Nutrient reference concentrations and trophic state boundaries in subtropical reservoirs

D. G. F. Cunha, A. P. Ogura and M. d. C. Calijuri

ABSTRACT

Nutrient criteria as reference concentrations and trophic state boundaries are necessary for water management worldwide because anthropogenic eutrophication is a threat to the water uses. We compiled data on total phosphorus (TP), nitrogen (TN) and chlorophyll *a* (Chl *a*) from 17 subtropical reservoirs monitored from 2005–2009 in the São Paulo State (Brazil) to calculate reference concentrations through the trisection method (United States Environmental Protection Agency). By dividing our dataset into thirds we presented trophic state boundaries and frequency curves for the nutrient levels in water bodies with different enrichment conditions. TP and TN baseline concentrations (0.010 mg/L and 0.350 mg/L, respectively) were bracketed by ranges for temperate reservoirs available in the literature. We propose trophic state boundaries (upper limits for the oligotrophic category: 0.010 mg TP/L, 0.460 mg TN/L and 1.7 μg Chl *a*/L; for the mesotrophic: 0.030 mg TP/L, 0.820 mg TN/L and 9.0 μg Chl *a*/L). Through an example with a different dataset (from the Itupararanga Reservoir, Brazil), we encouraged the use of frequency curves to compare data from individual monitoring efforts with the expected concentrations in oligotrophic, mesotrophic and eutrophic regional systems. Such analysis might help designing recovery programs to reach targeted concentrations and mitigate the undesirable eutrophication symptoms in subtropical freshwaters.

Key words | baseline concentrations, eutrophication, subtropical lentic systems, trophic state classification, water resources management

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INTRODUCTION

'*It became progressively clear that (1) nitrogen and phosphorus are the motors of the* [eutrophication] *process, (2) phosphorus is normally the more important factor, (3) nitrogen and phosphorus load to lakes provides the basis for explaining the degree of eutrophication, and (4) as a consequence, control of these factors would lead to the solution of the problem*' (Vollenweider 1987). The efforts to manage the negative effects of eutrophication have substantially widened from the 1960s. Nutrient and light were recognized as important drivers regulating the autotrophic metabolism in the water environment. At the present time, attempts to reduce nitrogen and phosphorus loads to the rivers, lakes and reservoirs are considered one of the crucial steps to the environmental recovery of over-productive aquatic systems worldwide.

The negative impacts of the anthropogenic eutrophication are comprehensively described in the literature, with special attention in the recent years to cyanotoxins (Sotero-Santos *et al.* 2006; Moschini-Carlos *et al.* 2009; Teneva *et al.* 2010), climate change (Fragoso *et al.* 2011) and prediction models for the nutrients and phytoplankton (Catherine *et al.* 2011). Eutrophication is thus a threat to the use of water such as drinking water supply, irrigation and energy generation. The effectiveness of the water resources management depends upon adequate techniques to explore the best potential of the freshwaters for direct uses and indirect ones such as the environmental services (e.g. biodiversity maintenance and flood regulation).

The establishment of nutrient criteria may aid in lake and reservoir management as: (i) nutrient reference concentrations can be compared with the observed concentrations in a certain aquatic system to assess the negative impacts of the anthropogenic activities (e.g. climate change and land use shifts); (ii) trophic state boundaries may help setting targeted nutrient concentrations to reach desirable trophic state conditions, which must be compatible with the different water uses; and

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(iii) by determining the targeted concentrations, it is possible to compare them with the actual concentrations and determine the required reduction in incoming nutrient loads. Modeling (Reckhow 1993; Cardoso *et al.* 2007; Freeman *et al.* 2009), regionalization and delimitation of ecoregions (Rohm *et al.* 2002), use of ecological indicators, biological indexes (Semenchenko & Razlutskij 2010), hydraulic flushing rates (Jones *et al.* 2008), land use records and historic concentrations (Jones *et al.* 2009) can aid in defining nutrient criteria and exploring the link between nutrients and chlorophyll *a*, which acts as an indirect measure of the biomass response.

Although lakes and reservoirs from temperate regions have been more intensely studied historically, some efforts were done in the recent years to better characterize tropical and subtropical aquatic ecosystems. Salas & Martino (1991) proposed a simplified trophic state model based on phosphorus concentrations in tropical lakes. A discussion of the suitability of models for nutrient–chlorophyll relationships developed in temperate regions and applied to tropical and subtropical lakes was explored by Huszar *et al.* (2006). Nutrient baseline conditions were estimated by Cunha & Calijuri (2011) for subtropical reservoirs through the selection of 'reference reservoirs' (i.e. those located in forested catchments). Cunha *et al.* (2011) presented a long-term record of nutrient availability in a Brazilian reservoir and diagnosed its trophic state current condition based on a regional comparison with other reservoirs.

We aimed to calculate total phosphorus and nitrogen reference concentrations in subtropical reservoirs through a different method than that used by Cunha & Calijuri (2011). Also, we defined nutrient boundaries for three broad trophic state categories (oligotrophic, mesotrophic and eutrophic) taking into account chlorophyll *a* concentrations, organized in ascending order, and then the associated nitrogen and phosphorus concentrations. In this study, we selected aquatic systems in the São Paulo State (Brazil) with remarkably different characteristics in terms of water chemistry, topographical and morphological attributes (e.g. area and depth) to make our dataset as reliable as possible. Also, given the importance of considering the natural variability when setting nutrient criteria in aquatic systems (Knowlton & Jones 2006), the assessed water bodies were comprehensively monitored over time (continuously during 5 years).

METHODS

We collected data on TP, TN and Chl *a* concentrations from 17 subtropical reservoirs (21 sampling sites) monitored by the São Paulo State Environmental Company for 5 years, from 2005 to 2009 (CETESB 2005, 2006, 2007, 2008, 2009). All reservoirs are located in the São Paulo State (Brazil), with different areas and ages (Table 1) (Figure 1).

Nutrient and Chl *a* concentrations were determined according to Standard Methods (APHA 2005) with samples from the water surface. The nutrient reference concentrations were determined according to the trisection method proposed by Buck *et al.* (2000) and described by Dodds *et al.* (2006). The Chl *a* concentrations were organized in ascending order and the data were divided in three sub-datasets, corresponding to the oligotrophic (lower third; 0th to 33rd percentile), mesotrophic (33rd to 66th percentile) and eutrophic (upper third; 66th to 100th percentile) categories. We determined general reference concentrations and not type-specific ones because we ran preliminary MANOVA (multiway analysis of variance) and the data from all reservoirs were considered statistically similar ($p > 0.05$). We also ran Spearman rank correlation test to verify the strength of the correlation between nutrients and chlorophyll *a* through the Spearman coefficients (ρ). Linear regression among the studied variables was used with a statistical significance of 95% ($p < 0.05$). Cumulative frequency curves were built separately for the oligotrophic, mesotrophic and eutrophic sub-datasets with the respective TP and TN and Chl *a*

Table 1 | Name, geographic coordinates, area and age of the subtropical reservoirs whose data were used to determine nutrient reference concentrations and trophic state boundaries

Reservoir	Geographic coordinates	Area (km^2)	Age (years)
Arrependido	22°19′ S; 50°01′ W	<1	>50
Barra Bonita	22°32′ S; 48°26′ W	310	47
Billings	23°47′ S; 46°35′ W	127	84
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
Guarapiranga	23°45′ S; 46°46′ W	27	>100
Itupararanga	23°36′ S; 47°17′ W	936	96
Jaguari	22°55′ S; 46°25′ W	56	29
Juqueri	23°20′ S; 46°39′ W	314	45
Jurumirim	23°15′ S; 49°00′ W	449	48
Rio Grande	23°46′ S; 46°32′ W	7	30
Rio Jundiaí	23°38′ S; 46°11′ W	17	31
Rio Preto	20°48′ S; 49°22′ W	<1	56
Santa Branca	23°20′ S; 45°47′ W	27	51
Taiaçupeba	23°34′ S; 46°17′ W	20	34
Tanque Grande	23°22′ S; 46°27 W	<1	52

Figure 1 | Map of São Paulo State, Brazil and the approximate location of the 17 studied reservoirs.

concentrations. We used all raw data to build such curves and no equation or function was applied to fit data. All the statistical analyses were performed with the software Systat 10®.

RESULTS AND DISCUSSION

Determination of reference concentrations

The Chl *a* concentrations were significantly correlated with TP ($\rho = 0.51$, $p < 0.05$) and TN ($\rho = 0.64$, $p < 0.05$), indicating that both nutrients probably played an important role regulating the phytoplankton development in all the studied reservoirs (Table 2). The median TN/TP ratios varied from 30 to 35, reinforcing the probability of nutrient co-limitation according to criteria presented by Guildford & Hecky (2000) (20 <TN/TP <50) and Dzialowski *et al.* (2005) (20 <TN/TP <46). Positive correlations between TP and Chl *a* (correlation coefficients $0.558 < r < 0.651$) and negative ones between ammonium and Chl *a* ($-0.656 < r < -0.456$) were reported in an eutrophic temperate reservoir (Perkins & Underwood 2000), suggesting limitation only

Table 2 | Spearman correlation coefficients (ρ) among total phosphorus (TP) and chlorophyll *a* (Chl *a*), total nitrogen (TN) and chlorophyll *a* and total phosphorus and total nitrogen for the analyzed subtropical reservoirs. The ratio TN/TP and the number of data (*N*) are also shown for each case

Correlation	All data ($N = 489$)	Oligotrophic sub-dataset ($N = 163$)	Mesotrophic sub-dataset ($N = 163$)	Eutrophic sub-dataset ($N = 163$)
TP × Chl *a*	0.51*	0.31*	0.31	0.30*
TN × Chl *a*	0.64*	0.28*	0.33*	0.38*
TP × TN	0.62*	0.40*	0.55	0.63*
Median TN/TP	33	35	32	30

*Significance correlation – linear regression is statistically significant ($p < 0.05$).

Table 3 | Reference total phosphorus (TP) and total nitrogen (TN) concentrations in subtropical reservoirs (this study) and a comparison with other values and ranges established for aquatic systems in other countries

Location	TP (mg/L)	TN (mg/L)	Reference
Brazil	0.010	0.350	This study
	0.015	0.500	Cunha & Calijuri (2011)
Europe	0.005–0.034	–	Solheim (2005)
	0.004–0.019	–	Cardoso *et al.* (2007)
Finland	0.010	–	Crouzet *et al.* (1999)
Norway	0.003	–	Crouzet *et al.* (1999)
Sweden	0.013	–	Crouzet *et al.* (1999)
United States	0.019–0.062	0.201– 0.695	Dodds *et al.* (2006)
	0.003–0.024	–	Soranno *et al.* (2008)
	0.020	–	Trowbridge (2009)
	0.026–0.086	0.476–0.900	Justus (2010)

by phosphorus. As nutrient limitation studies in tropical areas found no uniform TP or TN limitation and described significant seasonal and between-system variances (Fisher *et al.* 1995; Huszar *et al.* 2006), co-limitation may be more common than previously thought (Elser *et al.* 2007).

The most important nutrient and organic matter sources to the aquatic systems in the São Paulo State are the domestic wastewater discharges into the water bodies (Cunha *et al.* 2011). However, non-point sources are not negligible as runoff from agricultural areas exporting sediments and pollutants to the water bodies (Tian *et al.* 2010). Considering our sub-datasets separately, the Spearman coefficients were relatively similar within the different trophic state classes (ρ between 0.30–0.31 for TP × Chl *a*, ρ between 0.28–0.38 for TN × Chl *a*, and ρ between 0.40 – 0.63 for TP × TN, Table 2).

The reference TP and TN concentrations we calculated for the analyzed reservoirs were 0.010 and 0.350 mg/L, respectively (Table 3). These values were bracketed by baseline criteria established for other lentic systems in Europe (where TP reference concentrations ranged between 0.003 and 0.034 mg/L) and North America (where TP baselines varied between 0.003 and 0.086 mg/L and TN ones varied between 0.201 and 0.900 mg/L). The relative wide ranges for TP and TN in Europe and North America are due to the determination of specific reference values for different ecoregions in the territory. Although there is no consensus about the best method for estimating reference conditions, there was a reasonable agreement between the reference values we determined and those determined by Cunha & Calijuri (2011) through other technique, the best professional judgment method (0.015 mg TP/L and 0.500 mg TN/L).

Setting nutrient criteria is necessary to avoid aesthetic impairment and adverse effects on human health, biodiversity and water uses (Dodds & Welch 2000; Palmstrom 2005). Our results suggested that TP and TN limits in subtropical reservoirs would probably not be obtainable if they are set below 0.010 and 0.350 mg/L, respectively. TP benchmarks in biological communities were assessed by Soranno *et al.* (2008) for North American lakes. The authors established TP thresholds of 0.008 mg/L for zooplankton and 0.018 mg/L for phytoplankton metrics. These concentrations indicate limits above which nonlinear biological responses might be observed, with possible changes in control points of the ecosystem processes (Hildebrand *et al.* 2010).

Development of trophic state boundaries and application of nutrient criteria to the Itupararanga Reservoir

By dividing our dataset in three sub-datasets with increasing concentrations of Chl *a*, we could describe the expected TP and TN concentrations in the oligotrophic, mesotrophic and eutrophic reservoirs (Table 4). The respective median concentrations in these classes, which can be considered as boundaries between the trophic state categories, were 0.010, 0.030 and 0.058 mg/L for TP, 0.460, 0.820 and 2.0 mg/L for TN and 1.6, 8.6 and 34.8 μg/L for Chl *a*. We gathered data presented by Cunha & Calijuri (2011) for other subtropical lentic system (Itupararanga Reservoir) monitored during the years 2009 and 2010 and put it into a regional context with the other 17 reservoirs. We could thus further illustrate the application of the proposed reference concentrations and trophic state boundaries, exploring them as a tool for aiding in reservoir management.

According to the proposed trophic state boundaries, the Itupararanga Reservoir had median TP and Chl *a*

Table 4 | TP, TN and Chl *a* concentrations (minimum, maximum, median, mean, 10th and 90th percentiles) for the oligotrophic, mesotrophic and eutrophic reservoirs of our dataset and for the Itupararanga Reservoir. The number of data is shown for each case (*N*)

Dataset	Value	TP (mg/L)	TN (mg/L)	Chl *a* (μg/L)
Oligotrophic reservoirs ($N = 489$)	Minimum	<0.01	0.100	<0.1
	Maximum	0.380	7.2	3.7
	Median	0.010	0.460	1.6
	Mean	0.032	0.696	1.7
	10th percentile	<0.01	0.250	0.4
	90th percentile	0.08	1.2	3.2
Mesotrophic reservoirs ($N = 489$)	Minimum	<0.01	0.100	3.7
	Maximum	0.720	6.8	15.5
	Median	0.030	0.820	8.6
	Mean	0.047	1.2	9.0
	10th percentile	0.01	0.35	4.2
	90th percentile	0.09	2.3	14.5
Eutrophic reservoirs ($N = 489$)	Minimum	<0.01	0.300	15.6
	Maximum	3.2	30.0	1,804.3
	Median	0.058	2.0	34.8
	Mean	0.105	2.8	64.8
	10th percentile	0.02	0.710	18.3
	90th percentile	0.17	5.2	99.7
Itupararanga Reservoir ($N = 128$)[a]	Minimum	0.011	0.468	0.7
	Maximum	0.123	1.1	44.0
	Median	0.039	0.681	17.4
	Mean	0.046	0.732	18.0
	10th percentile	0.022	0.482	7.34
	90th percentile	0.075	0.972	28.8

[a]Data from Cunha & Calijuri (2011).

concentrations corresponding to the eutrophic state and median TN concentrations expected in mesotrophic aquatic systems. Therefore, a reduction of 74 and 51% in the median TP and TN concentrations in the Itupararanga Reservoir would be respectively necessary to reach the baseline conditions. Some authors argued that controlling nitrogen for trophic state reduction would provide limited benefit because nitrogen fixation continuously operates (Welch 2009). Since nitrogen loss is greater at high temperatures found in tropical–subtropical water bodies, fixation is probably an important source of this nutrient (Huszar *et al.* 2006). However, targeting both nutrients seems to be the most adequate option to alleviate eutrophication of the Itupararanga Reservoir, as suggested by Abell *et al.* (2010) for lake restoration in New Zealand. Recovery actions include external sources mitigation and eventual mechanisms to reduce internal loadings.

The cumulative frequency curves which are shown in Figure 2 provide an even more friendly tool to analyze the enrichment condition of a subtropical reservoir based on our criteria. The curves further illustrate how nutrient availability is expected to vary according to the trophic status in the subtropical reservoirs. Considering TP = 0.100 mg/L, for example, the probabilities of non-exceedance of such concentration were approximately 94% (for oligotrophic water bodies), 92% (mesotrophic) and 74% (eutrophic). On the other hand, the same percentages for TP = 0.02 mg/L were 64, 35 and 11%.

Probabilistic models can be useful for analyzing the exceedance frequency of water quality standards violations

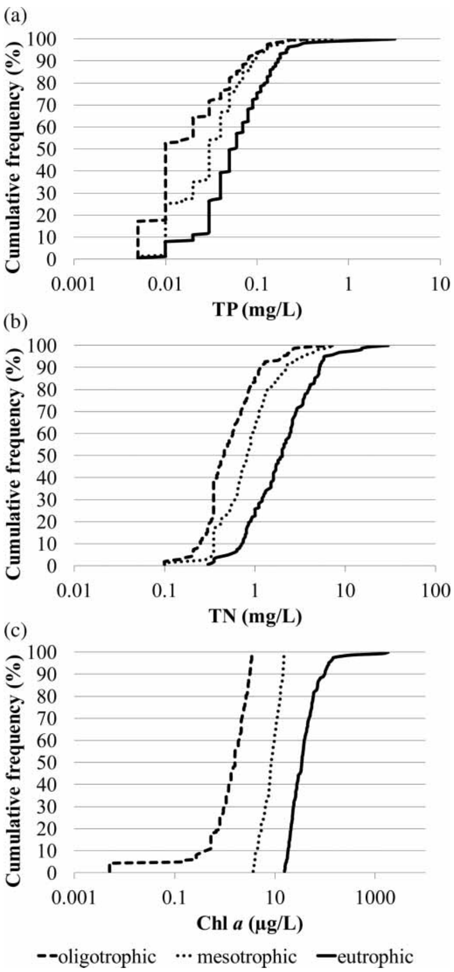

Figure 2 | Cumulative frequency curves based on a log scale for (a) total phosphorus (b) total nitrogen (TN) and (c) chlorophyll *a* (Chl) for the 17 reservoirs in the São Paulo State, Brazil, including the expected curves in oligotrophic, mesotrophic and eutrophic water bodies.

(Zhang & Arhonditsis 2008). The exceedance frequency for different chlorophyll *a* levels, based on the respective cumulative distribution, can be used to assess the aquatic system vulnerability to eutrophication, as reported for Lake Washington, United States (Arhonditsis *et al*. 2007). The frequency curves presented in Figure 2 may help the decision-making process by expressing the eutrophication risk of the reservoirs in a regional context and following a desirable probabilistic approach. Water management within these aquatic systems may be optimized to avoid extreme enrichment conditions and impairment to the water uses.

CONCLUSIONS

Considering the paucity of research on reference conditions and trophic state boundaries in subtropical reservoirs, our study was one of the first providing such information. Developing countries like Brazil are characterized by rapid shifts in the land use, population increase and lack of sanitation infrastructure. These are the main factors influencing negatively the water quality and imposing restrictions and risks to water drinking supply, irrigation and energy generation. Nutrient criteria development is thus mandatory. Our study revealed that the natural nutrient concentrations in subtropical reservoirs in the absence of (or with minor) anthropogenic activities should be approximately 0.010 mg/L for total phosphorus and 0.350 mg/L for total nitrogen. These baselines may guide environmental recovery plans and targeted nutrient concentrations in such reservoirs (e.g. a management plan with progressive water quality improvement). Trophic state boundaries were proposed and aided in diagnosing the enrichment condition of the Itupararanga Reservoir, which was taken as an example. Our analyses also suggested that the cumulative frequency curves are an interesting tool to promote a convenient level of condensation of monitoring data. The comparison of the results of single reservoirs (from individual sampling efforts in other subtropical water bodies) with the curves we presented may help in the decision-making process and in the identification of priority areas for water quality reclamation.

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