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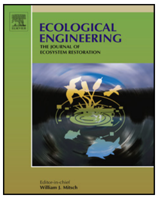

A trophic state index for tropical/subtropical reservoirs (TSI_{tsr})

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ABSTRACT

Trophic state is an important property of the aquatic ecosystems as it reflects the anthropogenic influence on water quality and the ecological functioning of rivers, lakes and reservoirs. Trophic state indexes provide an insight on how nutrient and light availability controls phytoplankton development. We analyzed data on total phosphorus (TP, $N = 931$), chlorophyll *a* (Chl *a*, $N = 848$) and Secchi disk depth (SDD, $N = 204$) monitored in 18 tropical/subtropical reservoirs from 1996 to 2009 by the Environmental Protection Agency of São Paulo State (Brazil) in a bimonthly basis. Through linear regression with paired data on "TP × Chl *a*" and "Chl *a* × SDD", we proposed a new trophic state index for tropical/subtropical reservoirs (TSI_{tsr}). Based on the annual geometric mean concentrations of TP and Chl *a*, we also assessed the risk of occurrence of individual episodes (e.g. Chl $a \geq 30$ μg/L or TP ≥ 50 μg/L) within six categories: ultraoligotrophic (U), oligotrophic (O), mesotrophic (M), eutrophic (E), supereutrophic (S) and hypereutrophic (H). The upper boundaries (as annual geometric means) are (μg/L): 15.9 (U), 23.8 (O), 36.7 (M), 63.7 (E) and 77.6 (S) for TP and 2.0 (U), 3.9 (O), 10.0 (M), 20.2 (E) and 27.1 (S) for Chl *a*. The lower boundaries for the hypereutrophic state were (μg/L) 77.7 (TP) and 27.2 (Chl *a*). Comparisons with criteria available in the literature suggested that trophic state limits established for temperate systems are not suitable for tropical/subtropical reservoirs and may overestimate their enrichment condition. Restrictions of the TSI_{tsr} are discussed in light of the limiting-nutrient concept, the spatial and temporal water quality variability and the use of Chl *a* as an indicator of phytoplankton density and biomass. The TSI_{tsr} may aid in reservoirs management as a starting point for analyzing data on water quality in the tropics/subtropics since this issue is of paramount importance worldwide.

1. Introduction

Artificial dams and reservoirs have been extensively built in Latin America, modifying natural aquatic systems to suit human activities. Such reservoirs were primarily built for energy generation in most cases, but are now used for other purposes, such as water supply, irrigation, flood control, recreation and fisheries. Anthropogenic eutrophication linked with excessive nutrient inputs from domestic wastewater, agricultural and urban runoff is threatening the different water uses worldwide, particularly in tropical and subtropical water bodies due to the population increase and a still poor sewage treatment infrastructure (Ortiz-Jiménez et al., 2006; Cunha et al., 2011). In Brazil, the phytoplankton seasonal variation, the impact of disturbances factors and their implications for Cyanobacteria dominance and the limiting factors for phytoplankton growth in artificial reservoirs were assessed in recent years (Angelini and Petrere, 2000; Sotero-Santos et al., 2006; Rivera et al., 2007; Chellappa et al., 2009; Cunha and Calijuri, 2011; Sant'Anna et al., 2011; Dantas et al., 2012). Eutrophication has also been affecting the reservoirs ecological balance and increasing their environmental vulnerability in Brazil (Figueirêdo et al., 2007; Rangel et al., 2012).

Trophic state indexes promote data grouping and organization, guiding decision making and aiding in the water resources management (e.g. Galvez-Cloutier and Sanchez, 2007; Yang et al., 2012). These indexes provide an insight on how nutrient, light availability and other factors stimulate algal biomass development (usually measured as chlorophyll *a*, Chl *a*) and contribute to the increase of the aquatic systems enrichment condition (Duka and Cullaj, 2009). However, there is no consensus on the mechanisms regulating nutrient–chlorophyll relationships in water bodies located in different climate regions (Huszar et al., 2006). Although one common view is that nitrogen limitation may be more frequent in tropical systems (Lewis, 2002), some authors reported that nitrogen did not explain a significant portion of chlorophyll variation in tropical/subtropical water bodies (e.g. Mazumder and Havens, 1998). Therefore, no established rule associating nitrogen or phosphorus limitation (or even co-limitation) with tropical/subtropical

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or temperate lakes and reservoirs is available thus far (Sterner, 2008).

A trophic state index for temperate lakes was proposed by Carlson (1977) considering empirical relationships among Chl *a*, total phosphorus (TP) and Secchi disk depth (SDD). This index has been frequently used by researchers and government institutions to indirectly estimate the algal biomass and indicate the eutrophication degree of lentic systems. However, the relationships and the equations for calculating the index should be adapted when applied to aquatic systems different from those from Carlson's study, otherwise they can lead to misconceptions when proceeding a trophic status assessment. Such adaptations can be related with adding new parameters and variables (e.g. satellite imagery for assessing SDD and Chl *a*—Olmanson et al., 2008; Sheela et al., 2011; toxic algae densities for evaluating the potential risk of toxins production—Sulis et al., 2011) or performing a specific calibration of the original Carlson's model based on regressions with local data (Cheng et al., 2001).

Salas and Martino (1991) proposed a simplified total phosphorus model and a trophic state classification for warm-water tropical lakes. These authors reported upper limits for the oligotrophic, mesotrophic and eutrophic status in relation to the geometric means of TP and Chl *a* concentrations. The classification presented by Salas and Martino (1991) was considered more appropriate to determine the trophic condition of seven lakes in Southeastern Brazil in comparison to that derived from the index proposed by Carlson (Petrucio et al., 2006), reinforcing the importance of establishing specific criteria for tropical/subtropical lakes and reservoirs.

In this paper, we aimed to propose a trophic state index for tropical/subtropical reservoirs (TSI_{tsr}) as well as limits for TP and Chl *a* concentrations for six trophic levels: ultraoligotrophic, oligotrophic, mesotrophic, eutrophic, supereutrophic and hypereutrophic. We also evaluated the probability of occurrence of individual critical episodes (e.g. Chl *a* higher than 30 μg/L or TP higher than 50 μg/L) for each of these categories. Previous studies have presented trophic state indexes and criteria for Southeastern reservoirs (e.g. Salas and Martino, 1991; Lamparelli, 2004), but the revision and update of such indexes are desirable. In this study, we selected reservoirs in the São Paulo State (Brazil) with different water chemistry, topographical features and morphological attributes. Such aquatic systems were comprehensively monitored from 1996 to 2009 to consider both natural and human-induced variability in the water quality, producing a significant number of available data.

2. Materials and methods

2.1. Study area

São Paulo State is located in the Southeast region of Brazil (Fig. 1) and has an area of approximately 248,000 km^2. The state has 41.2 million inhabitants with an associated demographic density of 168 inhabitants/km^2 (SEADE, 2011). According to Köppen (1936) climate classification, there are seven climate types in the São Paulo territory, whose differences are mainly related to average annual and monthly temperatures and precipitation. The most common climate types in the territory reflect tropical/subtropical conditions: *Cwa* (humid subtropical) and *Aw* (tropical wet and dry). The major impacts to the water quality are derived from the domestic and industrial wastewater discharges and the runoff from agricultural areas (mainly in the West part of the state) and urban ones (mainly in the East). Only 55% of the total volume of domestic wastewater are submitted to some level of treatment before being released into the water bodies (CETESB, 2011).

2.2. Data collection and analysis

We compiled data from 18 tropical/subtropical reservoirs (Table 1) that were monitored from 1996 to 2009, most of the time in a bimonthly basis, and sampled in the water surface in the lacustrine zone near the dam by CETESB (1996–2009), the Environmental Protection Agency of São Paulo State. TP and Chl *a* concentrations (μg/L) and SDD measurements (m) were used in our analyses. The selection of the reservoirs was based on data availability (i.e. all aquatic systems with available time series and paired data were selected). Analytical laboratory methods followed standard methods (APHA, 2005). Annual geometric means (Gmean) for each variable and reservoir were calculated through Eq. (1), considering *n* data of a given variable *x*.

$$\text{Gmean} = \sqrt[n]{x_1 x_2 x_3 \cdots x_n} \qquad (1)$$

We organized the annual Gmean of TP and Chl *a* in the ascending order for each variable and divided them in five subdatasets, corresponding to the ultraoligotrophic (0–20th percentiles), oligotrophic (20–40th), mesotrophic (40–60th), eutrophic (60–80th) and supereutrophic (80–100th) categories. The sixth category, corresponding to the hypereutrophic level, was defined considering data from the Billings and Barra Bonita reservoirs, which are among the most degraded aquatic systems in the state. The medians of the annual Gmean of TP and Chl *a* in such reservoirs were considered as the lower limits of this category. We also used the subdatasets to calculate the probability of occurrence of individual episodes of Chl *a* or TP concentrations higher than specific concentrations. The percentages of Chl *a* concentrations exceeding 10 μg/L, 30 μg/L and 50 μg/L and TP exceeding 30 μg/L and 50 μg/L were calculated for each of the six trophic state categories. These values were chosen because they are environmental standards established in the Brazilian legislation by the national council for the environment (CONAMA) (Table 2). Such legislation defines different classes of water and is based on the allowed water uses (Brasil, 2005). Also, these values were proposed as alert levels for actions concerning Cyanobacteria blooms and water uses (Chorus and Bartram, 1999).

We used linear regression to look for correlations between paired data on "TP × Chl *a*" and "Chl *a* × SDD" through a confidence level of 99% ($p^* < 0.01$). We obtained correlations that are generically expressed by Eqs. (2) and (3). These equations were substituted into Eq. (4), originally proposed by Carlson (1977). Finally, we determined Eqs. (5) and (6), which can be considered a version of the Carlson's model that was locally calibrated to better describe the tropical/subtropical reservoirs. The trophic state index for tropical/subtropical reservoirs (TSI_{tsr}) could then be calculated through the arithmetic mean between $TSI(TP)_{tsr}$ and $TSI(Chl\ a)_{tsr}$. We compared the new TSI_{tsr} and the respective trophic state boundaries with other indexes and criteria established for temperate and tropical water bodies available in the peer-reviewed literature.

$$\ln \text{Chl}\, a = \alpha \ln \text{TP} + \beta \qquad (2)$$

$$\ln \text{SDD} = \phi \ln \text{Chl}\, a + \gamma \qquad (3)$$

$$\text{TSI(SDD)} = 10\left(6 - \frac{\ln \text{SDD}}{\ln 2}\right) \qquad (4)$$

$$\text{TSI}\,(\text{Chl}\, a)_{\text{t sr}} = 10\left[6 - \left(\frac{\phi \ln \text{Chl}\, a + \gamma}{\ln 2}\right)\right] \qquad (5)$$

$$\text{TSI}\,(\text{TP})_{\text{t sr}} = 10\left[6 - \left(\frac{\phi(\alpha \ln \text{TP} + \beta) + \gamma}{\ln 2}\right)\right] \qquad (6)$$

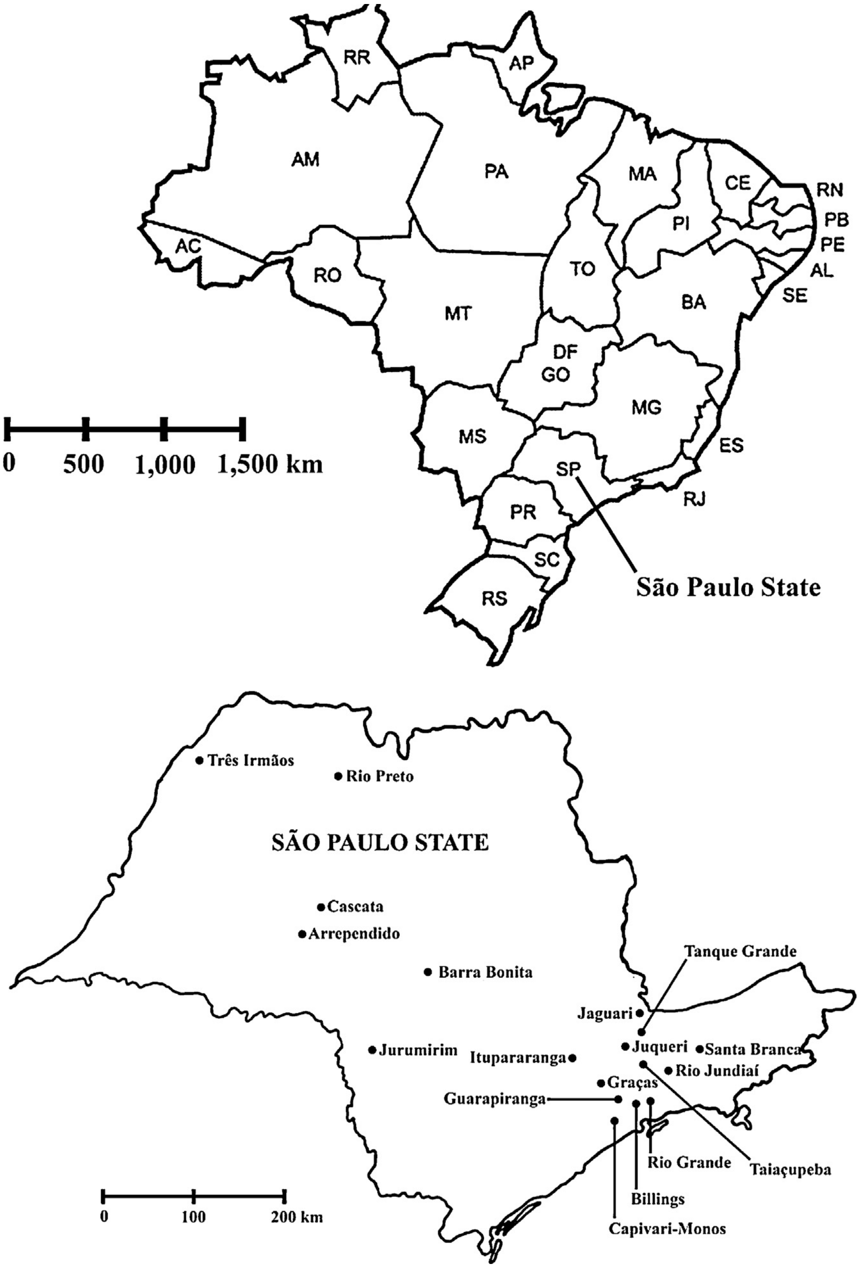

Fig. 1. Schematic maps of São Paulo State, Brazil and the approximate location of the analyzed tropical/subtropical reservoirs. Reference: Adapted from Cunha et al. (2012).

where α, ϕ: angular coefficients; β, γ: linear coefficients; TSI (Chl a)$_{tsr}$: Trophic state index for tropical/subtropical reservoirs in relation to the Chl a concentrations; TSI (TP)$_{tsr}$: trophic state index for tropical/subtropical reservoirs in relation to the TP concentrations; TSI$_{tsr}$: Trophic state index for tropical/subtropical reservoirs

3. Results

The annual Gmean concentrations varied between 6.9 µg/L and 124.5 µg/L for TP ($N=931$) and 0.7–40.6 µg/L for Chl a ($N=848$) within the studied tropical/subtropical reservoirs (Table 3). The minimum and maximum Gmean of the SDD measurements were 0.5 m and 2.4 m ($N=204$). Upper concentrations for TP and Chl a were defined for the ultraoligotrophic (U), oligotrophic (O), mesotrophic (M), eutrophic (E) and supereutrophic (S) categories (Table 4). The respective proposed limits considering annual Gmean concentrations are 15.9 µg/L (U), 23.8 µg/L (O), 36.7 µg/L (M), 63.7 µg/L (E) and 77.6 µg/L (S) for TP and 2.0 µg/L (U), 3.9 µg/L (O), 10.0 µg/L (M), 20.2 µg/L (E) and 27.1 µg/L (S) for Chl a.

The exceedance of specific TP and Chl a concentrations in each trophic state level was assessed as probabilities of occurrence of individual episodes in a random sample (Table 4). TP concentrations, for example, can exceed 30 µg/L with probabilities of 17% and 99% in the ultraoligotrophic and supereutrophic categories, respectively. The probabilities of Chl a concentrations higher than 50 µg/L were 9% for the eutrophic class, 34% for the supereutrophic and 37% for the hypereutrophic.

Significant correlations were found between TP and Chl a (Fig. 2, Eq. (7), $p^* < 0.01$) and Chl a and SDD (Fig. 2, Eq. (8), $p^* < 0.01$). Considering the Chl a boundary between the mesotrophic and eutrophic categories (10.0 µg/L), for example, the equivalent TP concentration calculated through Eq. (7) is 47.3 µg/L. We used the

Table 1
Name, geographic coordinates (latitude and longitude), area (km^2), age (years), water residence time (days) and maximum depth (m) of the 18 tropical/subtropical reservoirs whose data on total phosphorus, chlorophyll *a* and Secchi disk depth were used to determine the trophic state index and boundaries.

Reservoir	Geographic coordinates	Area (km^2)	Age (years)	Water residence time (days)	Maximum depth (m)
Arrependido	22°19′S; 50°01′W	<1	>50	–	–
Barra Bonita	22°32′S; 48°26′W	310	47	100	25
Billings	23°47′S; 46°35′W	127	84	620	35
Capivari-Monos	23°55′S; 46°43′W	7	>50	–	–
Cascata	22°12′S; 49°55′W	<1	38	–	–
Graças	23°39′S; 46°58′W	<1	93	1	–
Guarapiranga	23°45′S; 46°46′W	27	>100	145	15
Itupararanga	23°36′S; 47°17′W	936	96	184	20
Jaguari	22°55′S; 46°25′W	56	29	184	50
Juqueri	23°20′S; 46°39′W	314	45	–	–
Jurumirim	23°15′S; 49°00′W	449	51	323	40
Rio Grande	23°46′S; 46°30′W	7	30	319	–
Rio Jundiaí	23°38′S; 46°11′W	17	31	542	–
Rio Preto	20°48′S; 49°22′W	<1	56	–	–
Santa Branca	23°20′S; 45°47′W	27	51	60	46
Taiaçupeba	23°34′S; 46°17′W	20	34	55	12
Tanque Grande	23°22′S; 46°27′W	<1	52	–	–
Três Irmãos	21°02′S; 50°28′W	785	18	200	–

–: Not available.

Table 2
Upper limits (μg/L) for total phosphorus (TP), chlorophyll *a* (Chl *a*) and cyanobacteria density (cells/mL) according to the standards established by resolution CONAMA 357/2005 for the five different classes (Special, 1–4) of Brazilian freshwater lakes and reservoirs (retention time >40 days).

Class	Upper limits			Characteristics and main uses
	TP (μg/L)	Chl *a* (μg/L)	Cyanobacteria (cells/mL)	
Special	*	*	*	Best water quality (water supply and conservation)
1	20	10	20,000	Good water quality (wildlife protection, water supply after simplified treatment)
2	30	30	50,000	Intermediary water quality (no chronic toxicity)
3	50	60	100,000	Intermediary water quality (no acute toxicity)
4	*	*	*	Bad water quality (navigation)

CONAMA means “National Council for the Environment”.

* No upper limits were fixed. Pristine conditions must be maintained. Reference: Adapted from Brasil (2005).

generated Eqs. (7) and (8) to define the expression for calculating the trophic state index for tropical/subtropical reservoirs (TSI_{tsr}, Eqs. (9)–(11). The TSI_{tsr} values associated with the different trophic state categories (Table 4) were ≤51.1 (ultraoligotrophic), 51.2–53.1 (oligotrophic), 53.2–55.7 (mesotrophic), 55.8–58.1 (eutrophic), 58.2–59.0 (supereutrophic) and ≥59.1 (hypereutrophic).

$$\ln \text{Chl}a = 1.1002 \ln \text{TP} - 1.94072 \tag{7}$$

$$\ln \text{SDD} = -0.2512 \ln \text{Chl}a + 0.842257 \tag{8}$$

$$\text{TSI}_{\text{tsr}} = \frac{\text{TSI(TP)}_{\text{tsr}} + \text{TSI(Chl}a)_{\text{tsr}}}{2} \tag{9}$$

where

$$\text{TSI(TP)}_{tsr} = 10\left[6 - \left(\frac{-0.27637 \ln \text{TP} + 1.329766}{\ln 2}\right)\right] - \tag{10}$$

Table 3
Annual geometric mean (Gmean), minimum (Min) and maximum (Max) concentrations of total phosphorus and chlorophyll *a* (μg/L) and values of Secchi disk depth (m) in the analyzed tropical/subtropical reservoirs. The number of available data is shown for each case (*N*).

Reservoir	TP				Chl *a*				Secchi			
	Gmean (μg/L)	Min (μg/L)	Max (μg/L)	*N*	Gmean (μg/L)	Min (μg/L)	Max (μg/L)	*N*	Gmean (m)	Min (m)	Max (m)	*N*
Arrependido	19.3	10.0	90.0	14	4.0	1.6	14.7	14	–	–	–	–
Barra Bonita	124.5	10.0	3210	98	24.5	1.3	1804	98	1.3	0.6	2.7	28
Billings	44.8	10.0	210.0	115	40.6	6.9	210.5	96	0.9	0.3	1.7	80
Capivari-Monos	21.4	10.0	100.0	47	2.0	0.5	4.0	23	–	–	–	–
Cascata	58.1	10.0	180.0	26	39.7	3.3	141.9	25	–	–	–	–
Graças	29.1	10.0	720.0	48	5.6	2.4	11.4	48	–	–	–	–
Guarapiranga	69.7	10.0	3250	78	16.5	0.3	120.0	77	1.0	0.4	2.0	25
Itupararanga	18.8	10.0	130.0	95	4.4	0.4	22.8	92	–	–	–	–
Jaguari	11.3	5.0	50.0	48	2.8	<0.1	71.3	47	2.4	1.0	3.8	15
Juqueri	20.7	10.0	200.0	48	2.8	0.3	14.4	30	–	–	–	–
Jurumirim	15.6	10.0	70.0	35	0.7	<0.1	3.0	35	–	–	–	–
Rio Grande	36.6	10.0	150.0	30	11.5	2.3	27.5	29	–	–	–	–
Rio Jundiaí	35.9	10.0	190.0	48	16.2	5.9	54.4	48	1.3	1.3	1.3	1
Rio Preto	48.0	5.0	126.0	48	4.6	<0.1	43.3	48	0.5	0.1	0.8	12
Santa Branca	6.9	5.0	20.0	36	0.8	<0.1	9.3	35	2.4	1.0	3.8	23
Taiaçupeba	30.9	10.0	150.0	33	3.8	<0.1	37.4	36	1.0	0.5	1.7	20
Tanque Grande	21.6	10.0	380.0	48	1.4	<0.1	3.8	31	–	–	–	–
Três Irmãos	14.8	9.0	52.0	36	1.0	<0.1	5.0	36	–	–	–	–
Total				931				848				204

Table 4
Proposed trophic state categories (ultraoligotrophic, oligotrophic, mesotrophic, eutrophic, supereutrophic and hypereutrophic), including the respective annual geometric means for chlorophyll *a* and total phosphorus, the associated TSI_{tsr} (trophic state index for tropical/subtropical reservoirs) values and the probabilities of occurrence of individual episodes in a random sample (Chl $a \geq 10$ μg/L, Chl $a \geq 30$ μg/L, Chl $a \geq 50$ μg/L, $TP \geq 30$ μg/L and $TP \geq 50$ μg/L).

Trophic state category	Annual geometric mean of chlorophyll *a* (μg/L)	Probability of individual episodes within one year			Annual geometric mean of total phosphorus (μg/L)	Probability of individual episodes within one year		TSI_{tsr}
		Chl $a \geq 10$ μg/L (%)	Chl $a \geq 30$ μg/L (%)	Chl $a \geq 50$ μg/L (%)		$TP \geq 30$ μg/L (%)	$TP \geq 50$ μg/L (%)	
Ultraoligotrophic	≤2.0	<1	<1	<1	≤15.9	17	8	≤51.1
Oligotrophic	2.1–3.9	8	5	<1	16.0–23.8	37	17	51.2–53.1
Mesotrophic	4.0–10.0	9	4	<1	23.9–36.7	68	30	53.2–55.7
Eutrophic	10.1–20.2	45	24	9	36.8–63.7	86	54	55.8–58.1
Supereutrophic	20.3–27.1	76	63	34	63.8–77.6	99	88	58.2–59.0
Hypereutrophic	≥27.2	94	59	37	≥77.7	100	94	≥59.1

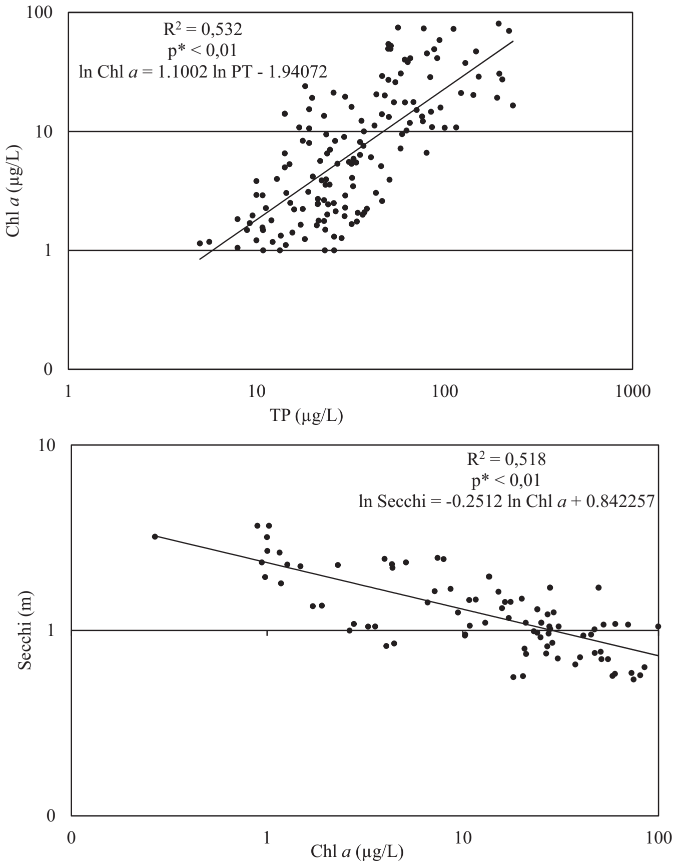

Fig. 2. Correlations between annual geometric mean concentrations of "total phosphorus (μg/L) versus chlorophyll *a* (μg/L)" and "chlorophyll *a* (μg/L) versus Secchi disk depth (*m*)" within the analyzed tropical/subtropical reservoirs.

$$TSI(Chla)_{tsr} = 10\left[6 - \left(\frac{-0.2512 \ln Chla + 0.842257}{\ln 2}\right)\right] \quad (11)$$

4. Discussion

Many factors are important for regulating the phytoplankton community in lakes and reservoirs, including micronutrients (Vrede and Tranvik, 2006; North et al., 2007), hydrology (Rangel et al., 2012), interactions with other biological communities (Sinistro et al., 2007; Hilt and Gross, 2008; Fonseca and Bicudo, 2010), operational procedures, management decisions in artificial reservoirs (Cunha et al., 2011; Wang et al., 2011) and climate change (Holland et al., 2012; Paerl and Paul, 2012; Sinha et al., 2012). However, nitrogen and phosphorus have been historically considered the main drivers of eutrophication (Vollenweider, 1987).

Temperate and tropical/subtropical aquatic systems have specific sensitivities to eutrophication (Huszar et al., 2006) because they are submitted to different levels of influence from climatological attributes and land use shifts, with associated changes in the water physical, chemical and biological characteristics (Ortiz-Jiménez et al., 2006). The prediction of trophic state may be more complex in tropical/subtropical freshwaters because there are more environmental constraints controlling nutrient dynamics and the phytoplankton responses in such water bodies. The main reason for establishing a specific index for tropical/subtropical reservoirs different from the Carlson's one is that the Carlson's model only considers the highest productive seasons in temperate lakes (spring and summer), whilst tropical/subtropical systems may have high primary production through all the year (e.g. Calijuri and Santos, 2001). The TSI_{tsr} calculus should thus comprise data from at least four annual sampling occasions (every three months) to account for seasonal variability, encompassing dry, rainy and intermediate periods.

High rainfall in tropical/subtropical regions may increment the nonpoint pollution from urban or agricultural areas and unbalance the biogeochemical cycles (Qin et al., 2010; Thothong et al., 2011). High temperatures increase evaporation rates (Freire et al., 2009) and possibly affect the depth and the circulation movements in the reservoirs water column. Although nitrogen losses are also favored by these higher temperatures (Lewis, 2002), some Cyanobacteria species are able to overcome this limitation through N-fixation (Haande et al., 2011). Therefore, phosphorus limitation was commonly reported in tropical/subtropical waters at least since the 1980s (Gianesella-Galvão, 1985). In recent years, a chain of simultaneous limitation by nutrients and light was proposed in different ecosystems because the transition from phosphorus to nitrogen limitation was considered not an established point anymore (Elser et al., 2007; Danger et al., 2008; Pahlow and Oschlies, 2009; Harpole et al., 2011; Lai et al., 2011).

When building a new trophic state for aquatic systems, one (e.g. Matthews et al., 2002) could argue that it would be interesting to include phosphorus, nitrogen and light (e.g. SDD or non biogenic turbidity) as drivers for Chl *a* concentrations, the biomass indicator. However, only TP and SDD were chosen for this purpose in our study because nitrogen probably plays a less important role under a reservoir management point of view (Schindler et al., 2008), even if there is co-limitation by nitrogen and phosphorus. Nitrogen abatement would be less effective for eutrophication control because there are natural mechanisms to replace this nutrient deficit (Wang and Wang, 2009). There is evidence from other studies that chlorophyll decrease in the long-term is achievable with phosphorus, not nitrogen, reduction (Welch, 2009; Cunha et al., 2011), leading to significant water quality improvement (Istvánovics and Somlyódy, 2001).

Caution is needed when comparing the TSI_{tsr} values and the associated total phosphorus and chlorophyll *a* boundaries with other criteria for temperate systems because the proposed TSI_{tsr} is based on annual geometric means of TP and Chl *a* (Table 4). The use of Gmean was considered desirable to minimize the importance of outliers and to indicate the central tendency of the reservoirs trophic state within at least one year of monitoring. Trophic state boundaries for temperate aquatic systems are more restrictive when compared to the limits for tropical/subtropical reservoirs (Table 5). We established a Chl *a* upper limit of 10 μg/L for the mesotrophic–eutrophic boundary, whereas Carlson (1977), Carlson and Simpson (1996) and Vollenweider and Kerekes (1982) set the same limit as ∼6 μg/L. Overestimation of trophic state in tropical/subtropical freshwaters may thus result from the use of temperate models when assessing the enrichment condition of such aquatic systems. One possible reason for such overestimation is that most temperate models were developed for lakes and not reservoirs. Since lakes usually have higher residence times than reservoirs, phytoplankton growth in the former aquatic systems might be more significant considering the same condition in terms of nutrient availability. Also, water transparency in tropical/subtropical water bodies is frequently smaller due to the higher inputs of suspended material as a consequence of land use shifts and intense rainfall.

When comparing the TP upper limits for the tropical/subtropical reservoirs with those presented by Salas and Martino (1991) for tropical lakes (also as geometric means), the boundaries were similar for the oligotrophic (23.8 μg/L vs. 21.3 μg/L) and mesotrophic (36.7 μg/L vs. 39.6 μg/L) categories. However, our upper TP concentration for the eutrophic class was 63.7 μg/L, which is significantly more restrictive than the concentration proposed by Salas and Martino (1991) for this category, 118.7 μg/L (Table 5). We proposed a "hypereutrophic" level to conveniently make a distinction between different degrees of highly productive systems: supereutrophic (TP annual Gmean: 63.8–77.6 μg/L) and hypereutrophic (TP annual Gmean: ≥77.7 μg/L). For Chl *a*, only the limits for the oligotrophic class of both studies (ours and Salas and Martino's) showed agreement (Table 5). All our limits for TP and Chl *a* were more restrictive than those proposed by Lamparelli (2004) for tropical/subtropical reservoirs (Table 5), what is probably related to the different datasets that were used in each study and also to other criteria (e.g. phytoplankton bloom risk) that were considered by Lamparelli when defining the trophic state limits for each category. Also, our correlation equations between "TP × Chl *a*" ($\ln \text{Chl } a = 1.1002 \ln \text{TP} - 1.94072$) and "Chl *a* × SDD" ($\ln \text{SDD} = -0.2512 \ln \text{Chl } a + 0.842257$) were different from those obtained by Lamparelli (2004) ($\ln \text{Chl } a = 1.23564 \ln \text{TP-}2.5136$ and $\ln \text{SDD} = -0.34 \ln \text{Chl } a + 0.92$), probably as a function of data availability (more data available for our study, especially for SDD).

Considering the vertical distribution of phytoplankton and the differences on TP concentrations with depth is always recommended, but our dataset was limited to surface samples. Also, since most of the studied reservoirs have average depths higher than 5 m, the TSI_{tsr} should not be applied to shallower reservoirs, considering the most intense sediment–water interactions in such ecosystems. Two of the studied reservoirs (Guarapiranga and Rio Grande) were submitted to the application of algaecides (mainly copper sulfate). However, there was a significant correlation between Chl *a* and TP even in such cases (Lamparelli, 2004).

As any other indexes, trophic state indexes have limitations that were early detected (Brezonik, 1984; Walker, 1984). The eventual discrepancy between the calculated scores for the TSI(TP), TSI(Chl *a*) and other TSI values composing the arithmetic mean of the final TSI result has long been identified as a problem to be considered (Osgood, 1982). Temporal and spatial asynchrony of trophic status has been observed (Xu et al., 2011). In some cases, the TSI(Chl *a*) value indicates oligotrophy and the TSI(TP) corresponds to an eutrophic condition (Almeida et al., 2012), what makes questionable the accuracy and effectiveness of the index for assessing trophic state. This problem is probably more common in rivers and running waters, where despite the usually phosphorus-rich conditions, the lower residence time and light availability (Soares et al., 2007) may restrict the phytoplankton biomass development. However, considering that indexes are based on annual means and correlations among TP, Chl *a* and other variables, they can portrait broad conditions and facilitate decisions regarding water management.

Obtaining statistically reliable estimates of mean (or maximum) Chl *a* concentrations is also a point of concern because monitoring data can be limited and/or present significant heterogeneity both in temporal and spatial terms (Knowlton and Jones, 2006a,b). Including a probabilistic approach in our trophic state categories was an attempt to attenuate this problem. Within the eutrophic category in our dataset, for example, although annual Chl *a* Gmean concentrations should be between 10.1 μg/L and 20.2 μg/L, there is a risk of ∼24% of individual episodes of Chl *a* higher than 30 μg/L. Under a practical point of view, this would represent a risk of 24% of no compliance with the standards established by the Brazilian legislation (Table 2) for "Class 2" aquatic systems. Similarly, the mesotrophic level is associated with a 30% risk of TP exceeding 50 μg/L, which is the upper limit for the fourth class of water quality condition in the Brazilian water bodies ("Class 3", Table 2).

The sole use of trophic state indexes does not allow the assessment of phytoplankton community composition. The assessment

Table 5
Comparison between the trophic state boundaries for total phosphorus and chlorophyll *a* (μg/L) presented by this research and those proposed for temperate (Carlson,1977; Carlson and Simpson, 1996; Vollenweider and Kerekes, 1982) and tropical (Salas and Martino, 1991) aquatic systems.

Trophic state category	Total phosphorus (μg/L)				
	Carlson (1977), Carlson and Simpson (1996)	Vollenweider and Kerekes (1982)*	Salas and Martino (1991)**	Lamparelli (2004)	Our study**
Ultraoligotrophic	–	≤2.5	–	≤8.0	≤15.9
Oligotrophic	≤12.0	2.6–8.0	≤21.3	8.1–19.0	16.0–23.8
Mesotrophic	12.1–24.0	8.1–25.0	21.4–39.6	19.1–52.0	23.9–36.7
Eutrophic	24.1–96.0	25.1–80.0	39.6–118.7	52.1–120.0	36.8–63.7
Supereutrophic	–	–	–	120.1–233.0	63.8–77.6
Hypereutrophic	≥96.1	≥80.1	≥118.8	≥233.1	≥77.7
Trophic state category	Chlorophyll *a* (μg/L)				
	Carlson (1977), Carlson and Simpson (1996)	Vollenweider and Kerekes (1982)*	Salas and Martino (1991)**	Lamparelli (2004)	Our study**
Ultraoligotrophic	–	≤0.7	–	≤1.2	≤2.0
Oligotrophic	≤2.6	0.8–2.1	≤3.6	1.3–3.2	2.1–3.9
Mesotrophic	2.7–6.4	2.2–6.3	3.7–6.7	3.3–11.0	4.0–10.0
Eutrophic	6.5–56.0	6.4–19.2	6.8–17.4	11.1–30.6	10.1–20.2
Supereutrophic	–	–	–	30.7–69.1	20.3–27.1
Hypereutrophic	≥56.1	≥19.3	≥17.5	≥69.2	≥27.2

* Annual arithmetic means.
** Annual geometric means.

of Cyanobacteria and toxins production (Dogo et al., 2011; Rangel et al., 2012) can be a desirable complementary study in multipurpose reservoirs, especially in those storing drinking water. Standards for the Cyanobacteria densities were established in the Brazilian regulations (Table 2). The phytoplankton metabolism and the physiological-related aspects are not expressed through the trophic state indexes. Chl *a* as an estimator of phytoplankton biomass has to be used with caution (Kasprzak et al., 2008). Dinoflagellates (Felip and Catalan, 2000) and some Cyanobacteria species (Vargas, 2012) can have relatively low chlorophyll content per biovolume. Since algae and cyanobacteria can have different accessory pigments (e.g. chlorophyll *b*, *c* and carotenoids), weak correlations between Chl *a* and phytoplankton total density can be found. The use of Chl *a* as a biomass indicator would underestimate the final value of the TSI in such cases.

Trophic state is an important property that is deeply related to ecosystem functioning and anthropogenic influence on water quality (Dodds and Cole, 2007). Trophic state measurements are submitted to many uncertainties (Lambou et al., 1983). Depending on the purpose of the analyses, other tools are available to complement the use of trophic state indexes, including modeling (Panikkar and Khan, 2008; Gubiani et al., 2011; Zhang and Rao, 2012), in situ experiments with nutrient addition (Perkins and Underwood, 2000; Hunt and Matveev, 2005), thermodynamic indices (Ludovisi and Poletti, 2003) and specific studies on biological communities, such as phytoplankton (Karadžić et al., 2010), zooplankton (Dejenie et al., 2012), aquatic macrophytes (Ginn, 2011), fish (Terra and Araújo, 2011) and heterotrophic bacteria (Rippey and Cabelli, 1989). Despite all the limitations of trophic state indexes, such an approach has its practical use for long term monitoring and management purposes. The proposed TSI_{tsr} may help water management and be a starting point for interpreting and organizing data on water quality in the tropics/subtropics.

5. Conclusions

Trophic state indexes are an important part of the water quality studies. Based on water variables that are relatively simple to measure and quantify, they are easy to calculate and simple to understand and explain. The main highlights of the proposed TSI_{tsr} and the associated TP and Chl *a* limits for the ultraoligotrophic, oligotrophic, mesotrophic, eutrophic, supereutrophic and hypereutrophic categories in tropical/subtropical reservoirs are: (i) trophic state criteria for temperate systems may overestimate the enrichment condition of tropical/subtropical reservoirs. The TSI_{tsr} is a calibrated version of the original Carlson index that is more appropriate for tropical/subtropical reservoirs; (ii) the probabilistic approach in our trophic state criteria may help the decision making process when managing reservoir eutrophication and estimating the risk of phytoplankton blooms; (iii) in comparison with previous investigations (e.g. Lamparelli, 2004), our study contributed to update and revise established indexes and criteria, since more data were available and for a longer period of time; (iv) the use of the TSI_{tsr} in other studies is encouraged to confirm its suitability for tropical/subtropical freshwaters.

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