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A comprehensive reservoir segmentation for hydrodynamics and water quality assessment

Segmentação de reservatórios para hidrodinâmica e avaliação da qualidade da água

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ABSTRACT

Reservoirs present different and intrinsic characteristics from the point of view of physical, chemical, and biological nature from other environmental systems. They therefore should be characterized differently for a better representation aiming for proper planning and management strategies. This paper analyzes eleven reservoirs and develops a classification and zonation strategy for those systems. First, temporal variation and statistical analysis are performed, followed by a residence time calculation, to assess the reservoir's dynamics. Next, stratification and spatial variation analysis are proposed to verify their necessity. Three of the reservoirs analyzed behave as lentic systems, with a high residence time. In addition, all three have significant tributaries, indicating the potential necessity of considering spatial variation for their classification, later verified in 3D modeling. Even if every reservoir is unique in its dynamics and characteristics, the classification scheme is suitable for different types of reservoirs, since it works like a decision tree, where input loads and hydrodynamics are considered.

Keywords: Reservoir classification; Residence time; Reservoir dynamics; Zonation.

RESUMO

Os reservatórios apresentam características diferentes e intrínsecas, do ponto de vista da natureza física, química e biológica, em relação a outros sistemas ambientais. Portanto, eles devem ser caracterizados de forma diferente para uma melhor representação, visando a estratégias adequadas de planejamento e gerenciamento. Este artigo analisou onze reservatórios e desenvolveu uma estratégia de classificação e zoneamento para esses sistemas. Primeiro, são realizadas análises estatísticas e de variação temporal, seguidas de um cálculo do tempo de residência, para avaliar a dinâmica do reservatório. Em seguida, são propostas análises de estratificação e variação espacial para verificar a necessidade de zoneamento. Três dos reservatórios analisados se comportam como sistemas lênticos, com alto tempo de residência. Além disso, todos os três têm afluentes significativos, indicando a necessidade potencial de considerar a variação espacial para sua classificação, posteriormente verificada na modelagem 3D. Mesmo que cada reservatório seja único em sua dinâmica e características, o esquema de classificação é adequado para diferentes tipos de reservatórios, pois funciona como uma árvore de decisão, em que as cargas de entrada e a hidrodinâmica são consideradas.

Palavras-chave: Classificação de reservatórios; Tempo de residência; Dinâmica de reservatórios; Zoneamento.

INTRODUCTION

Studies of river system classification usually associate an input (L, annual average, mass per time per segment) to a segment of a river, from point and diffuse sources, calculated through geoprocessing models or monitoring databases (Calmon et al., 2016). This input is associated with the reference flow rate (Q, volume per time) and the concentration C is calculated as $C = L/Q$ (mass per volume). This concentration is compared to the concentration limits for water quality assessments (Pessôa et al., 2015). In the diagnosis phase, values from measurements or modeling in the current system state are used; in the prognosis phase, expected variations in the basin are included, and in the planning phase, adaptation actions are considered (Petriki et al., 2017).

The same principle is used for reservoirs and they are considered as a simple section. However, several studies show that reservoirs follow different processes compared to other environmental systems (Shivers et al., 2018; Hayes et al., 2017; Irz et al., 2006), particularly rivers, as they are accumulation systems with different substance kinetics.

Reservoir zonation is observed not only through concentrations of water quality parameters but also by biological aspects. Santos et al. (2010) found spatial and temporal variations in the Funil reservoir (Paraíba do Sul River, in Rio de Janeiro, Brazil) considering the number of fish species.

In cases where many parameters measured over long periods are available, it is possible to define reservoir compartments with distinct characteristics and thus distinct water quality (Pompêo et al., 2015; Cardoso-Silva et al., 2014). A disadvantage of these classification and compartmentalization methods is the large requirement for measured data, both in space and time. Usually, for classification and regulation studies, not all these data are available. Instead, the classification diagnosis is even used to define monitoring strategies. Thus, mathematical models are used to complement the measurements and obtain enough information to classify and compartmentalize.

Another disadvantage of the methodologies presented is that the modeling is only valid for the reservoir studied, thus requiring a case-by-case analysis. To get around this limitation, there are initiatives to identify universal patterns in reservoirs, using databases with data from lakes and reservoirs around the world (Kirillin & Shatwell, 2016; Messager et al., 2016).

Even when using water quality indexes to classify these reservoirs, they are usually analyzed as a whole, regardless of the area they occupy. The most conventional lake classification is the one based on the trophic state used worldwide (Smaoune et al., 2021; Hoang et al., 2017). Nojavan et al. (2019) proposed an updated lake trophic classification model that is multi-variable, continuous, and classifies lakes in probabilistic terms, but without considering the spatial distributions inside each reservoir. Also, in order to improve the TSI, claiming the need for a range of classification for each reservoir, Chen et al. (2021) presented the Trophic State Footprint Index (TFI) based on the relationship of the response index (Chlorophyll a) and the main cause index (e.g., total phosphorus, total nitrogen).

Different types of classification are found in the literature, depending on the region and the specific interests related to each lake. Gądek et al. (2019) classified Tatra Mountain lakes (border between Slovakia and Poland) regarding the duration of the ice cover. Other classification schemes already proposed are about fish habitat (Petriki et al., 2017; Sutela et al., 2016; Krogman & Miranda, 2015).

Not only fish but also invertebrates are used for lake and reservoir classification, like macroinvertebrates (Pan et al., 2014), benthic invertebrates (Ozoliņš et al., 2021). Tison-Rosebery et al. (2023) presented a diatom-based index developed for French lakes, developed with data from 93 lakes, to monitor lake eutrophication.

These studies are based on measurements of water quality parameters and general reservoir characteristics and suggest spatial and temporal compartmentalization for the characterization of reservoir susceptibility. Suppose those spatial and temporal variations are not considered within the assessment and management phase. In that case, results for the reservoir status and critical regions and periods might be misleading or even wrong. This article investigates the hypothesis that reservoir compartmentalization will improve the identification of critical areas and periods, and therefore the related investments to reduce associated problems. Reservoir compartmentalization, in theory, is nothing new, but often is only done for a few specific water quality monitoring parameters, and not, as proposed here, including hydrodynamic and morphological aspects, as well as catchment characteristics.

Most of the classification schemes mentioned above treat the reservoir as a simple single-response unit. Therefore, there is a lack of defining proper management options for the reservoir as a whole and there is a need to classify/categorize different reservoir regions with specific management aims. This classification is the main objective of this paper. The data used was based on monitoring data and complemented with modeling data.

MATERIAL AND METHODS

Study site

The Paranapanema River is an important axis for generating electricity in Brazil, with a cascade of reservoirs on its main river. Some of these structures generate electricity and help with public, agricultural, and industrial supply. Its basin covers about 106,500 km^2, with 4.7 million inhabitants, concentrating approximately 2.1% of Brazil's Gross Domestic Product - GDP (Agência Nacional de Águas, 2016). Recently, the reservoirs in this river basin have been the subject of a study aimed at classifying their water bodies (Agência Nacional de Águas, 2021).

The Paranapanema River has eleven hydropower plants in operation, which has transformed its original course into a succession of contiguous reservoirs. The plants are as follows: Jurumirim, Piraju, Paranapanema, Chavantes, Ourinhos, Salto Grande, Canoas II, Canoas I, Capivara, Taquaruçu, and Rosana (Figure 1). They are classified into two basic types, according to their characteristics and types of operation, directly influencing the water quality and the distribution of aquatic communities, including fish fauna, as:

a) Accumulation reservoirs: Usually they have greater depth and wide flooded areas and may present quite accentuated water level variations (altimetric quotas). The water in the reservoir

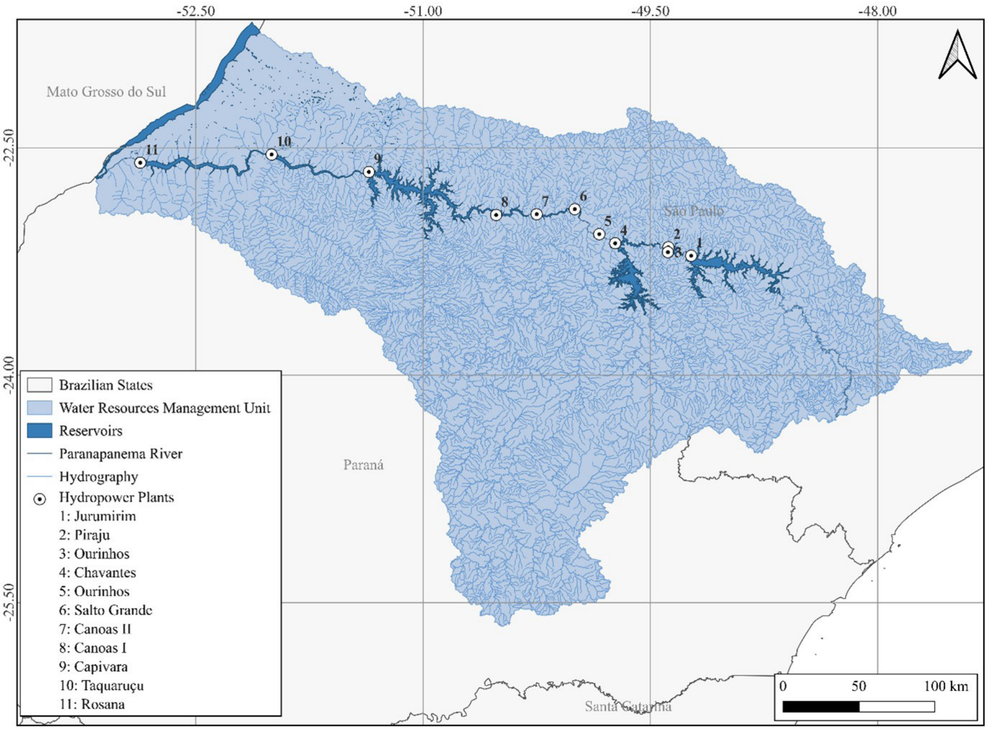

Figure 1. Location and reservoirs of the water resources management unit of Paranapanema River.

takes a long time to reach its complete renewal (possibly several months), in other words, a long residence time;

b) Run-of-river reservoirs: They may have higher to lower flooded areas and moderate depth, but the main characteristic is a low residence time (a few days or a few weeks until complete renewal).

The river system was differentiated from the lentic system following CONAMA Resolution nº 357 of 2005 (Brasil, 2005), which determines the lentic waters for residence times greater than 40 days. Residence time is defined as the average time it takes for the water to traverse the entire water body (1).

$$RT = \frac{Vol}{Q} \tag{1}$$

in which Vol is the reservoir volume (m^3), Q is the mean discharge (m^3/day) and RT is the residence time (days). The Paranapanema reservoirs' results are shown in Table 1 using annual averaged parameters.

The Jurumirim, Chavantes, and Capivara power plants belong to the accumulation category. They are lacustrine water bodies with a wide water surface and a dendritic shape. The others are run-of-river reservoirs. It has to be mentioned here already, that the resulting residence times are related to a full reservoir and mean annual discharge, thus may vary significantly over time.

Classification scheme

The analysis of the reservoirs followed the classification scheme illustrated in Figure 2, which could be applied to different systems. The proposed scheme consists of four main steps: as a first step, the reservoirs should be differentiated using residence time and thus dividing them between riverine environments (residence times smaller than 40 days) and reservoirs (residence times greater than 40 days).

In the second step, the temporal variation of the physical and chemical characteristics of the reservoirs should be analyzed using statistical analyses of the parameters involved (hydrological, geometric, water quality), to differentiate between dynamic and permanent systems, based on the coefficient of variation of the main parameters. For permanent systems, the temporal variations could be neglected, and the classification may be done using representative values (e. g., annual load, annual mean flow). For dynamic systems, a temporal variation analysis of the main parameters is recommended. In this step, it is also possible to identify the most critical parameter for water quality.

For a third step, the mixing regime (holomictic, meromictic, amictic, and no stratification) should be analyzed. Completely mixed reservoirs can be classified using simple strategies and do not need complex models. However, reservoirs that have stratification periods need more attention and the variation in the water column should be better analyzed, possibly including one-dimensional models.

As a fourth step, it should be determined whether the reservoir should be considered as a whole or whether the reservoir should be sectorized for classification and management purposes. This analysis can be done by data analysis or computational modeling to define if the horizontal variations in the water body could or not be neglected. In this case study, it was carried out using 3D modeling which was also compared with geostatistical clustering methods of the parameters involved.

Table 1. Water residence time for reservoirs in Paranapanema River Basin (Paraná and São Paulo states, Brazil).

Reservoir	Max. Normal level (m)	Area (km^2)	Volume (hm^3)	Q^1 (m^3/s)	Theoretical residence time (days)
Jurumirim	568.00	437.1	7011.21	223	364
Piraju	531.50	14.2	127.36	220	7
Chavantes	474.00	363.2	8873.84	347	296
Ourinhos	398.00	1.6	25.83	319	1
Salto Grande	384.67	5.8	53.02	459	1
Canoas II	366.00	19.9	159.00	471	4
Canoas I	351.00	27.0	223.27	489	5
Capivara	334.00	563.6	11746.33	1115	122
Taquaruçu	284.00	84.4	929.69	1175	9
Rosana	258.00	201.9	1996.24	1317	18

[1] Long-term mean annual discharge.

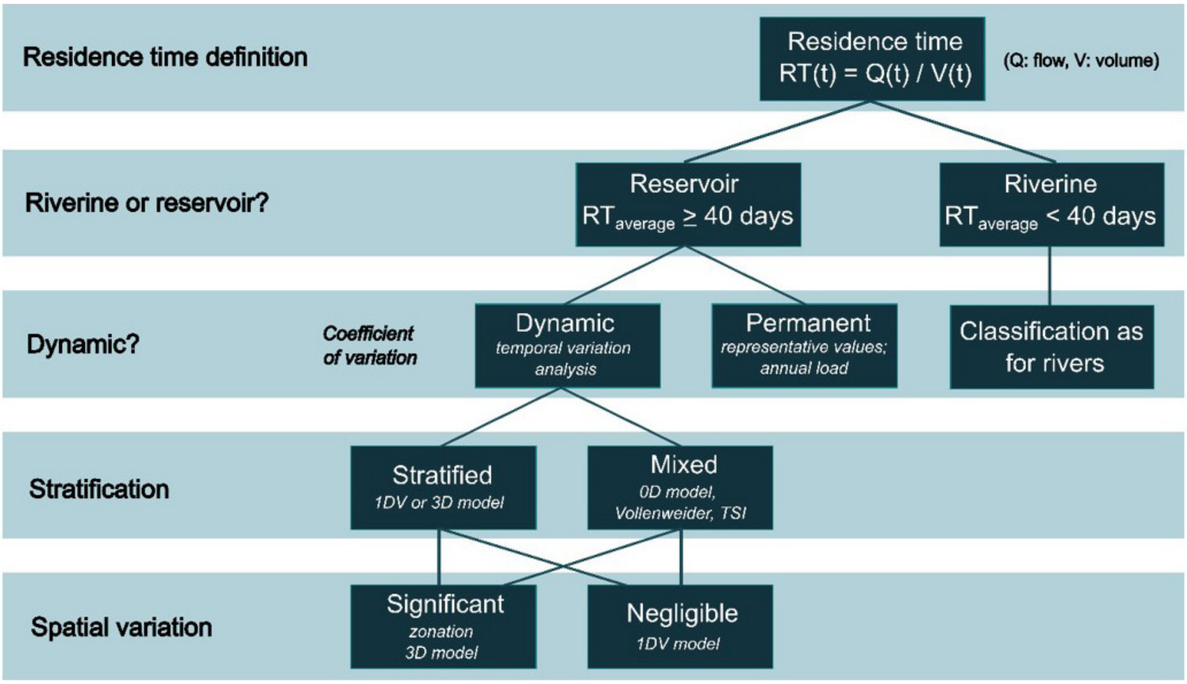

Figure 2. Reservoir classification scheme.

Analysis of reservoir dynamics

Data: temporal variation and statistical analysis

To understand the operation and hydrodynamics of reservoirs, it is essential to analyze the temporal and spatial variations that occur in them, as well as the environment in which they are inserted. Therefore, initially, these variations are analyzed in terms of inflow and outflow, water level, and reservoir volume (historical time series). The data used for this analysis were obtained from different sources, namely: HidroWeb (ANA), Department of Water and Electric Energy (DAEE), and Reservoir Monitoring System (SAR). Later the nutrient concentration was analyzed, based on historical time series from State Environmental Company of Sao Paulo (CETESB), as well as a complementary campaign in 2011 during the GIA project (Grupo Integrado de Aquicultura e Estudos Ambientais, 2013). The main statistical parameters analyzed were mean values, standard deviation (SD), amplitude, and coefficient of variation (CV), from 2005 to 2022 (period of available data in common for the 11 reservoirs). The parameters analyzed were: water flow, water level, reservoir volume, water temperature, dissolved oxygen (DO), biochemical oxygen demand (BOD) total phosphorus (TP), total nitrogen (TN), nitrate (NO_3), Ammonium (NH_4).

Residence time

The variation in water level and volume, as well as the variation in inflows and outflows, are directly correlated with the volume and water balance curve of each reservoir. Higher inflows than outflows increase the reservoir level, and vice versa. To better evaluate the consequence of all possible combinations of variables, characteristic parameters that combine the effect of volume variation with flow variation can be used. A widely used parameter is the fraction of volume by flow, resulting in a time magnitude, and called residence time. This is because the interpretation of the residence time (RT) is the average time it takes for a particle to cross the entire reservoir, which is the ratio between the volume and the flow of the water body (Bernardo, 2018).

However, this definition of residence time was made for permanent systems (Nauman, 2008), where inlet flow equals outlet flow, which does not necessarily apply to reservoirs with regulatory operations. For this purpose, for the three accumulation reservoirs the residence time series was calculated based on four proposed methods, listed in Equations 2 to 5:

$$RT_{in} = \frac{Vol}{Q_{in}} * \frac{1}{86400} \tag{2}$$

$$RT_{out} = \frac{Vol}{Q_{out}} * \frac{1}{86400} \tag{3}$$

$$RT_{dif} = \frac{Vol}{Q_{out} - Q_{in}} * \frac{1}{86400} \tag{4}$$

$$RT_{me} = \frac{2 * Vol}{Q_{in} + Q_{out}} * \frac{1}{86400} \tag{5}$$

Where:
- RT = residence time (days)
- Q_{in} = inflow discharge (m^3/s)
- Q_{out} = outflow discharge (m^3/s)
- Vol = reservoir total volume (m^3)

RT_{in} (Equation 2) is the conventional residence time, used in the literature (Nauman, 2008), and determines the time that the water needs, on average, to cross the reservoir, considering that the average flow in the reservoir is close to the inflow (often in flood periods). RT_{out} (Equation 3) is the residence time calculated with the outflow (turbines and spillway). This time corresponds best to the average path time of a particle passing the reservoir when it is mainly forced by the outflow (e.g., in a dry period).

The difference-based residence time (Equation 4) not only determines the time it takes for a particle to cross the entire reservoir but also indirectly indicates the rise and fall times of this particle in the water body. When its value is negative, there is a filling of the reservoir, while when positive, there is an emptying, so that the higher the magnitude of the residence time, the faster the particle travels vertically. Equation 5) is the residence time based on the average between Q_{in} and Q_{out}.

Extreme scenarios

Reservoirs can be of great importance in river systems, acting as regulators of water flow. To analyze that, a series of hydrodynamic and water quality modeling scenarios were proposed, with the aim of evaluating reservoirs in relation to their dynamics in the face of different conditions and forcings. These are called hypothetical scenarios, as they represent situations that combine characteristics of reservoirs (empty/full), tributaries (low/high flow), and loads (low/high) that have not necessarily already occurred. A summary of these scenarios is presented in Table 2. The meteorological data was gathered from the National Institute of Meteorology (INMET).

The model system MoRE (Modeling of Regionalized Emissions, Fuchs et al., 2017) was used to determine the input load of the scenarios, considering the point sources (wastewater, industrial discharges) and diffuse sources (land use, erosion) of the Paranapanema basin (Agência Nacional de Águas, 2020a). The modeling approaches of MoRE are grouped into emission pathways that are summed up: atmospheric deposition, erosion, surface runoff, drainage, groundwater, sewer systems, wastewater treatment plant, industrial direct drainage and abandoned mining. Complete information about the model can be found in Fuchs et al., 2017. In this scenarios, total phosphorus (TP), total nitrogen (TN), and biochemical oxygen demand (BOD) were considered.

Stratification analysis

Seasonal stratification is fundamental for all other processes that occur in the reservoir, physical, chemical, or biological (Boehrer & Schultze, 2008). It determines the transport of DO and nutrients in the water column as well as the light environment. Shallow lakes are more frequently mixed, having different behavior than deeper lakes that usually stratify during heating seasons, where a warmer layer is formed above the cooler and nutrient-rich deep layer (Kirillin & Shatwell, 2016). Therefore, the analysis of stratification of water bodies is one of the bases for reservoir classification.

For the Paranapanema case study, the stratification of the accumulation reservoirs was analyzed based on measurement data and simulations with a one-dimensional model, considering water temperature, DO, and TP profiles (Carvalho & Bleninger, 2021). The model used was the General Lake Model (GLM, Hipsey et al., 2019), the simulation was developed from 1980 to 2013, calibrated with measured data from 2011, and validated from 2012 to 2013. This model was chosen for an initial assessment

Table 2. Summary of the extreme scenarios proposed for reservoir simulations.

Scenarios	0 (Base)	1a	1b	2a	2b
Stratification	Yes	No	Yes	No	Yes
Inflow	Representative year	Strong	Strong	Historical Mean	Historical Mean
Water level	Representative year	Mean	Mean	Critical (drought)	Critical (drought)
Meteorological data	Representative year	Characteristic month of the mixed period	Characteristic month of the stratified period	Characteristic month of the mixed period	Characteristic month of the stratified period
Fish farming	Yes	Yes	Yes	Yes	Yes
Water quality	Yes	Yes	Yes	Yes	Yes

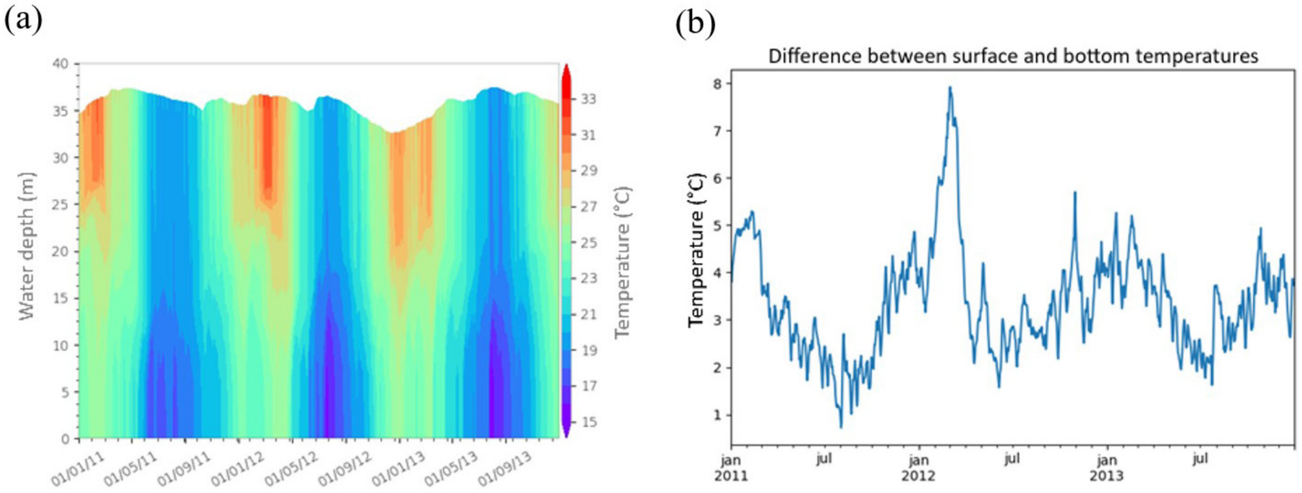

Figure 3. GLM results for the Jurumirim reservoir. (a) Development of the thermal profile and (b) temperature difference between surface and bottom, from 2011 to 2013. (Adapted from Agência Nacional de Águas, 2020b).

of reservoir stratification due to its low computational cost. The boundary conditions were time series of total inflow and water level for output. Meteorological time series were also included in the simulation.

The three lentic reservoirs showed some stratification during the summer, the peak appearing in January 2011 for the Jurumirim and Capivara reservoirs, and January 2012 for the Chavantes reservoir, with a difference between surface and bottom temperature of 7.8°C, 9°C and 14°C, respectively. The results of the periods of calibration and validation of the simulation for the Jurumirim reservoir are shown in Figure 3.

Spatial variation

In addition to temporal variations, reservoirs may have spatial variations in their characteristics. Unlike rivers, three zones are traditionally identified in reservoirs (Ji, 2008): the lotic/riverine zone, with higher speeds and characteristics similar to those of rivers; the lacustrine zone, represented by higher water column heights, lower velocities, and behavior similar to lakes; and the intermediate zone between the two. Therefore, an important question for the classification of these water bodies is: are the spatial variations in the concentration, transport, and mixing of substances significant in the reservoir?

To evaluate spatial variations and the need for reservoir zonation, hydrodynamic and water quality simulations were carried out using the Delft3D model (Deltares, 2014). Delft3D is a three-dimensional model widely used to solve problems related to reservoirs and thermal stratification (Soulignac et al., 2017; Wahl & Peeters, 2014; Smits et al., 2009) and water quality (Smits et al., 2009). The hydrodynamic module (Delft3D-Flow) simulates non-steady flows and transport due to meteorological forcing, including density effects. The water quality module (DELWAQ) allows the simulation of various substances, including nutrients, dissolved oxygen, micropollutants, and algae (Deltares, 2014).

For the Jurumirim reservoir, a model with a curvilinear grid was developed, with an average resolution of 150 x 200 m per cell, with approximately 19067 grid cells in the horizontal area and 10 vertical layers. The bathymetry of the reservoir is shown in Figure 4, together with the different tributaries considered in the model. The model was built with 9 boundary conditions, 8 of which were input conditions of tributary flow (Rio Paranapanema, Rio Santo Inácio, Rio Taquari, Ribeirão das Posses, Ribeirão da Jacutinga, Ribeirão São José do Pinhal, Ribeirão Bonito e Ribeirão do Macuco) and one output condition of level. Meteorological forces (wind, relative humidity, radiation, air temperature, cloud cover) were also considered. The reservoir was considered stratified in its initial condition (GLM results). The simulation was conducted for the representative year.

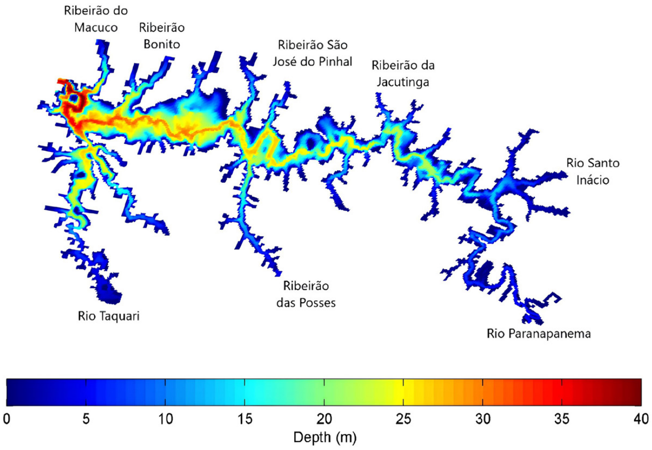

Figure 4. Bathymetry of the Jurumirim reservoir and the considered tributaries.

For zonation purposes, these results were used to test different zonation methods, described below.

a) **Morphological clustering zonation** is based on the hypothesis that distinct water quality regions are highly correlated with reservoir shapes, depths, and tributary locations. The different geometric/morphological parameters are then expected to correspond with different water quality regions. To test this hypothesis, different geometric and morphological combinations were analyzed and compared with the modeling results.

b) **The basin-based zonation** assumes that distinct water quality regions are highly correlated with the loads and flows of adjacent tributaries, enabling zoning based on these correlations. The reservoir branches near the larger basins and with higher loads are expected to have lower water quality compared to the other regions. To test this hypothesis, data from the basin and all subbasins were analyzed, ranked, and compared with modeling results.

c) **The hydrodynamic zonation** is proposed with the hypothesis that reservoirs have characteristic hydrodynamic regions. In these regions, we expect to observe distinct hydrodynamic conditions that prevail for significant periods. To test this hypothesis, velocity fields (intensity and direction) were analyzed. For these parameters, only simulation results were used since there are no measurements for the region.

d) **The water quality zonation** is based on the hypothesis that reservoirs have regions with different concentrations' patterns of water quality parameters. In these regions, we expect to observe distinct concentrations that prevail for significant periods. To test this hypothesis, concentration fields of the most critical parameter were analyzed using simulation results.

RESULTS AND DISCUSSION

Reservoir's dynamics

The historical series of discharge evaluated, even if short, have shown great variability, both inflow and outflow (Table 3, Table 4). This makes it interesting to consider at least high, medium, and low flows, to better understand the dynamics between hydrodynamics and water quality. At the decision level of 5%, all inflow time series seem to fit the normal statistical distribution (Figure 5).

The water level and volume time series are strongly linearly correlated, and their shape is always very similar. Both series seem to fit the normal statistical distribution, in addition to having low variability (Table 5 and Table 6). None of the reservoirs had a water level lower than the minimum necessary for its operation or the operation of the superficial spillway of the dams. The water level of Jurumirim, Chavantes, and Capivara reservoirs presents little variation, with a coefficient of variation below 1%. However, the standard deviation for these three reservoirs is greater than 1 m, while the others stay around 0.1 m. Unlike the water level, the volumes of the reservoirs have considerable variations. As shown by Pedrazzi et al. (2013), these temporal variations can also be reflected in zones inside the reservoir. Depending on its geometry, periods with higher or lower volumes can reveal different zones in terms of water quality. Given the importance of both parameters

Table 3. Basic statistics of the inflow time series, from 2005 to 2022, of the Paranapanema reservoirs.

Reservoir	Mean (m^3/s)	SD (m^3/s)	Minimum (m^3/s)	Maximum (m^3/s)	Median (m^3/s)	Amplitude (m^3/s)	CV (%)
Jurumirim	223.3	166.3	18.9	2060.6	172.0	2041.8	74%
Piraju	223.2	128.8	53.0	1226.0	193.0	1173.0	58%
Chavantes	345.4	225.1	76.9	4712.0	296.6	4635.1	65%
Ourinhos	335.3	223.6	76.5	2066.8	311.0	1990.2	67%
Salto Grande	460.7	272.9	114.7	3204.1	421.4	3089.4	59%
Canoas II	461.6	268.2	134.9	3061.6	418.0	2926.7	58%
Canoas I	497.5	286.9	139.0	3381.6	455.6	3242.6	58%
Capivara	1196.6	805.2	260.4	10960.1	998.5	10699.8	67%
Taquaruçu	1232.0	782.3	299.0	13438.0	1118.9	13139.0	63%
Rosana	1379.1	822.4	373.0	13897.0	1252.0	13524.0	60%

Table 4. Basic statistics of the outflow time series, from 2005 to 2022, of the Paranapanema reservoirs.

Reservoir	Mean (m^3/s)	SD (m^3/s)	Minimum (m^3/s)	Maximum (m^3/s)	Median (m^3/s)	Amplitude (m^3/s)	CV (%)
Jurumirim	225.4	131.3	59.0	1195.0	190.0	1136.0	58%
Piraju	223.2	128.9	53.0	1226.0	193.0	1173.0	58%
Chavantes	346.8	217.2	93.0	1993.0	329.0	1900.0	63%
Ourinhos	326.6	227.1	0.0	2069.0	304.9	2069.0	70%
Salto Grande	460.7	272.6	130.0	3176.0	421.0	3046.0	59%
Canoas II	460.6	267.5	134.0	3067.0	418.0	2933.0	58%
Canoas I	497.6	288.6	136.0	3415.0	452.0	3279.0	58%
Capivara	1201.7	761.9	282.0	13501.0	1102.0	13219.0	63%
Taquaruçu	1232.0	790.4	354.0	13647.0	1124.0	13293.0	64%
Rosana	1379.3	838.9	403.0	13482.0	1251.0	13079.0	61%

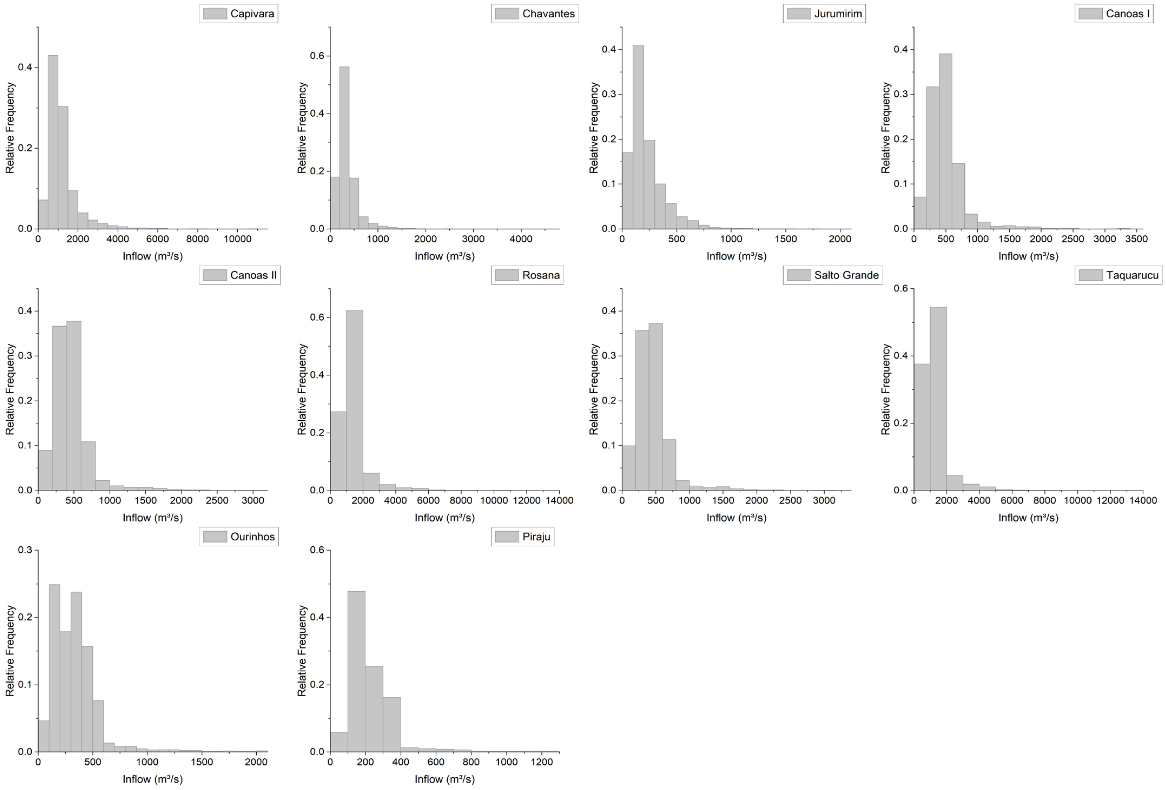

Figure 5. Histograms of the inflow time series, from 2005 to 2022, of the Paranapanema reservoirs.

Table 5. Basic statistics of the water level time series, from 2005 to 2022, of the Paranapanema reservoirs.

Reservoir	Mean (m)	SD (m)	Minimum (m)	Maximum (m)	Median (m)	Amplitude (m)	CV (%)
Jurumirim	564.9	1.8	560.9	567.8	565.5	6.9	0.3%
Piraju	531.5	0.1	531.3	532.1	531.5	0.8	0.0%
Chavantes	470.6	1.9	466.2	473.8	471.1	7.6	0.4%
Ourinhos	398.0	0.1	396.6	398.4	398.0	1.8	0.0%
Salto Grande	384.2	0.4	382.0	385.3	384.3	3.3	0.1%
Canoas II	365.9	0.1	365.6	366.3	366.0	0.7	0.0%
Canoas I	350.9	0.1	350.0	351.3	351.0	1.3	0.0%
Capivara	330.3	3.1	321.5	334.2	331.0	12.6	0.9%
Taquaruçu	283.6	0.1	282.7	284.2	283.6	1.4	0.0%
Rosana	257.7	0.1	256.6	258.1	257.7	1.5	0.1%

Table 6. Basic statistics of the volume time series, from 2005 to 2022, of the Paranapanema reservoirs.

Reservoir	Mean (m^3)	SD (m^3)	Minimum (m^3)	Maximum (m^3)	Median (m^3)	Amplitude (m^3)	CV (%)
Jurumirim	5690.8	720.8	4177.8	6926.0	5922.6	2748.2	13.0%
Piraju	125.6	1.1	122.6	133.9	125.5	11.3	1.0%
Chavantes	7597.3	685.1	6087.8	8794.8	7744.1	2706.9	9.0%
Ourinhos	24.5	0.3	19.3	25.8	24.4	6.5	1.0%
Salto Grande	47.7	4.1	24.7	62.1	48.5	37.3	9.0%
Canoas II	157.6	1.5	150.1	165.1	157.8	15.0	1.0%
Canoas I	220.6	3.9	195.5	230.9	221.0	35.4	2.0%
Capivara	9712.7	1635.7	5651.2	11851.0	9973.9	6199.8	17.0%
Taquaruçu	894.0	11.6	823.9	942.0	892.7	118.1	1.0%
Rosana	1940.3	28.4	1701.7	2026.1	1940.8	324.4	1.0%

within the models scenarios, it is interesting to create scenarios with reservoirs in at least three states: “full, normal, and empty”, to evaluate its influence on water quality.

Regarding concentration variations, Table 7, Table 8, and Table 9 present the contribution of TP, TN, and BOD loads, respectively, considering the Paranapanema River, Taquari River, other tributaries, and aquaculture inputs. According to Table 7, the Taquari River contributes 25% of the phosphorus load in the Jurumirim reservoir, while aquaculture contributes 8%. In the case of nitrogen, according to Table 8, the largest contribution comes from the Paranapanema River (40%) and from the Taquari River, 25%. The average annual load (kg/km^2/year) is lower than the estimated for agricultural watersheds (Li et al., 2015). In the case of BOD, the largest loads are from the Taquari River (47.2%) while the other affluents contribute 20.1% of the total load to the reservoir (Table 9).

In this case study, for all reservoirs, the phosphorus concentration was the critical parameter, originating from the basin loads and aquaculture. It was observed that Jurumirim, Chavantes, and Capivara reservoirs act as attenuators of inflows and forcings and that temporal variations do not need to be analyzed in detail for classification purposes.

The time series of the residence time were calculated for all reservoirs, from 2005 to 2022. Even though all the reservoirs showed large variations in residence time (Figure 6, Table 10), the only ones with an average of more than 40 days were Jurumirim, Chavantes and Capivara.

Run-of-river reservoirs have riverine characteristics and can be classified by the same approach as rivers since the hydrodynamics and water quality processes are different than lacustrine systems. Nine of the eleven Paranapanema reservoirs belong to this category, as shown in the previous analysis. Thus, the three accumulation reservoirs (Jurumirim, Chavantes, and Capivara) were analyzed in greater detail. Since the results for the three reservoirs were very similar, only the graphs for Jurumirim are shown. However, the statistics for the three reservoirs are presented.

Figure 7 presents the residence times for the Jurumirim reservoir from 2011 to 2022. Table 11 presents its basic statistics for RT_{in}, RT_{out}, and RT_{med}. The negative values in the RT_{dif} indicate that, for that time interval, the reservoir is filling.

Residence times present a great variability (CV) and amplitude of values, more pronounced in the Jurumirim reservoir, given its first position in the Paranapanema River cascade, which limits its operation capacity compared to the others. The residence time variability is between 40 to 65% around the mean (Table 11), which is considered significant and justifies the dynamic analysis of water quality in the accumulation reservoirs under these conditions. As shown by Rueda et al. (2006), this temporal variations occur

Table 7. The proportion of the TP load contributing to the Jurumirim reservoir in the Paranapanema River, Taquari River, other tributaries, and aquaculture.

Source	Mean inflow (m^3/s)	Area (km^2)	TP load (kg/day)	TP load (kg//km^2/year)	% of total load
Paranapanema river	125.45	10074.82	654.13	23.7	40%
Taquari river	56.48	4536.00	414.86	33.4	25%
Other tributaries	41.37	3322.49	440.55	48.4	27%
Aquaculture	–	-	122.94	-	8%
Total	–	17933.31	1632.48	-	100%

Table 8. The proportion of TN load that contributes to the Jurumirim reservoir in the Paranapanema River, Taquari River, other tributaries and aquaculture.

Source	Mean inflow (m^3/s)	Area (km^2)	TN load (kg/day)	TN load (kg//km^2/year)	% of total load
Paranapanema river	125.45	10074.82	8481.5	307.3	53%
Taquari river	56.48	4536.00	4275.03	344.0	27%
Other tributaries	41.37	3322.49	3012.39	330.9	19%
Aquaculture	–	-	292.87	-	2%
Total	–	17933.31	16061.79	-	100%

Table 9. The proportion of the BOD load contributing to the Jurumirim reservoir in the Paranapanema River, Taquari River, other tributaries, and aquaculture.

Source	Mean inflow (m^3/s)	Area (km^2)	DBO load (kg/day)	DBO load (kg/km^2/year)	% of total load
Paranapanema river	125.45	10074.82	19786.85	716.9	51%
Taquari river	56.48	4536.00	9573.4	770.3	25%
Other tributaries	41.37	3322.49	9293.5	1021.0	24%
Aquaculture	–	-	-	-	-
Total	–	17933.31	38653.75	-	100%

at seasonal and shorter scales, and the transport and mixing processes that occur inside the reservoir are closely related to it.

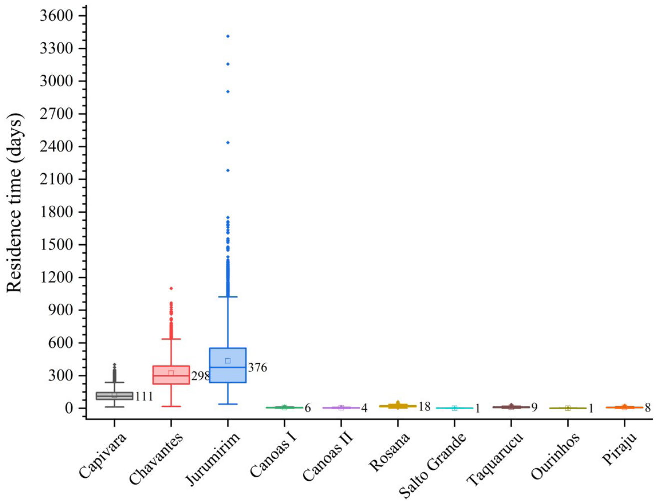

Figure 6. Boxplots of the residence time of the Paranapanema reservoirs (black numbers on the right side of the graphs are the median values).

After the time series analysis, 2012 was considered a representative year for the concentration and zonation analysis. Inflow variations (tributaries) are greater than reservoir variations, indicating that it is not very sensitive to temporal variations in inflow concentrations and acts as a buffer (Table 12). Furthermore, the differences between the base scenario and hypothetical scenarios were small. The base scenario is representative of the state of the reservoir.

Reservoir zonation

After analyzing the reservoir dynamics, it is important to evaluate the spatial variations and the necessity of a zonation for classification and management purposes. Four different types of zonation were analyzed, and at the end a proposal of the reservoir zonation guideline is presented, based on the results.

Hydrodynamic zonation analysis

The velocity fields for the Jurumirim reservoir in a mixed (a) and stratified (b) situation are shown in Figure 8. Results show regions with distinct velocities; however, the regions change at

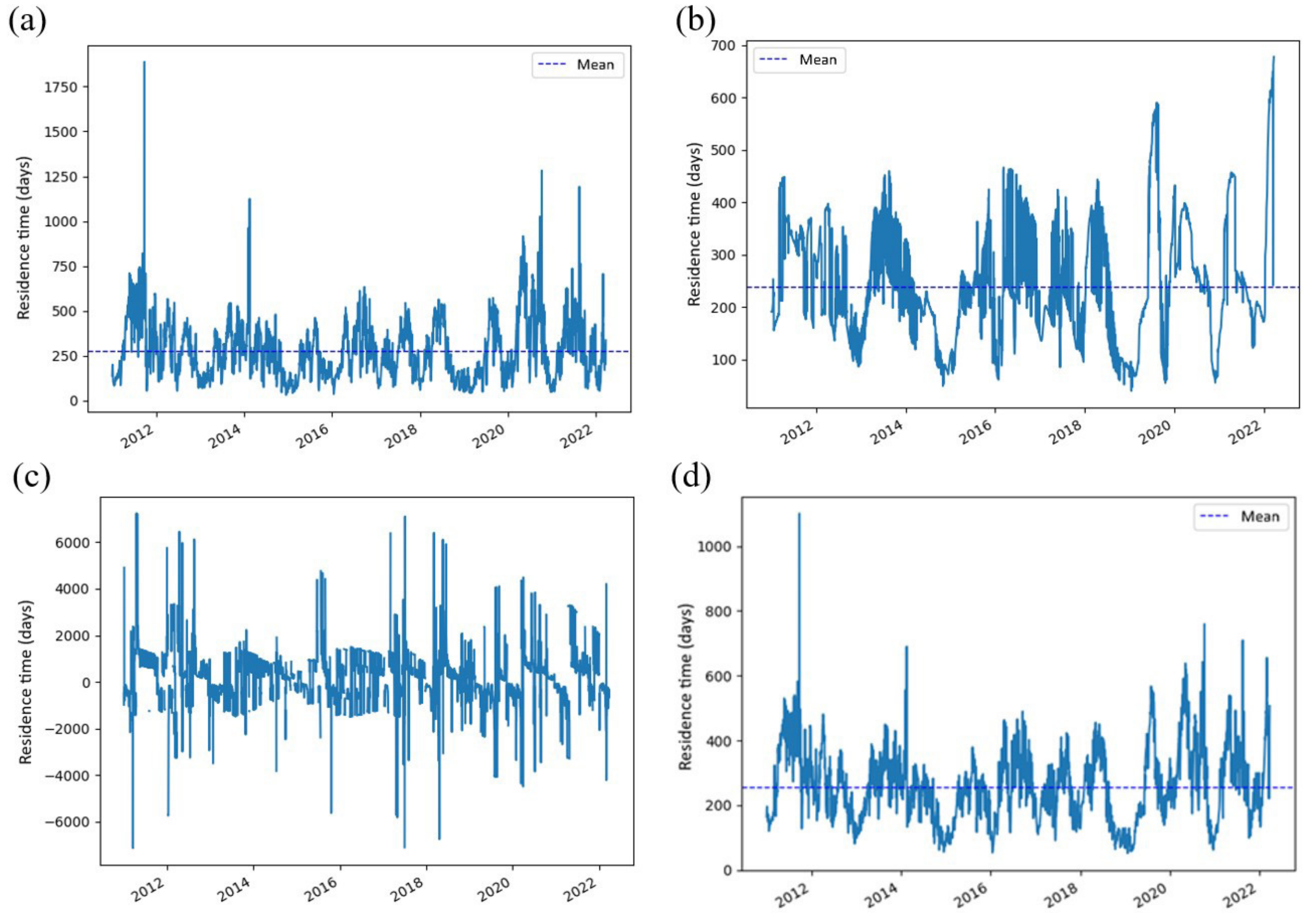

Figure 7. Time series of residence times at the Jurumirim reservoir. (a) TR_{in}, (b) TR_{out}, (c) TR_{dif}, and (d) TR_{me}.

Table 10. Basic statistics of the residence time, from 2005 to 2022, of the Paranapanema reservoirs.

Reservoir	Mean (days)	SD (days)	Minimum (days)	Maximum (days)	Median (days)	Amplitude (days)	CV (%)
Jurumirim	435	273	38	3413	376	3375	63%
Piraju	8	4	1	27	8	26	51%
Chavantes	323	147	18	1099	298	1081	45%
Ourinhos	1	1	0	4	1	4	61%
Salto Grande	2	1	0	5	1	4	53%
Canoas II	5	2	1	14	4	13	49%
Canoas I	6	3	1	18	6	18	50%
Capivara	119	54	12	402	111	391	45%
Taquaruçu	11	6	1	35	9	34	52%
Rosana	20	9	2	60	18	58	44%

Table 11. Basic statistics of the dynamic residence time series of the three lentic reservoirs, from 2005 to 2021.

	TRin (days)			TRout (days)			TRme (days)		
	Jur	Cha	Cap	Jur	Cha	Cap	Jur	Cha	Cap
Mean	435	8	323	360	343	117	363	321	113
SD	273	4	147	160	188	55	158	154	47
Min	38	1	18	66	50	10	53	33	11
Max	3413	27	1099	1000	894	385	1071	886	354
Median	376	8	298	337	277	102	333	278	105
CV	63%	51%	45%	45%	55%	47%	43%	48%	41%

Jur: Jurumirim; Cha: Chavantes; Cap: Capivara.

Table 12. Coefficients of variation and amplitude of water temperature, dissolved oxygen, total phosphorus, nitrate, and ammonium concentrations observed in the reservoirs and their intakes, for the year 2012.

		Jurumirim		Chavantes		Capivara	
		Amplitude	CV	Amplitude	CV	Amplitude	CV
Water temperature (°C)	Inflow	12.90	14%	13.40	15%	14.20	14%
	Reservoir	10.00	13%	3.80	6%	11.50	15%
Dissolved oxygen (mg/L)	Inflow	5.50	16%	4.70	13%	4.30	12%
	Reservoir	1.80	6%	0.60	3%	1.60	6%
Total phosphorus (mg/L)	Inflow	0.27	62%	0.55	77%	0.06	38%
	Reservoir	0.04	5%	0.03	5%	0.01	8%
Nitrate (mg/L)	Inflow	0.53	33%	0.79	42%	0.40	22%
	Reservoir	0.06	5%	0.11	27%	0.07	10%
Ammonium (mg/L)	Inflow	0.79	104%	2.16	173%	0.47	65%
	Reservoir	0.02	103%	0.04	88%	0.06	49%

Source: Adapted from Agência Nacional de Águas (2020b).

each time, and even on average do not show clear distinct regions. As shown by Oliveira et al. (2020), identifying the reservoir hydrodynamics can help to identify limnological zones within the reservoir, which have influence in the water quality. Reservoir hydrodynamics is dominated by wind and radiation, and the effect of tributaries is secondary, and only local velocities in reservoirs are low (cm/s or less). Velocities in most parts of the reservoir vary with meteorological forces that do not have a sufficient spatial pattern. Hydrodynamics in these reservoirs do not follow a unique spatial pattern, and thus the use of this parameter for zonation is not recommended. Areas with higher velocities in the two largest tributaries (Paranapanema and Taquari) stand out, however, only in the region near the inlet.

Basin-based zonation analysis

Figure 9 shows the result of the basin analysis for Jurumirim Reservoir, while Table 7 shows the ranking of the loads from the tributaries. The basins with the highest loads are correlated with regions of water quality concentrations. Thus, it is possible to zone the reservoir just by analyzing the loads entering the reservoir. As shown by Deeds et al. (2020), that applied a hydrogeomorphic-based lake classification in Maine (USA), the water quality of lakes and reservoirs is highly influenced by anthropogenic watershed activities and local-scale characteristics of lake basins. Zone boundaries can be defined using the boundaries of adjacent basins. The disadvantage is that this type of analysis does not result in

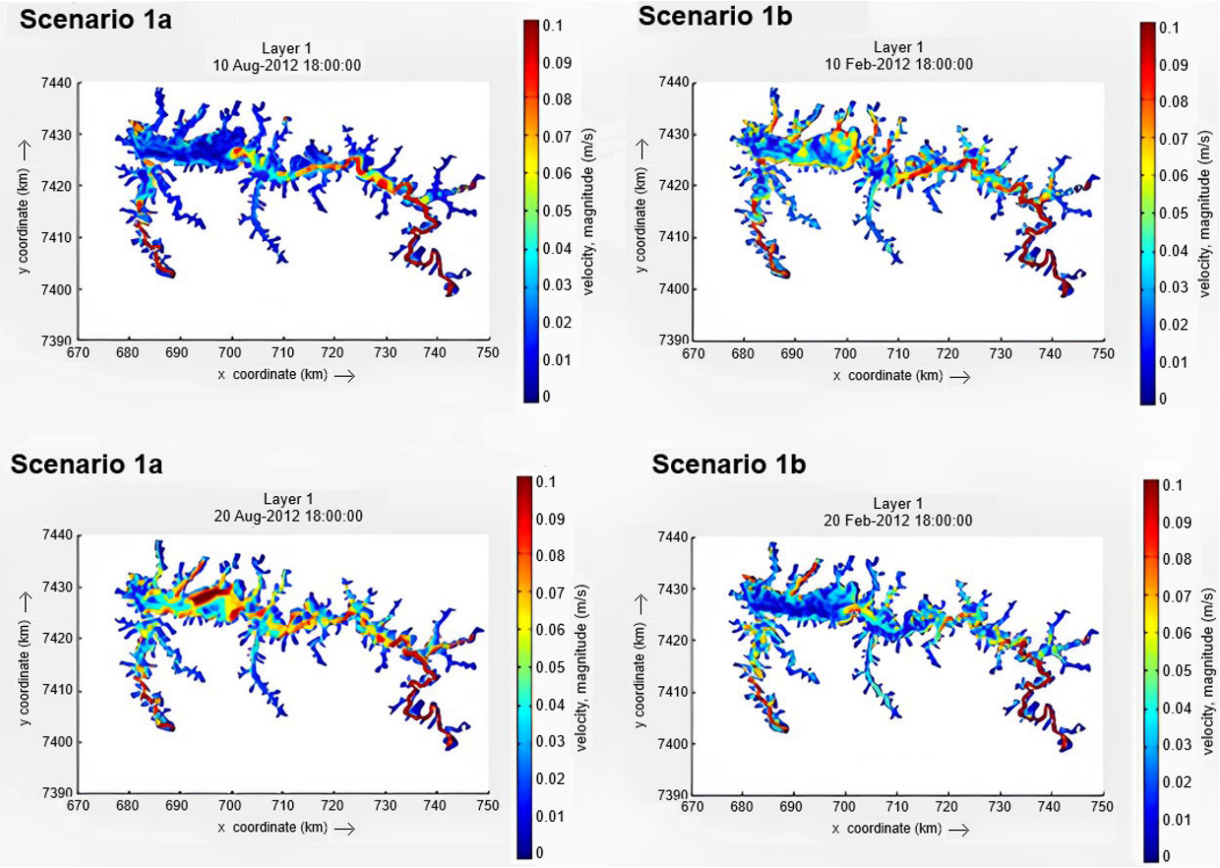

Figure 8. Surface velocity maps for Jurumirim Reservoir and four scenarios of a strong flow pulse entering the (a) mixed and (b) stratified situation for two different dates (Agência Nacional de Águas, 2020b).

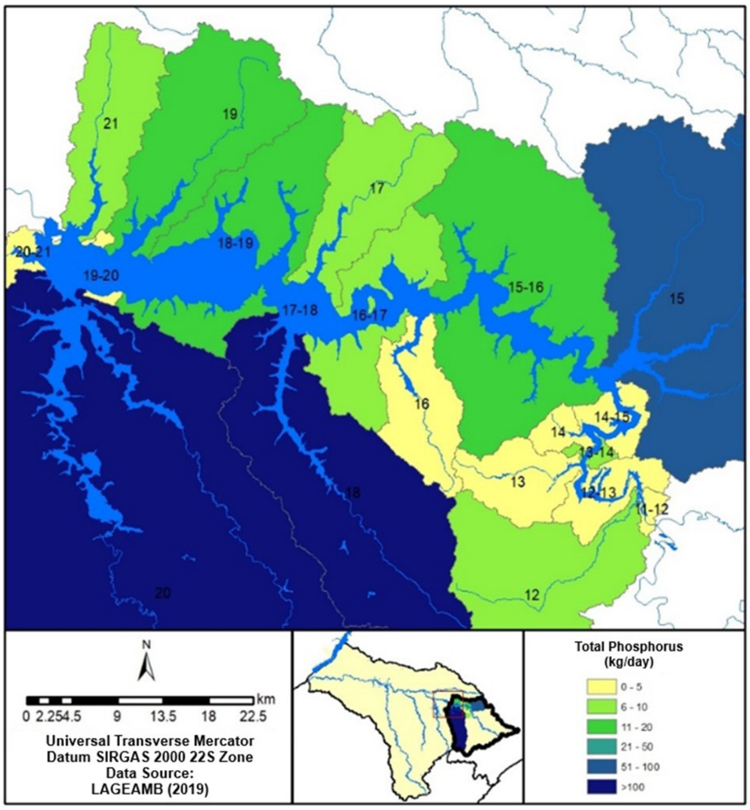

Figure 9. Estimation of Total Phosphorus load in the tributary basins of the Jurumirim Reservoir (Agência Nacional de Águas, 2019).

water quality concentrations. However, these can be estimated with simplified calculations (e.g. Vollenweider-type classifications).

The ranking of the main inputs allows the identification of the main sources. Gunkel et al. (2018) observed changes in Chlorophyll-a concentrations in the longitudinal profile of Itaparica Reservoir, in the semi-arid region of Brazil, indicating multiple contamination sources.

In this study case, the three rivers with the highest loads (Paranapanema, 40%, Taquari, 25%, and Ribeirão das Posses, 18%) represent 83% of the total phosphorus load entering the reservoir. In this case, to improve the water quality of the reservoir, more efficient measures should be recommended for these three rivers. Aquaculture contributes only 8% and was also shown in water quality modeling to have little relevance for water quality in this reservoir.

Water quality zonation analysis

The results of the water quality simulations indicated TP as a critical parameter. The spatial analyses showed four distinct main regions based on TP concentrations (Figure 10). However, these patterns are also observed in TN concentration, as shown in the boxplots (Figure 11). OD and DBO concentrations were very similar over the time in all sectors.

Contrary to hydrodynamic analyses, these regions are stable over time, indicating their potential for use as a zoning method. It should be noted that the two regions identified with high concentrations (in the figure, > 0.07 mg.L^{-1}) in the modeling are associated with tributaries in which there is a greater load compared to the others (Sectors 2 and 3). This suggests that tributaries are the main sources of potential water quality problems.

The stratified and mixed periods have differences; however, they highlight the same spatial zones. The areas with the highest concentrations do not change significantly between the strong pulse and the low-level moments, showing that the critical regions are independent of reservoir conditions and depend mainly on loads. Different from Pedrazzi et al. (2013), who showed temporal and spatial variations of measured concentrations at the Itupararanga Reservoir, in Brazil, already processed to map the trophic state index. In their case, the reservoir had different zones of trophic state index that change according to the period (dry or wet).

Geometric/morphological compartmentalization analysis

Inspired by the results of the water quality zonation and basin-based, the zonation based on the basic parameters of both

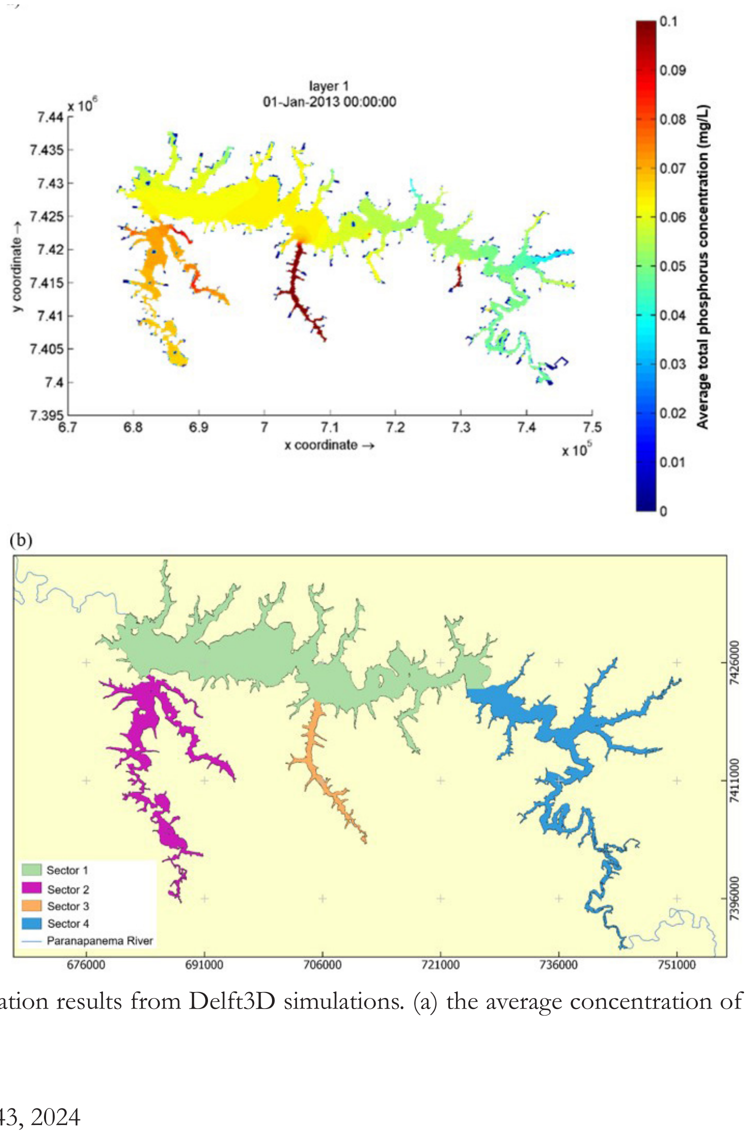

Figure 10. Water quality zonation results from Delft3D simulations. (a) the average concentration of total phosphorus in 2012, (b) resultant zoning.

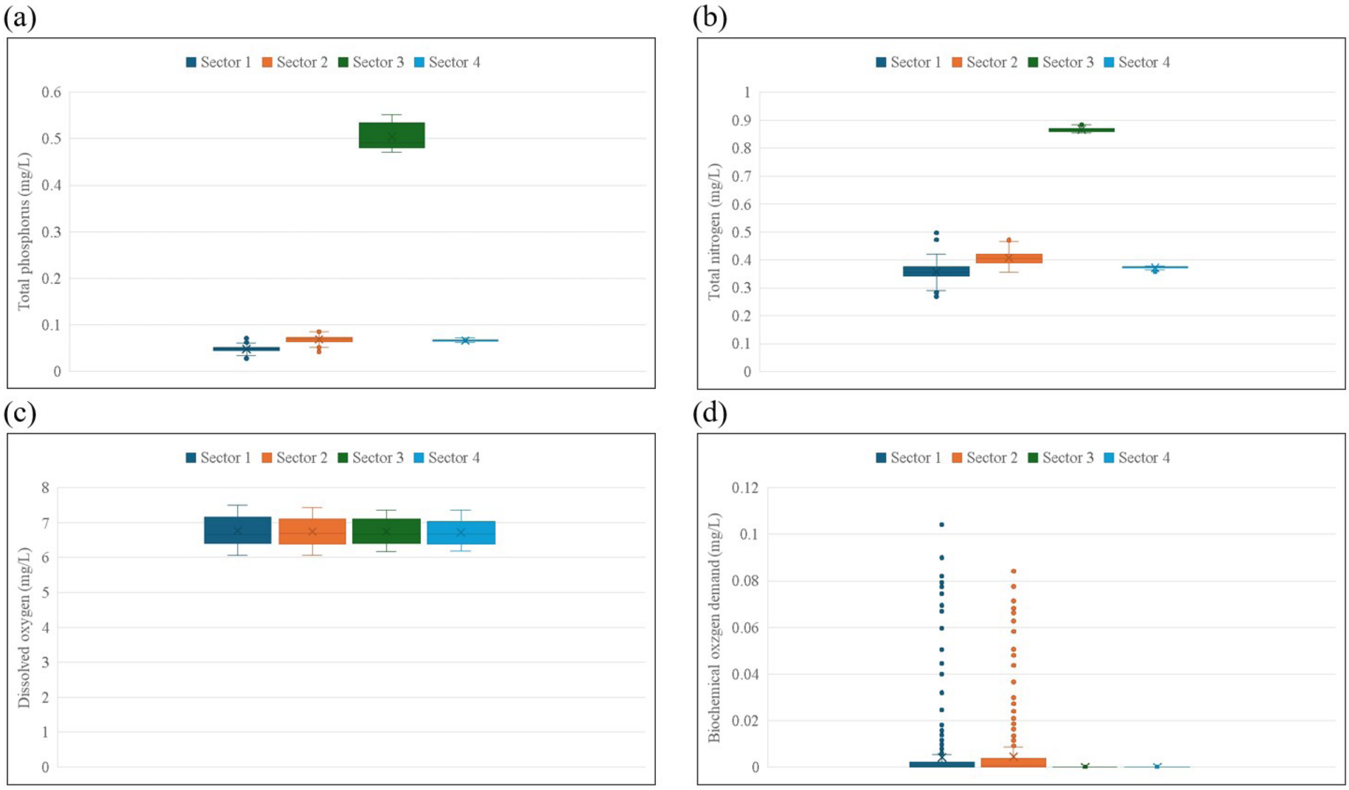

Figure 11. Water quality zonation results from Delft3D simulations – Boxplots of (a) TP, (b) TN, (c) DO, and (d) BOD concentrations in the sectors defined for the Jurumirim reservoir.

parties was elaborated. These are the reservoir bank coordinates and depths. Figure 12 shows the results of the k-means method, which correlates these parameters to obtain "clusters", then specific zones, with the more combined influence of these parameters. The separation into 3 sectors already results in a high score (last graph in Figure 12), and the obtained clusters have similarities with the results from modeling. However, the method does not provide concentration information and would have to be supplemented with load information for each sector (e.g. Vollenweider-type classifications).

Zonation proposition

The regions identified by the water quality parameters by both methods showed regions associated with tributaries with higher loads. This suggests that the tributaries are the main sources of potential water quality problems. This also led to the hypothesis of basing zoning on basin characteristics alone, analyzed as follows. From the results presented, the following zonation strategy is proposed.

1. Ranking of associated loads

In the ranking, the percentage of load for each source (tributary, fish farming) is calculated, and the largest sources (for example, all above 10%) are selected for zoning. Table 13 shows the example of the Jurumirim reservoir, resulting in 3 main zones (Paranapanema, Taquari, Ribeirão das Posses).

2. Hydrodynamic ranking

Knowing that large loads could be assimilated by reservoir arms that have large volumes and large flows, the hydrodynamic effect should also be evaluated specifically in the regions adjacent to the sectors identified in Step 1.

To do this, the volume of each sector will be calculated and estimates made for:

- Residence time in the sector/arm: $Volume_{sector} / Q_{in,sector}$
- Average velocity in the sector: $Q_{in,sector} / (Volume_{sector} x\ Length_{secto})$
- Characteristic numbers for water quality

It should be noted that these data are generally easy to obtain and process. The sectors with the lowest speed and/or longest residence time with the highest loads will be considered the most critical sectors.

3. Water Quality Classification

Zonation and ranking in steps 1 and 2 allow critical sectors of the reservoir to be identified but do not provide information on concentrations or classes for regulation purposes. Therefore, in this third step, the average concentrations in each sector should be calculated as $C_{sector} = \frac{Load_{in,sector}}{Q_{sector}}$. In addition, simplified conventional methods of Vollenweider type may be tested to obtain the trophic state of the system.

4. Refinement and validation

If necessary, to test, refine, or validate the zoning obtained with the water quality classification, there is a recommendation

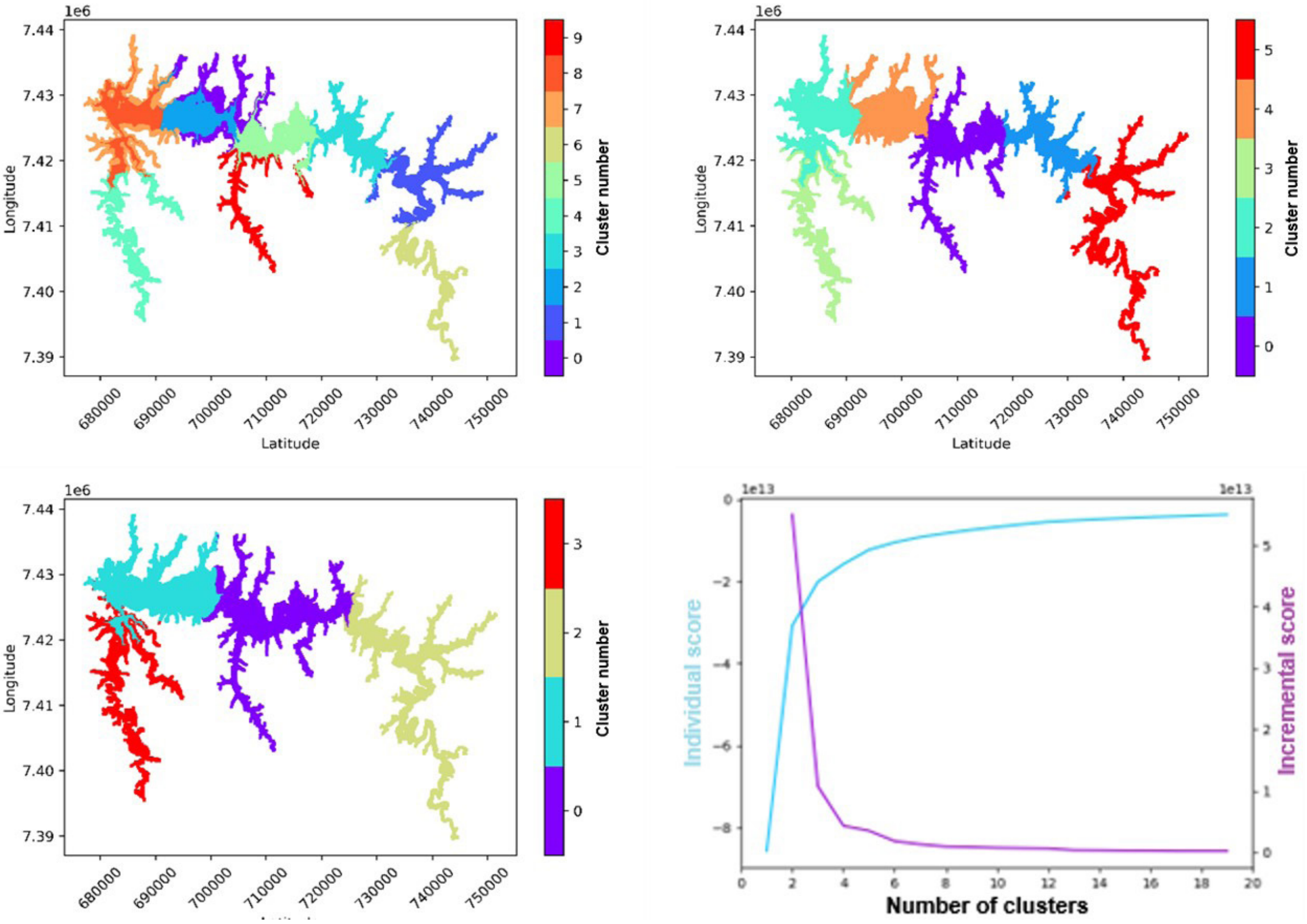

Figure 12. Results of the creation using the k-means method and the edge coordinates and depth. The different clusters illustrated depend on the number of clusters to be created (defined by the user) (Agência Nacional de Águas, 2020b).

Table 13. Basic parameters of adjacent sub-basins and absolute and relative contributions.

River	**Área (km^2)**	**Inflow (m^3/s)**	**Load (kg/day)**			**Load (%)**		
		Rainy	**BOD**	**TN**	**TP**	**BOD**	**TN**	**TP**
Paranapanema	10074	161.86	19787	8482	654	51%	53%	40%
Taquari	4536	62.01	9573	4275	415	25%	27%	25%
Santo Inácio	1411	19.42	2308	1015	66	6%	6%	4%
Rib. da Jacutinga	543	1.75	812	345	21	2%	2%	1%
Rib. Bonito	495	3.42	1134	380	29	3%	2%	2%
Rib. das Posses	405	3.33	3666	867	293	9%	5%	18%
Sao José dos Pinhais	304	1.60	913	261	20	2%	2%	1%
Rib. Macuco	163	1.32	460	144	11	1%	1%	1%
Aquaculture	-	-	-	293	123	0%	2%	8%
Total	17931		38653	16062	1632			

to do: (i) Comparison with Remote Sensing; (ii) Clustering with Statistical Parameters; (iii) 3D modeling

CONCLUSIONS

Reservoirs present different characteristics from distinct environmental systems (i.e rivers, coastal waters) and therefore should be characterized differently concerning regulation aspects. Many reservoirs with large, flooded areas may also be divided into various regions with similar behavior, but that stand out from the others.

The case study highligths that, even for different types of reservoirs, the application of the comprehensive classification scheme presented it is possible for a better understanding of the true hydrodynamic nature of the reservoir . Of all the eleven water bodies considered at the beginning, eight could be classified as run-of-river reservoir, and thus follow the river characterization for water quality. The three remaining, defined as lentic systems at the first step, were analyzed and classified as dynamic systems with significant spatial variability, requiring a zonation for better management.

Even though it is possible to identify zones with different hydrodynamic characteristics in the reservoir, they vary over time. Therefore, these variables are not suitable for zoning the reservoir in this case study. The zoning based on basin data is a good starting point, as it indicates the main load contributions in the sub-basins that influence the reservoir. The zoning based on water quality substances (in this case, the TP) showed distinct zones that remained the same over time. They also coincide with the incident load zones. The zoning based purely on geomorphological data showed the same pattern concerning water quality, indicating its great influence on the processes occurring inside the reservoir. Following the classification scheme, it was possible to verify the critical water quality parameter and assess the main regions of interest, which could facilitate management decisions.

However, it should be noted that the definition of the zones does not take into account, for example, (i) socio-economic aspects, (ii) hydrodynamic changes caused by the structures, (iii) the effect of internal loads, and (iv) seasonality. For internal structures (e.g., aquaculture, fish farming, floating photovoltaic systems), this classification scheme might not be enough. In this case study, the fish farming was small compared to the watershed load, and therefore had no significant effect on the water quality of the reservoir. Although this scheme could be an application to assist in a first decision on where to locate such structures, more elaborate studies should be conducted to assess the local effects and their impacts on the reservoir.

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Camila Bergmann Goulart: Development of the entire study, hydrodynamic and water quality modeling with Delft3D.

João Marcos Carvalho: 1D modeling, stratification analysis, and zoning based on clustering. He assisted in writing.

Julio Werner Yoshioka Bernardo: Worked on water quality modeling and load allocation methodology.

Bruna Arcie Polli: Hydrodynamic modeling.

Cristóvão Fernandes: Worked on coordinating the project, and defining the study guidelines. He assisted in writing.

Stephan Fuchs: Load modeling (MoRE), zonation analysis.

Tobias Bleninger: Worked on coordinating the project, and defining the study guidelines. He assisted in writing.

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