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RESEARCH ARTICLE

An abiotic typology and reference conditions for nutrients and chlorophyll-a in subtropical reservoirs (São Paulo State, Brazil)

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Abstract

The establishment of reference conditions and typology are two important steps in water resources management. The reference conditions enable the determination of how impacted an ecosystem is, while the typology facilitates the implementation of management procedures. A study of subtropical reservoirs in São Paulo State (Brazil) was performed to obtain (1) an abiotic typology, using principal component analysis (PCA) and cluster analysis (Ward's method with Euclidean distances), and (2) reference conditions for total phosphorus (TP), total nitrogen (TN), and chlorophyll-a (Chl-a) in the dry and rainy seasons for one of the established typologies. Two main statistical techniques were used: the lake population distribution approach and the trisection method. PCA identified an environmental gradient in the east-west direction, with reservoirs at higher latitudes and with larger dimensions in the west, and smaller reservoirs in eastern areas with higher altitude and higher average *annual rainfall*. The PCA and cluster analysis indicated that there were four main types of reservoirs. The nutrient criteria techniques, obtained for 13 type I rainy-east reservoirs, were not significantly different (*t* test, $p < 0.05$). Although the methods resulted in similar reference conditions, one-way ANOVA indicated significant differences between the seasons for Chl-a, which levels were slightly higher in the rainy season. As far as we know, this is the first study to simultaneously provide an abiotic typology and reference conditions for chlorophyll-a and nutrients in different seasons, considering subtropical reservoirs in South America. This investigation makes an important contribution to the monitoring and management of subtropical reservoirs, and the promotion of dialog between the scientific community and managers, aiming at ensuring the sustainability of water bodies.

Keywords Nitrogen · Phosphorus · Eutrophication · Management · Water quality · Nutrient criteria

1 Introduction

The determination of reference conditions is fundamental for the evaluation of impacts in ecosystems and for the implementation of remediation procedures. A number of countries have acknowledged the importance of using this approach in water resources management legislation, such as in the USA (Clean Water Act), Australia and New Zealand (National Agenda for Sustainable Water Management), and within the European Union (Water Framework Directive (WFD)). The reference condition usually considers the best attainable condition in the ecosystem, which is the expected least-disturbed ecological condition, achieved following prolonged use of the best possible management practices (Stoddard et al. 2006). This definition is considered in the present work, although several other definitions and interpretations have been proposed for the reference condition, as presented by Stoddard et al. (2006) and discussed by Bennion and Battarbee (2007).

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The reference condition can be established for a series of parameters and processes, where analysis of a greater number of variables and processes results in a better definition of the pristine conditions of a given ecosystem. For example, according to the WFD (EC 2000), the reference conditions should be established for general physicochemical, hydro-morphological, and biological-quality parameters, in order to be able to determine the ecological status of an aquatic ecosystem. The approaches that can be applied to identify the reference conditions include a comparison with data for a similar ecosystem without significant impacts (EC 2000; Gibson et al. 2000); use of compilations of historical, paleolimnological, and monitoring data (EC 2000; Bennion and Battarbee 2007; Gibson et al. 2000); mathematical models (EC 2000; Gibson et al. 2000); and expert judgment (EC 2000; Huo et al. 2018).

Among these approaches, the best method to establish reference conditions is considered to be the comparison of the study area with a similar ecosystem that has no significant impacts. However, in most countries, it can be difficult to find a water body with such conditions (Moss 2008; Hering et al. 2010). As an alternative, statistical techniques (Cunha et al. 2011; Herlihy et al. 2013; Salerno et al. 2014; Cheng and Li 2018) have been employed in several studies, especially for establishing nutrient reference conditions with the advantage of including the data natural variability (Gibson et al. 2000; Huo et al. 2018). For nutrients (nitrogen and phosphorus) and chlorophyll-a, which are variables associated with the eutrophication process, widely applied statistical methods are the lake population distribution approach (Gibson et al. 2000; Huo et al. 2018) and the trisection method (Dodds and Oakes 2004; Huo et al. 2018).

Both methods are based on the use of percentiles. In the lake population distribution method, the nutrient criteria are established using the 25th percentile of all lake data in a region regardless of whether or not they are impacted by human activities (Gibson et al. 2000; Huo et al. 2014b; Huo et al. 2018). However, if most of the lakes are impacted by nutrient inputs, the nutrient criteria can be overestimated, and in such conditions, a lower percentile can be applied to determine nutrient reference condition (Gibson et al. 2000), as the 5th percentile (Huo et al. 2014a; Huo et al. 2018). In the trisection method, on the other hand, the nutrient criteria are calculated based on the 50th percentile from the one-third of the best available lake dataset (Dodds et al. 2006; Cunha et al. 2011), in other words, the third of lakes with the lowest nutrient concentrations, which in theory would exclude data from the most impacted environments. Another important issue to be considered is the establishment of criteria for different periods of the year (Sánchez-Montoya et al. 2012), as there can be significant changes in the structure and functioning of aquatic ecosystems and their aquatic communities in different seasons.

For establishing the reference conditions, the concept of ecoregion is usually applied (Gibson et al. 2000; Dodds et al. 2006; Huo et al. 2013, 2018). However, although the use of ecoregions can justify some fluctuation in nutrient levels, this approach neglects the influence of factors present in a smaller scale of analysis, such as geology (Ice and Binkley 2003; Olson and Hawkins 2013). In order to better establish for natural oscillations in nutrient concentration within ecoregions, the concept of typology has also been employed to establish reference conditions (EC 2000; Moss 2008; Hering 2010).

The typology concept was introduced by limnologists in the early twentieth century. It was used in the 1960s (Moss 2008) and 1970s such as the study of Margalef et al. (1976) that established a typology for Spanish reservoirs. The typology gained new interest with the implementation of the WFD in the year 2000. The application of typology follows the principle that water bodies with similar ecological features feature similar sets of habitats and biological communities, as well as similar functioning. Under the WFD, the main aim of using typology is to determine the reference conditions and consequently the ecological status of the ecosystem. The ecological status refers to the deviation of the observed state of an aquatic ecosystem from its reference condition. According to the WFD recommendations, the main purposes of the definition of water body ecological types are to enable the establishment of the correct reference conditions (Kolada 2010; Langhammer et al. 2012) and to ensure that ecological status classifications are comparable within each category of ecosystems (rivers, lakes, transitional waters, and coastal waters) with similar characteristics (Ritterbusch et al. 2014). In this way, the reference conditions are established for each category of types, rather than for each water body, which facilitates the management process.

Defining the typology and reference conditions are two important steps in water resource management and ecosystem restoration. Assuming reservoirs have abiotic characteristics that allow them to be arranged in distinct groups which will have similar ecological functioning patterns, a typology based on the WFD was applied for reservoirs in São Paulo State (Brazil). Then for one of the settled typologies, with the largest database available, reference conditions were established for total phosphorus, total nitrogen, and chlorophyll-a, in different seasons, using two different statistical techniques: lake population distribution and trisection. We expect nutrient criteria and chlorophyll-a levels would be different between the dry and rainy seasons. As far as we know, this is the first study to simultaneously use an abiotic typology and reference conditions for nutrients in different seasons, applicable to subtropical reservoirs in South America. This research makes an important contribution in the context of reservoir monitoring and management.

2 Material and methods

2.1 Study area

São Paulo State, in the southeast region of Brazil, has an area of 248,219.481 km^2 (IBGE 2018). The vegetation is typical of tropical and subtropical forests (Cunha et al. 2011) with the dominance of the Atlantic forest in the east part of the State. There are five main climate classifications according to Köppen-Geiger in São Paulo; the mean air temperatures fluctuate between 15 and 25 °C and the annual rainfall between 1000 and 1400 mm (Cunha et al. 2011). The state has an extensive hydrographic network, with several reservoirs having been constructed, mainly for the generation of hydroelectric energy and for public water supply. São Paulo State is the most populous area of the country, with more than 45 million inhabitants and a demographic density of 166.25 per km^2 (IBGE 2018). São Paulo State has the highest industrial production, the highest gross domestic product (GDP), and the second highest human development index (HDI) of Brazil (IBGE 2018). Although the region has one of the best sanitation rates in the country (Cunha et al. 2011; IBGE 2018), many water bodies are affected by eutrophication problems caused by domestic wastewater discharges. According to the local environmental agency (CETESB) of 423 monitored points (rivers and reservoirs) in 2018, 25% were classified as eutrophic, 50% as mesotrophic, and 25% as ultra-oligotrophic and oligotrophic (CETESB 2018). In some reservoirs of the metropolitan region of São Paulo, one of the most densely populated regions in the world (21.5 million inhabitants), the excessive nutrient inputs have become a management challenge. In order to control the algal blooms that are a consequence of the eutrophication process, applications of algaecides such as copper sulfate are quite common and are responsible for mean levels of copper up to 74-fold (Leal et al. 2018) and 194-fold (Frascareli et al. 2018) higher than reference condition (15 mg/kg) in the sediments of the Guarapiranga and Rio Grande reservoirs, respectively.

The reservoirs in São Paulo State are not too deep (Table 1), and most of them are polymictic, a common characteristic of lakes and reservoirs in Brazil. Low levels of dissolved oxygen and anoxic conditions have been recorded in several reservoirs as Billings, Guarapiranga, Atibainha, Cachoeira, Jaguari, and Broa (CETESB 2018), especially because of the eutrophication intensification.

In the tropical and subtropical areas, seasonal variations are especially observed between dry and rainy seasons. Numerous studies in São Paulo reservoirs reveal there are alterations in biotic (Sampaio et al. 2002; Uehara et al. 2015; Santana and Ferragut 2016; Santana et al. 2017;) and abiotic composition (Rodgher et al. 2005; Uehara et al. 2015; Tercini and Méllo-Júnior 2016; Cardoso-Silva et al. 2018) in different seasons. Usually, investigations revealed the highest nutrient levels and chlorophyll-a during the rainy periods (Oliveira and Bicudo 2017; Cardoso-Silva et al. 2018) as a consequence of the nutrient input from the watershed. Some of the main morphometric characteristics of the reservoirs investigated in the present study are described in Table 1.

2.2 Typology

A total of 49 reservoirs monitored by the local environmental agency (CETESB) were selected (Fig. 1; Table S1, Supplementary Material - SM). The reservoirs belonged to 16 of the 22 Water Resources Management Units. These units are classified according to the predominant land use, with the aim of facilitating management procedures. The reservoirs analyzed belonged to the following units: predominantly industrialized (units 2, 5, and 6), in the process of industrialization (units 4, 8, 12, and 13), conservation (unit 14), and predominantly agricultural (units 15 to 22) (Annex III, State Law 9034/1994).

A type B typology was applied, according to the WFD recommendations (Annex II of the WFD; EC 2000), where each group of aquatic ecosystems (rivers, lakes, transitional waters, and coastal waters) may be classified using two distinct systems, A and B. The classification is based on climatic, geological, morphological, and hydrological conditions, expecting that different abiotic conditions will be associated with different biological and ecological characteristics. In other words, it is expected that a given biological community will present a high degree of probability of occurring under specific physical and chemical conditions (Ferreira 2009). In the European Union, the selection of system A or B is a Member State decision. System A consists of a series of categorized and mandatory variables, producing different types of water

Table 1 Descriptive statistic of morphometric characteristics for 49 reservoirs of São Paulo State

	Dimension km^2	Mean depth m	Altitude m	Volume km^3	Rain mm	Drainage area km^3
Minimum	0.2	0.3	210.0	0.5	1132.5	12.0
Maximum	2250.0	26.7	1200.0	21060.0	2195.1	574000.0
Mean	202.5	9.8	643.4	2639.3	1426.8	41912.8
Standard deviation	390.1	6.8	206.2	4953.0	168.2	116053.5

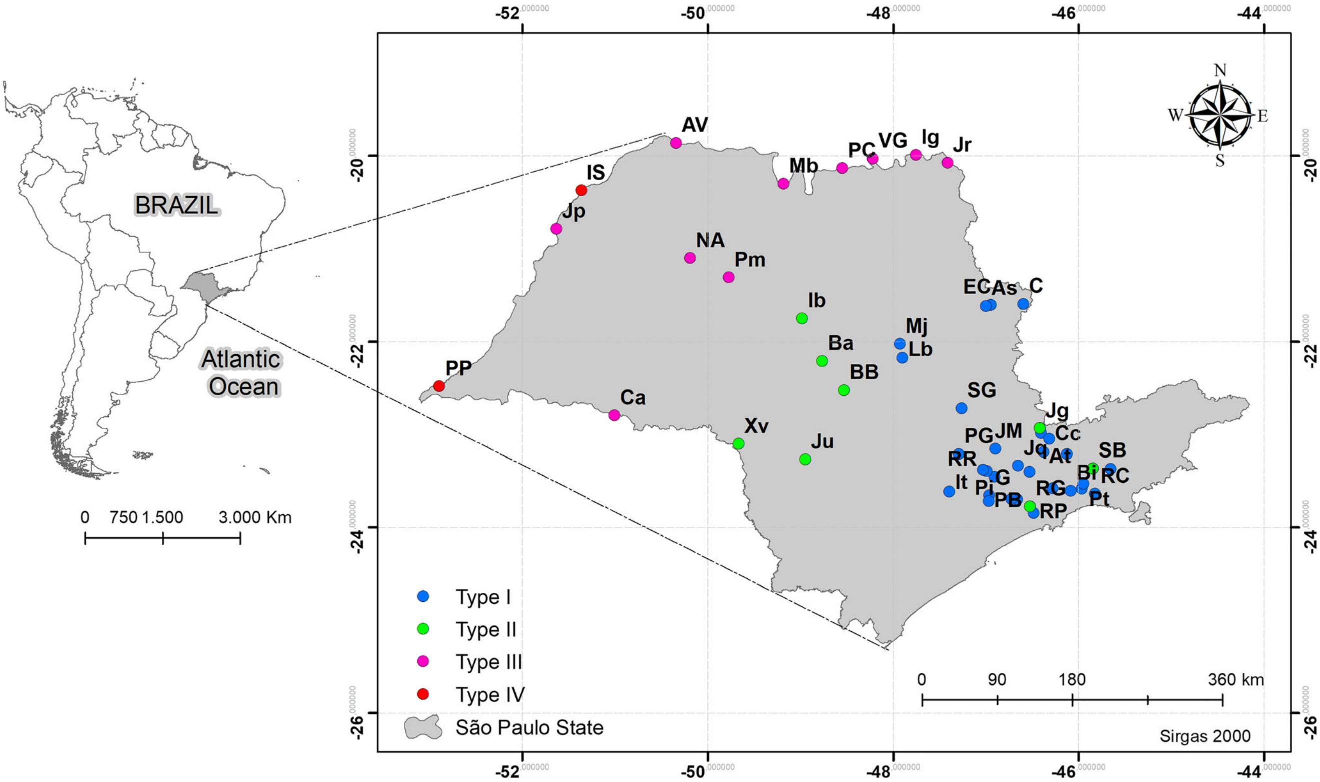

Fig. 1 Distribution of the analyzed reservoirs in São Paulo State. Explanations for types I (rainy east reservoirs), II (depth center reservoirs), III (larger west reservoirs), and IV (larger far west reservoirs) are in the "Typology" section

masses. In system B, in addition to the mandatory variables, a series of optional variables are listed, resulting in this method being more effective in most countries. In general, system A is unable to provide a credible ecological separation for the establishment of reference conditions in most waterbodies (Teresa Ferreira, Technical University of Lisbon, personal communication). For man-made or heavily modified water bodies, the differentiation into types is made according to the descriptors applicable to the category of surface water that most closely resembles the artificial or heavily modified water body analyzed (EC 2000). In the case of reservoirs, for example, descriptors for rivers and lakes can be used, because reservoirs can be considered as hybrid systems that present features of these two ecosystems (Ferreira 2009).

The obligatory variables employed were latitude, longitude, size, altitude, and mean depth. Data for latitude, longitude, and altitude were obtained for the dam areas, using the Google Earth program. The mean depth was obtained by considering the ratio between the size and volume of the reservoir under full supply conditions. Dimension and volume data were accessed from the Brazilian Dam Committee (CBDB) (http://www.cbdb.org.br/site/index.asp). For reservoirs not included in the CBDB list, information was obtained from the literature (Table S1, SM). As an optional variable, the mean annual rainfall was accessed from the Department of Water and Electric Energy (DAEE) (http://www.hidrologia.daee.sp.gov.br/). The rainfall data were for the stations located closest to the reservoirs. The drainage basin area was used as a specific variable for the reservoirs. The data for the reservoirs are provided in Table S1 (SM).

Although information concerning the dominant geology in the watershed is mandatory under the WFD, there are currently no data available for many of the reservoirs evaluated in this research. The WFD provides no explanations or evidence supporting the established geological classifications (Irvine et al. 2002), so the present work used data for the dominant soil types in the hydrographic basins, together with the corresponding potential fragilities of the soils. Differences in soil type are recognized to affect water quality and biological composition (Pilke and Mäntykoski 2002). This information was added after the first classification exercise for 25 of the 49 reservoirs analyzed. The data were obtained from the work of Bitencourt et al. (2020), who described six different soil types and their associated potential fragilities (H: high; L: low; M: medium; VL: very low; VHI: very high I; VHII: very high II).

Typology was established using two main multivariate techniques: principal component analysis based on a covariation matrix and cluster analysis (Ward's method and Euclidean distances) (Legendre and Legendre 1998). The groups were identified by a cluster analysis from the values obtained by the PCA scores 1 and 2. Data were previously standardized using the *Z*-score method (Gotelli and Ellison 2011). The statistical analyses were performed with PAST software (Hammer et al. 2001).

2.3 Reference conditions

Monitoring data for the period between 1998 and 2017 were obtained from the local environmental agency (CETESB) for 16 reservoirs of one of the typologies with the greatest amount of data available. All selected sampling points are located in the reservoir's dam area. Surface waters in the limnetic zone were collected according to CETESB (1988) and CETESB and ANA (2011) recommendations. The laboratory analyses were performed by CETESB, following standard methods (APHA 2005). The following variables were investigated: pH, electrical conductivity (EC), dissolved oxygen (DO), total phosphorus (TP), total Kjeldhäl nitrogen (TN), and chlorophyll (Chl-a). Transparency was not evaluated, because it was affected by the high turbidity characteristic of São Paulo State reservoirs, caused by high levels of suspended particulate matter derived from the predominant clay soils in the region. The samples were obtained once every 2 months, representing dry and wet seasons. Concentrations below the detection limit (DL) were changed by half the DL value, since these occurrences were less than 15% of the total dataset, as suggested by Olson and Hawkins (2013) and Herlihy et al. (2013). The lowest DL values were 0.01 mg TP/L, 0.02 mg TN/L, and 1.00 μg Chl-a /L.

Two main approaches were used to determine the reference conditions: the population distribution method (Gibson et al. 2000) and the trisection method (Buck et al. 2000). For these analyses, descriptive statistics (medians and percentiles) were obtained for TP, TN, and Chl-a. In the population distribution method, nutrient criteria and Chl-a were established using the 25th percentile of all lake data. In the trisection method, the nutrient criteria and Chl-a were calculated based on the 50th percentile (median) derived from one-third of the best available lake dataset (Dodds et al. 2006; Cunha et al. 2011; Huo et al. 2018). Relationships among the chemical and physical variables (TP, TN, Chl-a, pH, EC, and DO) were investigated using Pearson correlations.

3 Results and discussion

3.1 Typology

For better visualization of the PCA results, the Ilha Solteira (IS) and Porto Primavera (PP) reservoirs were removed from this analysis. The conditions of these ecosystems differed from those of the other reservoirs, in terms of drainage area, size, and volume, which led to the isolation of these points in the PCA arrangement (Fig. 1 SM). PP and IS reservoirs are threefold and 1.5-fold, respectively, larger in area and approximately 1.5-fold greater in volume than Três Irmãos reservoir, the third biggest reservoir in area and volume in the state of São Paulo.

After the removal of these reservoirs, 69.72% of the total data variance was explained by two PCs (Fig. 2). A division was observed between the reservoirs located in the east and west regions of São Paulo State. PC1 (Fig. 2, Table 2) separated reservoirs with higher latitudes (eigenvalue, 0.92) and larger dimensions (eigenvalue, 0.78), volume (eigenvalue, 0.79), and mean depth (eigenvalues, − 0.90), located in the west of the State, from small reservoirs with higher altitude (eigenvalue, 0.77) and higher average rainfall (eigenvalue, − 0.57), in the eastern region. Therefore, there were two main ecological types related to the latitude and size of the water body (higher dimension volume and mean depth), and subtypes determined by the altitude (eigenvalue, 0.77) and the longitude (eigenvalue, 0.52) (secondary gradients expressed by PC2).

A cluster analysis was then performed with the two main PCA axis, which indicated the existence of three reservoir types (Fig. 3), in the east-west direction, as well as a marked environmental gradient (Fig. 1 and Fig. S2, SM). This abiotic gradient revealed the need to establish specific ways to manage these water bodies, coincidentally reflecting the different uses and impacts in the hydrographic basins. Type I rainy east reservoirs generally occur in predominantly industrialized river basins, while type II depth center-south reservoirs occur in areas predominantly industrialized, undergoing industrialization and for conservation. Types III larger west and the type IV larger far west reservoirs are found in watersheds with predominance of agricultural activities (Annex III of State Law 9034/1994). The reservoirs Porto Primavera (PP) and Ilha Solteira (IS) which were removed from the PCA were classified as type IV.

Table 2 Loads of two principal components for the variables introduced in the PCA analysis. Values higher than 0.60 are given in bold

	PC 1	PC 2	PC 3
Lat (latitude)	**0.92**	− 0.18	0.08
Long (longitude)	− 0.70	0.52	− 0.12
D (dimension)	**0.78**	0.00	0.33
Z (depth)	**− 0.90**	0.19	0.10
Alt (altitude)	0.45	**0.77**	0.38
V (volume)	**0.79**	0.25	0.31
R (precipitation)	− 0.57	− 0.37	**0.73**
DA (drainage area)	0.57	− 0.15	0.00

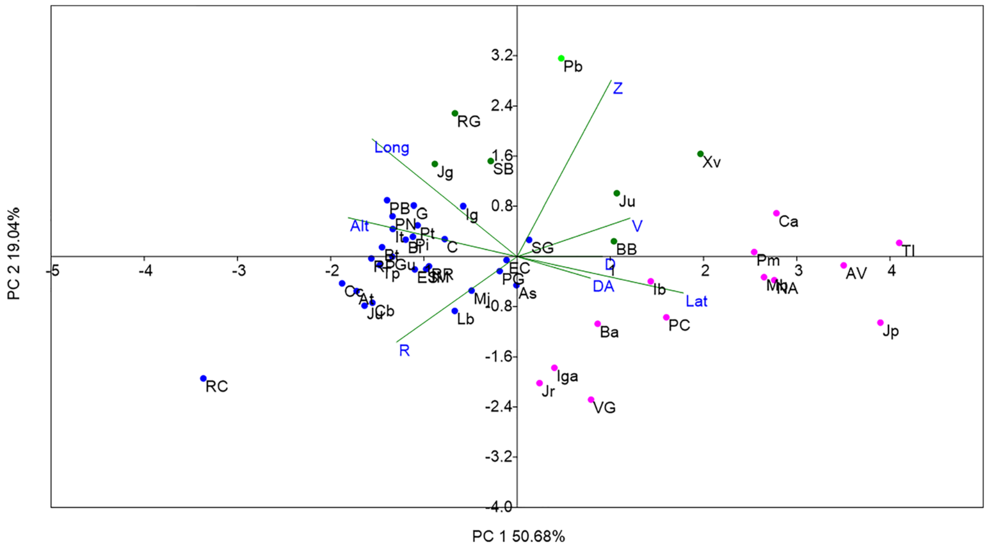

Fig. 2 Distribution obtained using principal component analysis (PCA) applied to data for 49 reservoirs in São Paulo State. The scores were obtained considering the variables latitude (Lat), volume (V), dimension (D), depth (Z), drainage area (DA), altitude (Alt), annual average precipitation (R), and longitude (Long)

The type I rainy east reservoirs, located in regions of higher altitudes and with higher mean rainfall (Figs. 2 and 3), due to proximity to the coast, are in a predominantly industrialized region with one of the highest population densities in the country (United Nations 2019). The consequent demand for water by industry and the population explain the large number of reservoirs in this area, creating a range of challenges for water resources management. One of the most serious challenges to be faced is the low water availability per inhabitant, due to both poor water quality and the growing population (ANA 2013). The Billings (Bi), Guarapiranga (Gu), and Salto Grande (SG) type I reservoirs, for example, have been impacted by metals (Silvério et al. 2005; Pompêo et al. 2013; Leal et al. 2018), drugs (Almeida and Weber 2005; López Doval et al. 2016), and eutrophication (Cunha et al. 2011; Dornfeld et al. 2006; Cardoso-Silva et al. 2014; Rietzler et al. 2016; Silva et al. 2018; Cardoso Silva et al. 2018).

The reservoirs categorized as type II depth center-south have the highest mean depth levels (Figs. 2 and 3) which may involve different processes of stratification and mixing of the water column with respect to shallower reservoirs. These presented lower altitude and decreased rainfall, compared to the type I reservoirs. The impacts in type II watersheds are mainly associated with industrialization. This type includes reservoirs constructed along the rivers Tietê (middle Tietê portion) and Paranapanema. Several studies have identified degradation of these reservoirs, especially due to eutrophication, such as the Barra Bonita (BB) reservoir (Sotero-Santos et al. 2006; Buzelli and Cunha-Santino 2013). Some of those reservoirs, located in the conservation watershed (Annex III, State Law 9034/1994), as Jurumirim (Ju) and Xavantes (Xv) can be more explored in scientific investigations in order to use them as reference ecosystems for type II reservoirs, as preconized by the WFD (EC 2000; Hering et al. 2010).

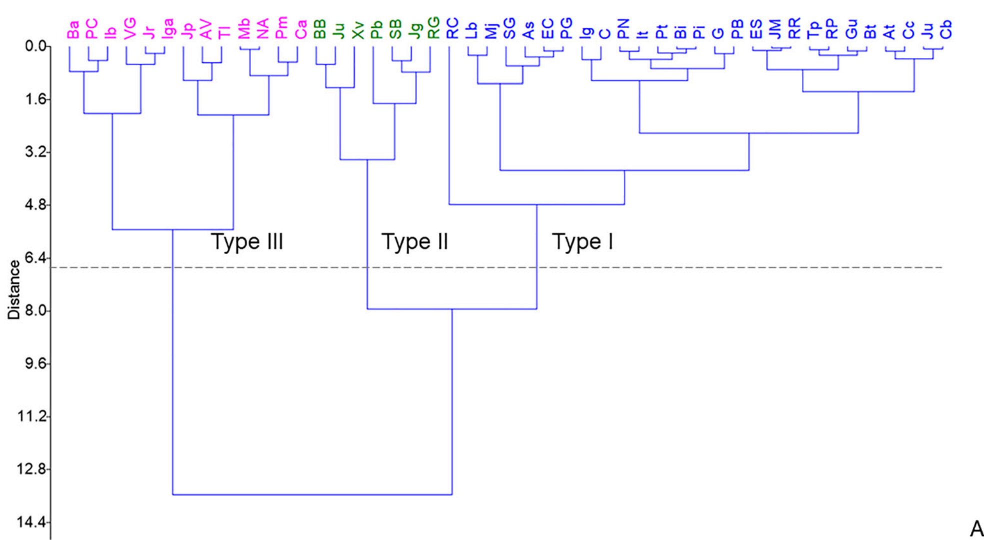

Fig. 3 Cluster analysis distribution (Ward's method, with Euclidean distances) of 49 reservoirs in São Paulo State

Reservoirs of types III larger west and IV larger far west, characterized by their large size, are in watersheds predominantly occupied by agricultural activities, and many of them are used for hydroelectric power generation. Attention must be employed in these reservoirs because they can be impacted by pesticides, especially because Brazil is one of the world's top-four largest pesticide-consuming countries (Paumgarten 2020). As far as we know, despite pesticides do not hinder the hydroelectric power generation, it can put at risk biological communities and prejudice potential multiple other reservoir uses. The only type IV reservoirs are the Porto Primavera (PP) and Ilha Solteira (IS) reservoirs, which have the largest dimensions and volumes. Both were constructed along the Paraná River for hydroelectric power generation. The Ilha Solteira reservoir, with an area of 1195 km^2, is ten times larger than Paris (105.4 km^2), Barcelona (101.4 km^2), or Lisbon (100 km^2). This large size necessitates ways of operating and managing these systems that differ from those employed for smaller reservoirs.

3.1.1 Soil type and potential fragility

The addition of the soil type variable in the establishment of the typology was performed for 25 of the 49 reservoirs initially analyzed. All these water bodies were classified as type I rainy east, except for Jaguari (Jg) and Santa Branca (SB) reservoirs type II depth center-south reservoirs. A cluster analysis was performed to identify the possible existence of subdivisions in these reservoir types (Fig. 4). The analysis corroborated the initial typology elaborated once no clear subdivisions were observed. Considering the soil type and potential fragilities, Jg and SB were considered type I reservoirs.

3.2 Reference conditions

3.2.1 Physico-chemical characteristics and limiting nutrients in the reservoirs

Table 3 shows the linear correlations; the Chl-a content was positively correlated (Pearson correlation > 0.45) with EC, TN, and TP (Table 3). Despite TP is considered to be the limiting nutrient in most aquatic freshwater ecosystems showing statistically significant correlations with the levels of Chl-a, in our database, Chl-a showed higher correlations with TN in both dry and rainy seasons. This was also observed by Huszar et al. (2006) and Beghelli et al. (2016). Huszar et al. (2006) evaluated 192 lakes in tropical and subtropical areas, while Beghelli et al. (2016) investigated the Itupararanga reservoir, one of the reservoirs analyzed in the present work. Beghelli et al. (2016) suggested that this finding could be explained by zooplankton predation, other nutrients, or light limitation.

The correlations of Chl-a with TN and TP were expected, given that increases of nutrients lead to increased primary productivity and consequent increases of chlorophyll-a levels and pH. The significant correlations between EC and Chl-a, TN, and TP could be explained by the fact that higher EC is associated with the eutrophication process.

For all the reservoirs, the N/P ratios suggested that they were predominantly limited by phosphorus (Table S2, SM) once N/P > 16 (Elser et al. 2009). The percentage of samples limited by N (N/P < 14), according to the reservoir, was lower than 23% (Table S2, SM). The percentage of samples limited by N, according to the reservoir, was lower than 23% (Table S2, SM). Changes of the limiting nutrient are quite common in tropical areas (Cunha et al. 2012), with a decrease of the water N:P concentration ratio being indicative of greater

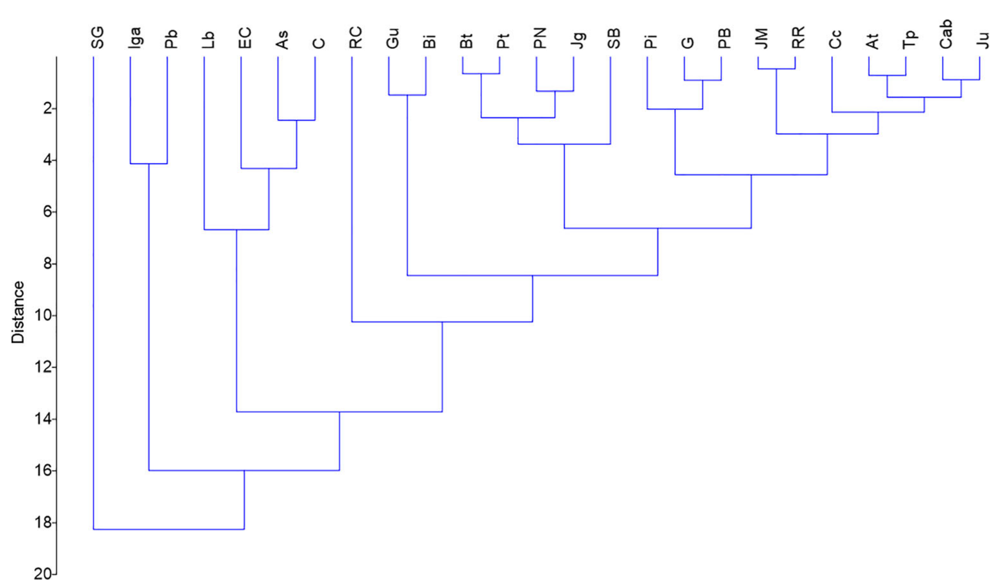

Fig. 4 Cluster analysis applied to 25 reservoirs in São Paulo State (Ward's method, with Euclidean distances)

Table 3 Pearson correlations among the variables, for 13 type I rainy east reservoirs, considering the rainy (n = 450) and dry seasons (n = 449) for the entire period analyzed. Values higher than 0.45 are given in bold and italics

		EC	DO	pH	TP	TN
Dry	DO	− 0.05*				
	pH	0.33*	0.19*			
	TP	0.42*	− 0.06	0.22*		
	TN	***0.45****	− 0.02	0.22*	0.28*	
	Chl-a	***0.52****	0.07	0.41*	0.36*	0.41*
Rainy	DO	0.01				
	pH	0.40*	0.21*			
	TP	0.43*	− 0.01	0.25*		
	TN	***0.45****	0.01	0.30*	***0.46****	
	Chl-a	***0.54****	− 0.03	0.46*	***0.54****	***0.51****

*Correlation significant at the < 0.05 level

N_2 fixation (Sardans et al. 2012). No significant differences between the dry and rainy seasons were observed for the molar N/P ratios (ANOVA: F = 0.59, df = 889.60, p = 0.44). Basic descriptive statistics for C, N, and P in each reservoir are in Table S3, SM.

3.2.2 Reference conditions establishment

Analysis using the t test indicated that there were no significant differences between the reference values obtained using the lake population distribution and trisection methods (p < 0.05) (Table 4). However, although the two methods provided similar reference conditions for nutrients and chlorophyll-a, the use of one-way ANOVA for all measured Chl-a concentrations revealed significant differences between dry and rainy seasons (F = 9.63, df = 896, p = 0.002). Higher mean concentrations in the rainy season were observed for TN (0.99 ± 2.82 and 0.89 ± 0.92 mg/L in the rainy and dry seasons, respectively) and Chl-a (33.41 ± 105.37 and 17.91 ± 33.84 ug/L in the rainy and dry seasons, respectively). These higher levels are explained by the characteristic increase in nutrients input from the watershed to the reservoirs in the rainy seasons (Smith et al. 2014; Cardoso-Silva et al. 2018), consequently increasing the phytoplanktonic biomass, which is usually evaluated using the Chl-a content. Actually, runoff is a decisive natural factor affecting the reference nutrient concentrations (Lewis Jr et al. 1999; Cheng and Li 2018). Hence, in tropical and subtropical areas, it is important to consider the dry and rainy seasons when establishing criteria for nutrients and Chl-a. In addition to the main nutrients, other factors that may contribute to seasonal differences of Chl-a include biological interactions (for example, zooplankton herbivory), other nutrients, temperature, and illumination.

The nutrient criteria obtained here were in agreement with previous work concerning the São Paulo State reservoirs (Cunha et al. 2012). In the earlier study, the trisection method was used to establish nutrient criteria, but the concept of typology was not employed, criteria were not established for different seasons, and a shorter database (5 years) was used. Table 5 shows nutrient criteria and Chl-a reference values for several other systems worldwide.

Considering the dry and rainy periods, it was expected that the trophic states of these environments would be ultra-oligotrophic, according to the TSI of Carlson (1977), adapted for tropical aquatic ecosystems by Cunha et al. (2013) (Table 6). However, for most of the time, the reservoirs exhibited nutrient and chlorophyll-a levels that exceeded the reference conditions, mainly because the reservoirs are located in regions strongly impacted by anthropic activities. The percentages of samples in non-compliance with the reference concentrations (Fig. 5a), are higher than 70% for TP, TN, and Chl-a. Samples were predominantly classified as mesotrophic and eutrophic in both seasons (Fig. 5b).

The eutrophication processes observed in most of the reservoirs, which have persisted for decades, were due to inadequate sewage collection and treatment. Ten of the reservoirs are situated in the Alto Tietê watershed (UGRHI 6), where the sewage collection rate (5th worst in São Paulo State) is still below 90% and the treatment rate (5th worst in the State) is around 50% (FABHAT 2018). A similar situation is observed

Table 4 Percentile and trisection methods applied to variables for 13 type I rainy east reservoirs of the São Paulo State (dry season, n = 450; rainy season, n = 449)

			Percentiles							Trisection
			5	10	25	50	75	90	95	
Dry	TP	mg/L	0.004	0.01	0.01	0.03	0.05	0.11	0.15	0.01
	TN	mg/L	0.09	0.22	0.25	0.60	1.04	1.72	2.52	0.25
	Chla	µg/L	0.80	1.07	2.94	6.72	15.02	35.15	57.62	2.00
Rainy	TP	mg/L	0.004	0.01	0.01	0.03	0.05	0.09	0.18	0.01
	TN	mg/L	0.13	0.25	0.25	0.57	1.10	1.87	2.55	0.25
	Chla	µg/L	1.25	1.86	3.43	8.91	22.78	62.28	122.64	2.52

Table 5 Reported nutrient criteria for TP and TN in freshwater ecosystems, and reference values for Chl-a

Ecosystem/location	Reference	Method	TP (mg/L)	TN (mg/L)	Chl-a (mg/m^3)
River/streams Distinct ecoregions (Kansas, USA)	Smith et al. (2003)	LPD	0.058 0.048 0.060 0.054	0.258 0.150 0.055 0.355	-
River/streams Distinct ecoregions (Kansas, USA)	Dodds and Oakes (2004)	LPD	0.023 0.031 0.059 0.023	0.566 0.70 0.659 0.215	–
Lakes/reservoirs (Kansas, USA)	Dodds et al. (2006)	RW; TR	0.019–0.062	0.201–0.695	–
Alpine lakes (Europe)	Wolfram et al. (2009)	HPM; MOD	–	–	1.9–3.3
River/streams (São Paulo, Brazil)	Cunha et al. (2011)	TR	0.04	0.34	–
Reservoir (São Paulo, Brazil)	Cunha et al. (2012)	TR	0.01	0.35	–
Lakes (China)	Huo et al. (2014a)	TR	0.025	0.55	1.6
		LPD	0.010–0.025	0.31–0.65	0.39–2.50
Shallow lakes (China)	Huo et al. (2014b)	TR	0.020	0.20	2.10
		MLR	0.017–0.022	0.177–0.215	0.58–2.83
Lakes (China)	Huo et al. (2015)	TR	0.005	0.11	0.86
		LPD	0.005	0.11	0.96
River (China)	Cheng and Li (2018)	RW; MLR	0.041–0.049	1.297–1.642	–

LPD lake population distribution, *RW* reference water body, *TR* trisection, *HPM* historical, paleolimnological, and monitoring data, *MOD* mathematical modeling, *MLR* multiple linear regression

for the other reservoirs, with four of the watersheds (UGRHI 5) presenting an average sewage collection rate of 92% and a treatment rate of 76% (FABH-PCJ 2018). The watersheds of two other reservoirs (UGRHI 2) present sewage collection and treatment of 73% and 15%, respectively (CBH-BS 2019).

The nutrient criteria and Chl-a established in this research were lower than the values established for class 1 and class 2 water bodies according to local legislation (Brasil 2005), where freshwater water bodies are classified using five categories, depending on their use. The uses of class 1 and class 2 water bodies are more restricted and consider the preservation of the natural balance of aquatic communities and the protection of aquatic communities, respectively. The mean values for Chl-a in the reservoirs were 9.74-fold and 6.09-fold higher than the predicted value for Chl-a (10 ug/L) in rainy and dry season. According to Brasil 2005, the TSI limit values, considering TP and Chl-a, are 54.9 (mesotrophic) and 58.2 (eutrophic) for classes 1 and 2, respectively, which are not coherent with the assumptions of preservation and protection of aquatic communities. Therefore, the threshold values for TP and Chl-a should be reviewed.

Based on the premise that different types have different characteristics and specific ecological functions, it is possible to presume that can be observed different nutrient and Chl-a criteria for each determined typology. Although the criteria may be different in the established typologies, we can expect the same standard of higher Chl-a levels in the rainy season, as this pattern has been observed in several reservoirs.

Table 6 Trophic state index (TSI) classifications (Cunha et al. 2013) for the nutrient criteria established in this work for 13 type I rainy east reservoirs

	Methods				TSI	
	Percentiles			Trisection	Classification	Values
	5	10	25			
					Ultra-oligotrophic	<51.1
					Oligotrophic	51.2 to 53.1
Dry	46.8	49.2	50.8	49.8	Mesotrophic	53.2 to 55.7
					Eutrophic	55.8 to 58.1
Rainy	47.2	49.2	51.1	50.6	Super-eutrophic	58.2 to 59.0
					Hyper-eutrophic	≥59.1

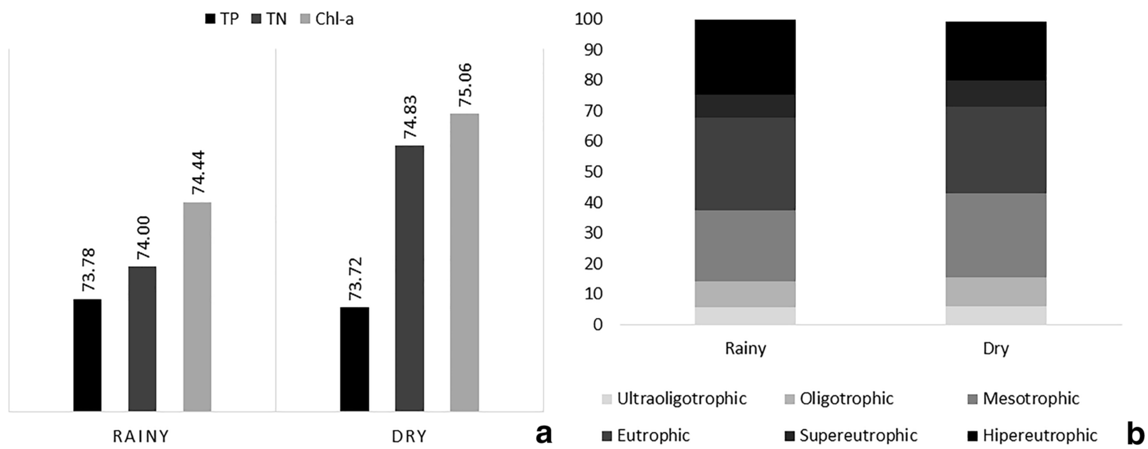

Fig. 5 Percentages of samples: in non-compliance with the reference concentrations (**a**) and according to trophic state index (TSI) in dry and rainy seasons in 13 type I rainy east reservoirs (**b**)

4 Conclusions and final considerations

The establishment of a typology and reference conditions can make an important contribution to water resource management strategies. In the present work, the typology identified an environmental gradient in the east-west direction of São Paulo State, revealing the existence of four major reservoir types, suggesting the need to manage these systems in different ways, since they naturally differed. Nutrient criteria and predicted Chl-a values were obtained for the type I rainy east reservoirs, because these reservoirs are exposed to a range of anthropogenic impacts and are more frequently monitored, resulting in large amounts of data. The two methods employed are not exclusive and were effective in determining nutrient criteria for TN and TP during different seasons. The nutrient criteria and Chl-a reference conditions were 0.01 mg/L (TP), 0.25 mg/L (TN), and 2.52-3.43 μg/L (Chl-a) in the rainy season, and 0.01 mg/L (TP), 0.25 mg/L (TN), and 2.00 − 2.44 μg/L (Chl-a) in the dry season. No significant differences were observed for the nutrient criteria, while the predicted Chl-a values were slightly higher in the rainy season and lower than the value established by local environmental legislation (10 μg/L). The differences between seasons could have been influenced by factors other than P and N, including ecological interactions (such as herbivory or competition), other nutrients, irradiation, and thermal stratifications. It is therefore recommended that seasonal variability should be considered in the establishment of reference conditions and that the standards established in local environmental legislation should be revised.

To sum up, the establishment of both typology and reference conditions can be used as a tool for managers in order to produce public policies, create plans, and implement programs for the recovery of water bodies, with a better definition of the objectives. For example, this system could be used to establish standards and limits for effluent discharges. We believe that this work should assist in encouraging closer dialogue between the scientific community and water resource managers, contributing to the sustainability of water bodies.

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Authors' contributions All authors contributed to the study conception and design as follows: Sheila Cardoso-Silva: conceptualization, writing original draft, formal analysis, investigation. Daniele Frascareli: visualization, investigation. Daniel C.V.R. Silva: editing, writing review. Rubens Cesar Lopes Figueira: formal analysis, writing review. Marisa Dantas Bittencourt: formal analysis. Viviane Moschini-Carlos: supervision, funding acquisition, project administration. Marcelo L. M. Pompêo: supervision, funding acquisition, project administration. All authors commented on previous versions of the manuscript and read and approved the final manuscript.

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Data availability (1) Part of datasets analyzed during the current study are available in the São Paulo environmental agency website, CETESB repository: https://cetesb.sp.gov.br/aguas-interiores/publicacoes-e-relatorios/ and (2) Part of the data analyzed during this study are included in this published article and its supplementary information files.

Compliance with ethical standards

Competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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