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Potential of the retention capability of a Neotropical reservoir (São Paulo State, Brazil)

Potencial da capacidade de retenção de um reservatório Neotropical (Estado de São Paulo, Brasil)

Flavia Bottino[1], Simone Pereira Casali[2], Marcela Bianchessi Cunha-Santino[3], Maria do Carmo Calijuri[4] and Irineu Bianchini Júnior[3*]

[1]Instituto Federal de Educação Ciência e Tecnologia de São Paulo, Rua Maria Cinto de Biaggi, 130, Jardim Santa Rosália, CEP 18095-410, Sorocaba, SP, Brasil

[2]Programa de Pós-Graduação em Engenharia Hidráulica e Saneamento, Escola de Engenharia de São Carlos, Universidade de São Paulo, Avenida Trabalhador São-Carlense, 400, CEP 13566-590, São Carlos, SP, Brasil

[3]Departamento de Hidrobiologia, Universidade Federal de São Carlos, Rodovia Washington Luiz, km 235, CEP 13595-905, São Carlos, SP, Brasil

[4]Departamento de Hidráulica e Saneamento, Escola de Engenharia de São Carlos, Universidade de São Paulo, Avenida Trabalhador São-Carlense, 400, CEP 13566-590, São Carlos, SP, Brasil

*e-mail: irineu@ufscar.br

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Abstract: Aim: Man-made reservoirs lead to several changes in their downstream rivers that depend on the hydraulic characteristics of the reservoirs. However, their multiple uses can also provide facilities that influence the ecosystem services that they provide. This study addressed the potential ability of a Neotropical reservoir to trap chemical species aiming to assess the role of these ecosystems to mitigate pollution. **Methods:** Retention capability modeling was examined for a small subtropical reservoir with high hydraulic retention time (> 100 days). The temporal ranges of 9 physical and chemical water variables over a five-year period were used to calculate the mass balance and to determine the retentive capability (alpha parameter) of the Itupararanga Reservoir (São Paulo State, Brazil). To explain the long-term mass balance of these variables, it was assumed that the reservoir is a completely mixed system with a step input. **Results:** The highest values of parametrized alpha (high retention capability) occurred in wet months (up to 500 mm) for all variables. High reaction rate constants (k) and low hydraulic flushing suggested that sink processes prevail over the export ones, mainly for total phosphorus. The rainfall pattern showed minor importance for trapping elements. **Conclusions:** In the Neotropics, hydraulic characteristics of the ecosystem (e.g., low area:volume ratio) are a tool for pollution management in man-made reservoirs.

Keywords: ecosystem services; mass balance; eutrophication; water resources management; subtropical reservoir.

Resumo: Objetivo: Os reservatórios artificiais desencadeiam várias mudanças em seus rios a jusante que dependem das características hidráulicas dos reservatórios. No entanto, seus múltiplos usos também podem fornecer recursos que influenciam os serviços ecossistêmicos que eles fornecem. Este estudo abordou a capacidade potencial de um reservatório Neotropical em capturar espécies químicas, com o objetivo de avaliar o papel desses ecossistemas na mitigação da poluição. **Métodos:** A modelagem da capacidade de retenção foi examinada para um pequeno reservatório subtropical com alto tempo de retenção hidráulica (> 100 dias). As variações temporais de 9 variáveis físicas e químicas da água ao longo de um período de cinco anos foram usados para calcular o balanço de massa e determinar a capacidade retentiva (parâmetro alfa) do reservatório Itupararanga (estado de São Paulo, Brasil). Para explicar o balanço de massa de longo prazo dessas variáveis, foi assumido que o reservatório seja um sistema completamente misturado com uma entrada em degrau. **Resultados:** Os maiores valores de assimilação (i.e., alta capacidade de retenção) ocorreram nos meses úmidos (até 500 mm) para todas as variáveis. Altos coeficientes de reação (k) e baixa descarga hidráulica sugerem que os processos de sumidouro prevalecem sobre os de exportação, principalmente para fósforo total. O padrão de precipitação mostrou menor importância para o aprisionamento dos elementos. **Conclusões:** Nos Neotrópicos, as características hidráulicas do ecossistema (e.g., baixa relação área: volume) são uma ferramenta para o gerenciamento da poluição em reservatórios artificiais.

Palavras-chave: serviços ecossistêmicos; balanço de massa; eutrofização; gestão de recursos hídricos; reservatório subtropical.

1. Introduction

Rivers are ecosystems that provide a range of essential services (drinking water, nutrient cycling, water pollution management, fisheries and aquaculture, transport of dissolved and suspended materials, habitats for a range of natural species) that support life on Earth (Van Cappellen & Maavara, 2016). Damming of natural rivers is an anthropogenic activity that represents one of the main disturbances for rivers and for their riparian areas, leading to both local and global consequences (Van Cappellen & Maavara, 2016; Akbarzadeh et al., 2019). Dams are mainly constructed for economic purposes, such as water irrigation, water supply, electricity generation and flood control. However, they can also act as a retention basin for pollutants and this has implications for eutrophication and/or for retention of biogenic elements that may cause concerns for water supply, navigation, biodiversity conservation and aesthetic issues (Bartoszek & Koszelnik, 2016; Cunha-Santino et al., 2017; Qin et al., 2020).

Hydraulic management (e.g., water level control) of reservoirs affects water quality due to the retention of elements derived from the drainage area and from point source pollution. Rainfall is essential for maintenance of the maximum water level and also influences the hydraulic retention time (HRT). HRT is an important variable that may control both sedimentation and biogeochemical reactions occurring in the water column. The retention capability of reservoirs is also affected by thermal stratification and hydrological conditions (Kerimoglu & Rinke, 2013). For instance, the occurrence of anoxic conditions in the hypolimnion (Cole & Hannan, 1990) can also induce the release of soluble elements from the sediments (Søndergaard et al., 2003).

Rainfall water inputs modify the HRT, and consequently the downstream flow of elements, hence altering reservoir retention capability causing changes in downstream ecosystems due to exportation of elements. In addition, if water input and volume change, then water column circulation is likely to affect the thermal stratification of the reservoir, with resulting consequences for a range of chemical and biological processes within the reservoir (Armengol et al., 1999; Teixeira et al., 2022). On the one hand, these changes can minimize the retention of elements, mimicking the original condition of the river (i.e., before reservoir construction). On the other hand, depending on water quality status, those conditions can increase the export of pollutants and toxic elements to downstream aquatic environments (Straškraba & Tundisi, 1999).

Understanding the role of rainfall pattern on the retention capability of reservoirs is useful for water management purposes (Straškraba, 1999). Most studies about river impoundment have focused on the loss of biodiversity, invasive species, landscape changes, water resources and social impacts (Hoeinghaus et al., 2009). Although several studies have examined the effects of dams on maintaining water quality and the amount of water they provide, relatively few studies have examined these effects in a quantitative, mathematically standardized way (e.g., Cunha-Santino et al., 2017; Bianchini Junior et al., 2019). This is of particular importance in tropical reservoirs, because in addition to sedimentation, material retention is closely linked to biological processes (e.g., autochthonous organic matter production), where high temperatures tend to support high values of chemical and biochemical reaction rates. On the contrary, the mineralization rates (also affected by temperature) tend to minimize the retention efficiency (Kennedy & Walker, 1990; Davidson & Janssens, 2006).

In this study, we address the potential of the retention capability in a Neotropical reservoir in which thermal stratification is usually present during the rainy season. We hypothesize that periods of low precipitation (i.e., dry season: spring and winter) increase the HRT, and therefore, the retention of sediment particles and other materials, making the effect of temperature secondary, through indigenous production, on the retention of the elements. This has implications for internal loading of the reservoir, and consequently for the water supply downstream. We chose the Itupararanga Reservoir, located in subtropical climate (Brazil), to adjust a retention capability model because this system is small, with electricity generation roughly proportional to the amount of rainfall. However, the model can be applied for any ecosystem with steady-state flow and with HRT high enough to reach equilibrium.

2. Materials and Methods

2.1. Study area

Itupararanga Reservoir (23°36'43.35"S; 47°23'49.87"W) located in the Middle Tietê River Basin in São Paulo State, Brazil is included in Water Resources Management Unit (UGRHI) 10, which has an area of 1 178 922.17 km^2. According to the classification proposed by Straškraba (1999), the reservoir is small (area ranging from 1 to 100 km^2) and Class B (15 days <HRT <1 year). As stated by the total phosphorus results obtained in the period of this survey (2007-2012), this reservoir is predominantly mesotrophic (*sensu* Vollenweider & Kerekes, 1982); total phosphorus concentrations range from 20 ± 13 μg/L in lacustrine zone and 31 ± 22 μg/L in the riverine zone. The climate of the region is Cwa (rainy summer and dry winter) according to Köppen (1931). It is characterized by the occurrence of a very rainy and hot season, between October and March, when more than 70% of the volume of rainfall is concentrated. The dry season (between April ans September) is cold with little rain (Abreu & Tonello, 2017). In the period 1991-2020, the average monthly rainfall in the region (State of São Paulo) is 120.6 mm (± 86.2 mm); on average, July and August are the months with the lowest rainfall (monthly accumulated averages: 26.8 and 23.7 mm, respectively) and December and January with the highest (228.3 and 286.6 mm, respectively). The average annual temperature is 20.8 °C (± 2.0 °C); on average, the lowest temperatures occur in June and July (17.8 and 17.7 °C, respectively) and the highest in January and February (22.9 and 23.1 °C, respectively); INMET (2022).

The reservoir was built in 1914 by damming the Sorocaba River that is formed by the junction of the Sorocamirim, Sorocabuçu and Una rivers (Figure 1). The main use of the reservoir is electric

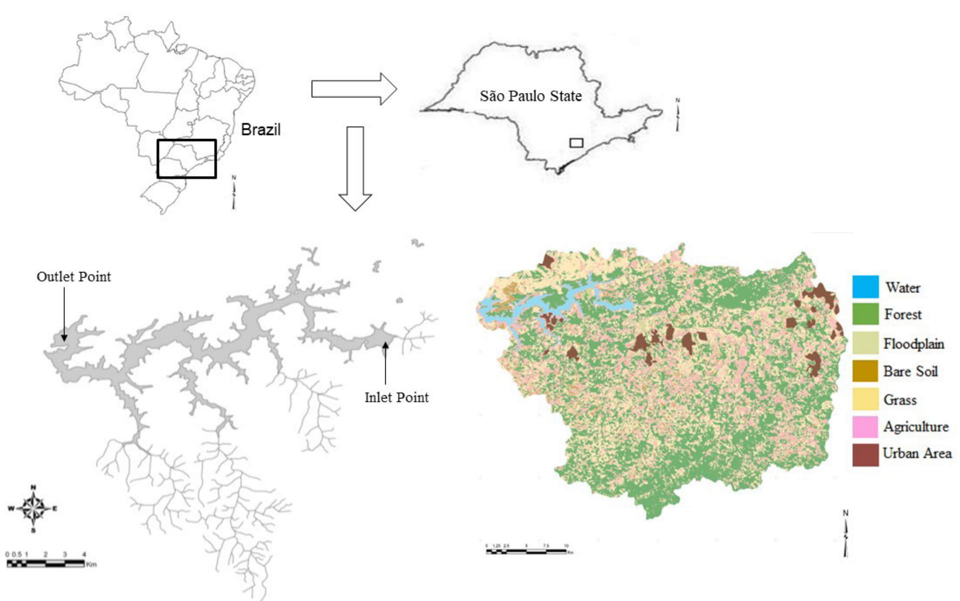

Figure 1. Location of São Paulo State in Brazil, Itupararanga Reservoir with the main tributaries and sampling points arrowed (Inlet Point: Headwater; Outlet Point: Dam) and the land use of Itupararanga basin.

power generation and water supply for about one million people. The reservoir is 26 km in length, with a drainage area of 936 km^2, and a shoreline length of 192.9 km (Table 1). On the right margin of the reservoir, there is an Environmental Protection Area with the Brazilian Savannah and Atlantic Forest species. In the left margin, the land use is predominantly agricultural, covering about 48% of the basin area (Secchin, 2012) (Figure 1). The presence of metals (Pb, Cu, Cr, Mn, Fe, Al, Zn) in the sediments of the Itupararanga Reservoir (usually with higher incidences and contents in riverine and transition regions) indicates a recent and weak pollution by agrochemicals and effluents (Rosa et al., 2015).

The adduction flows in the reservoir (generated mainly from the Sorocaba River) normally follow the rainfall regime. The effluent flows essentially result from: i) the maintenance of water for supply; ii) the operating rules of the hydroelectric power plant. Thus, normally, the volume of the reservoir tends to be greater in the spring-summer period. In turn, HRT temporal variations do not have a well-defined seasonality, as they result from the flow regime and water storage management (i.e., electricity generation, and water supply).

2.2. Sampling

Water samples were collected at 2 sampling points in the subsurface of the reservoir ($z \approx$ 10 cm): in the upstream region (headwater of the reservoir – inlet: 23.6245°S; 47.3364ºW) and in the dam region (limnetic region – outlet: 23.6153ºS; 47.3904ºW) (Figure. 1). The inlet point (located on the Sorocaba River) integrates the chemical and physical characteristics of the main tributaries of the reservoir; the tributaries (Una, Sorocabuçu and Sorocamirim rivers), which are primarily responsible for the tributary flow of the reservoir (over 90%). The choice of only two points (inlet and outlet) stems from the assumptions of calculating the mass balance of the reservoir (Bianchini Junior et al., 2019).

For mass balance calculations, the following variables were selected: electrical conductivity (EC; µS/cm), dissolved oxygen (DO; mg/L), water temperature (wT; ºC), pH, turbidity (NTU), total solids (TS; mg/L), chlorophyll-a (Chl-*a*; mg/L), total phosphorus (TP; µg/L), total Kjeldahl nitrogen (TKN; mg/L), and nitrate ($N\text{-}NO_3$; mg/L). Vertical profiles of water temperature, pH, OD, EC and turbidity were determined at the sampling points with a multiparameter probe (YSI Model 556 MPS).

To analyze the TKN, nitrate, TP and TS, the samples were collected and kept refrigerated (4 ºC) during transport to the laboratory. The samples used for chlorophyll-*a* determinations were filtered at the time of collection, and the filters were kept cool and in the dark until the concentrations were determined.

TKN concentrations were determined by the titrimetric method; nitrate, TP and chlorophyll-a concentrations were measured by colorimetry and TS by gravimetry; these analyses were performed in accordance with the APHA (2005). Assessments were conducted quarterly during the period from September 2007 to July 2012 (UFSCar, 2008; Bottino, 2011; Casali, 2014); the results of limnological surveys carried out by the environmental agency of the São Paulo State (CETESB) were also utilized (CETESB, 2010; 2011; 2012).

Table 1. Main characteristics of the Itupararanga Reservoir (CBA, 1993; ANEEL, 2005; UFSCar, 2008).

Characteristic	Data
Maximum operating quota	826.5 m
Drainage basin area	938 km^2
Volume (V)	3.02×10^8 m^3
Reservoir area (A0)	25.27 km^2
Shore line (L)	192.9 km
Maximum width (b)	1.60 km
Average width	0.97 km
Maximum Length (l)	26.0 km
Fetch Length 1	4.66 km
Fetch Length 2	4.45 km
Maximum depth (z_m)	35.0 m
Relative depth (z_r)	0.62%
Average depth (z)	12.0 m
Average Hydraulic Retention Time (HRT)	273 d
Average Hydraulic Flow (HF)	0.004 d^{-1}
Number of Renovations (ref. 2020)	130 times
Volume development (D_v)	1.02
Shore line development (D_L)	10.83

2.3. Mathematical modeling

To describe the mass balance of variables, it was assumed that the Itupararanga Reservoir is a completely mixed system with a step input (Equations 1 and 2; Chapra, 2008). These assumptions were adopted because they make it possible to perform reservoir mass balances quickly and simply. The selected model (Equation 2) is widely disseminated as it helps decision makers in activities aimed at improving water quality, maintaining autochthonous biodiversity and ecosystem services (e.g., effluent control actions as a function of downstream water quality). According to seasonal vertical thermal profile simulation (Ryan & Harleman, 1971), this reservoir is classified as warm monomictic (*sensu* Hutchinson & Löffler, 1956). However, it was possible to admit that it is a thoroughly mixed system because the main entrances and exits of the elements occur mostly primarily through the epilimnion and the metalimnion, since i) tributary water temperatures usually are closer to the epilimnion and hypolimnion temperatures, in this case, the inlet occurs over lake water (i.e., inlet type "overflow"); Ford (1990); ii) the reservoir is a shallow environment (average depth: 12 m) and reasonably exposed to wind action (fetch ca. 4.5 km); iii) the water outlet is 15 m above the elevation of the base of the dam; iv) determinations of vertical thermal profiles carried out in the reservoir (this study) indicated that the occurrence of thermal stratification is usually restricted to the lacustrine region, close to the dam; v) usually hypolimnion occurs at high depths (below 8-10 m).

$$\alpha = Q/V + k \quad (1)$$

$$C = W/\alpha V \left(1 - e^{-\alpha t}\right) \quad (2)$$

where: α = assimilation factor (d^{-1}) (Σ sink); k = first order reaction rate constant (d^{-1});
Q/V = hydraulic flushing (HF) (d^{-1}); Q = flow rate (average value on a monthly basis);
V = volume of the reservoir; C = steady state concentration (i.e., related to the dam area – outlet concentrations); W = the loading term (kg d^{-1}) (i.e., the daily load of substance, referring to the reservoir inlets); t = the time required to reach the equilibrium concentration.

The study used three basic assumptions: (i) the reservoir can be represented by a zero-dimensional model (i.e., Continuous Stirred Tank Reactor; CSTR); (ii) the reservoir is in a steady state (for any month, the initial and final values are constant), necessarily generating a "step" loading function (Jørgensen & Fath, 2010), the step input is essentially an "on-off" function that has a jump discontinuity at t = 0 (Chapra, 2008); (iii) the hydraulic retention time is long enough for the reservoir to reach equilibrium.

The selected model (Equations 1 and 2) assumes that the reservoir is in a stable phase (Cunha-Santino et al., 2017) and the limnological variable values downstream derive from the initial concentrations, except for the quantities of elements that were trapped (or released) in the reservoir (Teodoru & Wehrli, 2005) during the HRT period. The assimilation factor (α) obtained from the parameterization indicate that there were losses (e.g., sedimentation, biological absorption, chemical reactions and adsorption) or gains of the elements in the reservoir compared to the initial concentrations (in this case, derived from the inputs of the Sorocaba River, upstream of the reservoir). If α is positive and higher than hydraulic flushing (HF), the value indicates that the element is retained in the reservoir; therefore the retention of the element is greater than the flushing. If α is equal to HF, the retention is null, the element is only carried by the flow of the reservoir. The negative value of alpha or α < HF indicate that the retention is null, and the reservoir is the source of element (e.g., internal loading process, lateral runoff, point source of the element) (Cunha-Santino et al., 2017).

The model parameterization was performed calculating the assimilation factor (i.e., EC, DO, pH, TP, TKN, N-NO_3, TS, Turb, and Chl-*a*) in each month of the study. For this reason, the following were used in Equation 2: (i) the values of each input variable (W on a daily basis); (ii) the monthly average flow of the reservoir; (iii) the monthly average retention time; (iv) the average volume for the month. By substituting the value of alpha by an iterative method (Generalized Reduced Gradient algorithm; Fylstra et al., 1998), the values of the calculated variables (C parameter; Equation 2) were the same as the values determined *in situ* (outlet). To choose the date of the output variable value, the hydraulic retention time criterion was used, i.e., the value of the variable on the day of entry into the head of the reservoir compared with the value for the same variable after the time of HRT, at the dam. For this purpose, the monthly output data of the variables were interpolated.

2.4. Statistical analysis

We drew up a box chart graphic using the software Origin 8 to examine the variability of retention factor among the different variables. The relationship between HRT and retention capability of the reservoir was assessed by performing simple linear regression for TP. Linear regression was performed using the Origin 8 software, which uses the least squares method. The choice of total phosphorus for this analysis was due to its importance for defining the trophic state of the reservoir (Zhou et al. 2016).

3. Results

The wet season occurred from January to March and the dry season was from April to June (Figure 2a). The inflow and outflow (Figure 2b) were high mainly between 2009 and 2010 when the accumulated rainfall was higher than 600 mm in the wet season increasing the reservoir volume and decreasing its HRT (Figure 2c).

The maximum EC value (115 µS/cm) was in the dry season (August/08) and a sharp decrease occurred in the summer (37 µS/cm in March/11) (Table 2). The maximum EC retention was 32% (HRT = 182 d). In general, the DO concentrations were low (< 5.0 mg/L) mainly in the wet months during 2007-2011 (Table 2). The lowest DO concentrations (< 2.0 mg/L) were in 2009 (October/09 and December/09). The pH values (Table 2) were typically low in the dry season. However, October and December/09 showed the lowest values (≈ 5.9). The highest value was 8.6 in September/09. The highest pH decrease was 19% (HRT = 186 d). The wT variation corresponded to the seasonal variation (Table 2). The highest wT was 29 °C (November/09) and the lowest was 16.3 °C (August/08).

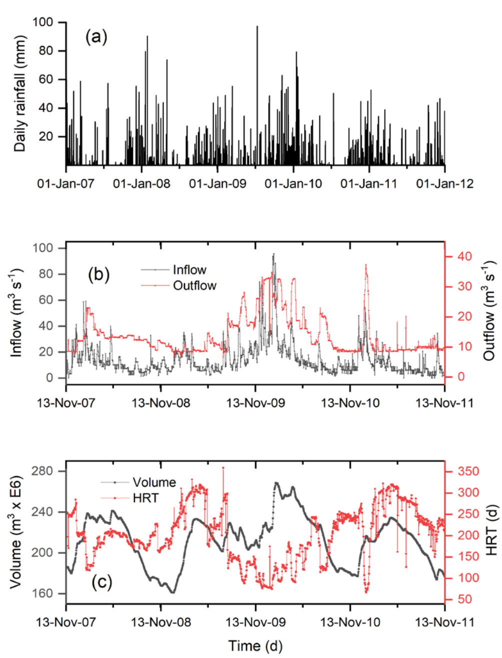

Figure 2. Daily rainfall in the dam area of Itupararanga Reservoir (a). Hydraulic characteristics of Itupararanga Reservoir: Flow data (b), and volume and Hydraulic Retention Time (HRT) (c); (Bottino, 2011; Casali, 2014; Votorantim Energia weather station: 23°36’43.35”S; 47°23’49.87”W).

The TS concentrations showed a low variation (Table 3). In the dry season of 2008, 2009 and 2010, the concentrations were high (80 to 104 mg/L). Turbidity (Table 3) was high in the wet months, and the maximum value (23 NTU) occurred in November/07. However, in August/08 and July/11 (dry season), the values increased (13 and 9.1 NTU, respectively). The maximum retention of TS and turbidity was 77% (HRT = 216 and 235 d, respectively).

The highest nutrient concentrations occurred in periods of high precipitation ranging from 74 to 80 µg/L for TP and up to 1.0 mg/L for TKN and maximum of 0.5 mg/L for $N\text{-}NO_3$ (Table 3). However, the wet season contributed to the increase of nutrient concentrations (from November to March). In September/09, the TKN concentration increased (1.13 mg/L). The Chl-*a* concentrations increased over time with the highest value (37 µg/L) in November/11 and the lowest values in November/09 (Table 3). The maximum retention was 74% for TP and 58.5% for TKN with HRT = 163 d and 126 d, respectively. For Chl-*a*, the maximum retention (49%) occurred when the HRT was lowest (99 d).

The alpha values showed the same pattern of temporal variation for EC, DO, pH, Turbidity and Chl-*a* (Figures 3 and 4). Regardless of seasonality,

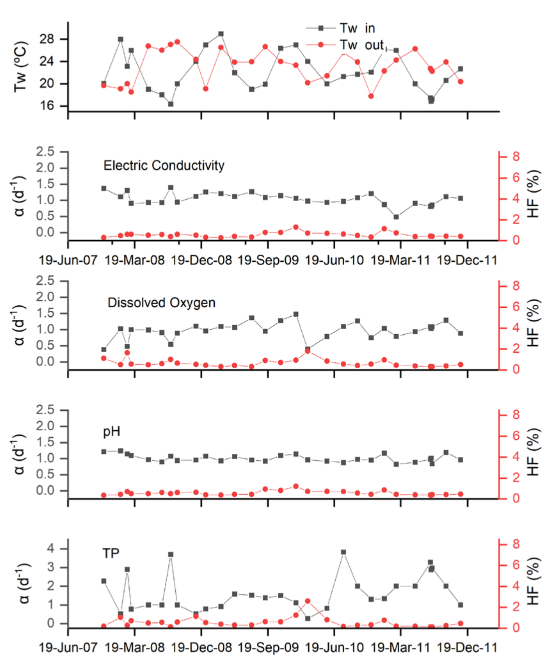

Figure 3. Water temperature changes in inlet and outlet sites of reservoir. Electric Conductivity, dissolved oxygen, pH, and Total Phosphorous (TP) retention parameters (α; black line and square), and hydraulic flows (HF; red line and circle) in terms of α percentage.

Table 2. Entry and exit times and respective values of electrical conductivity (EC), dissolved oxygen (DO), pH, water temperature (wT) and total phosphorus (TP) from the Itupararanga Reservoir.

Time (d)	Time+HRT	EC (µS/cm)		DO (mg/L)		pH		wT (ºC)		TP (µg/L)	
IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
13-11-07	05-07-08	101.0	73.7	3.0	7.8	8.1	6.6	20.1	19.7	75.7	33.3
22-01-08	26-07-08	82.0	73.9	8.0	7.8	8.3	6.7	28.0	19.1	20.0	38.9
18-02-08	23-06-08	96.0	73.5	3.8	7.8	7.6	6.6	23.1	20.0	87.1	30.1
05-03-08	02-09-08	73.0	80.6	8.0	8.0	7.7	7.0	26.0	18.5	20.0	25.7
15-05-08	05-12-08	74.0	79.1	7.7	7.8	6.7	6.9	19.0	26.8	20.0	20.0
10-07-08	06-01-09	77.0	82.8	7.7	8.5	6.6	7.4	18.0	26.0	20.0	20.0
15-08-08	13-02-09	115.0	82.5	4.3	8.0	7.7	7.1	16.3	27.1	73.9	20.0
11-09-08	01-03-09	78.0	82.2	6.9	7.7	6.6	7.0	20.0	27.5	20.0	20.0
27-11-08	12-05-09	88.0	78.4	8.4	7.6	7.4	7.7	24.0	24.4	20.0	38.1
06-01-09	29-08-09	84.0	66.8	7.8	8.2	7.9	7.4	27.0	19.1	30.0	38.5
10-03-09	01-01-10	78.0	64.5	8.2	7.5	7.2	7.7	29.0	26.5	20.0	22.0
05-05-09	07-12-09	74.0	66.1	7.2	6.8	7.4	7.0	22.0	23.9	40.0	25.3
14-07-09	04-03-10	76.0	59.8	8.2	6.0	7.0	7.3	19.0	23.9	30.0	19.8
08-09-09	02-01-10	70.0	64.5	7.1	7.5	7.1	7.7	19.9	26.7	30.0	21.8
11-11-09	02-03-10	69.0	60.0	7.8	6.1	8.0	7.3	26.4	24.0	30.0	20.0
12-01-10	25-03-10	61.0	57.4	7.7	5.2	8.2	7.2	27.0	23.3	20.0	18.0
02-03-10	21-07-10	62.0	63.4	3.4	8.6	7.1	7.4	24.0	20.2	20.0	73.6
20-05-10	18-10-10	64.0	68.3	6.3	8.0	6.5	7.1	20.0	21.4	20.0	24.5
27-07-10	06-01-11	66.0	68.2	8.3	7.6	6.8	7.8	21.3	25.6	80.0	20.9
23-09-10	26-03-11	74.0	68.6	9.1	7.2	6.8	7.0	21.7	23.9	30.0	15.0
18-11-10	15-07-11	75.0	62.1	6.9	9.2	7.3	7.6	22.1	17.8	20.0	15.5
11-01-11	20-04-11	61.0	70.2	7.7	7.4	8.2	7.0	26.2	22.3	20.0	15.0
01-03-11	03-12-11	37.0	75.9	5.8	7.3	7.0	8.5	26.0	24.3	20.0	10.0
18-05-11	25-02-12	70.0	77.4	6.6	7.1	6.8	7.7	20.0	26.3	20.0	10.0
20-07-11	28-04-12	63.0	77.5	7.7	7.1	7.1	7.3	17.5	22.8	32.8	10.0
23-07-11	01-05-12	63.6	77.6	7.4	7.2	7.5	7.3	16.9	22.5	28.7	10.0
27-07-11	05-05-12	66.5	77.6	7.9	7.2	6.2	7.4	17.2	22.3	29.7	10.0
22-09-11	12-04-12	85.8	77.2	8.8	6.8	8.6	7.2	20.6	23.9	20.0	10.0
21-11-11	01-07-12	81.9	77.1	7.3	8.3	7.2	7.5	22.7	20.4	10.0	10.0
Mininum		**37.0**	**57.4**	**3.0**	**5.2**	**6.2**	**6.6**	**16.3**	**17.8**	**10.0**	**10.0**
Average		**74.7**	**72.0**	**7.1**	**7.5**	**7.3**	**7.3**	**22.1**	**23.1**	**31.3**	**22.3**
Maximum		**115.0**	**82.8**	**9.1**	**9.2**	**8.6**	**8.5**	**29.0**	**27.5**	**87.1**	**73.6**

Table 3. Entry and exit times and respective values of total Kjeldhal nitrogen (TKN), nitrate (nitrogen basis; N-NO_3), total solids (TS), turbidity (Turb) and chlorophyll-*a* (Chl-$_a$) from the Itupararanga Reservoir.

Time (d)	Time+HRT	TKN (mg/L)		N-NO_3 (mg/L)		TS (mg/L)		Turb (NTU)		Chl-*a* (µg/L)	
IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
13-11-07	05-07-08	1.01	0.57	0.03	0.20	100.0	57.0	22.8	5.3	3.4	7.8
22-01-08	26-07-08	0.50	0.60	0.20	0.20	49.0	57.0	4.2	5.1		7.7
18-02-08	23-06-08	1.34	0.56	0.20	0.20	84.0	57.0	11.7	5.5	5.4	7.8
05-03-08	02-09-08	0.68	0.54	0.20	0.15	67.0	56.4	4.1	4.9	17.1	7.0
15-05-08	05-12-08	0.50	0.50	0.20	0.20	64.0	59.3	4.0	4.5	14.4	7.7
10-07-08	06-01-09	0.59	0.50	0.20	0.20	61.0	57.1	4.0	5.0	13.0	6.6
15-08-08	13-02-09	0.87	0.58	0.55	0.20	80.0	61.2	12.6	4.3	5.0	6.5
11-09-08	01-03-09	0.53	0.62	0.20	0.20	65.0	63.1	4.0	4.0	11.5	6.4
27-11-08	12-05-09	0.50	0.64	0.20	0.20	65.0	55.0	5.0	5.3	15.0	21.2
06-01-09	29-08-09	0.50	0.94	0.20	0.30	62.0	58.5	4.8	5.3	9.7	9.6
10-03-09	01-01-10	0.74	0.50	0.20	0.43	75.0	39.3	5.8	3.1	11.8	7.3
05-05-09	07-12-09	0.53	0.50	0.20	0.80	56.0	12.8	3.6	4.9	20.7	14.5
14-07-09	04-03-10	0.50	0.95	0.20	0.21	86.0	53.5	3.6	5.0	15.2	9.8
08-09-09	02-01-10	1.13	0.50	0.20	0.41	80.0	40.8	5.9	3.0	8.0	6.9
11-11-09	02-03-10	0.50	0.96	0.20	0.20	66.0	54.0	4.1	5.0	1.2	9.6
12-01-10	25-03-10	0.50	0.85	0.20	0.28	66.0	48.4	5.0	5.1	14.3	12.2
02-03-10	21-07-10	0.84	0.55	0.20	0.23	64.0	67.8	4.2	7.3	8.9	20.2
20-05-10	18-10-10	0.50	0.66	0.20	0.20	80.0	67.5	3.2	5.5	16.0	15.7
27-07-10	06-01-11	0.50	0.91	0.20	0.20	104.0	72.9	3.5	7.0	22.6	22.7

Table 3. Continued...

Time (d)	Time+HRT	TKN (mg/L)		$N\text{-}NO_3$ (mg/L)		TS (mg/L)		Turb (NTU)		Chl-*a* (µg/L)	
IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
23-09-10	26-03-11	0.57	0.70	0.20	0.20	94.0	58.1	5.0	5.3	14.9	17.7
18-11-10	15-07-11	0.92	0.14	0.20	0.51	42.0	51.7	5.9	11.3	21.7	36.9
11-01-11	20-04-11	0.63	0.60	0.20	0.20	64.0	56.2	5.8	5.5	27.1	16.5
01-03-11	03-12-11	0.76	0.91	0.20	0.20	64.0	80.8	5.4	6.3		22.6
18-05-11	25-02-12	0.50	0.77	0.20	0.20	56.0	57.4	5.6	6.6	10.4	19.6
20-07-11	28-04-12	0.12	0.64	0.54	0.20		53.0	9.3	4.0		14.6
23-07-11	01-05-12	0.10	0.64	0.55	0.20		53.3	9.7	3.8	9.9	14.4
27-07-11	05-05-12	0.16	0.64	0.55	0.20		53.6	9.7	3.6	9.7	14.1
22-09-11	12-04-12	0.72	0.66	0.20	0.20	50.0	51.7	5.2	4.7		15.9
21-11-11	01-07-12	0.85	0.80	0.20	0.20	80.0	74.8	5.1	3.9	24.7	14.4
Mininum		**0.10**	**0.14**	**0.03**	**0.15**	**42.0**	**12.8**	**3.2**	**3.0**	**1.2**	**6.4**
Average		**0.62**	**0.65**	**0.24**	**0.25**	**70.2**	**56.2**	**6.3**	**5.2**	**13.3**	**13.6**
Maximum		**1.34**	**0.96**	**0.55**	**0.80**	**104.0**	**80.8**	**22.8**	**11.3**	**27.1**	**36.9**

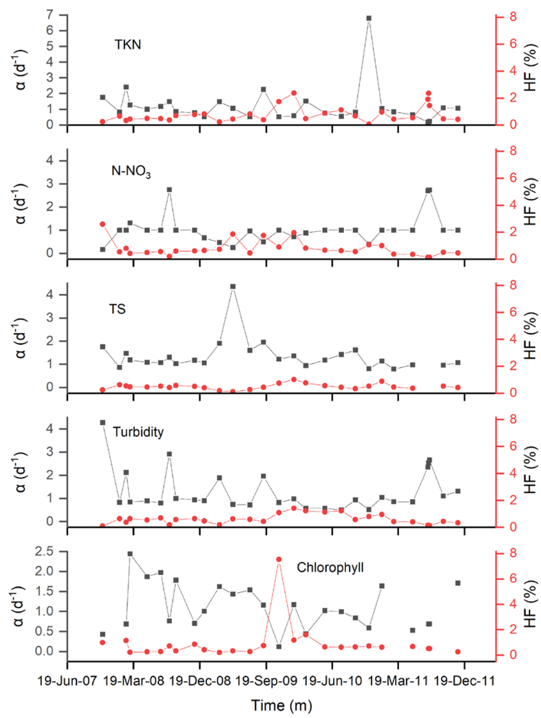

Figure 4. Total Kjeldhal nitrogen (TKN), nitrate (in N basis; $N\text{-}NO_3$), total solids (TS), turbidity, and chlorophyll-*a* retention parameters (α; black line and square), and hydraulic flows (HF; red line and circle) in terms of α percentage.

the highest values of parameterized alpha occurred in wet months (from 90 mm to 504 mm) for all variables. Nutrients (TP, NKT and $N\text{-}NO_3$) showed the highest alpha values (3.82 d^{-1}, 6.8 d^{-1}, 3.67 d^{-1}). In December/09 (monthly precipitation: 260 mm), the HF values were high for EC and pH (1.41% and 1.64% of alpha). When the precipitation exceeded 500 mm (January/10), the HF showed the highest values for DO, TS and Turbidity corresponding to 4.06%, 1.02% and 1.14% of alpha values, respectively. However, the highest HF percentage was 7.5% for Chl-*a* in November/09 when the highest monthly precipitation occurred (319 mm).

The estimation of retention potential resulted in 273 values of alpha parameter for 9 water variables and there were no negative values (Figure 5a). Nutrients, mainly TP and TKN showed the highest variation in the study period. Turbidity and chlorophyll *a* concentration also showed high data dispersion, while EC, DO, and pH had low variability. Taking into account that $\alpha = HF + k$ (Equation 1), the comparison of the composition of the alpha values indicated that the reaction rate constants (k) were much higher than the hydraulic flushing values, pointing out that for the conditions of the Itupararanga Reservoir (small reservoir with high HRT), the sink processes prevailed over the exportations. According to the results (Figures 4 and 5), the percent contributions of HF to the alpha values were low (less than 2%) for CE, pH, TS and turbidity. For DO and nutrients, the HF contribution was higher than 2% and for chlorophyll a, it was 7.53%. Overall, the TP retention capability of this reservoir did not show a substantial rise with HRT increase (Figure 5b). However, increasing flow makes HF assume more relevance (Figure 5c) in the retention capability due to the decrease of the reaction rate constant (k) to offset the assimilation factor (α).

4. Discussion

Damming a river change both water flow and the transport of materials, by altering settling or mineralization/immobilization patterns in the system (Kumwimba et al., 2022). The potential of retention and recycling by lentic ecosystems manifests itself across different spatial scales (Cheng & Basu, 2017). Our results demonstrated

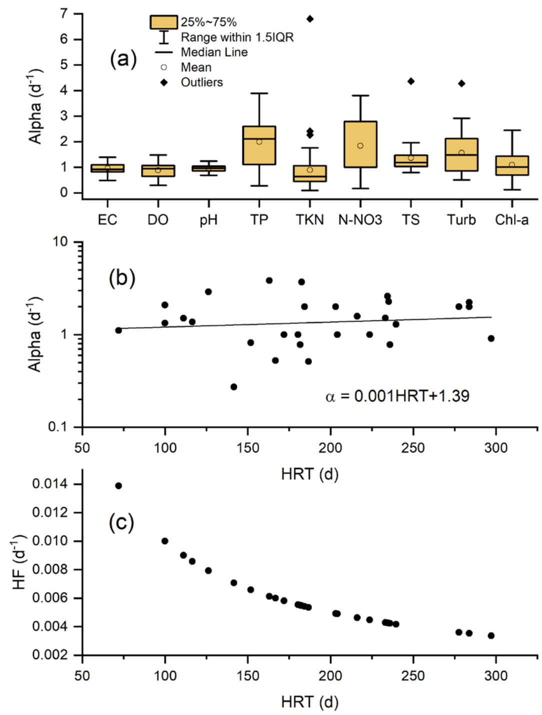

Figure 5. Alfa values for different water variables (a). Relationships between hydraulic retention time (HRT)of the Itupararanga Reservoir, and the retention capability (α) for total phosphorus (b), hydraulic flows (HF) (c).

that substances sink from inlet to outlet, despite seasonality, the high HRT of the system (in general > 120 days during the study period), a large drainage area, and a low variation of water level. The maintenance of similarity in the inflow and outflow even during low rainfall periods supports high HRT, which is the key factor controlling the mass balance in man-made reservoirs.

Retention time is the main factor related to the trapping of elements in reservoirs as it underpins the settling and biological processes that drive the nutrient loss, toxicity of sediments and the increase in phytoplankton (Kawara et al., 1998; Kõiv et al., 2011; Hansen et al., 2016). Many studies report the role of the reservoirs as retention basins that contribute to decreases of up to 70% of sediment flux (Dai et al., 2009), nearly 90% of suspended solids (Némery et al., 2016), approximately 12% of the global phosphorus loading (Maavara et al., 2015) and about 47% of nitrate (Cheng & Basu, 2017). Thus, HRT regulates the boundary of the role of a reservoir as a sink or source of compounds controlling the main ecological processes occurring within the system (Pacheco et al., 2015).

Modeling of the biogeochemistry characteristics of reservoirs, including the mass balances, is a valuable tool for water management, especially in the tropics where eutrophication is a major concern (Bartoszek & Koszelnik, 2016; Némery et al., 2016). By using 9 water variables, we observed in general decreased outlet concentrations in relation to the inlet conditions despite seasonality effects, except for DO. This reduction is an expected pattern for long-established reservoirs as the low variation of hydraulic characteristics (i.e. water level, drainage flow) allows the internal processing of the elements (Gonzaga et al., 2007; Araújo et al., 2011).

The high values of assimilation factor (α) indicated a high capacity of retention which is related to the high values of the reaction coefficient (k) that, in turn, depends on the HRT. High HRT decreases the HF supporting the reactions of mineralization or immobilization over time, hence contributing to the internal processing of elements, mainly in the hypolimnion, or in the sediments that may be a reactive fraction in many tropical reservoirs. In small reservoirs (low area:volume ratio), the reaction coefficient is inversely proportional to the hydraulic residence time. Inverse relationships were also observed between k and the surface area and depth of the water bodies, alluding to the strong size control on the reactivity of a water body (Cheng & Basu, 2017). As reservoir management flow tends to follow the pattern of precipitation, the hydrological conditions may be important to predict the retention. Therefore, changes in the rainfall regime influence the flushing of elements downstream. However, for the Itupararanga Reservoir, this relationship was not clear considering the increase in the precipitation in the dry season (from 235 to 661 mm) that generated HRT similar to the wet period but showed minor importance to the exportation of pollutants.

The model parameterization indicated a weak positive relationship of HRT and the assimilation factor, pointing out that, under current hydraulic conditions, the trapping of elements is prevalent. However, the HRT reduction (owing to the higher intensities and duration of rainfall) can contribute to the rise of internal loading (by changing the thermal stratification regime), which may increase the eutrophication due to the increase in water input derived from a cultured drainage area. It is widely known that dams affect the sediment transport and water transparency, and our results showed a similar pattern for retention of solids and turbidity (> 70%). Total phosphorus also showed retention up to 70%. Phosphorus is the main nutrient causing concerns for freshwater management and our results suggest that the outflow is a good predictor of retention capability of TP. For relatively constant volume, decreasing or increasing the outflow favors and disfavors, respectively, the assimilation factor. However, for intermediate values of outflow (≈ 9 – 20 $m^3 s^{-1}$), the retention capability is high because HRT remains high.

Phosphorus retention in reservoirs increases the reactivity of sediments in these ecosystems contributing to P internal loading in the long term, responsible for algal and cyanobacterial blooms and eutrophication (Harper, 1982; Cooke et al., 1993; Horne & Goldman, 1994; Vo et al., 2014; Qin et al., 2020). The model parameterization indicated that across the spatial scale from the headwater to the dam, the phosphorus trapping on the sediment increases due to the rising of oxidant conditions and neutral pH. These results have important implications for water quality and eutrophication control. However, when we consider this reservoir, there is an increase in cyanobacterial blooms (https://cetesb.sp.gov.br/aguas-interiores/publicacoes-e-relatorios/) even with low phosphorus concentration in the water column. Therefore, phosphorus trapping alone did not prevent phytoplankton growth, which is possibly influenced by transport of phytoplankton from tributary rivers, and nitrogen limitation (Beghelli et al., 2016).

Thermal stratification plays an important role in retention capability of reservoirs as part of the elements are trapped in the hypolimnion while the epilimnion remains element-poor due to uptake and metabolism by organisms, especially algae and cyanobacteria, in that part of the water column (Némery et al., 2016). This is especially important in warm monomictic systems (Hutchinson & Löffler, 1956), with progressive stratification over the year such as what frequently occurs in the tropics. These characteristics (i.e., effective retention of phosphorus, TS, turbidity and chlorophyll *a*) are relevant in a reservoir with catchment flow ranging from 2.1 to 6.5 m^3/s, qualifying this environment as a reliable source of water for supply, and reducing costs of treatment, mainly if the water catchment is derived from the epilimnion. In addition, the water quality improvement promotes the multiple uses of the reservoirs (irrigation, fishing, leisure). However, the monitoring of water inflow and outflow are important to an efficient management plan, considering that changes in the HRT could influence in the mass balance in the ecosystem.

Monitoring water flux is essential to support strategies for water management mainly in the tropics (Fowe et al., 2015). In this context, it is important to highlight that, by exclusively using input and output data, the calculations of the assimilation coefficients include characteristics of the elements circulation, regardless of the occurrence of thermal stratification of the aquatic environment. Thus, for example, in the case of phosphorus, occurrences of internal loading result in a decrease in the alpha value (i.e., lower retention capacity) or, in the case of predominance of this event, in negative values (i.e., the aquatic system is a source of phosphorus, resulting in higher outlet concentrations than inlet concentrations). On the other hand, if phosphorus is incorporated into the biomass (e.g., primary production), trapped in the hypolimnion or in the sedimentary surface of the environment with full circulation of the water column, the alpha value increases. A relevant difficulty factor in the application of this model is to define the period required for the longitudinal transport of the elements; in this case, the presence of thermal stratification may interfere with the calculation of the HRT. Specifically for the Itupararanga Reservoir, although the presence of the hypolimnion is frequent, its volume is very small in relation to the volumes of the epilimnion and metalimnion (Ryan & Harleman, 1971), not interfering substantially in the HRT calculation.

Changes in rainfall pattern would cause changes in HRT. In a land use change scenario, the input of pollutants will also increase due to the high runoff leading to the HRT decreasing, and consequently influencing the retention capability. The increase in rainfall events with high magnitude are a consequence of the human activities and may dramatically alter water quality. Changes in land use are one of the key factors affecting ecosystem services and human welfare due to its influence on the water quality (Costanza et al., 1997). In this context, the efficiency of retention capability of an aquatic ecosystem is closely connected with the current distribution of land use (Prokopová et al., 2019).

Reservoirs with low area:volume ratio and high HRT act as sink systems, producing a gradient of water quality improvement from headwater to the dam (Thornton, 1990; Straškraba, 1999). Thus, due to the strong prevalence of chemical and biochemical reactions (e.g., phytoplankton and macrophyte growths) over the hydraulic flow in the Itupararanga reservoir, in the scenario of increased temperature and maintenance of current flows, the retention of elements may be even more accentuated because the reaction rates are sensitive to the temperature variation (Jørgensen & Fath, 2010). In this situation, the longitudinal gradient of the concentrations should be more evident than those usually observed (UFSCar, 2008). However, in a scenario of increasing rainfall, the HRT can become more similar in the wet and dry seasons and the retentive capacity of an aquatic ecosystem may present some alterations (owing to the change in the thermal regime and the increase in internal loading), and the exportation of reactive elements would impact downstream environments, and their ecosystem services. Considering the changes in the water temperature and the shorter time of persistence of thermal stratification (i.e., increase in the period of complete circulation of the water column) owing to the increase in the flow rates, the toxic conditions prevalent in the hypolimnion may be exposed for a longer time. This could cause nutrient enrichment in the epilimnion, resulting in an increase in eutrophication, and leading to a decrease in the multiple uses of the reservoirs and changes in energy flows and trophic chains in the aquatic system. Finally, water intake from the bottom of the reservoir would damage the rivers downstream.

5. Conclusions

In the Itupararanga Reservoir, hydraulic characteristics determined a high capacity for the retention of elements, as demonstrated by the high reaction assimilation coefficient (α), due to high-rate constants (k), and low hydraulic flushing. Except for DO concentrations, all the selected values decreased from the inlet to the outlet. Seasonality was of minor importance to trapping elements, but retention capability is related to HRT, which is in turn linked to the hydrological, morphological, and biological characteristics of the ecosystem. However, the similarity of HRT during the wet and dry season indicated that hydraulic characteristics, such as low area:volume ratio were relevant for retention capability. In the tropics, small reservoirs with high HRT (> 120 days) can be used to retain elements considering the provisioning service (e.g., water supply). However, the sediment conditions must be recognized as an important source of pollutants if thermal stratification persists or if the oxidant conditions change, for example. Understanding the hydraulic characteristics of man-made reservoirs can help to provide informed management tools for these ecosystems that could improve the management of issues, such as phosphorus loading and eutrophication.

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