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TROPHIC STATE INDEX REVEALS HYPEREUTROPHIC NATURE OF A SUBTROPICAL URBAN LAKE

Silva, M.V.[a*] & Jati, S.[b]

[a]Programa de Pós-graduação em Ecologia, Laboratório de Limnologia, Departamento de Ecologia, Instituto de Biologia, Universidade Federal do Rio de Janeiro, Brazil.
[b]Núcleo de Pesquisas em Limnologia, Ictiologia e Aquicultura – NUPELIA, Laboratório de Ecologia do Fitoplâncton, Universidade Estadual de Maringá, Brazil.
*matheusvieirabio@hotmail.com (Corresponding author).

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ABSTRACT

As a consequence of the growth of large urban centers close to aquatic environments, the input of nutrients from specific or diffuse sources of contamination has significantly impacted the water quality of these water resources. One of the main impacts on these ecosystems is eutrophication, which occurs due to the excessive nutrient load, especially of phosphorus and nitrogen, that contributes to the development of primary producers at levels above natural growth. To categorize the trophic state of a subtropical urban lake situated in a remnant of Atlantic Forest, short-period sampling was conducted during the dry and rainy seasons (2018-2019). Water samples were collected from the surface of the lake, at the limit of the euphotic zone, and from the bottom. Principal Component Analysis (PCA) was used to summarize the variability of the limnological data, and the Trophic State Index (TSI) was used to identify the trophic state of the lake. Nutrient analyses of the water column showed high nutrient availability in the system, mainly of ammonia, nitrite and total phosphorus. All the environmental variables were greatly influenced by rainfall. It is noteworthy that the total concentration observed in the samples was within the limits specified by Brazilian legislation. The application of the TSI classified the lake as hypereutrophic. We recommend continued monitoring of the lake's limnological variables, in order to devise strategies to improve the water quality of the lake.

Keywords: Eutrophication, Water quality, TSI, Monitoring.

1 Introduction

Urban lakes, along with green areas, are ecosystems that have multiple uses, providing important services such as public water supply, recreation areas, flood control, and landscape beautification of urban centers (Almanza-Marroquín et al. 2016, Arya & Kumar 2023). These environments can also help control local temperature and humidity, consequently improving the quality of life for the population (Gao et al. 2019).

Historically, cities were built near aquatic ecosystems to maintain supply and ensure societal survival (Baptista et al. 2013). However, the expansion of large urban centers after the Industrial Revolution imposed environmental problems on these aquatic environments, particularly in relation to water quality (de Jonge et al. 2002).

Anthropogenic pressure around urban aquatic environments favors the processes of water eutrophication. This is a process whereby water bodies become over-enriched with nutrients, mainly phosphorus and nitrogen, as a direct result of urban population growth (Esteves 2011). Eutrophication is one of the most serious and difficult environmental problems to resolve in terms of the conservation and recovery of aquatic environments, and it is now considered a global environmental issue. Eutrophic environments are characterized by the depletion of dissolved oxygen and increased nutrient concentrations, especially nitrogen and phosphorus (Viana et al. 2009, Zhou et al. 2022, Silva et al. 2022, Akinnawo 2023).

The increase in these nutrient concentrations favors the intense development of primary producers, especially cyanobacteria and aquatic macrophytes, which can lead to severe management problems (Oberholster et al. 2006, Rosińska et al. 2017). This problem is exacerbated by the fact that many bloom-forming cyanobacteria species are potential toxin (cyanotoxin) producers. These complex molecules can bioaccumulate in the food chain, causing intoxication and even death in animals and humans (Silva & Jati 2024, Fabrin et al. 2020).

To monitor this issue, Trophic State Indicex (TSI) were developed to evaluate nutrient enrichment in the water and its effect on the excessive growth of aquatic primary producers. The TSI classifies water bodies into different trophic states. In general, the index takes into account chlorophyll-a concentrations, which can be an efficient proxy for aquatic productivity, and total phosphorus. There is a correlation between phytoplankton biomass and chlorophyll-a and total phosphorus concentrations, thus the TSI serves as the basis for classifying aquatic ecosystems according to their trophic state (Reynolds 2006, D'Alessandro & Nogueira 2018). The TSI can aid in decisions on the risks of algal blooms, as well as in controlling the eutrophication of aquatic environments, which is a global concern for decision-makers in water resource management (Bucci & Oliveira 2014).

The aim of this study was to limnologically characterize and determine the trophic state of Ingá Park Lake, a subtropical lake located in an urban remnant of Atlantic Forest.

2 Material and Methods

2.1 Study Area

The Municipality of Maringá is situated in the northwest region of the State of Paraná, Brazil (23°25'S and 51°25'W). It has an average annual rainfall of between 1500 and 1600 mm and average annual temperatures of between 20°C and 25°C (Santos 2003). The Ingá Park encompasses an area of 47.3 hectares and is one of the last remaining remnants of Atlantic Forest in the region, serving as the primary recreational environment for the population (Bovo & Amorim 2009). It is covered by pristine forest, being located within the phytogeological region of seasonal semideciduous forest (Maack 1981). The main lake in Ingá Park occupies approximately a fifth of the total park area (Vaz 1998) (Figure 1).

Currently, the lake volume is largely maintained through rainwater drainage systems, as most of the natural springs that existed within the park, such as the emergence of the water table, have dried up due to slope impermeabilization and increased groundwater extraction in the vicinity of the park. As a result, there is no water renewal into the lake. Its water volume is greatly reduced during the dry season and replenished during the rainy season, with very rare episodes of water overflow through the dame gate, which is of the free weir type (Jati 2019, Silva & Jati 2024).

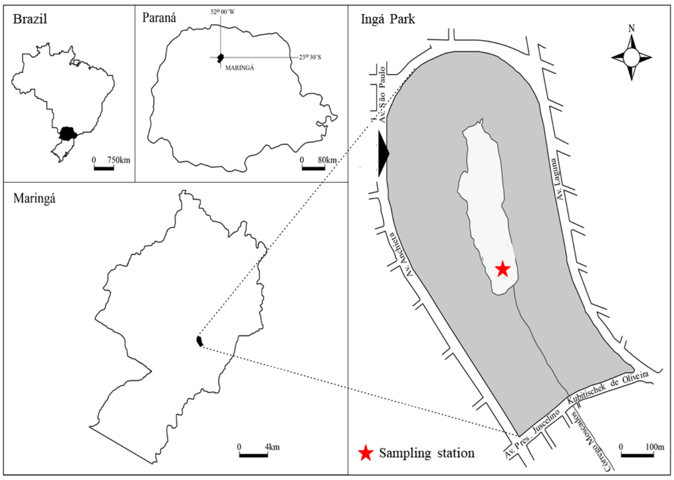

Figure 1. Location map of Ingá Park lake, Maringá, Paraná, Brazil.

2.2 Sampling and analysis

Sampling of total phytoplankton and environmental abiotic variables was carried out during the dry season, between May and June 2018m and during the rainy season, between January and February 2019. Ten collection days were established for each period, with a three-day interval between each collection. Depth samplings followed a gradient of light availability, with collections from the subsurface, at the boundary of the euphotic zone (Euphotic), and from the hypolimnion (Bottom), totaling 60 samples.

Abiotic variables such as water temperature (Temp, °C), pH, maximum depth (Zmax, m), euphotic zone (Zeu, m) calculated as 2.7 times the Secchi disk depth, electrical conductivity (Cond, $\mu S.cm^{-1}$), and dissolved oxygen (DO, $mg.L^{-1}$) were collected in situ using portable digital potentiometers. Water turbidity (Turb, NTU) was measured with a turbidity meter. Concentrations of phosphate and total phosphorus ($\mu g.L^{-1}$; Golterman et al., 1978), nitrate ion, ammonium ion, and total nitrogen ($\mu g.L^{-1}$; Mackereth et al., 1978) were estimated. For the determination of chlorophyll-a, 400 mL of the sample was filtered using a 47 mm-diameter glass fiber microfilter, and chlorophyll-a concentrations were quantified by extraction in 90% (V/V) acetone, with readings taken on a spectrophotometer at wavelengths of 663 nm and 750 nm. Measurements of samples acidified with 0.1N hydrochloric acid (HCl) were also conducted (Golterman, 1978). Rainfall data for the study period were obtained from the meteorological station of the State University of Maringá.

2.2 Data Analysis

Principal Component Analysis (PCA; Legendre & Legendre 1998) was employed to summarize environmental variability during each study period (dry and rainy) and across all lake compartments (surface, euphotic zone boundary, and bottom in the PCA. All available environmental variables were utilized: water temperature, dissolved oxygen, pH, Secchi depth, nitrate (NH3), ammonium (NH4), Tubidity, total phosphorous and maximum depth. The PCA was conducted using the R statistical software (R Core Team 2023) and the statistical packages "Vegan" (Dixon 2003), "factoextra" (Kassambara & Mundt, 2017), "factoMineR" (Lê et al., 2008).

The Trophic State Index (TSI) was also calculated, to aid in visualizing the overall trophic level of the environment and its effect on water quality. The TSI was determined using equations that consider the concentration of chlorophyll-a (CHL) and total phosphorus (TP), following the method described by Alves et al. (2012) and Andrietti et al. (2016). The classification of the aquatic environment, according to the TSI, is summarized in Table 1. Equations 1, 2, and 3 were used to determine the TSI, where:

Equation 1

$$TSI\,(TP) = 10. \left\{ 6 - \left[\frac{0{,}42 - 0{,}36.\ln(TP)}{\ln(2)} \right] \right\} - 20$$

Equation 2

$$TSI\,(CHL) = 10. \left\{ 6 - \left[\frac{-0{,}7 - 0{,}6.\ln(CHL)}{\ln(2)} \right] \right\} - 20$$

Equation 3

$$TSI = \frac{TSI\ (TP) + TSI\ (CHL)}{2}$$

TSI (TP): is the trophic state index determined for phosphorus.

TSI (CHL): is the trophic state index determined for chlorophyll-a.

TP: is the total phosphorus concentration measured at the water surface, in µg L-1.

CHL: is the chlorophyll-a concentration measured at the water surface, in µg L-1.

The classification of the aquatic environment, according to TSI, is given in six trophic levels:

Table 1. Trophic Classification according to the Trophic State Index (TSI)

Trophic State	TSI Range	Description
Ultraoligotrophic	≤51.1	Extremely low productivity, very clear water
Oligotrophic	51.1≤ TSI ≤53.1	Low productivity, clear water
Mesotrophic	53.2≤ TSI ≤55.7	Moderate productivity
Supereutrophic	58.2≤ TSI ≤59	High productivity, possible algal blooms
Eutrophic	>59.1	Very high productivity, frequent algal blooms

Adapted from ANA (2015) and Cunha et al., (2013).

3 Results

3.1 Environmental and Limnological Characterization of Lake Ingá

There were no rainfall events during the sampling days of the dry season, nor in the ten days preceding the collections. However, during the rainy season, several episodes of rainfall occurred on the sampling days, with rainfall ranging from 5 mm to 35 mm. In the context of a subtropical environment, water temperature also stood out as a parameter of seasonal importance. Total phosphorus maintained its concentrations at between 23.2 $\mu g.L^{-1}$ and 68.7 µg $\mu g.L^{-1}$, presenting higher values during the dry season (Figure 2A). Among the various nutrients present in the water, the concentration of ammonium ion (NH4) increased nearly fourfold during the rainy season (average of 246.6 $\mu g.L^{-1}$) compared to the dry season (average of 68.51 µg $\mu g.L^{-1}$) (Figure 2B). Similarly to total phosphorus, the lake also showed higher nitrate values in the dry season compared to the rainy season (Figure 2C). The lake also showed higher concentrations of dissolved oxygen during the dry season (Figure 2D). In the dry season, lower temperatures were observed, ranging from 18.9ºC to 23.5ºC. On the other hand, in the rainy season, the water temperature remained consistently high throughout the entire sampling series, fluctuating between 27.1 and 29.8 ºC (Figure 2F). Chlorophyll-a varied from 26.17 $mg.L^{-1}$ in the dry season to 22.17 $mg.L^{-1}$ in the rainy season.

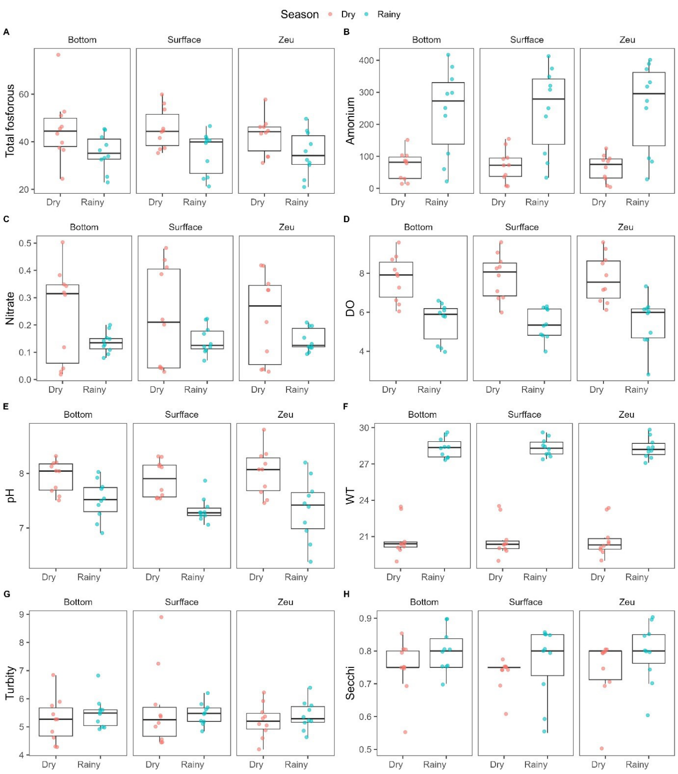

Figure 2. Mean values and standard deviations of Total phosphorous (A), Amonium (B), Nitrate (C), DO- Dissolved Oxygen (D), pH (E), WT-Water Temperature (F), Turbidity (G), Secchi (H) in Ingá Lake. These variables were estimated during the period from May to June 2018 (dry season) and January to February 2019 (rainy season) across three strata (Surface, Euphotic Zone Boundary (Zeu), and Bottom). Biovolume and density values were logarithmically transformed.

The first two axes of the Principal Component Analysis (PCA) accounted for 60% of the variability in the environmental data, highlighting periods of higher and lower rainfall. On Axis 1 (41,8%), a negative correlation was observed between pH (-0.59), dissolved oxygen (-0.92), and NO_3-N (-0.32) during the dry season. On the other hand, water temperature (0.76), PO_4-P (0.53), and NH_4-N (0.87) exhibited positive correlations with the rainy season (Figure3).

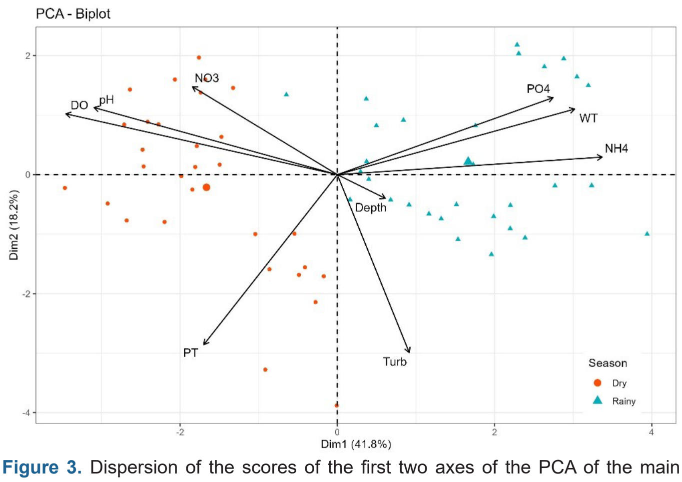

Figure 3. Dispersion of the scores of the first two axes of the PCA of the main physical-chemical variables of the water distributed by the days of sampling in the lagoon. Zmax -(Depth), dissolved oxygen- (DO), hydrogenion potential-(pH), water temperature- (Temp), ammonium ion- (NH4), nitrate – (NO3), phosphate- (PO4), Turb-Turbidity.

The application of the Trophic State Index (TSI) to the average values of Total Phosphorus (TP) and Chlorophyll-a characterized the lake in Ingá Park as hypereutrophic. The TSI values were higher during the dry season, indicating a deterioration in the trophic conditions of the water with decreased rainfall (Table 2). The index values were higher for total phosphorus, 120,8 (dry season) and 120,2 (rainy season), compared to chlorophyll-a, 110 and 111, dry and rainy seasons, respectively. Based on the calculations of the TSI equations, which consider the concentrations of total phosphorus and chlorophyll-a, it was possible to classify the lake in Ingá Park lake as hypereutrophic (TSI > 59), as it exhibited a TSI of 115.7 during the dry season and 115 during the rainy season (Table 2).

Table 2. Valores calculados para o Índice de Estado Trófico (TSI) segundo as concentrações de fósforo total (PT) e Clorofila-a (CHL) para os períodos seco e chuvoso.

			TSI
Dry season	TSI (TP)	120.8	**115.7**
	TSI (CHL)	110.6	
Rainy season	TSI (TP)	120.2	**115**
	TSI (CHL)	109.7	

4 Discussion

Ingá Park Lake was characterized according to its environmental conditions as a shallow, dynamic, and hypereutrophic environment, with limnological characteristics influenced by seasonal rainfall. This regional climatic factor is crucial in the dynamics of urban lakes since the inflow of water into the system leads to habitat expansion and consequent limnological alterations, such as resource dilution and an increase in suspended solids (Nabout & Nogueira, 2011).

The variation in the lake's limnological variables was marked by anomalous periods of higher and lower rainfall. The rainy season, characterized by higher rates of rainfall and air temperature compared to the dry season, may influence the metabolic alteration of the environment. The lake presented borderline concentrations in relation to what is stipulated by Brazilian legislation (CONAMA 357/05, Brazil 2005). Due to the high concentrations of nutrients and the low renewal rate of its water, nutrient retention in the sediment is expected. When resuspended, this can influence the lake's primary community, leading to events of algae and cyanobacteria blooms (Silva & Jati 2024). Even though an increasing trend in nutrient concentration was observed during the rainy season, long-term trends will only be evidenced with continued lake monitoring.

The analysis of the Trophic State Index (TSI) classified the lake as hypereutrophic, with an increasing trend in the index value during the rainy season due to habitat expansion and the deterioration of water quality, particularly due to increased nutrient concentrations. The TSI is considered a consistent measure of environmental degradation, with the hypereutrophic state being the same as that attributed to the Billings Reservoir, a highly polluted reservoir in São Paulo (BR), the largest city in Latin America (Cunha & Calijuri, 2011; Bem et al., 2013). Assigning a hypereutrophic classification to this lake raises significant concern, as it is primarily used for recreational activities involving indirect water contact, such as paddle boating and kayaking.

When interpreting the results, it is important to consider that the trophic state index (TSI) for phosphorus should be understood as a measure of the potential for eutrophication, while the TSI for chlorophyll-a should be understood as the environment's response to artificial phosphorus enrichment (Cunha et al., 2013). In aquatic environments where the eutrophication process is established, the indices for phosphorus and chlorophyll-a coincide, indicating the same trophic state. However, if the eutrophication process is limited by other factors such as temperature or turbidity, the TSI values for chlorophyll-a will be lower, classifying the environment as having a lower trophic state than that calculated for phosphorus concentrations (Cucio & Porto, 2015).

Increased rainfall can increase nutrient concentrations in aquatic ecosystems, as the rainwater carries nutrients from marginal areas into these ecosystems. However, nutrient concentrations in the Ingá Park Lake did not increase during the rainy season. A study by Silva & Jati (2024) in this environment showed that rainfall increased the density and biovolume of phytoplankton, particularly potentially toxic Cyanobacteria species with a high capacity for bloom formation. In this study, rainfall appeared to indirectly influence phytoplankton by diluting suspended solids and improving light availability, resulting in higher biomass values during this period. Because the density of cyanobacteria is eight times higher than the limit established by Brazilian legislation of 10 mm³/L, as stipulated in CONAMA Resolution 357/2005 (Conselho Nacional do

Meio Ambiente) (Brasil, 2005), Ingá Park Lake was classified as Class 4, whereby the environment can only be used for landscaping purposes.

5 Conclusions and Recommendations

This pioneering study examines the trophic state of Ingá Park Lake. It observed poor water quality, assigning a hypereutrophic classification to the lake regardless of the seasonal period. However, a parallel study evaluating the phytoplankton community showed high densities and biomass of potentially toxin-producing cyanobacteria, with blooms occurring during the rainy season. Consequently, it is necessary to increase control over secondary contact activities in the lake to protect the population from potential contamination.

It is essential to establish partnerships between the local population, research institutions, NGOs, and government agencies to implement and monitor recovery and preservation actions for the lake. We also recommend systematic analyses to identify, typify, and quantify toxins in the lake water, along with constant monitoring of abiotic variables, considering seasonal variations in rainfall, to guide the management of this environment.

The local population should be aware of the lake recovery actions being carried out, and should hold authorities accountable and remain alert to potential water-related issues. To this end, it is necessary to develop environmental education and awareness programs, emphasizing the importance of preserving the water resources and reducing pollution, in order to improve quality of life and environmental conservation.

The recovery of this ecosystem must address anthropogenic impacts in the drainage basin. Soil impermeabilization and anthropogenic occupation of the basin are significant sources of increased nutrient input. Actions to remove nutrients directly from the lake without broader measures in the drainage basin are merely palliative. Reducing phytoplankton biomass, cyanobacterial blooms, and nutrient concentrations in the lake depends on stopping the discharge of untreated domestic sewage into the lake.

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