Brazilian
Journal of
Biology®

ISSN 1519-6984 (Print)
ISSN 1678-4375 (Online)

Original Article

Monitoring subtropical aquatic ecosystems: evaluating the use of Trophic State Indices (TSI) and Aquatic Life Protection (API) as baseline indices by monitoring an urban reservoir in southeastern Brazil

Monitoramento de ecossistemas aquáticos subtropicais: avaliação da utilização dos Índices de Estado Trófico (IET) e de Proteção da Vida Aquática (IVA) como índices básicos por meio do monitoramento um reservatório urbano no sudeste do Brasil

A. C. C. R. de Deus[a,b*] and D. M. S. Matos[c]

[a]Companhia Ambiental do Estado de São Paulo – CETESB, Setor de Comunidades Aquáticas, São Paulo, SP, Brasil
[b]Universidade Federal de São Carlos, Programa de Pós-graduação em Ecologia e Recursos Naturais, São Carlos, SP, Brasil
[c]Universidade Federal de São Carlos, Departamento de Hidrobiologia, São Carlos, SP, Brasil

Abstract

The use of indices is recommended for continuous monitoring and assessment of aquatic ecosystems, as they summarize the technical complexity of the results of multiple analyzes performed and translate these results into quality classes that reflect the actions taken and indicate ways to recover and conserve the resources. Environmental trophic state indices provide information on how nutrients, light availability and other factors promote the development of algal biomass and contribute to increased enrichment status of aquatic systems. Lamparelli's Trophic State Index (TSI) distinguishes between lentic (lower phytoplankton productivity) and lotic (higher phosphorus concentrations and lower chlorophyll-a concentrations) environments. The Aquatic Life Protection Index (ALPI) reflects water quality based on the trophic state of the environment, determines the degree of toxicity to biota and indicates deficiencies in variables and conditions essential for the protection of aquatic life. The indices were applied to a long data series to monitor the Guarapiranga Reservoir, an urban reservoir in the state of São Paulo in southeastern Brazil, which suffers from the urbanization of its surroundings and the discharge of domestic wastewater. The evaluation of the time series from 1978 to 2021 using these indices showed a deterioration in the trophic status and conservation of aquatic life in the reservoir and in one of its tributaries. Considering that the joint assessment of the two indices provides an approach to environmental conservation, their long-term use reflected changes and impacts on the environment and showed the best-preserved sites. Both indices are suitable for application in a baseline network in subtropical environments. They can pinpoint locations for better monitoring and are sensitive to environmental changes.

Keywords: reservoir, monitoring, cyanobacteria-bloom, trophic-state-index, aquatic-life-protection-index.

Resumo

A utilização de índices é indicada no monitoramento e avaliação permanente de ecossistemas aquáticos, pois eles sintetizam a complexidade técnica do resultado das variáveis e traduzem esses resultados em classes de qualidade, refletindo ações implementadas e apontam caminhos para a recuperação e conservação de recursos. Índices do estado trófico do ambiente fornecem uma visão sobre como nutrientes, disponibilidade de luz e outros fatores estimulam o desenvolvimento da biomassa algal contribui para o aumento do enriquecimento da condição dos sistemas aquáticos. O Índice do Estado Trófico (IET) Lamparelli diferencia ambientes lênticos (menor produtividade fitoplanctônica) e lóticos (maiores concentrações de Fósforo e menores concentrações de Clorofila-a). O Índice de Proteção da Vida Aquática (IVA) reflete a qualidade da água com base no estado trófico do ambiente, determina o grau de toxicidade para a biota e ainda indica deficiência em variáveis e condições essenciais para a proteção da vida aquática. Os índices foram aplicados a uma longa série de dados no monitoramento do Reservatório Guarapiranga, um reservatório urbano, localizado no Estado de São Paulo, sudeste do Brasil, que sofre com ocupação urbana em seu entorno e aporte de efluentes domésticos. A avaliação da série temporal de 1978 a 2021 com esses índices mostrou piora na condição trófica e de preservação da vida aquática no reservatório e em um dos tributários. Considerando que a avaliação conjunta dos dois índices fornece um enfoque de conservação ambiental, sua utilização em longo prazo refletiu alterações e impactos ao ambiente, mostrando ainda os locais mais conservados. Os resultados mostraram que os dois índices são indicados para aplicação em uma rede básica em ambientes subtropicais, aptos a indicar locais para aprimoramento do monitoramento e sensíveis às alterações ambientais.

Palavras-chave: reservatório, monitoramento, floração-cianobactérias, índice-estado-trófico, índice-preservação-vida-aquática.

---

*email: adeus@sp.gov.br
Received: February 9, 2024 – Accepted: May 28, 2024

1. Introduction

The declining quality of freshwater is one of the most critical challenges for human health, given its reliance on clean water, a concern that is anticipated to be exacerbated by future climate change. Globally, aquatic ecosystems face imminent threats from various factors such as overexploitation, water pollution, changes in water flow, habitat destruction, and the invasion of exotic species (Forio and Goethals, 2020). The Integrated Water Resources Management (IWRM), implemented at the World Water Forum in 2009 (UN Environment Programme, 2021), constitutes a complete and comprehensive strategy for the sustainable and fair governance of water resources. The fundamental principles of IWRM requires a continuous monitoring, evaluation and adjustment of management strategies based on new information and changing conditions. Thus, permanent monitoring is essential to evaluate temporal changes while the evaluation of these data indicates the state of these ecosystems (Forio and Goethals, 2020).

More than one-third of the Earth's renewable freshwater is used for agricultural, industrial, and domestic purposes, resulting in water pollution and consequent chemical contamination and eutrophication (Schwarzenbach et al., 2006). Aquatic ecosystems worldwide are threatened by resource exploitation, water pollution, alteration of water flow, habitat destruction or degradation, and invasion by exotic species (Forio and Goethals, 2020). Ongoing monitoring and assessment of aquatic ecosystems is necessary because monitoring provides data on changes in these environments over long periods of time, while assessment of these data indicates the status of these ecosystems (Forio and Goethals, 2020).

The development of a water quality monitoring network must be comprehensive, practical and consider variations in space and time of biological, physical and chemical processes to understand the environmental impacts stemming from various water-dependent activities (Lobato et al., 2015; Bettencourt et al., 2021). Several approaches can be used to detect and evaluate the impacts of human activities on water quality, with emphasis on traditional chemical analyses, bioindicators and toxicity tests. The integrated use of these methodologies improves the ability to understand degradation processes in aquatic ecosystems (Rörig et al., 2007). These tools facilitate the periodic evaluation of indicators such as dissolved oxygen (DO), temperature (T), total solids (TS), turbidity (TUR), nitrogen, and total phosphorus (TP). However, the analysis of individual indicators hinders comprehensive conclusions about water quality, thus potentially compromising effective water resources management (Uddin et al., 2021; Castro et al., 2023).

Several studies in hydrographic basins have employed multivariate statistical analysis and integrated indicators into environmental quality indexes which take into account the interactions among different parameters (Lamparelli 2004; Carneiro et al., 2020; Monte et al., 2021; Castro et al., 2023). Thus, the use of different indexes enhances the accuracy and reliability of assessments.

The Trophic State Index (TSI; Carlson, 1977) modified by Toledo Junior et al. (1983) for tropical habitats, provide insights about how nutrients, light and other environmental factors stimulate the development of algal biomass, generally measured as chlorophyll a, and to the increased enrichment condition of aquatic systems (Cunha et al., 2013). Lotic systems have higher concentrations of phosphorus and lower concentrations of chlorophyll-a when compared to the lentic ones which are more influenced by seasonality (CETESB, 1999, Lamparelli, 2004). In general, at the beginning of spring, the increase in water temperature, nutrients and light increase the eutrophication, while in the winter period, habitat conditions are generally less favorable to the eutrophication (CETESB, 1999).

The Aquatic Life Protection Index (ALPI; Zagatto et al., 1999) has been considered one of the most complete indices to evaluate the quality of aquatic ecosystems as it reflects the quality of water based on the trophic state of the environment in terms of the degree of toxicity for aquatic biota (Duarte dos Santos et al., 2017). It differs from the indexes used in the assessment of water for human consumption or primary contact recreation, as its calculation considers the Minimum Variable Index for the Preservation of Aquatic Life (IPMCA), in addition to the TSI. The IPMCA is based on the presence and concentration of toxic substances (TS; cadmium, chromium, dissolved copper, lead, mercury, nickel, zinc and surfactants), essential variables (VE; dissolved oxygen, pH, and toxicity analyses) with weightings following (CETESB, 1999). Over the years, this index has been applied by the Environmental Company of the State of São Paulo (CETESB), Brazil, in the evaluation of water bodies which demand special protection of their aquatic communities (CETESB, 2021). Yet, in 2003, the water monitoring in São Paulo state included biological community indices (phytoplankton, zooplankton, benthos) and cyanobacteria cell counts in the analysis of phytoplankton communities, complementing the assessment of water quality and aquatic life protection (CETESB, 2004).

The monitoring of the Guarapiranga reservoir started in 1978, initially establishing three monitoring points (CETESB, 1979), with an additional point incorporated in the year 2000. The population is concentrated on the right and left banks of the Guarapiranga reservoir (especially in the northern quadrant); the settlement on the right bank has a high population density (COBRAPE 2018). Using the long time series of monitoring data from the Guarapiranga Reservoir, São Paulo, Brazil, from 1978 to 2021, this study aims to evaluate the baseline indices for a monitoring network of aquatic ecosystems in subtropical environments.

2. Methods

2.1. Study area

The Guarapiranga hydrographic basin (23°43' S and 46°32' W) covers an area of 631 km2 and includes the municipalities of São Paulo, Cotia, Embu, Embu-Guaçu, Itapecerica da Serra, Juquitiba, and São Lourenço da Serra (SIGAM, 2023). The Guarapiranga reservoir has a circumference of 85 km, an area of 33.91 km^2 at an elevation of 740 m, a volume of 194x106 m^3, and average and maximum depths of 5.7 m

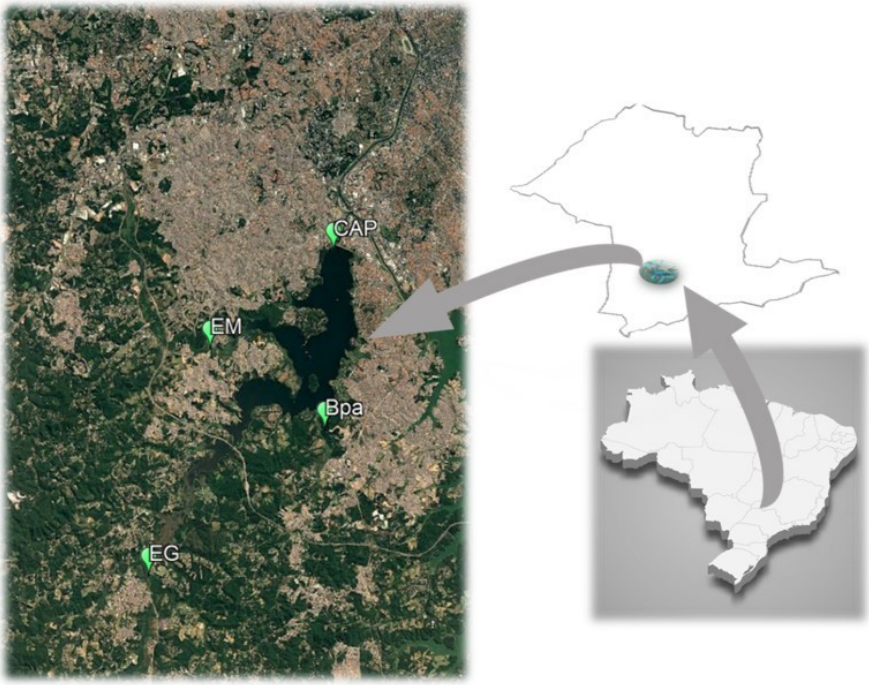

Figure 1. Location of the Guarapiranga reservoir, in the metropolitan region of São Paulo city-Southeast of Brazil, with water quality monitoring points, Where: CAP= SABESP catchment, Bpa= Parelheiros river, EM= Embu Mirim river and EG= Embu Guaçu river. Source: CETESB and Google Earth.

and 13.0 m, respectively (São Paulo, 2010, Figure 1). Data included in CETESB's Inland Water Quality reports show that Guarapiranga Reservoir had an average residence time of nearly 102 days from 2008 to 2021 (CETESB 2008-2021).

The basin drains an area of nearly 64,000 hectares and provides water supply for about 4 million people in the São Paulo metropolitan region (SIGAM, 2023).With a storage capacity of 171 billion liters of water, Guarapiranga is the main source of the Guarapiranga system (SABESP, 2021a). The Guarapiranga reservoir is responsible for producing 15.000 liters of water per second and is responsible for the public supply of a large part of the southern and southwestern zone of Greater São Paulo (SABESP, 2021a). The monthly rainfall from 1978 to 2021 is presented in Figure 2. Further information about the probes consulted is listed in the Supplementary Material.

In 2000, the Guarapiranga system was connected to the Taquacetuba branch of Billings Reservoir by pumping a tributary of the Parelheiros River to supplement the outflow of the reservoir, which was losing its supply capacity (Zorzal-Almeida et al., 2017). The São Paulo State Basic Supply Company (SABESP) began operating the raw water system from the Taquacetuba Branch to the Guarapiranga Reservoir in August 2000 with an operating license for 2.0 m3/s (CETESB, 2001).

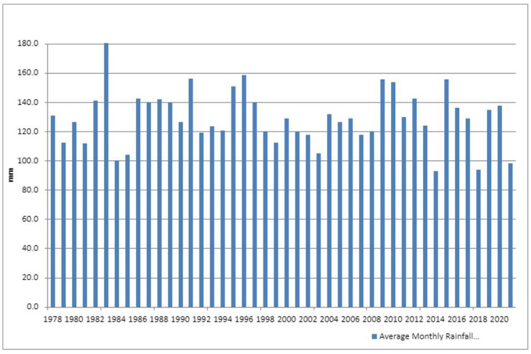

Figure 2. Averaged monthly rainfall (mm) from 1978 to 2021, in the municipalities of São Paulo, Diadema, São Bernardo do Campo, Embu, Embu Guaçu, Itapecerica da Serra and Taboão, located in the Guarapiranga basin. Data from the Department of Water and Electric Energy (DAEE, 2023).

2.2. Economic progress and the need for environmental monitoring

The state of São Paulo, located in southeastern Brazil, was already the country's most important economic population center in 1950. In the 21st century, this state could be classified as the 36th largest economy in the world in terms of GDP generated (Luna and Kein, 2019). The city of São Paulo began the process of industrialization at the beginning of the 20th century with the wealth derived from coffee cultivation and experienced intense development (Soares, 2021). The population of São Paulo city, capital of São Paulo state in the southeast of Brazil, increased from 65,000 in 1890, 240,000 in 1900 to 11,451,245 inhabitants in 2019 (Prefeitura de São Paulo, 2009). The high energy demand in this region led to the construction of the Guarapiranga reservoir in 1906 (SABESP, 2021a; EMAE, 2023) but, since 1929, after the severe climatological water scarcity event occurred in 1920 it has been used to supply drinking water (Araújo, 2017).

The construction of the Guarapiranga reservoir by "The São Paulo Tramway, Light and Power Co" was a consequence of the strong economic growth of the state of São Paulo at the beginning of the 20th century (SABESP 2021a; Soares 2021). The reservoir, which was created by damming the Guarapiranga River, also known as Embu-Guaçu, and 17 other smaller rivers, was originally used to generate electricity. In 1928, the Guarapiranga reservoir became the main source of public water supply in the municipality of São Paulo and beginning in 1958, Guarapiranga Reservoir has been used primarily for public supply (CETESB, 2003; DAE, 1964; Queiroz, 1964; Whately and Cunha, 2006).

Around 1970, the population in the catchment area increased rapidly. Many of the houses were of low standard, and sewage from these settlements was discharged untreated into the reservoir (Whately and Cunha, 2006). By 1974, the arms of Guarapiranga Reservoir were substantially populated. During the period between 1980 and 1985, the municipalities of Embu, Itapecerica da Serra, and the municipality of São Paulo in the Parelheiros region became more populated (CETESB, 2003).

In response to the deterioration of the aquatic ecosystem quality in the Guarapiranga basin, regular monitoring of the reservoir's water quality started in 1978 (CETESB, 1979). In the early 1990s, an outbreak of *Anabaena solitary* Klebahn (currently named as *Dolichospermum solitarium* Klebahn) occurred in the reservoir, leading to numerous cases of gastroenteritis and dermatitis associated with the quality of the supplied water (Beyruth et al., 1992). As these blooms interfered with water treatment processes, algaecides such as copper sulfate and hydrogen peroxide were employed to manage them (Beyruth et al., 1992). The use of copper sulfate for controlling algal/cyanobacterial blooms notably increased, particularly after 1990 (Beyruth, 1996).

According to SABESP, approximately 3,160 tons of copper sulfate were applied to Guarapiranga Reservoir from 1981 to 2011 to control phytoplankton (CETESB, 1983; Lamparelli et al., 2000; CETESB, 2004-2012), while from 2014 to 2021, 3,694 tons of copper sulfate were applied to the Guarapiranga reservoir to control phytoplankton (SABESP 2016, 2017, 2018, 2019, 2021b, 2022). The amount of copper sulfate used in the reservoir to control algal and cyanobacterial blooms therefore fluctuates, with an increasing trend over the years. Although the effect of the algaecide in the short term facilitates the management of the reservoir and its use as a source, recurrent applications tend to be ineffective because they can favor resistant strains of cyanobacteria (García-Villada et al., 2004).

Since 1975, CETESB has used the Water Quality Index (WQI), which was developed to evaluate the quality of water for public supply, taking into account aspects related to the treatment of these waters (CETESB, 2022). This index was developed and adapted from a study conducted in 1970 by the National Sanitation Foundation of the United States (CETESB 2022). Zorzal-Almeida et al. (2017) used the available database to assess the evolution of the trophic state of the Guarapiranga reservoir and Semensatto et al. (2021) applied the WQI to the same data series.

In 1998, CETESB presented for the first time the assessment of stream quality in terms of the degree of trophicity and protection of aquatic life through the use of the Trophic State Index (TEI) and the Aquatic Life Protection Index (ALPI) (CETESB, 1999). Later, in 2003, CETESB monitoring was expanded to include indices of biological communities (phytoplankton, zooplankton, benthos) and to include cell counts of cyanobacteria in the analysis of phytoplankton communities, thus complementing the assessment of environmental quality with respect to the protection of aquatic life (CETESB, 2004).

2.3. Long term data series and Quality indices

For the calculation of the different indexes of water quality, we used data about total phosphorus (PT), chlorophyll-a, total copper, dissolved copper, thermotolerant coliforms, *Escherichia coli* and pheophytin-a, collected from 1978 to 2021 for points Cap, EM and EG and from 1999 to 2021 for point Bpa. Based on the information obtained from Infoáguas System (Sistema Infoáguas, 2023), we used the data available for the following points: 1) EMGU00800 (renamed as EG), located on the Embu-Guaçu River; EMMI02900 (renamed as EM), located on the Embu-Mirim River; GUAR00100 (renamed as BPa), in the Parelheiros river; GUAR00900 (renamed as Cap), located in the Sabesp catchment area (Figure 1).

The Trophic State Index (TSI), as well as the TSI for total phosphorus (TSI-PT) and the TSI for chlorophyll-a (TSI-CL) were calculated for the period from 1978 to 2021. The total phosphorus and chlorophyll-a represent the trophic state (Lamparelli, 2004) and TSI-PT is a measure of potential eutrophication since phosphorus acts as the causative agent of the process. The TSI-CL represents the assessment of Chlorophyll-a, indicating the consequent phytoplankton growth rate. In the modification proposed by Lamparelli (2004), a new intermediate class of trophy was established, between the Eutrophic and Hypereutrophic classes, called Supereutrophic using different values of chlorophyll and phosphorus. The Aquatic Life Protection Index (ALPI, Zagatto et al., 1999) has five water quality categories: Optimal, Good, Regular, Poor and Very Poor. The result for this classification is obtained by integrating data from the TSI (Lamparelli, 2004) and the results of the Index of Minimum Variables for the Preservation of Aquatic Life (IPMCA), which is composed of the group of essential variables and the group of toxic substances.

The methodology used for the indexes calculation is presented in the Supplementary Material.

2.4. Data analysis

Linear regression models were used to predict the value of each index for each sampling point over time, from 2011 to 2021. A principal component analysis (PCA) was carried out, considering the indices and variables (chlorophyll-a, pheophthin-a, dissolved copper, total copper, thermotolerant coliforms, *E. coli* and total phosphorus), considering the correlation between the groups. The analysis of variance (ANOVA) and Pearson correlation were used to measure the correlation between TSI-PT data and the following variables: chlorophyll-a, pheophthine-a, dissolved copper, total copper, thermotolerant coliforms, *E. coli* and total phosphorus, for the period from 1978 to 2021 Analysis were performed in the R environment (R Core Team, 2020) and in the Past software (Hammer et al., 2001).

3. Results and Discussion

When evaluating the time series, we can observe that the concentrations of total phosphorus (1978 to 2021) and subsequent concentrations of chlorophyll-a (1999 to 2021) varied both in relation to the sampling points and temporality. The increase in phosphorus concentrations over the decades occurred at all points evaluated, but is particularly evident in the Embu Mirim river (EM) and the SABESP Catchment (Cap) (Figure 3). At points in the reservoir (Cap and Bpa), where the water retention time is longer, the pattern of increase in chlorophyll-a concentration showed the intensification of the activity of the phytoplankton community (Figure 3).

The quality of the two rivers contributing to the reservoir, Embu Guaçu (EG) and Embu Mirim (EM), has shown signs of anthropogenic impact since monitoring began, but not to the same extent. The phosphate concentration, which classified the rivers mainly as mesotrophic in that year according to the TSI PT classification (Figure 3), reached 0.166 mg/L in the Embu Mirim river, in a period in which the river had a eutrophic characteristic (TSI PT).

The water quality of the Embu Mirim River (EM) has continued to deteriorate over the years, as evidenced by the deteriorating condition of the TSI (Figure 4). The quality of the Embu Guaçu and Embu Mirim Rivers deteriorated gradually over the years, but was more pronounced in the Embu Mirim River, whose watershed was more exposed to the impacts of urban settlement than the Embu Guaçu watershed (Semensatto et al., 2021). This situation

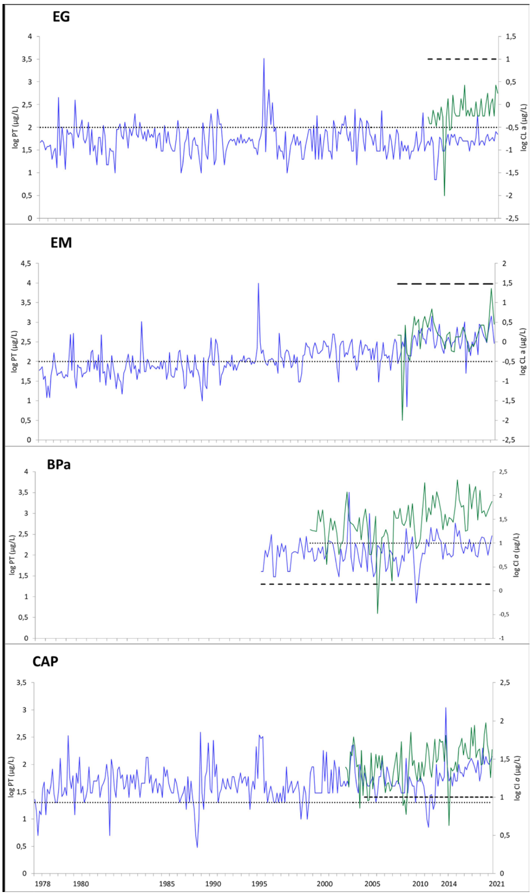

Figure 3. Change in concentration of total phosphorus and chlorophyll-a at sampling sites from 1978 to 2021 and from 1999 to 2021, respectively (Graphs A, B, C, and D). Graphs A to D: logPT(µg/L), logCl *a* (µg/L), log LimPT (µg/L), log LimCl *a* (µg/L). EG: Embu-Guaçu river; EM: Embu-Mirim river; BPa: Parelheiros branch; CAP: SABESP catchment.

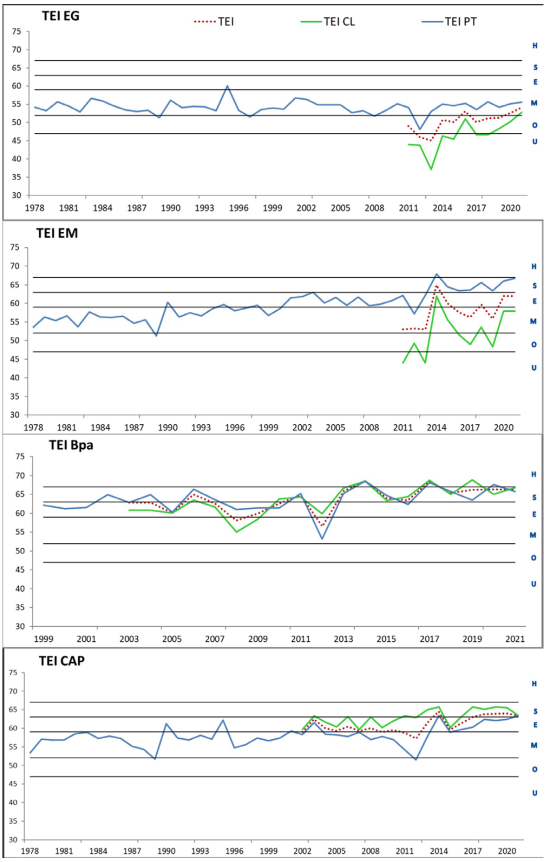

Figure 4. Evolution of annual trophic state assessment by TSI index (Graphs: A, B, C, and D). The lines in the TSI diagrams represent the environmental classification categories: Hypereutrophic, Supereutrophic, Eutrophic, Mesotrophic, Oligotrophic, Ultraoligotrophic. Graphs A to D: TSI PT (µg/L), TSI Cl *a* (µg/L) , TSI (µg/L). EG= Embu-Guaçu river, EM= Embu-Mirim river, BPa= Parelheiros branch, CAP= SABESP catchment.

reflects the impacts to which the Embu Mirim River is exposed, mainly through the input of organic matter from untreated domestic wastewater, as evidenced by the high concentrations of *Escherichia coli* (CETESB, 2022).

We noted a tendency toward rising phosphorus concentrations and eutrophication at specific reservoir points - the Parelheiros branch (Bpa) and SABESP Catchment (Cap), based on quarterly data of TSI and TSI-PT from 2011 to 2021 (Figure 5). The regression curves obtained with TSI-CL data for this period did not indicate a clear trend (Figure 5). The regression curves obtained with the VAT data also indicated a worsening in the conditions of the reservoir points - Parelheiros arm (Bpa) and the SABESP Catchment (Cap) (Figure 5). There was also an indication of improvement in the conditions of the Embu Mirim River throughout the time series with VAT data (Figure 5, Table 1). The indication of improvement in the conditions of the Embu Mirim River in relation to the preservation of aquatic life from 2015 is probably related to the worsening in the quality of this river resulting from the drought recorded between 2013 and 2014 (Figure 2).

According to Strasktaba and Tundisi (2013), the retention time of water in a reservoir has effects on water quality. This fact arises from the greater availability of nutrients with the increase in residence time, favoring cyanobacteria blooms (Tundisi and Matsumura Tundisi, 2008). The average residence time in the Guarapiranga reservoir (102 days according to CETESB, 2008-2021) can be seen as a factor in the accumulation of nutrients.

The results confirm the assessment of the deterioration of the trophic state of the Guarapiranga reservoir by Zorzal Almeida et al. (2017), with the best water quality being found near the Embu Guaçu river. The phosphate concentrations found by Kleerekoper (1939) would classify Guarapiranga Reservoir, when it was called Lago de Santo Amaro, as an ultraoligotrophic environment, since the results of the analyzes in that study were below the 0.001 mg/L quantification limit. Four decades later, data from the catchment area in 1978 (CAP) showed that the reservoir had phosphate concentrations of between 0.023 and 0.082 mg/L (Sistema Infoáguas, 2023). Although in the 1970's the reservoir had mainly mesotrophic characteristics (Figure 4), there was a period when it reached the eutrophic state according to the TSI PT classification.

The scenario of worsening eutrophication of the reservoir in general became more common as monitoring progressed from 2012 to 2021. Relevant during this period was the influence of the water status of the Taquacetuba Branch in Billings Reservoir, which was reversed by that of the Parelheiros River – Bpa (CETESB, 2013, 2014, 2019, 2021) on the water quality of Guarapiranga (Figure 4). The condition of the Parelheiros River-Branch (Bpa), which has reached the hypereutrophic state, reflects the severe eutrophication of the reservoir (Figure 4), while the artificial "flattening" of the TSI at Catchment Point (CAP) indicates the use of algaecides to control the activity of the phytoplankton community.

Beyruth et al. (1997) pointed out that the quality of water in the Guarapiranga is highly dependent on climatic factors, the operation of the reservoir and the use of the basin. In this sense, the influence of rain is a factor that must be considered in the dynamics of the reservoir and its tributaries, as it may carry material to the water bodies of the basin and concentrate or dilute pollutants (Soares et al., 2019). In years of low rainfall, water quality deteriorates, often due to the input of domestic sewage (CETESB, 2007). The dry period, which historically lasts from April to September, was more pronounced in 2014 and 2021, with annual rainfall in 2014 (1,055 mm) 26% less than the average of the previous 19 years (CETESB 2015); 2021 had a rainfall of 1,067 mm, 23% less than the average of the previous 26 years (CETESB 2022). Therefore, it is possible that the variations in TSI and VAT of the reservoir points (CAP and Bpa) and Embu Mirim River observed during this period are related to this drought.

Following the classification of Zagatto et al. (1999), the evaluation of the points by VAT, showed that the degradation of the condition of the Embu Mirim River is very severe, especially in years with low rainfall (Figure 5). The condition of the Embu Guaçu River was consistently "good," with alternating improvements and occasional deteriorations. The result of the Embu Guaçu River shows that this habitat has good conditions and is resilient even in low rainfall years.

In the central part of the reservoir, the arm of the Parelheiros River is in a predominantly "poor" condition, with occasional deteriorations (Figure 5). This situation is the result of the detour of water from Billings Reservoir, as well as pressures created by tributaries and the Parelheiros

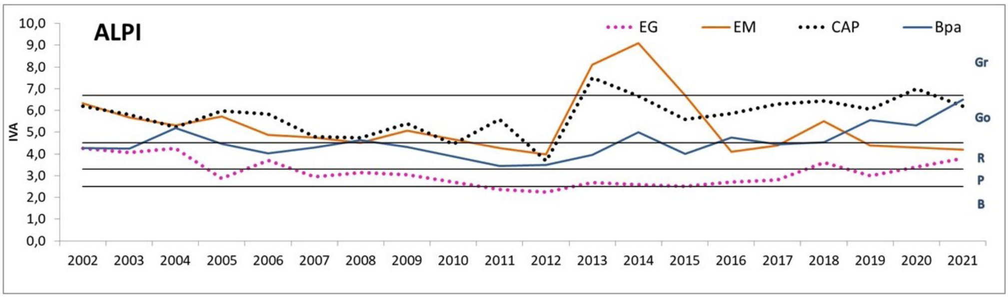

Figure 5. Evolution of the quality rating of the rivers Embu Guaçu (EG), Embu Mirim (EM), branch of the Parelheiros River (Bap) and SABESP catchment (CAP) from 2002 to 2021 according to the index ALPI. The lines in the graph represent the classification categories of the environment: Great (Gr), Good (Go), Regular (R), Poor (P), Bad (B).

Table 1. Results of the statistical tests applied to the TSI results and variables. R (2020) and Past (Hammer et al., 2001) software were used.

Statistical tests				
TSI				
Linear Regression				
TSI as a function of sampling areas	Multiple R-squared: 0.6907	F: 78.15	p-value: < 2.2e-16	Significant difference: all areas differ from each other
TSI as a function of sampling date and areas	Multiple R-squared: 0.6907	F-statistic: 78.15	p-value: < 2.2e-16	Significant difference between sampling dates and areas
ANOVA followed by the TUKEY test				
TSI as a function of sampling areas	Sum of squares: 4479	F: 89.16	P: <2e-16	Significant difference
	TUKEY	EM-EG	P: 0.0000000	Significant
		CAP-EG	P: 0.0000000	Significant
		Bap-EG	P: 0.0000000	Significant
		CAP-EM	P: 0.0041645	Significant
		Bap-EM	P: 0.0000000	Significant
		CAP-EM	P: 0.0063660	Significant
TSI as a function of date and sampling areas	Sum of squares: 4576.3	F: 100.8806	p-value: < 2.2e-16	difference
ALPI as a function of date and sampling areas	Sum of squares: 222.6	F: 31.91	p-value: < 8.36e-16	difference
	TUKEY	CAP-EG	P: 0.0000825	Significant
		EM-EG	P: 0.0000000	Significant
		Bap-EG	P: 0.0000000	Significant
		EM-Cap	P: 0.0034184	Significant
		Bap-Cap	P: 0.0003907	Significant
		Bap-EM	P: 0.9432811	Not Significant
Variables				
ANOVA followed by the TUKEY test				
Analysis of variance of TSI FT and variables - chlorophyll-a, phaeophthin-a, dissolved copper, total copper, thermotolerant coliforms, *E coli*, and total phosphorus from 1978 to 2021	Sum of squares: 912,516	F: 21,25	P: 3,7E-20	Significant difference
	TUKEY	TSI FT – Diss Copper	P: 0	Significant
		Diss Copper - Total Copper	P: 1,34E-05	Significant
		Diss Copper - Therm Col	P: 0	Significant
		Diss Copper - Total Phosp	P: 0	Significant
		TSI PT- *E.coli*	P: 0,008375	Significant
		Diss Copper - *E.coli*	P: 7,28E-03	Significant
		Therm Col - *E.coli*	P: 0,04605	Significant
		E.coli- Total Phosp	P: 0,008375	Significant

River (CETESB, 2006, 2013). The area near the SABESP water intake had a condition between "normal" and "poor", a result of high copper concentrations due to the use of algaecides to control algal and cyanobacterial blooms (CETESB, 2006, 2013). In this regard, the poor quality verified by VAT is likely due to the use of algaecides, as high copper concentrations were detected on several occasions, highlighting the ecological importance of the use of algaecides for the ecosystem (CETESB, 2006, 2013, 2018).

The linear regression analysis of the studied sites with the data from TSI and TSI PT showed a tendency of phosphorus enrichment and eutrophication at the sites of the reservoir - Parelheiros river branch (Bpa) and SABESP water intake (CAP) (Figure 6). The regression plots

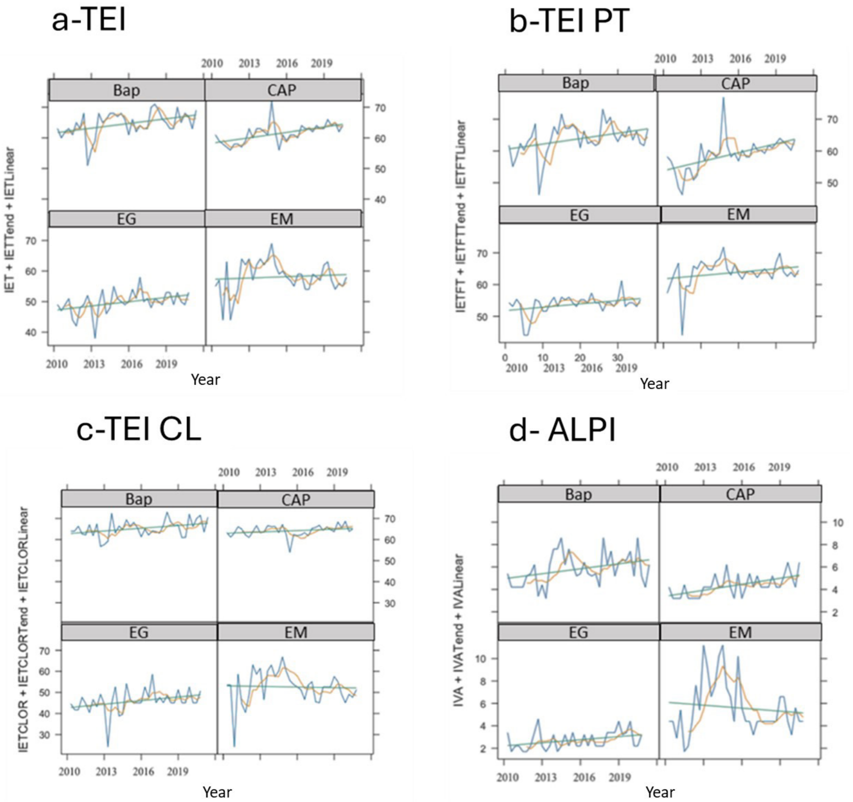

Figure 6. Evolution of the index (blue line), trend line and linear regression (green line) for TSI (a-), TSI-P (b-), TSI-CL (c-) and ALPI (d-) data collected at the following sites of Guarapiranga reservoir, São Paulo municipality, from 2011 to 2021: Embu Guaçu river - EG (a), Embu-Mirim river - EM (b), Parelheiros branch - Bap (c) and SABESP catchment - CAP (d).

generated with the data from TSI-CL do not show a clear trend (Figure 6). The regression plots made with the data from VAT also showed a deterioration in the condition of the reservoirs - Parelheiros river branch (Bpa) and SABESP water intake (CAP) (Figure 6). There was also evidence of improvement in the condition of the Embu Mirim River throughout the time series with VAT data (Figure 6, Table 1). The evidence of improvement in the condition of the Embu Mirim River in terms of maintaining aquatic life from 2015 is likely related to the increase in rainfall (Figure 2).

Analysis of variance (ANOVA) performed on the TSI data shows significant differences between areas, except between the Embu Mirim River (EM) and the Parelheiros river branch (Bap) (Table 1). This result reflects the similar TSI values of the Embu Mirim River (EM) and the Parelheiros River branch (Bap), a result of the similar impacts faced by these localities due to sanitary wastewater contributions. The analysis of variance performed with the TSI data as a function of the date of sampling showed a significant difference, confirming the change in the environment over the decades.

The result of ANOVA, performed with the data from TSI FT and the variables in the period from 1978 to 2021, showed the occurrence of a significant difference and Tukey's test indicated a significant statistical difference between TSI FT, thermotolerant coliforms, E. coli and total phosphorus with dissolved copper. There was also a significant difference between Escherichia coli and total copper, thermotolerant coliforms and total phosphorus. The results suggest the use of copper sulfate with a high concentration of organic material.

Pearson correlation analysis (Figure 6) performed with Past software (Hammer et al., 2001) between TSI-FT and the variables for the entire time series showed a strong correlation between TSI-FT and thermotolerant coliforms (0.758); dissolved copper and E coli (0.763); thermotolerant coliforms and total phosphorus (0.850); and total phosphorus and E coli (0.839). There was also a moderate correlation between dissolved copper and total phosphorus (0.550). This result again indicates the presence of copper sulfate along with the source of sanitary contamination, as evidenced by the correlation of E. coli with total phosphorus, which links the sources of organic matter with sewage contamination.

A principal component correlation analysis (PCA) was used to verify the arrangement of the collection sites in relation to the environmental gradient represented by the set of values of the index results (IETClor, IETPT, TSI, ALPI) and the variables total copper and dissolved, chlorophyll-a, pheophytin-a, thermotolerant coliforms and *E. coli* during the period from 2011 to 2021 (Figure 7). The result could explain almost 81% of the correlation

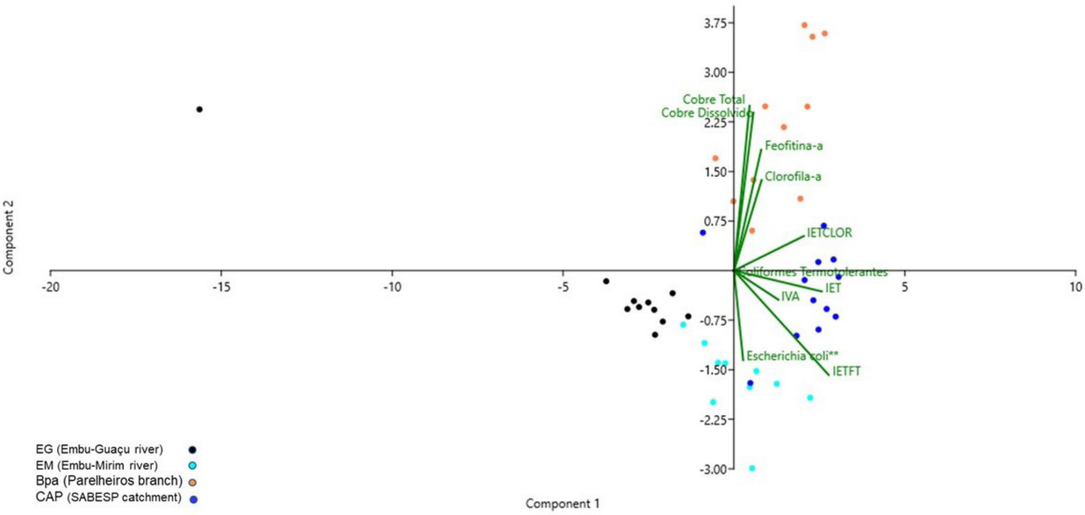

Figure 7. Result of principal component analysis of correlation – PCA – with the result of indices (TSI, TSI PT, IETCL and ALPI) and variables (total and dissolved copper, chlorophyll-a, pheophytin-a, thermotolerant coliforms and *Escherichia coli*) from 2011 to 2021

when components 1 and 2 were considered. Component 1 was strongly correlated with TSI and TSI FT, while component 2 was correlated with dissolved and total copper and pheophytin.

The results showed that the data grouped the most eutrophic environments and those affected by the use of copper sulfate to control algal/cyanobacterial blooms. The approach of the Embu Mirim River to the reservoir sites reflects the most polluted condition of the site and shows the worst classifications based on TSI PT and VAT.

4. Conclusion

The indices assessed in this study reflected both the contribution that the monitored environments have received and the different anthropogenic pressures that each site has experienced over time. The degradation of water quality in the study area was constant at the reservoir and Embu Mirim River sites for more than four decades, as shown by the analyzes of TSI and ALPI indices. The varying degree of degradation in the areas around the reservoir had an impact on the long-term water quality results.

The improved quality of the Embu Guaçu River, located in the Capivari Monos Environmental Protection Area, which partially protects it from urban expansion, was also captured by the indices, as were the various stress factors affecting it. The results of the indices for the Embu Mirim River, which is surrounded by an urban environment and exposed to the pressures and pollution caused by the changes in this environment, inevitably lead to a loss of quality in the aquatic ecosystem. In the central part of the reservoir, the indices have shown the effects of increasing organic pollution from sanitary sewage and the deterioration of the aquatic environment. The indices have also identified cyanobacterial blooms as a consequence of the eutrophication of the aquatic ecosystem, which has been combated for decades through the use of algicides to enable the treatment of water to supply the population.

The deterioration of reservoir quality pointed out by ALPI could be related to the application of algaecides. Evaluation of the TSI and ALPI indices shows the deterioration in this environment, exacerbated by the detour of water from Taquacetuba to Guarapiranga. The deteriorating water quality in the reservoir, reflected in ALPI, indicates that the protection of the aquatic community is compromised in terms of ecotoxicity.

The results show that the TSI and ALPI indices evaluated in this study reflect the quality of the environment and the impacts to which they are exposed, both in the short and long term, especially those under intense human pressure. As the focus of these indices is on information about the state of conservation of the environment and not only on the quality of water as a resource for treatment and consumption, their application in environmental monitoring provides an integrating response for the aquatic ecosystem. Ecosystem integrity is critical to maintaining water quality. The study has shown that the introduction of indices indicating the locations of water quality loss and the likely causes is a good approach to monitoring the environment of interest.

Assessing the viability of the aquatic environment in terms of the toxicity provided by ALPI is particularly important given the large number of stressors present in virtually all aquatic habitats today. The aquatic ecosystem in anthropogenic environments is severely affected by potential sources of toxicity to the community, and the use of an index that can assess not only the presence but also the intensity of this toxicity is essential for monitoring these waters.

Habitat modification and degradation is one of the main causes of biodiversity loss. Monitoring the aquatic environment is an essential tool for identifying stressors, both at an early stage (first signs of change) and for corrective action on established stressors. Over time, monitoring often involves expanding sampling sites and, most importantly, incorporating monitoring of biological communities at selected sites as indicated by the baseline indices, TSI and ALPI. In this way, the time series data showed that the combined use of Lamparelli Trophic State Index (TSI 2004) and the Aquatic Life Protection Index (Zagatto et al., 1999) is appropriate, in terms of facility, accuracy and efficiency, for the development of a basic monitoring network in subtropical waters.

Acknowledgements

ACCRD thanks to CETESB and DMSM thanks to CNPq (Grant 312381/ 2020-4).

References

ARAÚJO, R., 2017. São Paulo, a Light e a Represa Guarapiranga. In. C. E. M. Bicudo & D. Bicudo (Eds.), 100 anos da Represa Guarapiranga: lições e desafios. Curitiba: Editora CRV.

BETTENCOURT, P., FULGÊNCIO, C., GRADE, M. and WASSERMAN, J.C., 2021. A comparison between the European and the Brazilian models for management and diagnosis of river basins. *Water Policy*, vol. 23, no. 1, pp. 58-76. http://doi.org/10.2166/wp.2021.204.

BEYRUTH, Z., 1996. Comunidade fitoplanctônica da Represa de Guarapiranga: 1991-1992. Aspectos ecológicos, sanitários e subsídios para reabilitação da qualidade ambiental. São Paulo: Universidade de São Paulo, Tese de Doutorado.

BEYRUTH, Z., CALEFFI, S., ZANARDI, E., CARDOSO, E. and ROCHA, A.A., 1997. Water quality of Guarapiranga Reservoir, São Paulo, Brazil, 1991–1992, Internationale Vereinigung für theoretische und angewandte Limnologie. *Verhandlungen*, vol. 26, no. 2, pp. 675-683. http://doi.org/10.1080/03680770.1995.11900801.

BEYRUTH, Z., SANT'ANNA, C.L., AZEVEDO, M.T.P., CARVALHO, M.C. and PEREIRA, H.A.S.L., 1992. *Toxic algae in freshwaters of sao paulo state. Algae and environment: a general approach*. São Paulo: Sociedade Brasileira de Ficologia.

CARLSON, R.E., 1977. A trophic state index for lakes. *Limnology and Oceanography*, vol. 22, no. 2, pp. 361-369. http://doi.org/10.4319/lo.1977.22.2.0361.

CARNEIRO, L., OSTROSKI, A. and MERCURI, E.G.F., 2020. Trophic state index for heavily impacted watersheds: modeling the influence of diffuse pollution in water bodies. *Hydrological Sciences Journal*, vol. 65, no. 15, pp. 2548-2560. http://doi.org/10.1080/02626667.2020.1828588.

CASTRO, R.M., MARCIONILIO, S.M.L.O., MORAIS, W.A., ALVES, W.S., OLIVEIRA, L.D., TEIXEIRA, M.B. and OLIVEIRA, D.M.S., 2023. Spatiotemporal analysis of water quality indicators in a watershed in Brazilian Cerrado. *Water Science and Technology: Water Supply*, vol. 23, no. 3, pp. 1161-1176. http://doi.org/10.2166/ws.2023.061.

COMPANHIA BRASILEIRA DE PROJETOS E EMPREENDIMENTOS – COBRAPE, 2018 [viewed 9 February 2024]. PLANO DE DESENVOLVIMENTO E PROTEÇÃO AMBIENTAL (PDPA) DA APRM GUARAPIRANGA. *Elaboração e Revisão dos Planos de Desenvolvimento e Proteção Ambiental das Áreas de Proteção e Recuperação dos Mananciais da Região Metropolitana de São Paulo*. São Paulo: COBRAPE. Available from: https://smastr20.blob.core.windows.net/mananciais/PDPA%20%20APRM%20Guarapiranga.pdf.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 1979 [viewed 9 February 2024]. *Relatório de qualidade das águas superficiais no estado de São Paulo 1978*. São Paulo: CETESB, 244 p. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/relatorio-aguas-superficiais-1978.pdf

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 1983. *Controle das fontes de poluição localizadas nas áreas de proteção de mananciais*. Camboriú: ABES, 12 p.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 1999 [viewed 9 February 2024]. *Relatório de qualidade das águas superficiais no estado de São Paulo 1998*. São Paulo: CETESB, 371 p. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/relatorio-aguas-superficiais-1999.zip

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2001 [viewed 9 February 2024]. *Relatório de qualidade das águas superficiais no estado de São Paulo 2000*. São Paulo: CETESB, 214 p. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/volume12.zip

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2003 [viewed 9 February 2024]. *Relatório de qualidade das águas superficiais no estado de São Paulo 2002*. São Paulo: CETESB, 279 p. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/relatorio_anual_aguas_int_2003.zip

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2004 [viewed 9 February 2024]. *Relatório de qualidade das águas superficiais no estado de São Paulo 2003.* São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/relatorio_anual_aguas_int_2003.zip.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2006 [viewed 9 February 2024]. *Desenvolvimento de índices biológicos para o biomonitoramento em reservatórios do Estado de São Paulo*. São Paulo: CETESB, 146 p. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/03.zip

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2007 [viewed 9 February 2024]. *Relatório de qualidade das águas interiores do estado de São Paulo 2006 / CETESB.* São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/relatorio_2006.zip.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2013 [viewed 9 February 2024]. *Qualidade das águas superficiais no estado de São Paulo 2012 [recurso eletrônico] / CETESB*. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/relatorio-aguas-superficiais-2012-substituido-em-060513.zip.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2014 [viewed 9 February 2024]. *Qualidade das águas superficiais no estado de São Paulo 2013 [recurso eletrônico] / CETESB*. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/relatorio-aguas-superficiais-2013-parte1.pdf

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2015 [viewed 9 February 2024]. *Qualidade das Águas Interiores no estado de São Paulo 2014*. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2013/11/Cetesb_QualidadeAguasSuperficiais2014_ParteI_vers%C3%A3o2015_Web.pdf

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2018 [viewed 9 February 2024]. *Qualidade das Águas Interiores no estado de São Paulo 2017 [recurso eletrônico] / CETESB*. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2018/06/Relat%C3%B3rio-de-Qualidade-das-%C3%81guas-Interiores-no-Estado-de-S%C3%A3o-Paulo-2017.pdf.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2019 [viewed 9 February 2024]. *Qualidade das Águas Interiores no estado de São Paulo 2018 [recurso eletrônico] / CETESB*. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2019/10/Relat%C3%B3rio-de-Qualidade-das-%C3%81guas-Interiores-no-Estado-de-SP-2018.pdf.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2021 [viewed 9 February 2024]. *Qualidade das Águas Interiores no estado de São Paulo 2020*. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2021/09/Relatorio-Qualidade-das-Aguas-Interiores-no-Estado-de-Sao-Paulo-2020.pdf

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2004-2012 [viewed 9 February 2024]. *Qualidade das águas interiores no estado de São Paulo. São Paulo: CETESB*. (Série Relatórios, ISSN 0103-4103). Publicado anteriormente como: Relatório de qualidade das águas interiores no estado de São Paulo; Relatório de qualidade das águas superficiais no estado de São Paulo; Qualidade das águas superficiais no estado de São Paulo. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/publicacoes-e-relatorios/.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2008-2021 [viewed 9 February 2024]. *Qualidade das águas interiores no estado de São Paulo. São Paulo: CETESB. (2008-2021). (Série Relatórios, ISSN 0103-4103). Publicado anteriormente como: Relatório de qualidade das águas interiores no estado de São Paulo; Relatório de qualidade das águas superficiais no estado de São Paulo; Qualidade das águas superficiais no estado de São Paulo*. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/publicacoes-e-relatorios/.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO – CETESB, 2022 [viewed 9 February 2024]. *Qualidade das Águas Interiores no estado de São Paulo 2021*. São Paulo: CETESB. Available from: https://cetesb.sp.gov.br/aguas-interiores/wp-content/uploads/sites/12/2022/11/RAI-2021-Relatorio-Qualidade-das-Aguas-Interiores-no-Estado-de-Sao-Paulo.pdf

COMPANHIA DE SANEAMENTO BÁSICO DO ESTADO DE SÃO PAULO – SABESP, 2016. *1º Relatório de Monitoramento da Qualidade da Água para Atendimento do Plano de Aplicação de Algicidas para a Represa Guarapiranga. Processo CETESB nº 33/10688/14*. São Paulo: SABESP.

COMPANHIA DE SANEAMENTO BÁSICO DO ESTADO DE SÃO PAULO – SABESP, 2017. *Relatório de Monitoramento da Qualidade da Água para Atendimento do Plano de Aplicação de Algicidas para a Represa Guarapiranga. Processo CETESB nº 33/10688/14*. São Paulo: SABESP.

COMPANHIA DE SANEAMENTO BÁSICO DO ESTADO DE SÃO PAULO – SABESP, 2018. *Relatório de Monitoramento da Qualidade da Água para Atendimento do Plano de Aplicação de Algicidas para a Represa Guarapiranga. Processo CETESB nº 33/10688/14*. São Paulo: SABESP.

COMPANHIA DE SANEAMENTO BÁSICO DO ESTADO DE SÃO PAULO – SABESP, 2019. *Relatório de Monitoramento da Qualidade da Água para Atendimento do Plano de Aplicação de Algicidas para a Represa Guarapiranga. Processo CETESB nº 33/10688/14*. São Paulo: SABESP.

COMPANHIA DE SANEAMENTO BÁSICO DO ESTADO DE SÃO PAULO – SABESP, 2021a [viewed 9 February 2024]. Água – Mananciais - Guarapiranga. Sabesp » Água » De onde vem? 2021. Available from: http://site.sabesp.com.br/site/interna/Default.aspx?secaoId=31

COMPANHIA DE SANEAMENTO BÁSICO DO ESTADO DE SÃO PAULO – SABESP, 2021b. *Relatório de Monitoramento da Qualidade da Água para Atendimento do Plano de Aplicação de Algicidas para a Represa Guarapiranga. Processo CETESB nº 33/10688/14*. São Paulo: SABESP.

COMPANHIA DE SANEAMENTO BÁSICO DO ESTADO DE SÃO PAULO – SABESP, 2022. *Relatório de Monitoramento da Qualidade da Água para Atendimento do Plano de Aplicação de Algicidas para a Represa Guarapiranga*. Processo CETESB nº 080347/2021-09. São Paulo: SABESP.

CUNHA, D.G.F., CALIJURI, M.C. and LAMPARELLI, M.C., 2013. A trophic state index for tropical/subtropical reservoirs (TSItsr). *Ecological Engineering*, vol. 60, pp. 126-134. http://doi.org/10.1016/j.ecoleng.2013.07.058.

DEPARTAMENTO DE ÁGUAS E ENERGIA ELÉTRICA – DAEE, Centro Tecnológico de Hidráulica e Recursos Hídricos – CTH. 2023 [viewed 9 February 2024]. *Banco de Dados Hidrológicos*. Portal do Departamento de Águas e Energia Elétrica. Available from: http://www.hidrologia.daee.sp.gov.br/

DUARTE-DOS-SANTOS, A.K., CUTRIM, M.V.J., FERREIRA, F.S., LUVIZOTTO-SANTOS, R., AZEVEDO-CUTRIM, A.C.G., ARAÚJO, B.O., OLIVEIRA, A.L.L., FURTADO, J.A. and DINIZ, S.C.D., 2017. Aquatic life protection index of an urban river Bacanga basin in northern Brazil, São Luís - MA. *Brazilian Journal of Biology = Revista Brasileira de Biologia*, vol. 77, no. 3, pp. 602-615. http://doi.org/10.1590/1519-6984.01016 PMid:27706393.

EMPRESA METROPOLITANA DE ÁGUAS E ENERGIA S.A – EMAE, 2023 [viewed 9 February 2024]. *Histórico*. Available from: http://emae.com.br/historico/

FORIO, M.A.E. and GOETHALS, P.L.M., 2020. An integrated approach of multi-community monitoring and assessment of aquatic ecosystems to support sustainable development. *Sustainability*, vol. 12, no. 14, pp. 5603. http://doi.org/10.3390/su12145603.

GARCÍA-VILLADA, L., RICO, M., ALTAMIRANO, M., SÁNCHEZ-MARTÍN, L., LÓPEZ-RODAS, V. and COSTAS, E., 2004. Occurrence of copper resistant mutants in the toxic cyanobacteria Microcystis aeruginosa: characterisation and future implications in the use of copper sulphate as algaecide. *Water Research*, vol. 38, no. 8, pp. 2207-2213. http://doi.org/10.1016/j.watres.2004.01.036 PMid:15087203.

HAMMER, Ø., HARPER, D.A.T. and P. D. RYAN. (2001). PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Paleontologia Eletronica*, vol. 4, no. 1, pp. 1-9.

KLEEREKOPER, C.J., 1939. Estudo Limnológico da Represa de Santo Amaro em São Paulo. *Boletim da Faculdade de Filosofia, Ciências e Letras, Universidade de São Paulo*, vol. 2, pp. 11-151. http://doi.org/10.11606/issn.2318-5988.v2i0p11-151.

LAMPARELLI, M.C., 2004 [viewed 9 February 2024]. *Grau de trofia em corpos d'água do Estado de São Paulo - avaliação dos métodos de monitoramento*. São Paulo: Instituto de Biociências da Universidade de São Paulo, 238 p. Tese de Doutorado. Available from: https://www.teses.usp.br/teses/disponiveis/41/41134/tde-20032006-075813/publico/TeseLamparelli2004.pdf

LAMPARELLI, M.C., CARVALHO, M.C. and RIBEIRO DE SOUZA, R.C., 2000. Water and sediment quality as a response to nutrients and metals (Al, Fe and Cu) in Guarapiranga Reservoir, São Paulo, Brazil. *SIL Proceedings, 1922-2010*, vol. 27, no. 5, pp. 3199-3205. https://doi.org/10.1080/03680770.1998.11898269.

LOBATO, T.C., HAUSER-DAVIS, R.A., OLIVEIRA, T.F., SILVEIRA, A.M., SILVA, H.A.N., TAVARES, M.R.M. and SARAIVA, A.C.F., 2015. Construction of a novel water quality index and quality indicator for reservoir water quality evaluation: a case study in the Amazon region. *Journal of Hydrology*, vol. 522, pp. 674-683. http://doi.org/10.1016/j.jhydrol.2015.01.021.

LUNA, F.V. and KLEIN, H.S., 2019. História Econômica e Social do Estado de São Paulo 1850-1950. São Paulo: Imprensa Oficial. 528p.

MONTE, C.N., SALDANHA, E.C., COSTA, I., NASCIMENTO, T.S.R., PEREIRA, M.S., BATISTA, L.F. and PINHEIRO, D.C., 2021. The physical-chemical characteristics of surface waters in the management of quality in clearwater rivers in the Brazilian Amazon. *Water Policy*, vol. 23, no. 5. https://doi.org/10.2166/wp.2021.258.

PREFEITURA DE SÃO PAULO, 2009 [viewed 9 February 2024]. *Histórico Demográfico do Município de São Paulo. Censo de 1900*. Available from: http://smul.prefeitura.sp.gov.br/historico_demografico/1900.php.

QUEIROZ, V.O.S., 1964. Abastecimento de água na Cidade de São Paulo. *Revista do DAE*, no. 52, pp 29-48.

R CORE TEAM, 2020. *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing. Available from: https://www.R-project.org/.

RÖRIG, L.R., TUNDISI, J.G., SCHETTINI, C.A.F., PEREIRA-FILHO, J., MENEZES, J.T., ALMEIDA, T.C.M., URBAN, S.R., RADETSKI, C.M., SPERB, R.C., STRAMOSK, C.A., MACEDO, R.S., CASTRO-SILVA, M.A. and PEREZ, J.A., 2007. From a water resource to a point pollution source: the daily journey of a coastal urban stream. *Brazilian Journal of Biology = Revista Brasileira de Biologia*, vol. 67, no. 4, pp. 597-609. http://doi.org/10.1590/S1519-69842007000400003 PMid:18278310.

SÃO PAULO. SECRETARIA DO MEIO AMBIENTE, COORDENADORIA DE PLANEJAMENTO AMBIENTAL, COMPANHIA BRASILEIRA DE PROJETOS E EMPREENCIMENTOS – COBRAPE, 2010. *Atualização do Plano de Desenvolvimento e Proteção Ambiental da Bacia do Guarapiranga*. São Paulo: Secretaria do Meio Ambiente.

SCHWARZENBACH, R.P., ESCHER, B.I., FENNER, K., HOFSTETTER, T.B., JOHNSON, C.A., VON GUNTEN, U. and WEHRLI, B., 2006. The challenge of micropollutants in aquatic systems. *Science*, vol. 313, no. 5790, pp. 1072-1077. http://doi.org/10.1126/science.1127291 PMid:16931750.

SEMENSATTO, D., LABUTO, G., ZORZAL-ALMEIDA, S. and MCRAE, D.V., 2021. Spatio-temporal changes in water quality in the Guarapiranga reservoir (São Paulo, Brazil): insights from a long-term monitoring data series. *Environmental Monitoring and Assessment*, vol. 193, no. 7, pp. 380. http://doi.org/10.1007/s10661-021-09167-y PMid:34081214.

SISTEMA INFOÁGUAS, 2023 [viewed 9 February 2024]. *Qualidade das Águas Superficiais*. Avaiable from: https://sistemainfoaguas.cetesb.sp.gov.br/

SISTEMA INTEGRADO DE GESTÃO AMBIENTAL – SIGAM, 2023 [viewed 9 February 2024]. *Guarapiranga Sustentável*. Available from: https://sigam.ambiente.sp.gov.br/sigam3/Default.aspx?idPagina=7756

SOARES, R.D.B., CRUZ, R.W.L. and SILVA, C.E., 2019 [viewed 9 February 2024]. A influência da precipitação na variabilidade da qualidade da água do rio Parnaíba. *Brazilian Journal of Development*, vol. 5, no. 9, p. 16645-16674. Avaiable from: https://ojs.brazilianjournals.com.br/ojs/index.php/BRJD/article/view/3463/3622

SOARES, R.S., 2021. Industrialização, urbanização e eletrificação de São Paulo: indicadores de um mesmo processo (1880-1930). *URBANA: Revista Eletrônica do Centro Interdisciplinar de Estudos sobre a Cidade*, vol. 12, p. e020017. https://doi.org/10.20396/urbana.v12i0.8664317.

STRASKTABA, M. and TUNDISI, J.G., 2013. *Diretrizes para o gerenciamento de lagos: gerenciamento da qualidade da água de represas*. São Carlos: ILEC/IIE.

TOLEDO JUNIOR, A.P., TALARICO, M., CHINEZ, S.J. and AGUDO, E.G., 1983. A aplicação de modelos simplificados para a avaliação de processo da eutrofização em lagos e reservatórios tropicais. In: *Congresso Brasileiro De Engenharia Sanitária*, 1983, Camboriú. Camboriú: Associação Brasileira de Engenharia Sanitária. 34 p.

TUNDISI, J. G. and MATSUMURA TUNDISI, T., 2008. *Limnologia. São Paulo*: Oficina de Textos, 632 p.

WHATELY, M. and CUNHA, P.M., 2006. *Guarapiranga 2005: como e por que São Paulo está perdendo este manancial: resultados do diagnóstico socioambiental participativo da Bacia Hidrográfica do Guarapiranga*. São Paulo: ISA, Instituto Socioambiental.

ZAGATTO, P.A., LORENZETTI, M.L., LAMPARELLI, M.C., SALVADOR, M.E.P., MENEGON JUNIOR, N. and BERTOLETTI, E., 1999. Aperfeiçoamento de um índice de Qualidade de Águas. *Acta Limnologica Brasiliensia*, vol. 11, no. 2, pp. 111-126.

ZORZAL-ALMEIDA, S., BICUDO, D., LAMPARELLI, M., FAUSTINO, S., CARLA, F. and BICUDO, C., 2017. Avaliação do Índice de Estado Trófico e sua aplicação na represa Guarapiranga em longa série temporal. In: E.M. BICUDO and D.C. BICUDO, eds. *100 anos da represa Guarapiranga: lições e desafios*. Curitiba: Editora CRV, pp. 401-428.

UDDIN, M., NASH, S. and OLBERT, A.I., 2021. A review of water quality index models and their use for assessing surface water quality. *Ecological Indicators*, vol. 122, pp. 107218. http://doi.org/10.1016/j.ecolind.2020.107218.

UN ENVIRONMENT PROGRAMME, 2021 [viewed 9 February 2024]. *Progress on Integrated Water Resources Management. GLOBAL INDICATOR 6.5.1 UPDATES AND ACCELER ATION NEEDS*. United Nations Environment Programme, 110p. Available from: https://www.unwater.org/sites/default/files/app/uploads/2021/09/SDG6_Indicator_Report_651_Progress-on-Integrated-Water-Resources-Management_2021_EN.pdf.

Supplementary Material

Supplementary material accompanies this paper.

Appendix 1 - List of automatic precipitation data probes of the Department of Water and Electric Energy.
Appendix 2 - Calculation Methodology.

This material is available as part of the online article from https://doi.org/10.1590/1519-6984.283148.