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Eutrophication potential of lakes: an integrated analysis of trophic state, morphometry, land occupation, and land use

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(With 2 figures)

Abstract

Despite being inside a protected area, Lake Sumidouro has been impacted by the anthropogenic occupation of the surrounding area since the 1970's, compromising the ecological integrity of the lake and the sustainable use of natural resources. This study examined the current trophic classification of the lake and developed methods for improving it through an integrated analysis of morphometric and limnological parameters, land use and land occupation in the watershed, and eutrophication potential. Data for the limnological parameters, land use and land occupation, and morphometric characteristics of Lake Sumidouro were collected in the rainy and dry seasons of 2009 and 2010. Depending on the trophic classification system used, Lake Sumidouro is classified as oligotrophic to hypereutrophic. In our study, the highest concentration of nutrients occurred in the rainy season, indicating that high nutrient inputs played an important role during this period. Areas of anthropogenic occupation comprised approximately 62.9% of the total area of the watershed, with pasture and urban settlement as the main types of land use. The influent total phosphorus load was estimated to be 15,824.3 kg/year. To maintain mesotrophic conditions, this load must be reduced by 29.4%. By comparing the isolated use of trophic state indices, this study demonstrated that comparing the trophic state classification with morphometric analyses, land use and land occupation types in the watershed, and potential phosphorus load provided better information to guide management actions for restoration and conservation. Furthermore, this approach also allowed for evaluating the vulnerability of the environment to the eutrophication process.

Keywords: water quality, trophic indices, phosphorus, restoration, conservation.

Potencial de eutrofização de lagos: uma análise integrada do estado trófico, morfometria, uso e ocupação do solo

Resumo

A lagoa Sumidouro apesar de incluída em área protegida tem sido impactada pela ocupação antrópica desde os anos 70, com riscos consideráveis à sua integridade ecológica e utilização sustentável de seus recursos naturais. Este estudo teve como objetivo discutir a classificação trófica comumente utilizada propondo reforça-la através de uma análise integrada dos parâmetros morfométricos e limnológicos, usos e ocupação do solo na bacia e o cálculo do potencial de eutrofização. Parâmetros limnológicos, levantamento dos usos e ocupação do solo e dados morfométricos da lagoa Sumidouro foram medidos nos períodos de chuva e seca de 2009 e 2010. Dependendo do sistema trófico utilizado a lagoa Sumidouro tem sido classificada desde oligotrófica até hipereutrófica e, no presente estudo apresentou as maiores concentrações de nutrientes durante os períodos de chuvas, demonstrando o papel dos maiores aportes neste período. Do total de sua bacia hidrográfica as áreas antropizadas totalizam *c.* 62,9% da área total, sendo que pastagens e ocupação urbana constituem os usos principais. Neste estudo, estimou-se a carga total afluente de fósforo neste ambiente como sendo 15.824,3 kgP/ano. Para manter uma condição de mesotrofia esta carga deverá ser reduzida em 29,4% deste total. Comparado com o uso isolado de índices de estado trófico, este estudo demonstrou que uma associação da classificação do estado trófico com análises morfométricas, usos e ocupação do solo da bacia e potencial de contribuição de fósforo fornece melhor indicação para ações de gestão visando a recuperação e conservação além de também contemplar, a vulnerabilidade dos ambientes ao processo de eutrofização.

Palavras-chave: qualidade da água, índices tróficos, fósforo, recuperação, conservação.

1. Introduction

The trophic state, or stage of eutrophication, of a body of water has been associated with the study and management of cultural eutrophication of lakes. The tropic state concept focuses on variables that are directly or indirectly related to primary productivity (i.e., algae and aquatic plants) (Dodds and Cole, 2007).

Naumann and Thienemann were the first to classify lakes into oligotrophic and eutrophic types in the early part of the twentieth century (Esteves, 1988). Naumann characterized temperate lakes on the basis of their plant production and was in large part concerned with visual or aesthetic symptoms of eutrophication. Thienemann, in contrast, emphasized the degree of hypolimnetic oxygen depletion in summer and the benthic organisms associated with eutrophication (Chapra and Dobson, 1981). This typology has proven to be inapplicable to tropical lakes because these ecosystems show metabolic patterns completely different from temperate lacustrine ecosystems (Esteves,1988).

Trophic classification systems were initially developed for temperate environments (e.g., Carlson, 1977; OECD, 1982). In an attempt to evaluate eutrophication in tropical areas, several indices that consider the particular characteristics of tropical environments were also developed. For example, the index developed by Toledo et al. (1983), which was constructed similarly to the Carlson's (1977) index, is calculated in a way that gives less weight to the variable "water transparency," which is directly affected by the high turbidity of tropical waters during most of the year. Salas and Martino (1991) proposed a simplified trophic model based on phosphorus levels. More recently, Lamparelli (2004) proposed a modified index based on the Carlson's (1977) index.

According to Dodds and Cole (2007), knowing a lake's trophic state provides basic information that can be used to measure biotic integrity, monitor human influence, and guide restoration planning. Eutrophication is influenced by both anthropogenic and natural factors (Liu et al., 2010). Because of the complex nature of eutrophication, an increasing number of studies are directed toward broader-scale analyses of lakes and reservoirs threatened by this environmental problem. Such analyses involve not only physical and chemical parameters and, trophic state indices but also their relationship with morphology, land use, and land occupation (Nõges et al., 2003; Fraterrigo and Downing, 2008; Taranu and Gregory-Eaves, 2008; Nõges, 2009; Liu et al., 2010). Morphological parameters, such as the depth and volume of the lake, are assumed to be significantly related to nutrient concentrations or eutrophication state (Armengol and Miracle, 1999; Hamilton et al., 2001; Taranu and Gregory-Eaves, 2008; Liu et al., 2010). It is widely accepted that any changes in land use directly impact water quantity and quality (Goonetilleke et al., 2005). Watersheds dominated by agricultural or urbanized land export nutrients to bodies of water at higher rates than undisturbed watersheds. Therefore, land use is directly related to nutrient inputs into bodies of water (Arbuckle and Downing, 2001; Knoll et al., 2003; Sand-Jensen and Staehr, 2007; Taranu and Gregory-Eaves, 2008).

Because of the importance of Lake Sumidouro in the central karstic region of the state of Minas Gerais, Brazil, and specifically its importance to Sumidouro State Park, the lake was selected for use in this study. We examined the trophic classification commonly accepted in the limnological literature using an analysis of the relationships between morphometric and limnological parameters, an evaluation of land use and land occupation in the watershed, and a calculation of the eutrophication potential of the local environment.

We found that an integrated analysis of limnology, trophic state, lake morphometry, watershed use and occupation, and potential influent phosphorus load enabled a more accurate evaluation of environmental quality and the vulnerability of the environment to eutrophication. In addition, the analysis provided information to support the implementation of restoration and conservation measures at Lake Sumidouro.

2. Material and Methods

2.1. Study site

Lake Sumidouro (19°32'10"S; 43°57'00"W) is located in the central region of the state of Minas Gerais, within the limits of the protected area Sumidouro State Park (Figure 1). The lake is the largest body of water of karstic origin in the region. It is located at an altitude of 650 m and is bordered to the north by the district of Fidalgo and the municipality of Pedro Leopoldo and to the south by seasonal semideciduous and deciduous forest. Both vegetation types are part of the Atlantic Forest biome.

According to the Köppen classification, the climate in the region is of the type Aw, which includes humid tropical regions with dry winters and rainy summers, mean annual temperatures above 18° C in the coldest month, and mean annual precipitation between 1,000 and 1,500 mm (Patrus, 1998).

Despite being part of the Carste de Lagoa Santa Environmentally Protected Area, the Sumidouro Lake watershed experienced considerable long-term impacts resulting from changes in the matrix of land occupation. Furthermore, inadequate sanitation infrastructure in the region has impacted the lake environment and, due to the high vulnerability of karstic regions to environmental degradation, makes restoration of the lake very complex.

2.2. Limnological data and trophic level

Limnological parameters were measured in the rainy and dry seasons of 2009 and 2010 at two sampling locations (limnetic and littoral zones). Sampling was performed in February and September of 2009 and March and July of 2010. Dissolved oxygen, pH. and water transparency were measured *in situ*. Water samples were collected at the subsurface level (0.5 m) for analyses of chlorophyll-*a*, total phosphorus (P), soluble reactive phosphorus (PO_4-P), total

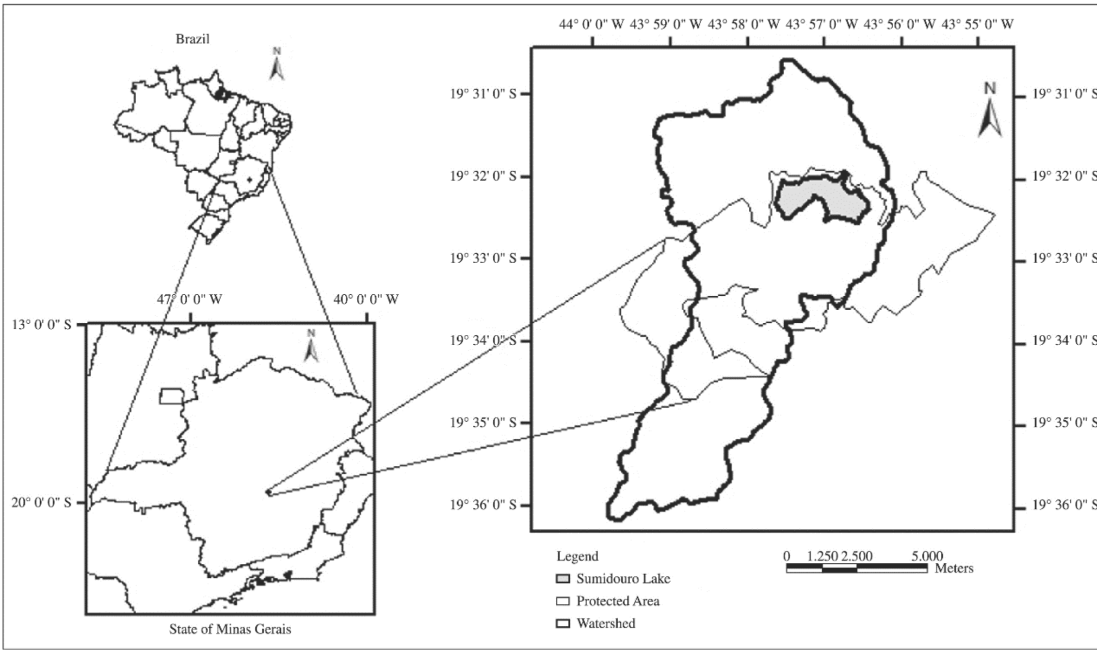

Figure 1. Location of Lake Sumidouro (Minas Gerais, Brazil). Note the boundaries of the watershed and the protected area Sumidouro State Park.

nitrogen (N), nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+) and analyzed according to Lorenzen (1967), Koroleff (1976), Golterman et al. (1978), and Mackeret et al. (1978). Trophic level was evaluated by analyzing the limits of the trophic classification of temperate environments developed by Carlson (1977) and that of the OECD (1982). Indices that take into account the particularities of tropical environments were also considered, including Carlson (1977) modified by Toledo et al. (1983), Salas and Martino (1991), and Carlson (1977) modified by Lamparelli (2004).

2.3. Bathymetry and morphometric parameters of Lake Sumidouro

For the morphometric characterization of Lake Sumidouro, a bathymetric survey was performed in April 2011 using a Hummingbird Piranha–2XM probe. Depth measurements were obtained from 21 parallel transects that were perpendicular to the longer axis (length) of the lake. Using the bathymetric data, the following primary and secondary morphometric parameters were obtained: maximum depth, total volume, lake area, surface contribution area, maximum length, and maximum width. Values for these parameters were obtained from measurements performed with the ArcGIS 9.3 ® software (ESRI Inc.) using images from the Landsat 5 satellite. The secondary parameters mean depth, relative depth, perimeter development, and volume development were calculated according to Wetzel (2001). The bathymetric maps were elaborated using a historic series of Landsat 5 satellite images provided by the Brazilian National Institute of Spatial Research (Instituto Nacional de Pesquisas Espaciais (INPE)) and depth data collected in the dry and rainy seasons of 2009 and 2010. Values for the primary and secondary morphometric parameters were determined for each of these four periods.

2.4. Watershed land use and land occupation

For the survey of the land use and occupation, a visual and/or digital interpretation of satellite images was performed, followed by field visits to ground-truth our interpretations. The methodological sequence consisted of the following steps: image selection, assembly of color composites and a cartographic base, georeferencing of images with the aid of the cartographic base, digital processing of images, interpretation and quantification of land use classes, and qualitative analysis of the results.

2.5. Estimating maximum phosphorus load

The calculations for estimating maximum phosphorus load accounted for variation in phosphorus concentrations released into the water by different types of land use. Mean values for phosphorus per unit area and existing human population were determined for each type of land use. Phosphorus concentrations were based on population estimates from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística (IBGE), 2010) and theoretical estimates of external phosphorus loads proposed by Salas and Martino (1991).

Estimates for the influent phosphorus load to the lake from raw domestic sewage were obtained using a contribution rate of 1 kg P/inhabitant/year (Salas and Martino, 1991). For the load resulting from cattle operations, the following factors were considered: area of pasture currently in use in the watershed, mean carrying capacity of pastures in the region (1.5 cattle/0.01 km^2) (IMA, 2011), and a contribution rate of 7 kg P/animal/year, according to OPS (2001). Estimates of phosphorus concentrations in the lake and the acceptable influent load were obtained according to Salas and Martino (1991), respectively, in the following manner (Equations 1 and 2):

$$P = \frac{L.10^3}{V.(\frac{1}{t} + \frac{2}{\sqrt{t}})} \qquad (1)$$

$$L = \frac{P.V(\frac{1}{t} + \frac{2}{\sqrt{t}})}{10^3} \qquad (2)$$

Where:
P=Predicted median annual in-lake total phosphorus (TP) concentration (gP/m^3);
L=Areal total phosphorous load (kgP/year);
V=Lake water volume (m^3);
t=Hydraulic retention time (year).

The value of 0.025 mg/L of phosphorus was used as the threshold for determining eutrophy (Vollenweider, 1968) (Equation 2). This value was also used as the quality standard for total phosphorus concentration for freshwater bodies categorized as Class 1 in the Brazilian federal legislation for the classification of freshwater (Brasil, 2005) case of Lake Sumidouro.

2.6. Statistical analyses

Analyses were performed with R 2.11.0 software. Table 1 summarizes the statistical data for the limnological and morphologic parameters of Lake Sumidouro. There were significant differences among year, season and sampling location (limnetic or littoral zone) for the limnological parameters and significant differences between year and season for the morphological parameters. A Shapiro-Wilk test was used to verify the normality of the data distribution. Student's t-tests were used for variables with a normal distribution and Mann-Whitney tests were used for variables that did not show a normal distribution. The relationships between morphological and limnological parameters were obtained with a Spearman's test. A principal components analysis (PCA) was performed, and the relationship between the two sets of variables (morphological and limnological parameters) and season of the year was tested using Spearman's tests.

3. Results

3.1. Trophic state of Lake Sumidouro

Because trophic classifications are completed on an annual basis, the mean values for the dry and rainy seasons in 2009 and 2010 were analyzed. The eutrophic class was the predominate class according to both the Carlson's (1977) index and the system proposed by the OECD (1982). According to both systems, Lake Sumidouro was

Table 1. Summary of the descriptive analysis of limnological and morphological parameters of Lake Sumidouro in 2009 and 2010.

	N	Mean	Standard deviation	Minimum value	Maximum Value
Limnological parameter					
Ammonia (µg 1^{-1})	8	60.79	47.10	10.21	139.88
Nitrite (µg 1^{-1})	8	0.68	0.77	0.00	2.08
Nitrate (µg 1^{-1})	8	9.17	7.50	0.29	19.53
Total nitrogen (µg 1^{-1})	8	338.94	171.55	147.48	612.38
Orthophosphate (µg 1^{-1})	8	1.65	1.06	0.36	2.82
Total phosphorus (µg 1^{-1})	8	46.08	25.14	26.38	85.41
Chlorophyll *a* (µg 1^{-1})	8	10.03	5.61	1.60	17.74
Dissolved oxygen (mg 1^{-1})	8	7.70	2.05	4.15	9.00
pH	8	7.45	0.18	7.14	7.74
Transparency (Secchi disk) (m)	8	0.75	0.58	0.25	1.75
Morphometric parameters					
Maximum depth (m)	8	3.55	0.91	2.70	4.40
Mean depth (m)	8	0.71	0.37	0.36	1.10
Volume (10^4 m^3)	8	57.23	45.24	14.76	99.86
Area (Km^2)	8	0.68	0.30	0.39	1.04
Relative depth (%)	8	0.39	0.02	0.36	0.42
Maximum length (m)	8	1,545.00	403.79	1,164.00	1,964.00
Maximum width (m)	8	694.75	189.85	511.00	927.00
Perimeter (km)	8	4.90	0.97	3.95	6.02
Volume development	8	0.56	0.17	0.40	0.75
Perimeter development	8	1.72	0.05	1.67	1.78

considered mesotrophic in 2010, chlorophyll *a* was used as the evaluation parameter. According to the OECD (1982) system, the lake was considered hypereutrophic when including the Secchi disk values (Table 2).

The indices proposed for tropical environments (Carlson (1977) modified by Toledo et al., 1983; Salas and Martino, 1991; and Carlson (1977) modified by Lamparelli, 2004) showed discrepant results for the trophic state of Lake Sumidouro, with the tropic state varying from oligotrophic to hypereutrophic as shown in Table 2.

3.2. Limnological and morphological data for Lake Sumidouro

There were no differences in the limnological parameters between the dry and rainy season ($p \geq 0.05$). However, the mean values for nutrients and chlorophyll *a* were higher in the rainy season. In the rainy season, total nitrogen, total phosphorus, orthophosphate, and chlorophyll *a* had mean concentrations of 345.38 µg 1^{-1}, 55.65 µg 1^{-1}, 2.10 µg 1^{-1}, and 13.12 µg 1^{-1}, respectively, in the dry season and 332.49 µg 1^{-1}, 36.51 µg 1^{-1}, 1.20 µg 1^{-1}, and 6.95 µg 1^{-1}, respectively, in the rainy season. There were no significant differences in the limnological parameters between sampling locations (limnetic and littoral zones) or years (2009 and 2010) ($p \geq 0.05$), except for nitrite, which showed a higher mean concentration in 2010 than in 2009 ($p<0.05$).

Resolution Number 357 of the Brazilian National Environmental Council (Conselho Nacional de Meio Ambiente (CONAMA)) established water quality standards for Brazilian freshwater bodies (Brasil, 2005). Lake Sumidouro showed mean concentrations of total phosphorus that were higher than the limit established for Class 1 water bodies in both the rainy (55.65 µg 1^{-1}) and dry (36.51 µg 1^{-1}) season. Additionally, during the rainy season, chlorophyll *a* was higher than the limit of 10 µg/L^{-1} established for Class 1 waters.

There were no significant differences in the morphological variables between years ($p \geq 0.05$). However, there were significant differences between seasons ($p<0.05$), with higher means occurring in the rainy season. Mean values for morphological variables in the dry and rainy seasons were 2.70 and 4.40 m, respectively, for mean depth; 14.91 and 99.55 10^4 m^3, respectively, for volume; and 0.96 and 0.41 km^2, respectively, for area. Perimeter development was the only variable that showed a higher value in the dry season, when surface contours on the lake were more irregular. Perimeter development had mean values of 1.68 in the rainy season and 1.77 in the dry season. Large seasonal variation in morphological characteristics is typical of karstic aquatic ecosystems because they depend on the rainfall regimes, which are associated with the water table and the flow systems of the karstic aquifers.

Table 3 shows the correlations between the limnological and morphological variables by the Spearman's test. Correlation coefficients greater than 0.70 were considered significant ($p \leq 0.05$). The results indicated that chlorophyll *a* increased with mean depth, relative depth, and the index of volume development. Maximum depth was positively correlated with water transparency, which favored phytoplanktonic biomass (chlorophyll *a* concentrations).

Table 2. Trophic state classification for Lake Sumidouro according to Carlson (1977); OECD (1982); Carlson (1977) modified by Toledo et al. (1983); Salas and Martino (1991); and Carlson (1977) modified by Lamparelli (2004), based on mean values for the dry and rainy seasons in 2009 and 2010.

Trophic Model/Index	Year	Value	Trophic Classification
Carlson (1977) TP (µg 1^{-1})	2009	59.55	Eutrophic
	2010	59.32	Eutrophic
Carlson (1977) Chlorophyll *a* (µg 1^{-1})	2009	56.57	Eutrophic
	2010	46.76	Mesotrophic
Carlson (1977) Secchi (m)	2009	59.29	Eutrophic
	2010	58.36	Eutrophic
OECD (1982) TP (µg 1^{-1})	2009	60.78	Eutrophic
	2010	39.64	Eutrophic
OECD (1982) Chlorophyll *a* (µg 1^{-1})	2009	14.16	Eutrophic
	2010	5.21	Mesotrophic
OECD (1982) Secchi (m)	2009	1.05	Hypereutrophic
	2010	1.12	Hypereutrophic
TSI Carlson (1977) modified by Toledo et al. (1983)	2009	42.24	Oligotrophic
	2010	43.70	Oligotrophic
Salas and Martino (1991) TP (µg 1^{-1})	2009	60.78	Mesotrophic
	2010	39.64	Mesotrophic
TSI Carlson (1977) modified by Lamparelli (2004)	2009	65.49	Supereutrophic
	2010	61.74	Eutrophic

In contrast, the concentration of dissolved oxygen was negatively correlated with volume, area, maximum length, perimeter, and perimeter development.

Major trends in the 10 limnological variables were evaluated using a PCA, in which the first two principle components explained 60% of the total variability in the data. The sampling units were separated according to the seasonality (Figure 2a). Higher values of nitrate and dissolved oxygen were grouped with dry season, whereas higher values of chlorophyll *a*, pH, water transparency, and ammonia were grouped with rainy season.

The separation between sampling units was a function of the response of the morphological variables to seasonality. For the morphological data, 92.8% of the total variation was explained in the first principal component (Figure 2b). Rainy season was associated with higher values of the morphometric variables (maximum depth, mean depth, volume, area, relative depth, maximum length, perimeter, and index of volume development), higher nutrient, pH, and water transparency levels were detected when the lake had a higher volume, area, and mean depth.

Table 3. Correlation matrix between the limnological and morphological variables according to the Spearman's test. Significant correlations are indicated in bold text.

Variables	Chlorophyll *a*	Dissolved Oxygen	Secchi
Maximum depth (Zmax)	0.655	–0.671	**0.697**
Mean depth (Zmean)	**0.781**	–0.350	0.572
Volume (V)	0.390	**–0.850**	0.676
Area (A)	0.390	**–0.850**	0.676
Relative depth (Zrel)	**0.772**	–0.079	0.411
Maximum length (L)	0.390	**–0.850**	0.676
Maximum width (W)	0.488	–0.650	0.624
Perimeter (P)	0.390	**–0.850**	0.676
Volume development (Dv)	**0.781**	–0.350	0.572
Perimeter development (Dp)	–0.390	**0.850**	–0.676

3.3. Land use and land occupation in the watershed and estimates of maximum phosphorus load

Lake Sumidouro represented approximately 32.3% of the area of the watershed, which was comprised of seasonal forest cover, *cerrado* remnants, and 4.78% bodies of water. The remaining area (62.92%) included the following uses: pasture/field (55.01%), rural/urban area (6.66%), agricultural areas (0.62%), mining (0.4%). and pisciculture (0.23%). The watershed overlaps two districts: the district of Fidalgo, belonging to the municipality of Pedro Leopoldo, with 2,595 inhabitants; and the district of Lapinha, belonging to the municipality of Lagoa Santa, with 3,921 inhabitants (IBGE, 2010). Therefore, a total of 6,516 inhabitants contributed to the phosphorus load through sewage, which is disposed of *in natura* in bodies of water or septic tanks in the region (COPASA, 2009). The number of head of cattle was 1,282.5, based on a total pasture area in the watershed of 8.55 km^2 and a mean carrying capacity for the region of 1.5 head of cattle per 0.01 km^2 (IMA, 2011). The phosphorus loads from runoff from forested areas (104.8 kgP/year), agricultural use (10 kgP/year), and urban use (216 kgP/year), in addition to the loads produced by human and cattle populations, comprised a total load of 15,824.3 kgP/year.

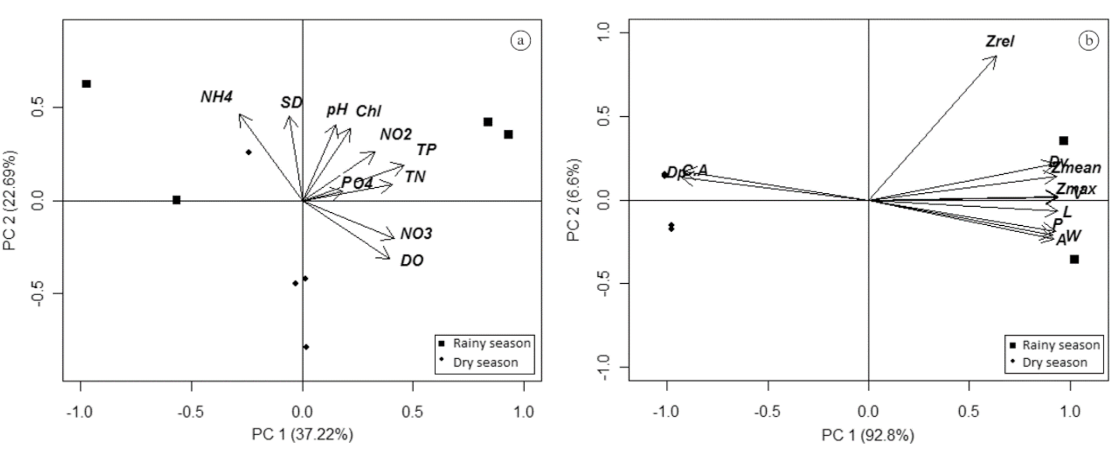

Figure 2. Ordination of sampling units by Principal Components Analysis (Axes 1 and 2) as a function of limnological (a) and morphometric (b) variables measured in Lake Sumidouro in the rainy and dry season in 2009 and 2010. *DO: dissolved oxygen; SD: Secchi disk; Chl: chlorophyll a; TP: total phosphorus; PO4: soluble reactive phosphorus; NO3: nitrate, NO2: nitrite; and NH4: ammonia. Abbreviations of morphometric parameters follow those in Table 3.*

The period of water retention, which was obtained using the ratio of volume (57.23 10^4 m^3) to influent flow rate (0.517 m^3/s) was 12.8 days, and the estimated value of phosphorus concentrations in the lake was 0.035 mg/L, which is typical of a mesotrophic environment according to OPS (2001). To maintain this trophic condition, the influent load must be reduced from 15,824.3 kgP/year to 11,173.29 kgP/year (a reduction of 29.4%), assuming a maximum phosphorus concentration of 0.025 mg/L.

4. Discussion

Lake Sumidouro was classified at different trophic levels depending on the trophic classification system used. For the Carlson's (1977) index and the classification system proposed by the OECD (1982), the differences were most likely due to these two classification systems being developed for temperate environments. Thus, the systems were not necessarily applicable in tropical and subtropical environments, which typically have a higher tolerance for high phosphorus and algal biomass levels. Kitaka et al. (2002) have suggested phosphorus concentrations of 50 to 60 $\mu g\ L^{-1}$ for meso-eutrophic environments, which was true for Lake Sumidouro during the rainy season. These values are higher than those established for temperate environments in the same category. Similarly, the model proposed by the OECD (1982) considers an eutrophic environment to have a phosphorus concentration of $\geq 35\ \mu gL^{-1}$, which is much lower than the limits proposed for the same trophic classification for tropical systems.

The use of different parameters (e.g., total phosphorus, chlorophyll *a*, and water transparency) contributed to the inconsistency among the classification systems. In this study, Lake Sumidouro was classified as mesotrophic according to the Salas and Martino's (1991) index, which uses total phosphorus concentrations as the central indicator of quality. However, the lake was classified as eutrophic to supereutrophic according to the Carlson's index modified by Lamparelli (2004), which uses data for chlorophyll *a* concentrations in addition to total phosphorus. Similarly, Lamparelli's (2004) index uses a set of parameters that tends to result in bodies of water being classified at a higher trophic level. According to the author, this allows for distinguishing between environments with high concentrations of chlorophyll *a* and total phosphorus. These findings stress the fact that there is not necessarily correspondence among existing models for trophic categories, which limits the widespread use of such classification systems. Mercante and Tucci-Moura (1999) recommend the cautious use of such indices as the only indicator of the potential of a trophic state. According to these authors, the temporal and spatial dynamics of the physical, chemical, and biological variables in the aquatic system must be considered, along with the regional particularities of the watershed.

The morphometric variables and analyses of land use and land occupation in the watershed were considered in the environmental evaluation, mainly in reference to their role in cultural eutrophication. The size of the lake and the watershed, for example, are important aspects because they affect nutrient flow, not only from superficial runoff and input from subterraneous waters but also from the re-suspension of sediments induced by the wind (Nõges, 2009; Liu et al., 2010; Sheela et al., 2011). Lake Sumidouro showed higher nutrient concentrations and higher values for the morphometric variables in the rainy season, most likely due to higher loads originating from the watershed. Therefore, the dilution factor was not a determinant for the decrease in nutrient concentrations during this period. Chlorophyll *a* followed a similar trend, showing a positive correlation with mean depth, which increases water transparency. This pattern was also detected by Liu et al. (2010).

Nutrient concentrations decreased in the dry season, most likely because of the decrease in nutrient inputs from the watershed and because of the assimilation of the nutrients by the macrophyte community, which grows rapidly during that time of year. This result is corroborated by the higher values for perimeter development during the dry season. Variation in the shore of the water body enables the development of a more extensive littoral vegetation. Therefore, during the dry season, even with a higher involvement value (ratio of the area of the lake the area of the watershed), there was a decrease in nutrient concentrations and an increase in dissolved oxygen concentrations.

Changes in land use and vegetation cover are driven by complex interactions among environmental and socio-economic factors (Hietel et al., 2004). Coutinho and Barbosa (1986) stressed the importance of anthropogenic impacts and the necessity of regulating the use of water from karst lakes and activities in their watersheds. Lake Sumidouro is a priority for restoration and conservation actions in this region, not only because it is located in a fully protected conservation unit (Sumidouro State Park) but also because of the high vulnerability of karstic drainages to environmental degradation.

Catchment export nutrients to aquatic ecosystems are influenced by land use practices, for example, watersheds dominated by agriculture, typically export nutrients at higher rates (Knoll et al., 2003; Taranu and Gregory-Eaves, 2008; Vanni et al., 2011). Pasture was the main type of land use in the watershed and thus the main source of nutrients. Part of the pasture area was incorporated into Sumidouro State Park. Although these areas are likely to be converted to natural vegetation by processes of regeneration or replanting, they are commonly invaded by bovines and equines, showing the lack of protection of the area. Manure production causes a P surplus to accumulate in soil, some of which is transported to aquatic ecosystems (Carpenter et al. 1998). Furthermore, the nutrient inputs from urban areas to this lake are significant and mainly reach the lake via the Samambaia river, the lake's main tributary, which drains the districts of Fidalgo and Lapinha. These districts lack any type of sewage treatment (COPASA, 2009). As a result, Lake Sumidouro is prone to eutrophication. Despite its short retention period (12.8 days, which favors water renewal, the lake receives a significant phosphorus inputs that are constantly present in the water column due to the re-suspension of sediments that results from the shallow depth of the lake.

Of the indices for tropical environments examined here, the Carlson's (1977) index modified by Toledo et al. (1983) was not adequate. This index underestimated the trophic state of the lake (classified as oligotrophic) despite the use of additional variables, most notably, water transparency. However, water transparency is particularly critical in tropical waters, which are usually turbid during rainy periods. Alternatively, the indices developed by Salas and Martino (1991) and Carlson (1977) modified by Lamparelli (2004) seemed more appropriate for the lakes in this region because they did not underestimate the trophic state and took phosphorus concentrations into account. Phosphorus is an element that acts as limiting factor for primary production and whose availability is fundamental for the definition of the trophic level in aquatic ecosystems.

Given the large variation observed among the results of the indices evaluated in this study, we concluded that the isolated use of a single trophic state index should be performed with caution because the index may not represent the true environmental conditions in a given area. Furthermore, our results suggest that, regardless of which index is used, it should be integrated into an analysis with other environmental quality indicators for the study area. Morphometric analyses and the evaluation of land use and land occupation in the watershed are particularly important. Anthropogenic impacts such as point and nonpoint source pollution are the main determinants of lake eutrophication, Liu et al. (2010) noted that some natural factors, such as lake morphology that reflect lake buffer capacity to nutrient inputs can also play important roles in explaining the eutrophication status.

Lake Sumidouro must meet the classification of Class 1 waters, which is designed for example for the protection of aquatic communities and the supply for human consumption after treatment simplified. Currently, this lake shows limnological characteristics, including total phosphorus and chlorophyll *a*, that are above the limits established for this class. This result indicates the need for urgent actions regarding the regulation of land use in the watershed, such as limiting or prohibiting activities that are incompatible with ecosystem health and the health of the local population. Examples of urgently needed actions include the collection, treatment, and disposal of the sanitary sewage that is currently released into this environment. This action would directly reduce phosphorus inputs. Furthermore, according to Schindler (2012), it is the only method that has had proven success in reducing eutrophication in lakes. Slowing and halting the process of eutrophication is essential for maintaining the mesotrophic state of Lake Sumidouro.

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