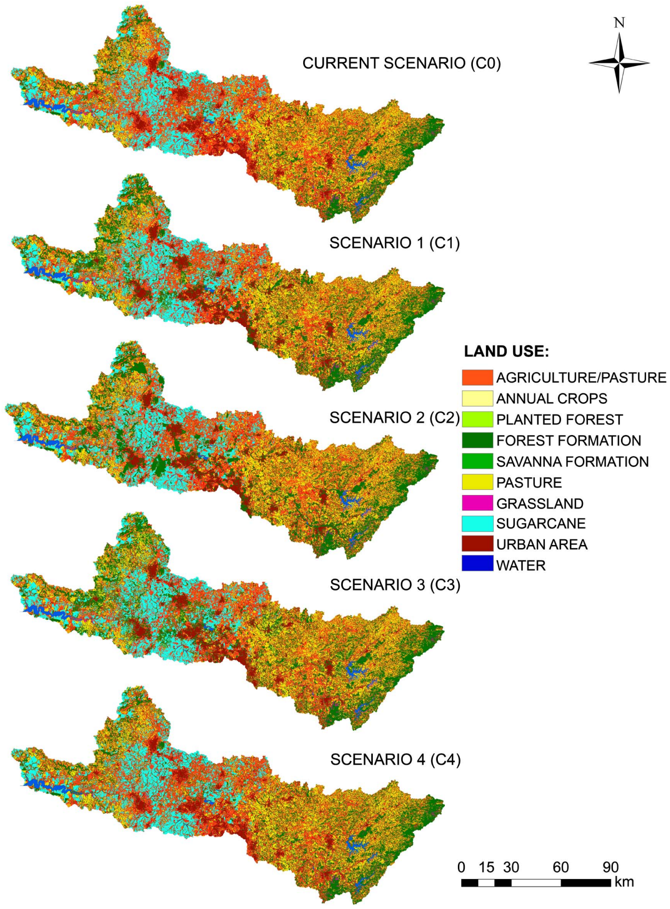

Fig. 3. Land use and occupation scenarios for simulation with SWAT model. Current scenario (C0), Scenario 1 (C1), Scenario 2 (C2), Scenario 3 (C3), and Scenario 4 (C4).

Multicriteria analysis is used to define preferences or priorities, mainly for solving problems related to the sustainable use of natural resources, as well as for decision making. According to Ferraz and Vettorazzi (1998), the choice of priority areas for conservation is usually related to cartographic modeling, more specifically with the overlapping of information plans (maps), which represent criteria or factors used in a prioritization process. Lopes et al. 2022 used multicriteria analysis and overlapping maps to define key areas for improving the management of the Piracicaba River basin or, rather, defining priority areas for the implementation of projects for environmental services in places that presented problems with regard to quality and water availability, sediments, and erosion.

Therefore, in the definition of Scenarios 1 (C1), 2 (C2), and 3 (C3) (Fig. 3), maps of priority areas were used, defined from the multicriteria analysis carried out by Lopes et al. (2022) in which the most restrictive predictive scenario (with the greatest number of priority areas) adequate within each studied objective was chosen; later, the areas classified as high and very high priority were reclassified as forest formation (FRSE).

Scenario 1 (C1) was extracted from the identification of areas that have susceptibility or problems related to erosion and sediment production, causing an increase of 6.78% of forest areas in the basin (Lopes et al. 2022) (Table 1). Scenario 2 (C2) was obtained from the identification of areas that have potential for water conservation, increasing the classification of forest areas in the basin by 7.27% (Lopes et al. 2022) (Table 1). Scenario 3 (C3) was obtained from the identification of areas that have problems related to water quality, and that resulted in an increase in forest areas in the basin by 8.82% (Lopes et al. 2022) (Table 1).

Table 1. Percentage of occupation of the land use class for each scenario

	Scenario (%)				
Land use	C0	C1	C2	C3	C4
Pasture	17.87	17.3	16.92	17.84	17.2
Planted forest	3.17	3.16	3.14	3.16	3.11
Sugaarcane	13.35	13.34	12.64	13.33	13.2
Urban/nonvegetated area/mining	5.37	5.37	5.37	5.37	5.22
Water	1.55	1.55	1.55	1.55	1.55
Agriculture/pasture	40.26	34.10	34.73	31.59	36.66
Forest formation	17.30	24.08	24.57	26.12	21.97
Savannah formation	0.02	0.02	0.02	0.02	0.02
Grassland	0.47	0.46	0.42	0.46	0.43
Annual crops	0.65	0.62	0.64	0.56	0.64

Scenario 4 (C4) was generated in accordance with Brazilian legislation (LAW No. 12,651) (BRASIL 2012) which considers permanent preservation areas (APPs), marginal strips of any natural watercourse; areas around natural lakes and ponds, areas around artificial water reservoirs, resulting from damming natural water courses; and areas around springs, whatever their topographical situation. However, these APP areas or strips have a length according to the size of the water resource.

Therefore, the definition of this scenario (C4) was established from marginal strips along the rivers, that is, riparian areas of 50 m. For this, a buffer of 50 m was created in the drainage network of the basin and later reclassified as forest formation (FRSE) and added to the current scenario, generating an increase of 4.67% in forested areas (Table 1).

Economic Valuation

Valuation was made using the avoided costs for regulating the quantity and quality adequacy of water provision services, respectively, in terms of water storage or water flow regulation and water quality maintenance.

Cost Avoided by Storage or Regulation of Water Flow

In a hydrographic basin, the distribution of rainfall is not equal throughout its extension; then, from the outputs of the SWAT model, the average annual precipitation data (mm) were spatialized and the basin divided into homogeneous regions according to the volume of precipitated water.

To obtain the amount of water infiltrated in each land use class, the SWAT-Check software outputs from the land use summary table were used, which presents the hydrological balance by use and land cover. Thus, from rainfall, evapotranspiration, and runoff data for each land use, the infiltration coefficient was obtained [Eq. (1)]

$$K = \frac{\mathrm{Pc} - \mathrm{SURQ} - \mathrm{ET}}{\mathrm{Pc}} \quad (1)$$

where K = infiltration coefficient for land use and land cover (nondimensional); Pc = precipitation (mm); SURQ = runoff (mm); and ET = evapotranspiration (mm). With knowledge of the infiltration coefficient for each land use and homogeneous region, it was possible to obtain the infiltrated water volume. To obtain the cost for storage or regulation of water flow, the following equation was used:

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$$\mathrm{CAP} = 10.\mathrm{VCC}.A.\sum_{ij=1}^{n} P(K_{\mathrm{FRSE}} - K_i) \quad \text{for all } K \text{ em que } A_{Cj} < A_{C0} \tag{2}$$

where CAP = value for the storage or regulation of water flow (R\$ $\mathrm{ha^{-1}\,year^{-1}}$) (1.00 U\$ = R\$5.55 at the time of the studies); VCCA = recommended amount for collecting raw water in the Piracicaba River basin, and because it is a basin in which the charge for the use of water resources is in the domain of the union, the value is R\$0.0140 $\mathrm{m^{-3}}$ (ANA 2020); P = annual precipitation (mm $\mathrm{year^{-1}}$); A = area of the land use class within each scenario (ha); K = infiltration coefficient for a given soil use and coverage; K_{FRSE} = infiltration coefficient for forest formation areas; i = variation of land use and coverage; and j = variation of the scenarios.

The condition $A_{cj}<A_{c0}$ was imposed because there will only be positive storage variation if the area of a given use in the analyzed scenario is smaller than the area of the same use in C0; that is, if the area of a given use and occupation of the land do not change comparing the two scenarios, the water storage will be the same. Therefore, only the K of the land use classes that suffered a decrease in area in relation to the C0 scenario will be considered.

The K_{FRSE} of forest formation was used as a basis because water storage in the watershed, or water yield for the water table, is increased by the presence of forests because of the increased infiltration of rainwater into the soil, helping to regulate water flow and increased recharge of underground aquifers. Finally, the avoided effects and costs were verified, simulating the changed scenarios of land use and occupation by homogeneous region.

Costs Avoided by Maintaining Water Quality

To obtain the cost of maintaining water quality, the following equation was used:

$$\mathrm{CMQA} = \frac{Q.31536000.\mathrm{Ta}}{A}(\mathrm{CP_{C0}} - \mathrm{CP_{Ci}}) \quad \text{for all } \mathrm{CP_{Ci}} < \mathrm{CP_{C0}} \tag{3}$$

where CMQA = cost of maintaining water quality (R\$ $\mathrm{ha^{-1}\,year^{-1}}$); Q = long-term average flow ($\mathrm{m^3\,s^{-1}}$); Ta = average water treatment tariff (R\$ $\mathrm{m^{-3}}$); CP = participation coefficient of each basin in the polluting load of phosphorus, nitrogen, or sediments (nondimensional); A = basin area (ha); and i = variation of the scenarios.

Hydrographic basins with significant vegetation indices produce much a smaller volume of pollutants than urbanized hydrographic basins because of the lower population density and retention of chemical substances by forest and floodplain formations. Thus, there is a reduction in the contribution of pollutant loads to water bodies, improving the quality of water from forested basins and consequently minimizing treatment costs. Thus, load of phosphorus, nitrogen, and sediments simulated in the SWAT model per hydrological response unit (HRU) was evaluated within each scenario, and the percentage of participation (CP) of each scenario was subsequently quantified in the polluting load in the analyzed subbasin [Eqs. (4) and (5)]

$$\mathrm{CP_{co}} = \left(\frac{\mathrm{Pco_{nfs}}}{\mathrm{Pci_{nfs}} + \mathrm{Pco_{nfs}}}\right) \tag{4}$$

$$\mathrm{CP_{ci}} = \left(\frac{\mathrm{Pci_{nfs}}}{\mathrm{Pci_{nfs}} + \mathrm{Pco_{nfs}}}\right) \tag{5}$$

where $\mathrm{CP_{CO}}$ = subbasin's participation coefficient in the polluting load of phosphorus, nitrogen, or sediments in the current scenario (C0); $\mathrm{CP_{CI}}$ = coefficient of participation of the subbasin in the polluting load of phosphorus, nitrogen, or sediments in the compared scenario; $\mathrm{Pco_{NFS}}$ = phosphorus, nitrogen, or sediment polluting load (kg) of the subbasin in the current scenario (C0); and $\mathrm{Pci_{NFS}}$ = phosphorus, nitrogen, or sediment polluting load (kg) of the subbasin in the compared scenario.

Table 2. Average water tariff and standard deviation, average flow, and areas of the Piracicaba River subbasins

Subbasin	Average water tariff (standard deviation) (R\$ $\mathrm{m^{-3}}$)	Average flow ($\mathrm{m^3\,s^{-1}}$)	Area ($\mathrm{km^2}$)
Atibaia	2.58(±0.56)	41.4742	2,839
Camanducaia	1.78(±0.57)	15.1756	1,039
Corumbataí	1.82(±0.99)	23.0754	1,714
Jaguari	1.92(±0.62)	48.0758	3,291
Piracicaba	2.10(±0.47)	50.8054	3,703
Cantareira system	1.85(±0.70)	6.8462	1,939

The $\mathrm{CP_{CI}}<\mathrm{CP_{CO}}$ condition means that scenarios with a higher percentage of forest formation area have a lower contribution of pollutants when compared to the C0 scenario. When $\mathrm{CP_{CI}} \geq \mathrm{CP_{CO}}$, the scenario under study does not bring benefits; that is, there is no reduction in nitrogen, phosphorus or sediment loads.

The long-term average flow was obtained by the flow regionalization method for the state of São Paulo, developed by Wolff et al. (2014), which provides an online platform (Wolff 2013) for consulting reference flows for any basin in the state of São Paulo.

The water treatment tariffs were obtained from the Regulatory Agency for Sanitation Services for the Piracicaba, Capivari, and Jundiaí River basins (ARESPCJ) and the Environmental Sanitation Company of the State of São Paulo (SABESP) (ARESPCJ 2019; SABESP 2019). To analyze the avoided cost, the average tariff and standard deviation of the municipalities within the area of each subbasin were considered (Table 2).

Results and Discussion

Fig. 4 shows the homogeneous regions in relation to rainfall; according to the spatialization of the average annual precipitation, eight homogeneous regions were obtained, classified from A to H, with the eastern headwater subbasins receiving a greater volume of rainfall and those close to the mouth receiving smaller volumes (west).

The infiltration coefficients obtained for each land use were 0.35 (AGRL), 0.31 (AGRR), 0.44 (EUCA), 0.55 (FRSE), 0.34 (FRST), 0.42 (PAST), 0.47 (RNGE), 0.23 (SURG), and 0.22 (URBN).

The infiltration coefficient was considered in Eq. (2) only for the use classes that changed in comparison with the C0 scenario. The most sensitive class when converted to FRSE was the AGRL class (Table 1 and Fig. 5). In Scenario C4, which considered FRSE in a 50-m range around watercourses, it was possible to observe that the most irregular use classes within this scenario were areas with AGRL and PAST.

Fig. 5 shows changes in land use and occupation by homogeneous regions. The only classes that did not change in all scenarios were FRST and WATR. Given that Scenarios C1, C2, and C3 were generated from the multicriteria analysis, and the URBN class is considered a restriction for defining priority areas (Lopes et al. 2022), this class continued with the same percentage of area in these scenarios. However, many cities have watercourses within their territory, causing the reduction of the URBN class in Scenario C4. Homogeneous regions B, C, E, and F were those with the greatest increase

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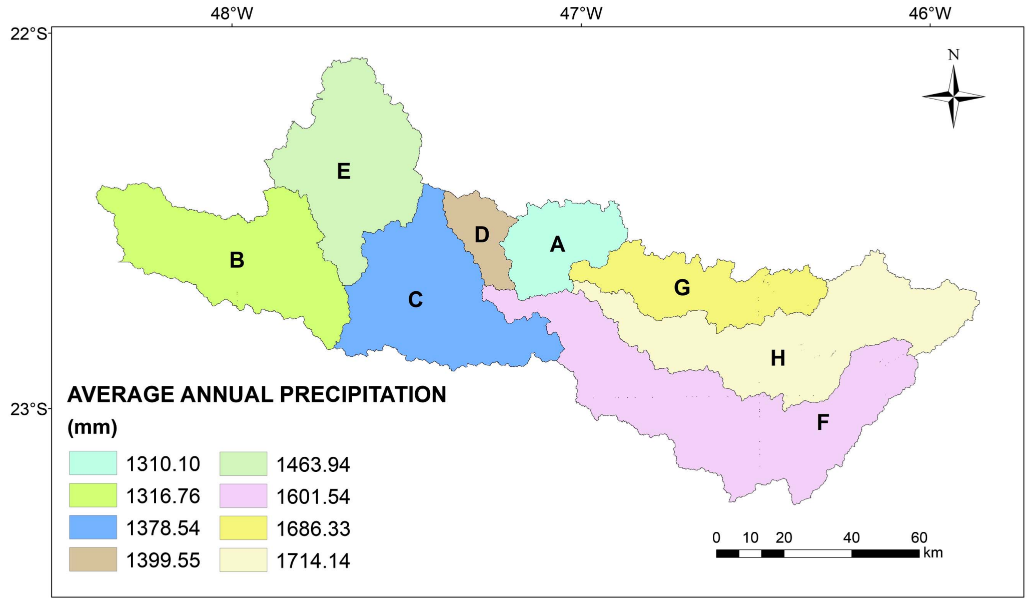

Fig. 4. Homogeneous regions in relation to rainfall in the Piracicaba River basin.

Land use	A (726.3 km²) C0	C1	C2	C3	C4	B (1871 km²) C0	C1	C2	C3	C4	C (1832 km²) C0	C1	C2	C3	C4	D (361.3 km²) C0	C1	C2	C3	C4
FRSE	5,98	7,80	10,11	7,87	10,85	13,71	23,14	21,64	24,88	18,02	3,22	11,53	16,62	17,60	8,16	9,13	10,15	12,40	15,07	12,94
FRST	0,04	0,04	0,04	0,04	0,04	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,03	0,03	0,03	0,03
EUCA	1,07	1,07	1,07	1,07	1,06	2,32	2,31	2,31	2,31	2,29	0,06	0,06	0,05	0,06	0,06	0,26	0,26	0,26	0,26	0,25
RNGE	0,34	0,34	0,26	0,33	0,27	0,24	0,24	0,09	0,24	0,22	0,03	0,03	0,03	0,03	0,03	0,11	0,11	0,11	0,11	0,10
PAST	11,10	10,99	10,60	11,06	10,52	17,12	16,48	15,68	17,07	16,52	3,59	3,39	2,69	3,55	3,47	2,77	2,74	2,42	2,74	2,63
AGRR	3,51	3,44	3,49	3,33	3,47	0,27	0,20	0,27	0,18	0,27	1,70	1,62	1,65	1,47	1,70	1,45	1,45	1,45	1,41	1,45
SUGC	20,28	20,28	19,84	20,28	20,07	20,58	20,54	19,57	20,52	20,40	31,36	31,34	29,51	31,31	30,93	37,11	37,09	36,40	37,06	36,58
AGRL	53,25	51,61	50,16	51,58	49,30	40,17	31,51	34,84	29,21	36,68	43,59	35,59	33,01	29,54	39,51	47,64	46,68	45,43	41,82	44,53
URBN	3,90	3,90	3,90	3,90	3,89	0,85	0,85	0,85	0,85	0,84	15,80	15,80	15,80	15,80	15,50	1,00	1,00	1,00	1,00	0,98
WATR	0,53	0,53	0,53	0,53	0,53	4,73	4,73	4,73	4,73	4,73	0,64	0,64	0,64	0,64	0,64	0,50	0,50	0,50	0,50	0,50

	E (1714 km²) C0	C1	C2	C3	C4	F (2839 km²) C0	C1	C2	C3	C4	G (1039 km²) C0	C1	C2	C3	C4	H (2203.4 km²) C0	C1	C2	C3	C4
FRSE	13,94	24,28	25,15	28,81	18,19	28,17	34,72	35,83	32,75	32,43	15,33	21,70	17,71	23,60	21,17	26,68	30,18	28,63	32,62	31,77
FRST	0,09	0,09	0,09	0,09	0,09	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
EUCA	4,03	4,01	3,87	4,02	4,00	4,34	4,34	4,34	4,34	4,25	3,60	3,60	3,55	3,60	3,55	5,25	5,25	5,25	5,25	5,14
RNGE	0,09	0,09	0,09	0,09	0,08	1,23	1,22	1,16	1,23	1,16	0,28	0,26	0,27	0,28	0,26	0,50	0,49	0,49	0,50	0,48
PAST	14,52	12,38	12,48	14,45	14,06	21,11	20,80	20,39	21,11	20,38	31,71	30,99	30,98	31,70	30,41	27,00	26,89	26,68	26,99	25,88
AGRR	0,24	0,22	0,23	0,20	0,23	0,09	0,09	0,09	0,08	0,09	0,13	0,10	0,13	0,09	0,13	0,30	0,30	0,29	0,17	0,30
SUGC	23,44	23,44	21,81	23,44	23,19	1,06	1,06	0,97	1,06	1,06	0,63	0,63	0,63	0,63	0,63	0,02	0,02	0,02	0,02	0,02
AGRL	39,73	31,57	32,35	25,00	36,29	35,91	29,69	29,14	31,33	32,83	45,71	40,12	44,14	37,50	41,41	35,52	32,13	33,90	29,72	31,84
URBN	3,78	3,78	3,78	3,78	3,73	6,68	6,68	6,68	6,68	6,39	2,38	2,38	2,38	2,38	2,21	2,73	2,73	2,73	2,73	2,56
WATR	0,14	0,14	0,14	0,14	0,14	1,41	1,41	1,41	1,41	1,41	0,22	0,22	0,22	0,22	0,22	2,01	2,01	2,01	2,01	2,01

Fig. 5. Area percentage of land use classes for each homogeneous region (A, B, C, D, E, F, G, H) and type of scenario (C0, C1, C2, C3, C4) analyzed. Agriculture/pasture (AGRL); annual crops (AGRR); planted forest (EUCA); forest formation (FRSE); savanna formation (FRST); pasture (PAST); grassland (RNGE); sugar cane (SURG); mining, urban area, and nonvegetated area (URBN); and water (WATR).

in areas with the FRSE, with an average increase of 8.66%, 10.05%, and 11.25%, respectively, for Scenarios C1, C2, and C3. For the other homogeneous regions (A, D, G, and H) these increases were smaller, corresponding to an average of 3.18% for Scenario C1, 2.93% for Scenario C2, and 5.51% for Scenario C3. Analyzing Scenario C4 and all homogeneous areas, the average increase in the FRSE class was 4.67%.

Table 3 shows the avoided costs related to the storage or regulation of water flow per unit area (R\$ ha^{-1} $year^{-1}$) and the avoided cost considering that all areas of Scenarios C1, C2, C3, and C4 with the FRSE class were actually reforested (R\$ $year^{-1}$). Among the scenarios, C1 was the one with the lowest costs per unit of area, resulting in an average avoided cost of R\$96.47 ha^{-1} $year^{-1}$. Scenarios C2 and C3 had an average corresponding to R\$112.87 and R\$107.28 ha^{-1} $year^{-1}$, respectively. Jalón et al. (2017), estimated the economic value of regulating water flow in basins in Spain and found values close to the results of this study, with values ranging from R\$19 to R\$254 ha^{-1}.

Table 3. Avoided costs related to the storage or regulation of water flow for each homogeneous region (HR) (A, B, C, D, E, F, G, H) and analyzed scenario (C1, C2, C3, C4)

	CAP (R$ ha^{-1} ano^{-1})				CAP (R$ ano^{-1})			
HR	C1	C2	C3	C4	C1	C2	C3	C4
A	77.03	132.06	77.03	143.06	35,751.28	83,696.72	38,280.51	94,242.86
B	138.26	108.76	138.26	160.38	475,205.72	411,316.40	580,889.91	215,564.54
C	133.17	108.08	133.17	150.54	438,040.41	763,559.06	767,233.39	290,166.21
D	97.97	97.97	135.20	170.47	10,766.41	38,960.76	63,372.58	44,334.99
E	98.38	153.71	98.38	217.25	492,069.68	614,604.72	781,594.04	227,346.09
F	58.30	118.83	76.23	134.53	609,710.03	701,089.10	437,511.55	387,306.17
G	106.24	75.55	99.16	141.65	221,450.65	72,910.29	304,013.91	195,659.08
H	62.39	107.99	100.79	143.99	274,240.73	143,478.49	473,439.75	367,838.83

Note: CAP = avoided costs related to the storage or regulation of water flow.

Scenario C4 resulted in the highest avoided costs, with an average of R$157.73 ha^{-1} year^{-1}. This cost increase in Scenario C4 in relation to other scenarios was because of the reduction of the URBN class and, consequently, the difference between the infiltration coefficients between the FRSE and URBN classes. This fact results in a greater difference in the amount of infiltrated water, also showing that reforested urban areas would bring more benefits in relation to the amount of water stored or infiltrated, generating higher avoided costs. Marques et al. (2017) evaluated the economic value of regulating the flow of water in urban areas, using scenarios for increasing the permeable area and estimating values in the order of magnitude between R$4.95 million and R$1,274.27 million.

Among the homogeneous regions, areas B and C (both in the Piracicaba river subbasin and urbanized) (Table 3) were the regions that showed the highest avoided costs, equivalent to an average of R$135.71 ha^{-1} year^{-1} for Scenarios C1 and C3, R$108.42 ha^{-1} year^{-1} for Scenario C2, and R$155.46 ha^{-1} year^{-1} for Scenario C4.

Analyzing and considering that all priority areas of the predictive scenarios were reforested, that is, that the condition of land use was currently the areas Scenarios C1, C2, C3, and C4 established, the costs avoided in the homogeneous areas studied would vary between R$10,766.41 to R$ 781,594.04 year^{-1} (Table 3).

Regarding the homogeneous regions, areas B, C, E, and F are equivalent to the subbasins of the Piracicaba, Corumbataí, and Atibaia Rivers, and consequently they presented a higher percentage of areas that deserve to be reforested. Thus, they are related to higher avoided costs for storage or regulation of water flow, reaching R$609,710.03 year^{-1} for area F of Scenario C1, R$763,559.06 year^{-1} for area C of Scenario C2, R$781,594.04 year^{-1} for area C of Scenario C3, and R$387,306.17 year^{-1} for area F of Scenario C4 (Table 3).

Gopal (2016) proposes that the assessment of ecosystem services and their valuation should be based on environmental flows, more specifically, on river flows. Furthermore, he emphasizes that, when linking ecosystem services to flow regimes, it is important to recognize that changes in flow can occur at any or all stages of low, medium, or peak flows. Thus, the distribution of monthly precipitation for the Piracicaba River basin is observed in Fig. 6(a), in which, between the months of May and September, the height varies from 28.76 (August) to 58.73 mm (July), and between the months of October and April, the precipitation averages vary between 97.46 (April) and 330.35 mm (January); that is, there is great seasonality in the distribution of rainfall during the year. Therefore, water storage, yield, and availability also change, affecting the values of costs that could be avoided throughout the year.

Fig. 6(b) shows the monthly cost per area unit, according to which in January, the avoided value reaches R$41.16 ha^{-1} for Scenarios C1, C2, and C3 and R$54.11 ha^{-1} for Scenario C4. In August, for Scenarios C1, C2, and C3, the value is R$3.58 ha^{-1}, and for C4, it corresponds to R$4.71 ha^{-1}. Considering that all priority areas of the scenarios were reforested [Fig. 6(c)], the value avoided by the storage or regulation of water flow for the month of January would be R$570,448, R$643,617, R$772,666, and R$401,293, respectively, for Scenarios C1, C2, C3, and C4.

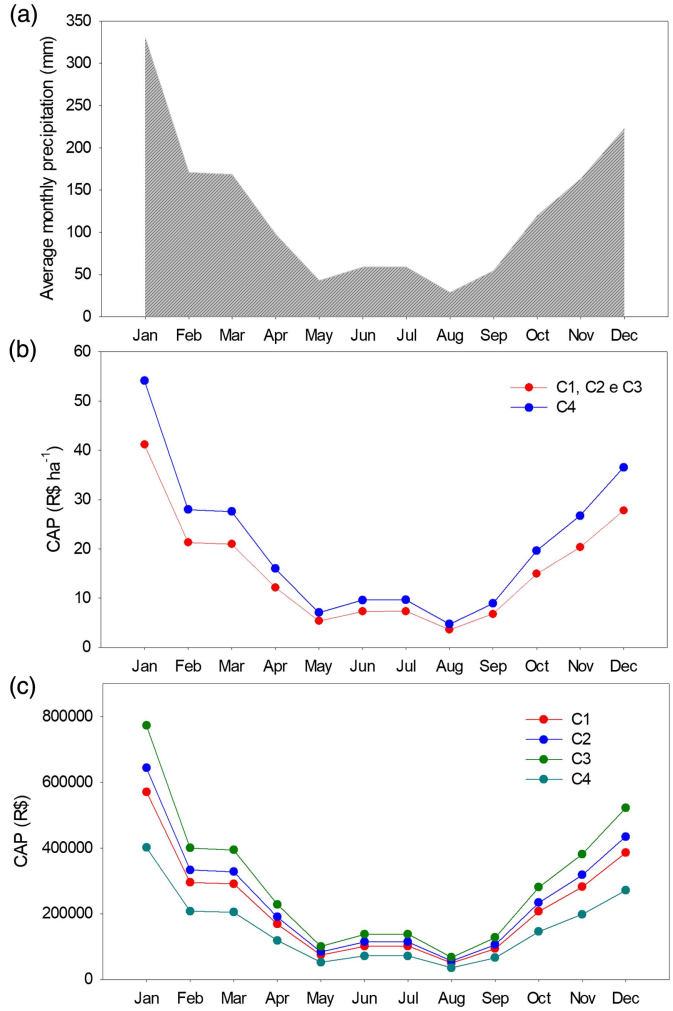

Fig. 6. Monthly avoided cost related to storage or regulation of water flow (CAP) for each analyzed scenario.

Table 4. Participation coefficients (PCs) of each scenario in the contribution of nitrogen, phosphorus, and sediment load

Subbasin	C0	C1	C0	C2	C0	C3	C0	C4
				Nitrogen				
Atibaia	0.5316	0.4684	0.5392	0.4608	0.5288	0.4712	0.5205	0.4795
Camanducaia	0.5386	0.4614	0.5091	0.4909	0.5591	0.4409	0.5289	0.4711
Corumbataí	0.5469	0.4531	0.5392	0.4608	0.5971	0.4029	0.5203	0.4797
Jaguari	0.5187	0.4813	0.5121	0.4879	0.5324	0.4676	0.5238	0.4762
Piracicaba	0.5603	0.4397	0.5306	0.4694	0.5675	0.4325	—	—
Cantareira system	0.5318	0.4682	0.5019	0.4981	0.5226	0.4774	0.5301	0.4699
				Phosphorus				
Atibaia	0.5300	0.4700	0.5452	0.4548	0.5108	0.4892	0.5094	0.4906
Camanducaia	0.5133	0.4867	0.5319	0.4681	0.5115	0.4885	0.5220	0.4780
Corumbataí	0.5005	0.4995	0.5097	0.4903	0.5063	0.4937	0.5024	0.4976
Jaguari	0.5189	0.4811	0.5316	0.4684	0.5157	0.4843	0.5131	0.4869
Piracicaba	0.5312	0.4688	0.5302	0.4698	0.5301	0.4699	—	—
Cantareira system	0.5609	0.4391	0.5783	0.4217	0.5290	0.4710	0.5300	0.4700
				Sediments				
Atibaia	0.5271	0.4729	0.5243	0.4757	—	—	0.5002	0.4998
Camanducaia	0.5285	0.4715	0.5170	0.4830	0.5083	0.4917	0.5160	0.4840
Corumbataí	0.5317	0.4683	0.5066	0.4934	0.5062	0.4938	—	—
Jaguari	0.5240	0.4760	0.5115	0.4885	—	—	—	—
Piracicaba	0.5441	0.4559	0.5325	0.4675	—	—	—	—
Cantareira system	0.5264	0.4736	0.5321	0.4679	—	—	—	—

For the same scenarios, the minimum values occur in the month of August, with respective values of R$49,662, R$56,032, R$67,267, and R$34,936. This indicates that the greater the flow or quantity of water, the greater the cost avoided by the increase in storage or regulation of water flow. Similar results were reported by Xie et al. (2017), who assessed the temporal variation in the value of ecosystem services in China and found the highest values between the months of May and September, a period in which there is an increase in temperature and precipitation in that country.

Table 4 shows the participation coefficients of each scenario in the contribution of nitrogen, phosphorus, and sediment load. In Scenario C4, the Piracicaba subbasin did not contribute to a decrease in the supply of nitrogen and phosphorus nutrients. Within the same scenario, the subbasins of Corumbataí, Jaguari, Piracicaba, and Cantareira also did not provide a reduction in the sediment load. It is also observed that there was no reduction in sediment transport in the subbasins of Atibaia, Jaguari, Piracicaba, and Cantareira within the C3 scenario. This is due to the fact that Scenario C3 comes from the identification of areas that have water quality problems, which in turn will be reforested and do not coincide with areas that contribute to the sediment load. Therefore, there is no analysis of the avoided cost for the mentioned subbasins because the simulation of the scenarios in the model does not follow the $CPci < CPco$ criterion [Eq. (3)].

The best scenario for evaluating the cost avoided by maintaining water quality is C3 because it came from the identification of areas that have water quality problems with a higher-priority area and, consequently, with a higher FRSE class (Lopes et al. 2022); therefore, the average cost avoided by maintaining water quality (disregarding the Cantareira system) based on the nitrogen variable was R$991.15 ha^{-1} $year^{-1}$ [Fig. 7(a)]; already considering the phosphorus variable, the average cost avoided was R$273.23 ha^{-1} $year^{-1}$ [Fig. 7(b)].

Regarding the sediment variable [Fig. 7(c)], Scenario C1 was the result of the multicriterial analysis with the objective of identifying areas that have susceptibility or problems related to erosion and sediment production; therefore, the average cost avoided by maintaining water quality in this scenario (disregarding the Cantareira system, which is already included within the Atibaia and Jaguari Rivers basins) was R$565.58 ha^{-1} $year^{-1}$ [Fig. 7(a)].

Using nitrogen load as a base generates a reduction in cost when compared to phosphorus and sediment, and this is due to its greater variation within the different land uses analyzed. According to the average avoided cost and standard deviation, the subbasin areas of the Corumbataí, Piracicaba, and Camanducaia Rivers have the greatest variations in nitrogen input if they are reforested.

Phosphorus, nitrogen, and sediments have high concentrations in urban centers, and sediment production occurs under certain conditions of relief characteristics, soil type, and management and use of that soil (Goonetilleke et al. 2005). The Atibaia and Piracicaba subbasins showed the greatest variations in phosphorus nutrient and sediment production, which is highly correlated with high urban density.

According to C0 scenario, the Cantareira system has 39.55% of its total area composed of forest formation and 7.79% of planted forest; that is, almost 50% of the area is composed of forest, which explains the lack of reduction in sediment production and low average avoided cost and standard deviation when compared to the other subbasins (Fig. 7). With this, the Cantareira system area served as a validation standard, where for areas with high forest cover, the avoided cost is very low, or it does not generate benefits when land use and land cover are changed; on the other hand, for areas where the percentage of forests is low, that is, where there is high agricultural activity or urban areas, the avoided costs are high, as they generate great benefits related to the reduction of the polluting load; that is, the more benefits the change of land use generates, the greater the avoided cost, which is a well-known fact in almost all valuation studies.

Soriano et al. (2016) assessed the value of ecosystem services in Spain. The average value for water quality regulation in 2012 was R$884.47 ha^{-1} $year^{-1}$, reaching a maximum of R$12,879.14 ha^{-1} $year^{-1}$; on the other hand, for erosion control, the average value corresponded to R$209.11 ha^{-1} $year^{-1}$, reaching a maximum of R$1,534.27 ha^{-1} $year^{-1}$. That values were with the same order of magnitude as this study.

The Project for Payments for Environmental Services, called Projeto Oásis, whose objective is to protect remnants of the Atlantic

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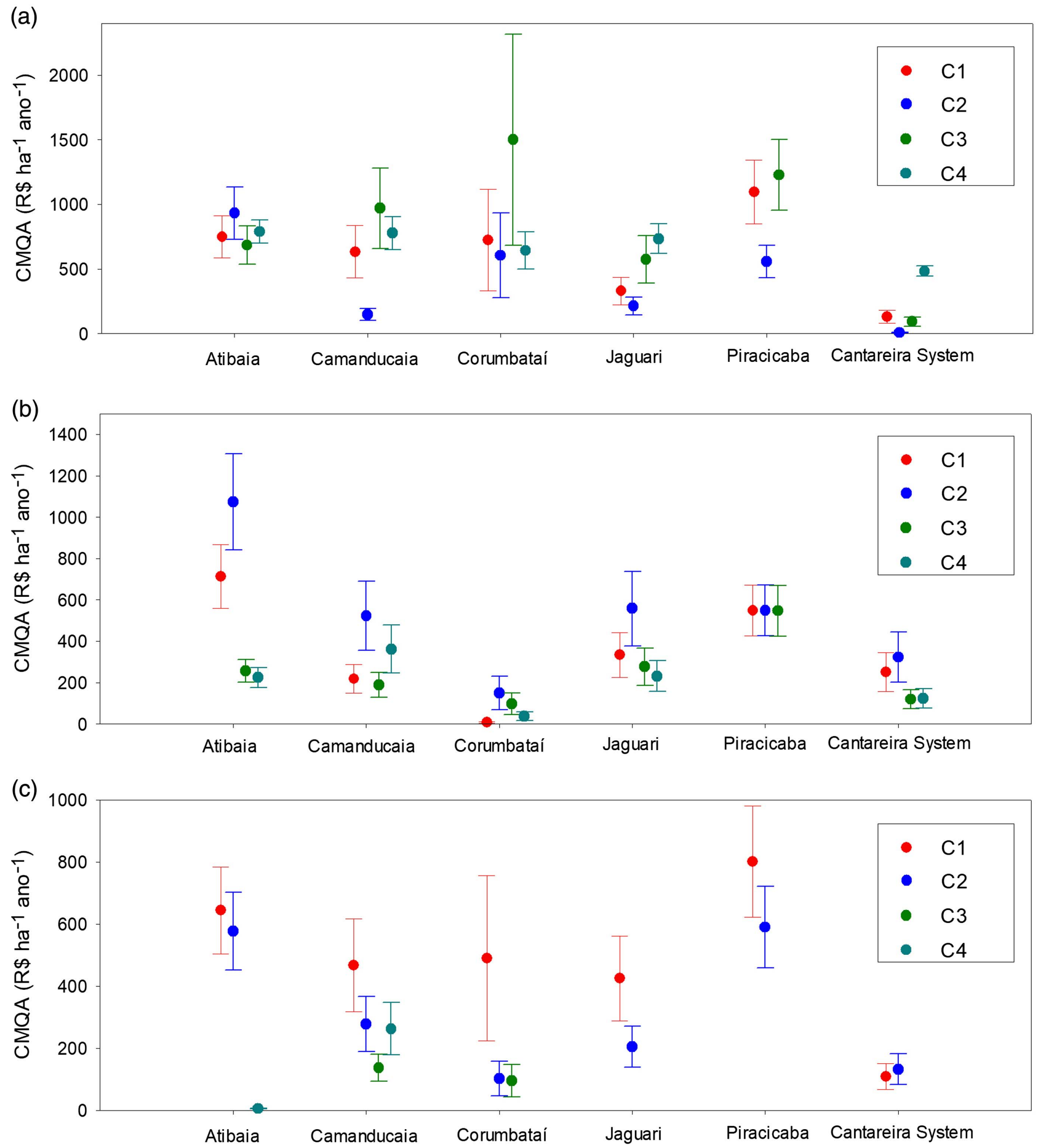

Fig. 7. Costs avoided by maintaining water quality (CMQA) based on the variables: (a) nitrogen; (b) phosphorus; and (c) sediment.

forest and associated ecosystems located within the spring areas of the metropolitan region of São Paulo, developed a methodology that defines a reference value for payment per hectare per year for services provided by the preserved natural area in relation to water storage (Whately and Hercowitz 2008). Water regulation was valued at R$99.00 ha^{-1} $year^{-1}$, a value that is similar to the average cost estimated in this work for storage (base yield) of water in Scenarios C1, C2, and C3.

In the Oasis Project, the maintenance of water quality was valued at R$196.00 ha^{-1} $year^{-1}$ (Nunes et al. 2013). The value of R $196.00, attributed to water quality, was estimated based on the amount of total phosphorus present in the water. The average value estimated in this work, considering the phosphorus, nitrogen, and sediment variables, was higher than the value presented in the Oasis Project because the methodology used in the Oasis Project considered a water treatment tariff of only R$0.054 m^{-3} with reference to the year 2003. The tariffs currently used in the municipalities of the Piracicaba River basin vary between R$0.56 and R$3.54 m^{-3}. In addition, there is also a variation in tariffs over the years, which will possibly increase avoided costs in the coming years.

Checking the total avoided cost for the Piracicaba River basin for each scenario, C4 presents the lowest value because it is related to the smallest reforested area, corresponding to R$1.8 million $year^{-1}$; in Scenarios C1 and C2, the values were, respectively, R$2.5 million and R$2.8 million $year^{-1}$. C3 has a reforested area of 8.82% more than the current scenario, being the largest among all the studied scenarios and consequently presenting the highest avoided cost due to the storage or regulation of water flow (R$3.4 million $year^{-1}$).

The Piracicaba River basin is located within the Water Resources Management Unit of the Piracicaba, Capivari, and Jundiaí River basins, called PCJ basin (PCJ 2020). The PCJ basin has a charge for the use of water resources, which is one of the management instruments of the National Water Resources Policy, established by Federal Law No. 9,433/97, and aims to give the user an indication of the real value of water, encourage the rational use of this resource, and obtain financial support for the recovery of hydrographic basins (BRASIL 1997). According to the collection report for the collection of water use, in 2019, the total transferred to investments in the basin itself was equivalent to R$11.2 million, and the annual average between the years 2006 to 2019 was R$15.2 million (ANA 2020). Analyzing the total cost avoided due to water storage and water yield for the Piracicaba River basin for each scenario, the values represent 16.07% (C4) and 30.36% (C3) of the total transferred in 2019 and 11.84% (C4) and 22.37% (C3) of the average annual amount transferred; that is, it represents a high amount when compared to the total collected for investments in the basin.

Considering that all areas of the scenarios were reforested and using nitrogen as a base, the cost avoided by maintaining water quality in the Piracicaba River basin would reach a maximum of R$141.7 million year^{-1} (C3) and a minimum of R$18.8 million year^{-1} (C4), corresponding to 66.71% and 8.85%, respectively, of the total accumulated collected transferred (2006–2019) for water use charges. Analyzing phosphorus, the maximum cost avoided would be R$71.6 million year^{-1} (C2) and at least R$9.4 million year^{-1} (C4), which corresponds to respectively 33.71% and 4.43% of the total accumulated collected transferred (2006–2019) through the charge for the use of water. Considering the production of sediments, a maximum of R$45.1 million year^{-1} (C1) and at least R$16.5 million year^{-1} (C4) would be avoided, corresponding to respectively 21.23% and 7.77% of the total accumulated collected transferred (2006–2019) for water use charges.

In order to verify what other benefits the scenarios could provide, Fig. 8 shows the mean annual variations in surface runoff (Qsup), lateral runoff (Qlat), contribution from the shallow and deep aquifer (Qgw), total aquifer recharge (Totalgw), water yield (Qtotal), evapotranspiration (ET), and variation in sediment production (Sed).

The removal of vegetation leaves makes the soil surface more exposed to the direct action of raindrops, facilitating the movement of water on the surface, decreasing the infiltration speed, and consequently generating greater surface runoff (Cardoso et al. 2012; Rodrigues et al. 2013). Thus, it can be observed that the forest restoration scenarios, when compared to the C0 scenario (Fig. 7), demonstrated lower surface runoff, greater lateral runoff, greater contribution of aquifers to water yield, greater aquifer recharge, lower total water yield, and greater evapotranspiration height.

Pereira et al. (2014) also evaluated the effect of changing land use and occupation scenarios on the water balance using the SWAT model and found greater surface runoff in the pessimistic scenario, in which the classes that occupied most of the basin were pasture and agriculture. In the scenario where native forest occupied 97% of the basin area, surface runoff and water yield were lower and evapotranspiration increased.

In agricultural areas, poor soil use, intensive mechanization, monoculture, destruction of permanent preservation areas, and high use of chemical inputs can change the natural characteristics of the soil, causing depletion, degradation, and erosion (Oliveira et al. 2012). Because most of the areas that were reclassified as FRSE were agricultural (Table 1), a decrease in sediment production can be seen in the reforested scenarios, especially in the C3 scenario, with a reduction of 0.765 Mg ha^{-1}.

Xie et al. (2017) assessed the value of ecosystem services and found that forests make the largest contribution, accounting for 46.0% of the total value, and among ecosystem services, regulatory services provide the highest component, 71.3% of the amount. Therefore, increasing the forested area in the Piracicaba River basin can be an effective option to provide services for regulating flow and maintaining water quality.

The relationship between water and forest depends on several site-specific variables, such as the type of soil and vegetation, climate, slope of the land, and type of management adopted, among others, which are related to multiple interactions. This makes it difficult to isolate a variable to identify its impact on certain parameters of the ecosystem (Whately and Hercowitz 2008). Lara-Pulido et al. (2018) carried out a meta-analysis of the economic assessment of ecosystem services in Mexico and concluded that economic assessment is a powerful tool to clarify the importance of ecosystem services to various sectors; however, in order to have reliable estimates, these authors recommend the use of models, especially the SWAT model that is used in this study, as it is considered a robust model and has evolved a lot in the last 30 years.

Forest cover positively influences soil hydrology, improving infiltration, percolation and water storage processes, in addition to reducing surface runoff and reducing the erosion process. The effects of deforestation translate into reduced evapotranspiration and water infiltration into the soil, thus intensifying runoff and soil loss, which leads to increased river flow and annual sedimentation (Honda and Durigan 2017; Tambosi et al. 2015).

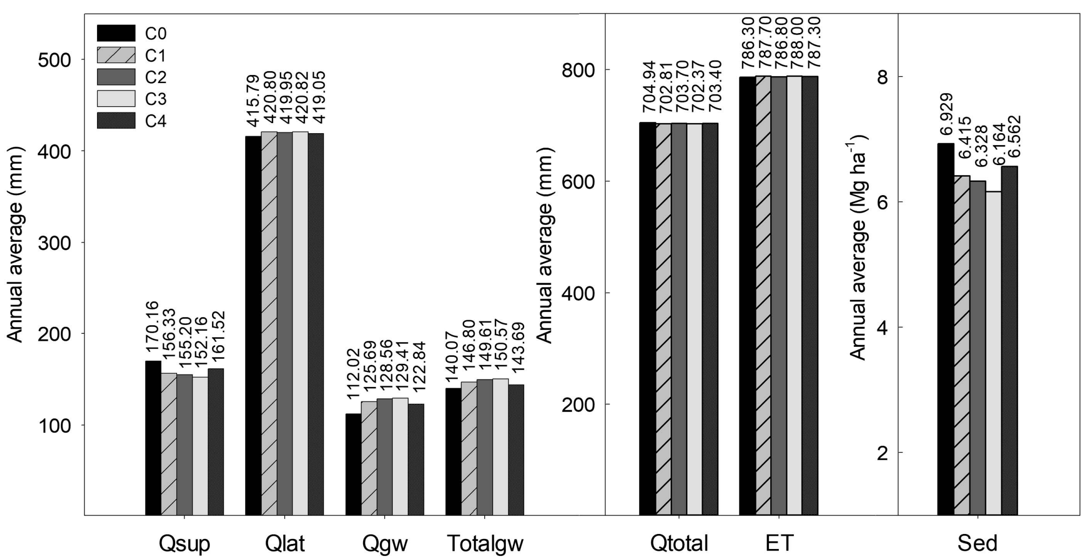

Fig. 8. Average annual change in surface runoff (Qsup), lateral runoff (Qlat), shallow and deep aquifer contribution (Qgw), total aquifer recharge (Totalgw), water yield (Qtotal), evapotranspiration (ET), and production of sediments (Sed) for Scenarios C0, C1, C2, C3, and C4.

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One of the advantages of increasing water infiltration into the soil and reducing surface runoff is the guarantee of a greater volume of water in the dry season; that is, the water that infiltrates contributes to the water table, thus maintaining the riverbeds in times of drought and contributing to the filling of water reservoirs. The metropolitan region of São Paulo is experiencing several problems related to the availability of water, especially in the dry season; therefore, the projects of payments for environmental services that exist in the basin and aim to increase the storage of water in the soil from practices conservationists and reforestation (Richards et al. 2015; Taffarello et al. 2016, 2017; ANA 2019a) help maintain water availability and quality. Therefore, based on the identification of strategic areas that require conservation practices and where projects for Payments for Environmental Services can be implemented (Lopes et al. 2022), such actions provide greater economic benefits related to the costs avoided by regulating the quantity and quality of water in specific periods and places of the Piracicaba River basin.

Regardless of the methodology available or used for the economic assessment of ecosystem services, there will be the advantage of offering a basis for dialogue with policy makers (Gopal 2016) because the recognition of the economic value of water drives the development of countries, and from it, it is possible to reduce revenue losses and mainly generate benefits to the ecosystem. Future applications of this approach can tweak or refine the method in various directions and monetary valuation can also be extended to the amount of compensation paid to landowners for conservation or restoration of natural resources in the Piracicaba River basin. Therefore, the practice of forest restoration or recovery can generate avoided costs related to the benefit of flow regulation and water quality improvement; however, other benefits may occur in the ecosystem, such as regulation of air quality, climate, erosion, soil quality, pollination, diseases, and others, as shown in other studies that also use the avoided costs method to verify the economic and environmental benefits (Mehvar et al. 2018; Capotorti et al. 2019; Boithias et al. 2016; Foudi et al. 2017; Brito et al. 2018).

Conclusion

1. Changes in land use and occupation affect environmental services for regulating flow and maintaining water quality, thus showing which strategic areas presented in the scenarios can be used as units for providing ecosystem services.
2. It was possible to estimate values for regulating the quantity and quality adequacy of water provision services, respectively, in terms of water storage or flow regulation and maintenance water quality. The average cost avoided by water storage in the studied scenarios ranged from R\$96.47 to R\$157.73 ha^{-1} $year^{-1}$. The average cost avoided by maintaining water quality based on the nitrogen variable was R\$991.15 ha^{-1} $year^{-1}$; already considering the phosphorus variable, the average cost was R\$273.23 ha^{-1} $year^{-1}$, and, for the sediment variable, it was R\$565.58 ha^{-1} $year^{-1}$.
3. It was also possible to verify which strategic area, if reforestation or conservation practices applied, would yield greater monetary and hydrological benefits, that is, how much cost would be avoided or reduced if applied in correct areas. Thus, the application of tools such as SWAT and valuation methods such as those presented in this paper can be especially useful in new development plans for the Piracicaba River basin and other hydrographic regions to support decision makers regarding level of occupation and future consequences, both in economic and hydrological terms.
4. The values estimated have an order of magnitude similar to those of other studies carried out in Brazil and worldwide.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Acknowledgments

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