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Eutrophication Indicators in Billings Reservoir, São Paulo: Support for Urban Planning and Water Resource Management

Fabiano Sampaio Rodrigues dos Santos
Master Student, UNINOVE, Brazil.
fabianorodrigues.eng@uni9.edu.br
ORCiD 0009-0008-8676-4859

Andreza Portella Ribeiro
Professor, PhD, UNINOVE, Brazil.
andrezp@uni9.pro.br
ORCiD 0000-0002-1763-4558

Anderson de Oliveira
Master Science, UNINOVE, Brazil.
PhD Student, USP, Brazil
anderx100@gmail.com
ORCiD 0000-0001-6720-6394

Jorge L Gallego
Professor, PhD, Universidad de Medellín, Colombia.
jlgallego@udemedellin.edu.co
ORCiD 0000-0002-8462-1124

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Eutrophication Indicators in Billings Reservoir, São Paulo: Support for Urban Planning and Water Resource Management

ABSTRACT

Objective: To assess water quality in the Billings Reservoir by calculating the Trophic State Index (TSI) using total phosphorus (TP) and chlorophyll-a (Chl-a) as indicators, in order to support urban planning and water resource management in the Metropolitan Region of São Paulo.

Methodology: Analysis of secondary data from CETESB (2020-2022) for 9 monitoring stations regarding indicator quantification in samples collected during dry and rainy seasons. The relationship between TP and Chl-a was assessed through statistical inference tests, controlling for spatial variability among sampling sites. TSI was calculated according to Lamparelli's (2004) methodology, and results were spatially distributed in thematic maps using QGIS software.

Originality/Relevance: The study provides an updated diagnosis of one of Brazil's most important water sources, supplying approximately 21 million inhabitants, while contextualizing institutional and socioeconomic constraints that hinder water resource management in the Metropolitan Region of São Paulo.

Results: The reservoir exhibited predominantly supereutrophic and hypereutrophic conditions, with maximum TP and Chl-a concentrations of 510 µg/L and 511 µg/L, respectively, exceeding by up to 51 times the limits established by CONAMA Resolution 357/2005. ANCOVA confirmed that TP is the predominant factor in Chl-a variation ($F=30.65$; $p<0.001$). Sampling sites directly receiving water pumped from the Pinheiros River maintained the highest concentrations and TSI values, especially during the rainy season.

Theoretical/Methodological Contributions: The integration of statistical analysis with TSI spatial distribution facilitates communication of technical results to public managers, constituting a replicable approach for assessing other urban reservoirs.

Social and Environmental Contributions: The study provides an updated technical diagnosis supporting investment prioritization in basic sanitation and effluent treatment in the Billings basin. Quantification of the impact of Pinheiros River pumping on water quality offers elements for operational management decisions. The work also highlights the situation of irregular occupation (~1 million people without adequate sanitation), supporting the development of watershed recovery programs aligned with SDGs 6 and 14 of the 2030 Agenda.

KEYWORDS: Eutrophication. Water Quality. Billings Reservoir.

Indicadores de Eutrofização na Represa Billings, São Paulo: Apoio ao Planejamento Urbano e à Gestão de Mananciais

RESUMO

Objetivo: Avaliar a qualidade da água da Represa Billings mediante cálculo do Índice de Estado Trófico (IET), utilizando fósforo total (PT) e clorofila-a (CL) como indicadores, para subsidiar o planejamento urbano e a gestão de mananciais na Região Metropolitana de São Paulo.

Metodologia: Análise de dados secundários da CETESB (2020-2022) para 9 estações de monitoramento, em relação à quantificação dos indicadores em amostras coletadas em períodos seco e chuvoso. A relação entre PT e CL foi observada por meio de testes de inferência estatística, controlando-se as variabilidades espaciais entre pontos de coleta. O IET foi calculado segundo metodologia de Lamparelli (2004) e os resultados foram espacializados em mapas temáticos utilizando o software QGIS.

Originalidade/relevância: O estudo fornece diagnóstico atualizado de um dos mais importantes mananciais do Brasil, que abastece cerca de 21 milhões de habitantes, e contextualiza limitações institucionais e socioeconômicas que dificultam a gestão hídrica na Região Metropolitana de São Paulo.

Resultados: O reservatório apresentou condição predominantemente supereutrófica e hipereutrófica, com concentrações máximas de PT e CL de 510 µg/L e 511 µg/L, respectivamente. Os valores chegam a superar em 51 vezes os limites estabelecidos pela Resolução CONAMA 357/2005. A ANCOVA confirmou que o PT é o fator preponderante na variação da CL ($F=30{,}65$; $p<0{,}001$). Os pontos receptores diretos do bombeamento do Rio Pinheiros mantiveram as maiores concentrações e IET, especialmente no período chuvoso.

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Contribuições teóricas/metodológicas: A integração de análise estatística com espacialização do IET facilita a comunicação dos resultados técnicos para gestores públicos, constituindo-se em uma abordagem replicável para avaliação de outros reservatórios urbanos.

Contribuições sociais e ambientais: O estudo fornece diagnóstico técnico atualizado que subsidia a priorização de investimentos em saneamento básico e tratamento de efluentes na bacia da Billings. A quantificação do impacto do bombeamento do Rio Pinheiros sobre a qualidade da água oferece elementos para decisões de gestão operacional do sistema. O trabalho também evidencia a situação de ocupação irregular (~1 milhão de pessoas sem saneamento adequado), apoiando a elaboração de programas de recuperação de mananciais alinhados aos ODS 6 e 14 da Agenda 2030.

PALAVRAS-CHAVE: Eutrofização. Qualidade da Água. Reservatório Billings.

Indicadores de eutrofización en el embalse Billings, São Paulo: Apoyo a la planificación urbana y a la gestión de manantiales

RESUMEN

Objetivo: Evaluar la calidad del agua del Embalse Billings mediante el cálculo del Índice de Estado Trófico (IET) utilizando fósforo total (PT) y clorofila-a (CL) como indicadores, con el fin de apoyar la planificación urbana y la gestión de recursos hídricos en la Región Metropolitana de São Paulo.

Metodología: Análisis de datos secundarios de CETESB (2020-2022) para 9 estaciones de monitoreo en relación con la cuantificación de indicadores en muestras recolectadas durante períodos secos y lluviosos. La relación entre PT y CL fue evaluada mediante pruebas de inferencia estadística, controlando la variabilidad espacial entre los sitios de muestreo. El IET fue calculado según la metodología de Lamparelli (2004), y los resultados fueron espacializados en mapas temáticos utilizando el software QGIS.

Originalidad/Relevancia: El estudio proporciona un diagnóstico actualizado de una de las fuentes hídricas más importantes de Brasil, que abastece aproximadamente 21 millones de habitantes, contextualizando las limitaciones institucionales y socioeconómicas que dificultan la gestión de recursos hídricos en la Región Metropolitana de São Paulo.

Resultados: El embalse presentó condiciones predominantemente supereutróficas e hipereutróficas, con concentraciones máximas de PT y CL de 510 µg/L y 511 µg/L, respectivamente, superando hasta 51 veces los límites establecidos por la Resolución CONAMA 357/2005. El ANCOVA confirmó que el PT es el factor preponderante en la variación de CL ($F=30,65$; $p<0,001$). Los sitios de muestreo que reciben directamente el agua bombeada del Río Pinheiros mantuvieron las mayores concentraciones y valores de IET, especialmente durante la temporada lluviosa.

Contribuciones Teóricas/Metodológicas: La integración del análisis estadístico con la distribución espacial del IET facilita la comunicación de resultados técnicos a los gestores públicos, constituyendo un enfoque replicable para la evaluación de otros embalses urbanos.

Contribuciones Sociales y Ambientales: El estudio proporciona un diagnóstico técnico actualizado que apoya la priorización de inversiones en saneamiento básico y tratamiento de efluentes en la cuenca de Billings. La cuantificación del impacto del bombeo del Río Pinheiros sobre la calidad del agua ofrece elementos para decisiones de gestión operacional del sistema. El trabajo también evidencia la situación de ocupación irregular (~1 millón de personas sin saneamiento adecuado), apoyando la elaboración de programas de recuperación de cuencas alineados con los ODS 6 y 14 de la Agenda 2030.

PALABRAS CLAVE: Eutrofización. Calidad del Agua. Embalse de Billings.

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1 INTRODUCTION

Access to potable water is directly linked to the human, social, and economic development of society, including for human consumption, agriculture, industrial processes, energy production, water transportation, recreation, and the discharge of all kinds of waste (Viana, 2005).

In September 2015, the United Nations General Assembly took place in New York City, USA, with the participation of 193 member states of the United Nations (UN). This meeting resulted in a global action plan, the 2030 Agenda.[1], which established 17 Sustainable Development Goals (SDGs). Together, they aim to eradicate all forms of poverty, combat inequalities, and address climate change by 2030, ensuring that "no one is left behind." Among the various SDGs, two of them, SDG 6 - Clean Water and Sanitation and SDG 14 - Life Below Water, are directly linked to the protection and supply of water in the world (UN HABITAT, 2020).

It is estimated that 97.5% of the planet's available water is salty, making it unsuitable for human consumption, agricultural sustainability, industrial processes, hydroelectric power generation, and the maintenance of freshwater ecosystems. The remaining 2.5% of available freshwater is largely difficult to access, either located in glaciers (69%) or trapped in dense aquifers (30%). Only 1% of this freshwater is available in rivers, lakes, dams, and springs around the world. Brazil is a privileged country, as 12% of this total is available within its territory (National Water and Basic Sanitation Agency - ANA, 2023).

During their economic and industrial development, cities have often failed to develop social development plans, impacting all public spheres, particularly the housing sector, where irregular construction is being developed, often in protected water source areas. This puts water security at risk and compromises the quality of stored water (Oliveira, 2021). This is the reality of the Billings Reservoir, which is also one of the main water sources in the São Paulo Metropolitan Region (RMSP), with approximately 15% of its territory occupied by irregular constructions. This means that nearly 1 million people live in informal settlements that lack adequate wastewater collection and treatment systems (Instituto Socioambiental - ISA, 2008).

The monitoring and control of water quality stored in reservoirs or aquifers is carried out by federal agencies, such as the National Environmental Council (CONAMA), with its resolutions (357/2005) and (396/2008), which define acceptable quality standards for surface and groundwater. The Brazilian Ministry of Health (MH), through ordinance (888/2021), established the parameters for the potability of water for human consumption and other purposes.

At the regional level, in the state of São Paulo, this monitoring and control is carried out by the Environmental Company of the State of São Paulo (CETESB). To this end, CETESB uses various protocols in the field and in laboratories, with periodic sampling for chemical, physical, and biological tests, including analysis of pH, conductivity, turbidity, fecal coliforms, phosphorus (P), nitrogen (N), chlorophyll a, among others (CETESB, 2022).

One of the main problems related to the integrity of water resources is the change in trophic state, which can occur with variations in the nutrient load in the water body.

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[1]General Assembly Resolution A/RES/70/1

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Significant inputs of P and N cause eutrophication, which can be a natural or anthropogenic phenomenon. In the former case, it results from the slow aging of the environment, as the input of nutrients and organic matter is a consequence of soil erosion and sediment transport by rainfall over the years (Van-Gingel, 2011; Tromboni; DODDS, 2017).

Anthropogenic eutrophication is a consequence of the discharge of nutrient-rich domestic and industrial effluents, which favors the excessive growth of plants such as phytoplankton, microscopic algae that live suspended in the water column and contain chlorophyll, mainly type 'a', an essential pigment for these organisms to carry out photosynthesis, converting sunlight into chemical energy (Doering et al., 2006; Liang et al., 2020). With eutrophication, water use becomes inadequate, as algal proliferation results in high concentrations of toxins and bacteria, increased turbidity, bad odors, among other affected parameters (Ansari et al., 2011), which implies considerable additional costs in the treatment process (CETESB, 2017).

Excessive algal blooms (biomass) also indicate that the water body is enriched with organic matter that will decompose, increasing the demand for dissolved oxygen and reducing its availability. This phenomenon, called hypoxia, can be harmful to aquatic life, resulting in the death of fish and other organisms (Liang et al., 2020).

Thus, assessing trophic state is a parameter used to evaluate water quality. To this end, existing biomass is determined based on TP, chlorophyll a (CL), and turbidity levels (Lamparelli, 2004). Trophic state must be constantly monitored in water sources used for public supply, recreation, hydroelectric power plants, and other uses (Buzelli; Cunha-Santino, 2013). In the case of Billings, despite continuous water quality monitoring conducted by CETESB at various georeferenced points, it remains possible to explore the relationship between human activities, the discharge of domestic and industrial effluents, and their contribution to the intensification of water pollution.

Therefore, the objective of this study is to evaluate the water quality of the Billings Reservoir, using parameters to calculate the trophic state index, in order to gather more detailed information on the impact of the direct input of untreated effluents into the reservoir's aquatic system.

1.1 Contextualization of the Study Area

The State Water Resources Policy of the state of São Paulo, established by Law No. 7.663/1991, represented a milestone in water resource management in Brazil. Its main objective was to ensure that the state's water bodies provided water in sufficient quantities and with adequate quality standards for various purposes, such as human supply, economic development, and the preservation of aquatic ecosystems. The law also provided for the creation of a State Water Resources Plan (SWRP), defining hydrographic divisions and units, to enable regionalized management that took into account the specificities of different river basins.

The development of the first SWRP and the creation and structuring of the 22 Water Resources Management Units (WRMU) in the state of São Paulo were consolidated by Law No. 9,034/1994. This plan established management and planning instruments, such as the River

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Basin Committees and the State Water Resources Council, which began to coordinate actions and promote decentralized and participatory management of water resources.

Law No. 16,337/2016, which repealed Law No. 9,034/1994, maintained the WRMU management structure, but incorporated new guidelines to improve integrated and participatory water management, with greater participation of private entities and research institutes in the preparation of plans for sub-basins and specific areas, in addition to strengthening integration with the Multi-Year Plan (MYP) and encouraging water reuse.

This article will focus on WRMU 06 – Alto do Tietê (AT), one of the most important basins, as its boundaries virtually coincide with those of the São Paulo Metropolitan Region (SPMR). Thus, it serves almost half of the state's population—20.8 million inhabitants, from the 39 municipalities of the SPMR. WRMU 06-AT collects 83% of the effluent produced and has a very low treatment rate, around 52% of the effluent generated. It incorporates the Billings Reservoir and the Rio Grande and Guarapiranga Reservoirs (São Paulo, 2020).

The Billings Reservoir—the study area—was built in 1925 with the sole purpose of generating power for the municipality of Cubatão through the Henry Borden Plant. However, due to industrial development and massive population growth in the Greater ABC region in the following decades, the process of capturing water from the dam to supply the population began in 1958, and pumping it to the Rio Grande and Guarapiranga reservoirs (São Paulo, 2020).

With an area of approximately 127 km², a water surface area of 100 km², and a maximum depth of 19 m (Figure 1), the Billings is subdivided into eight units, called branches and tributaries: the Rio Grande, Rio Pequeno, Capivari, Pedra Branca, Taquacetuba, Bororé, Cocaia, and Alvarenga. Its area covers the entire municipality of Rio Grande da Serra, and partially the municipalities of Diadema, Ribeirão Pires, Santo André, São Bernardo do Campo, and São Paulo (GEOTEC, 2021).

The subdivisions within the reservoir exist for operational and water quality management reasons. The Braço do Rio Pequeno serves as a water transfer point from the Billings Reservoir to the Rio Grande Reservoir, which acts as a reservoir, receiving water from the Billings Reservoir and directing it to the Alto Tietê production system. Similarly, the Braço do Taquacetuba serves as a water transfer point for the Guarapiranga Reservoir, also contributing to the supply of the Alto Tietê.

According to the Secretariat of Infrastructure and Environment, the Billings Reservoir is an important water source for the SPMR, and its management involves several challenges, such as irregular water source occupation, conflicts over water use, and the need to guarantee water quality for the population (São Paulo, 2020).

The Billings Reservoir is classified, according to CONAMA Resolution 357/2005, as belonging to the Special Class and Class 2. Special Class waters are intended for human consumption with simplified treatment and aim to preserve aquatic ecosystems, as well as protect natural species breeding grounds, such as environmental preservation areas. Class 2 waters are suitable for human consumption with conventional treatment, primary contact recreation activities, irrigation, and fishing. However, the tributaries that flow into the Billings Reservoir are classified as Class 4, indicating that these bodies of water are only suitable for navigation and landscaping purposes and are not suitable for human consumption or contact.

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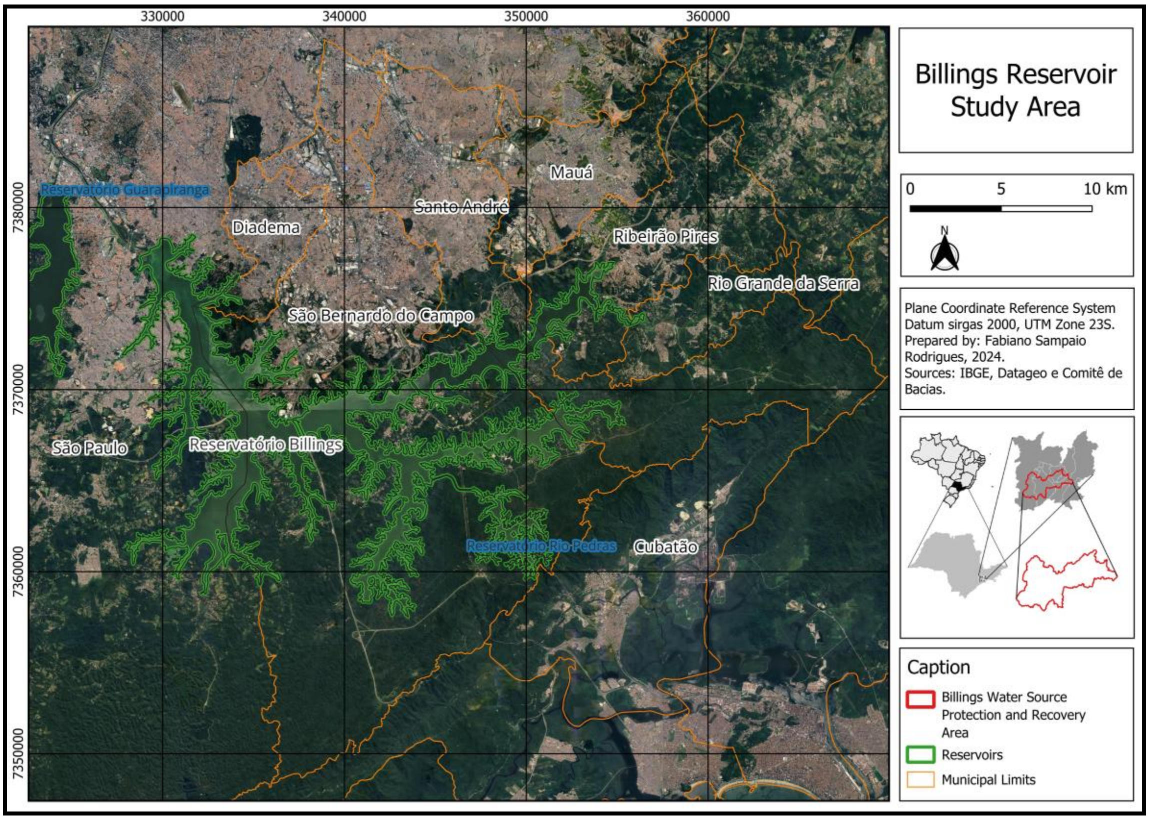
This discrepancy between the water quality of the reservoir and its tributaries results in a major challenge for the SPMR supply.

Figure 1 - Delimitation of the Study Area - Billings Reservoir



Source: Santos (2024).

2 MATERIALS AND METHODS

Each year, CETESB issues a report on inland water quality in the state of São Paulo, which presents a compilation of information from all WRMUs, comparing analytical results from the last five years and the methods used for sampling and laboratory testing (CETESB, 2022).

Although CETESB's sampling network includes 11 monitoring points at the Billings Reservoir, which includes its tributaries (Figure 2), the research will focus on nine points, the characteristics of which are presented in Table 1.

It is also important to highlight that CETESB does not follow a fixed standard for collections. Campaigns are conducted according to logistical and priority criteria defined by the agency itself (CETESB, 2020; 2021; 2022). Data collection was performed using the INFOAGUAS platform[2], referencing quantification of TP and CL concentrations, published by CETESB, for the Billings Reservoir water quality monitoring campaigns between 2020 and 2022. Table 2 shows how the number of samples, by point and seasonality, varied over three years; totaling 102 samples, of which 45 correspond to the rainy months and 57 to the dry months.

[2]Retrieved - https://sistemainfoaguas.cetesb.sp.gov.br/AguasSuperficiais/RelatorioQualidadeAguasSuperficiais

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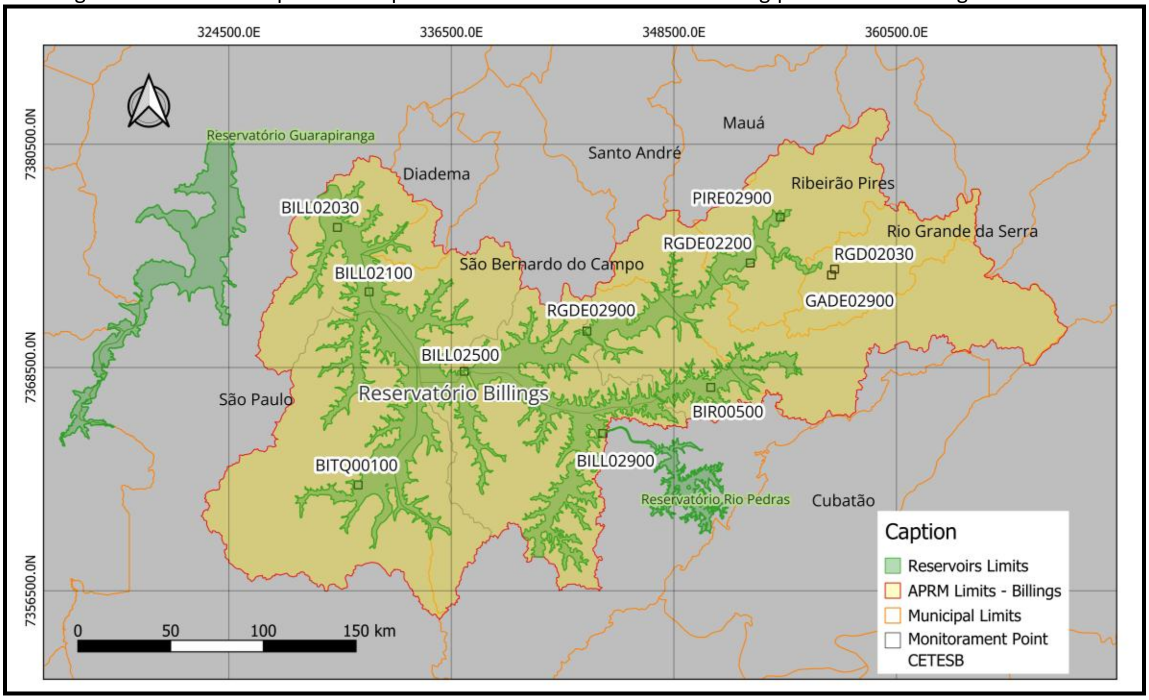
Quantitative data on TP and CL concentration were organized in Excel spreadsheets and presented in tables and graphs, boxplot type, considering the period studied.

Figure 2 - Location map of the 11-points water collection and monitoring points at the Billings Reservoir.



Source: Basin Committee (2021); prepared by the authors (2023).

Table 1 – Monitoring points at the Billings Reservoir, considered in this study.

Point Code (CETESB)	Characteristic	Class*	Sabesp Collection
BILL 02030	Indicates the water quality condition at the reservoir inlet.	2	No
BILL 02100	7 km from the Pedreira dam - reflects the dilution of water pumped from the Pinheiros River to the reservoir	2	No
BILL 02500	In the narrowing (of the width of the channel) near the Rodovia dos Imigrantes, it affects the dispersion of pollutants	2	No
BILL 02900	Indicates the quality of the waters at the reservoir outlet, at the Summit Control Automatic Station, which flow to the Henry Borden Hydroelectric Plant for power generation purposes.	2	No
BIRP 00500	2 km upstream (upstream) from the Caminhos do Mar Highway	Special	No
BITQ 00100	In the bay located at the end of Tomekichi Inouye Street (SABESP intake)	Special	Yes
RGDE 02030	1 km after the mouth of the Rio Grande or Jurubatuba, close to the SABESP transposition.	2	No
RGDE 02200	At Clube Prainha Tahiti Camping Náutica, at Km 42 of the SP-31 highway	2	No
RGDE 02900	Near the Anchieta highway, next to the SABESP intake	2	Yes

Source: CETESB (2020); *CONAMA 357/2005.

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Table 2 – Number of collections carried out per point, in Billings, considering seasonality.

Point Code (CETESB)	Rainy				Dry			
	2020	2021	2022	Total	2020	2021	2022	Total
BILL02030	1	1	2	4	0	3	2	5
BILL02100	2	1	2	5	2	3	2	7
BILL02500	1	1	2	4	0	3	2	5
BILL02900	1	1	2	4	0	3	2	5
BIRP00500	1	0	2	3	0	3	2	5
BITQ00100	2	1	2	5	3	3	2	8
RGDE02030	2	2	2	6	2	2	2	6
RGDE02200	1	3	3	7	2	4	2	8
RGDE02900	1	3	3	7	2	4	2	8
Collections	45				57			

Source: Infoáguas (CETESB); adapted by the authors.

2.1 Statistical Treatment

Analysis of Covariance (ANCOVA) was applied to the TP and CL data set. This statistical approach combines elements of analysis of variance (ANOVA) and linear regression, allowing for the adjustment of covariates and providing a more accurate understanding of differences between groups (Shieh, 2023). ANCOVA adjusts for (or controls for) natural differences between collection points, preventing these variations from interfering with the assessment of the significant influence of TP on CL concentrations. This adjustment reduces residual error—that is, the unexplained variation between groups—and, consequently, increases the statistical power of the test, providing greater precision in comparisons. Thus, it is possible to infer whether the observed relationship between CL and TP actually reflects the latter's influence on the amount of biomass, isolating the influence of the singularities of each collection point. Prior to applying ANCOVA to adjust for asymmetry, extreme values, and high variability in the dataset (102 observations), TP and CL concentrations were normalized using the natural logarithm. All assumptions were tested: (i) the homogeneity of the slopes between TP and CL was confirmed, indicating that the relationship between these variables was maintained at all collection points; (ii) the linearity of the relationship between TP and CL was met, as well as homoscedasticity between groups and normality in the data distribution (Dos anjos, 2006). ANCOVA was performed using the *Python* statistical program, with the statsmodels package, to fit the model and conduct the necessary tests.

2.2 Trophic State Index

As already mentioned, the Trophic State Index (TSI) allows classifying the quality of reservoirs and water bodies into different degrees of trophy, based on the presence of nutrients and their effect on algae growth, indicated by the concentration of chlorophyll a (Lamparelli, 2004).

The TSI, developed by Lamparelli (2004), was an important innovation for monitoring water quality in subtropical water bodies, such as reservoirs in Brazil. This index was designed to more accurately capture the conditions and response of water bodies in regions with specific climatic and ecological characteristics, which differ from the patterns observed in temperate areas, for which other trophic indices were originally developed (Carlson, 1977).

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Water bodies in subtropical regions typically have specific characteristics, such as higher temperatures. "Warmer" water accelerates the metabolism of aquatic organisms, as these species are adapted to these environments, including macrophytes and algae (Souza, 2024). The subtropical ecosystem is more responsive; that is, small variations in P concentration, which is the limiting factor for primary production, can generate large changes in trophic state (Lamparelli, 2004).

To present the trophic levels at CETESB collection points, the ANA website was used, where files related to WRMU 6 – AT: Billings Reservoir were identified in shape file format. Classifications and image processing were performed using the *free* QGIS *software*.

The TSI calculations in this study were performed based on Equations 1 to 3 (Table 3). The trophy classes for the TSI results are shown in Table 4.

Table 3 – TSI calculation adopted by CETESB, for lentic bodies.

Lentic Water Body (Reservoirs)	Where
TSI (CL) = 10 x (6-((0,92-0,34 x (nl CL))/nl 2)) **[1]** TSI (TP) = 10 x (6-(1,77-0,42 x (nl TP)/nl 2)) **[2]**	**TP:** em µg/L; measured at the surface of the water, in µg/L; **CL:** em µg/L; measured at the surface of the water, in µg/L; **nl:** natural logarithm.
TSI = [TSI (TP) + TSI (CL)] / 2 **[3]**	CETESB: nos meses em que estejam disponíveis dados de ambas as variáveis

Source: Lamparelli (2004); CETESB (2021).

Table 4 – Trophy degrees based on TSI calculations and their ranges.

Class	Weighting	Description
Ultraoligotrophic	TSI ≤ 47	Low nutrient concentration; not harmful to the environment.
Oligotrophic	47 < TSI ≤ 52	Body of water with low nutrient production; not harmful.
Mesotrophic	52 < TSI ≤ 59	Produção de nutrientes em nível intermediário; possibilidade de interferência.
Eutrophic	59 < TSI ≤ 63	High nutrient production, low transparency, environment affected by human actions; its use may be compromised
Supereutrophic	63 < TSI ≤ 67	High nutrient production, low transparency, frequent changes due to human actions; flowering of macrophytes.
Hipereutrophic	TSI> 67	Body of water with high concentrations of organic materials, low oxygenation in the water; deaths of aquatic species, impaired livestock activities.

Source: Lamparelli (2004); CETESB (2021).

3 RESULTS AND DISCUSSION

This section presents the analysis of the data TP and CL published by CETESB between 2020 and 2022, considering seasonal variations: the dry season, for collections between April and September, and the rainy season, for collections between January and March and October and December.

The results in Table 1 indicate that TP and CL levels frequently exceeded the quality reference values established by CONAMA Resolution 357/2005, whose maximum permitted values are 20 µg/L for TP and 10 µg/L for CL, in water intended for human consumption. The critical levels found in the Billings Reservoir contribute to the hypertrophic condition of the reservoir, characterized by algal blooms and impaired water quality.

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Table 1 - Range of Total Phosphorus (TP) and Chlorophyll (CL) Concentrations in Billings Reservoir (2020-2022).

Code (CETESB)	2020		2021		2022	
	TP (μg/L)	**CL** (μg/L)	**TP** (μg/L)	**CL** (μg/L)	**TP** (μg/L)	**CL** (μg/L)
Bill 02030	60ʳ - *	79ʳ - *	30ᵈ – 370ʳ	30ᵈ – 508ʳ	60ᵈ – 390ʳ	37ᵈ – 270ʳ
Bill 02100	50ʳ – 350ʳ	57ʳ - *	30ᵈ – 510ʳ	30ᵈ – 510ʳ	50ᵈ – 410ʳ	28ᵈ – 395ʳ
Bill 02500	80ʳ - *	58ʳ - *	20ᵈ – 250ʳ	23ᵈ – 270ʳ	30ʳ – 170ʳ	34ᵈ – 210ʳ
Bill 02900	30ʳ - *	27ʳ - *	20ᵈ – 60ᵈ	17ʳ – 37ᵈ	10ʳ – 60ᵈ	16ʳ – 70ʳ
BIRP 00500	10ʳ - *	28ʳ - *	20ᵈ – 200ʳ	16ᵈ – 37ᵈ	10ʳ – 70ᵈ	31ʳ – 42ʳ
BITQ 00100	30ᵈ – 100ᵈ	38ʳ – 55ʳ	20ᵈ – 190ᵈ	34ᵈ – 81ʳ	50ʳ – 60ʳ	31ᶜ – 106ᶜ
RGDE 02030	20ᵈ – 100ʳ	12ʳ – 53ʳ	20ʳ – 70ʳ	1ʳ – 2ʳ	20ᵈ – 290ᵈ	0,5ᵈ – 3ʳ
RDGE 02200	20ᵈ – 60ᵈ	17ʳ - *	20ᵈ – 100ʳ	14ᵈ – 111ᵈ	40ʳ – 300ᵈ	17ᵈ – 33ʳ
RGDE 02900	20ʳ – 130ᵈ	18ʳ - *	20ʳ – 130ᵈ	4ᵈ – 29ʳ	20ʳ – 260ᵈ	6ᵈ – 23ʳ
r: rainy; d: dry; *only one collection per year or value not reported						

Source: Infoáguas (CETESB 2020; 2021; 2023); adapted by the authors.

For the parameters presented in Table 1, in 2020, the lowest TP concentration, 10 μg/L, was recorded at point BIRP 00500 during the rainy season, while the maximum value, 130 μg/L, was found at point RGDE 02900 during the dry season. For CL, point RGDE 02030 had the lowest concentration, 12 μg/L, and point Bill 02030 had the highest, 79 μg/L, both during the rainy season.

In 2021, the minimum TP concentration was 20 μg/L, observed at point RGDE 02900 during both the dry and rainy seasons, while the maximum value, 510 μg/L, was recorded at point Bill 02100 during the rainy season. For CL, point RGDE 02030 had the lowest concentration, at 1 μg/L, and point Bill 02100 had the highest, also at 510 μg/L, both during the rainy season.

In 2022, the lowest TP concentration was 10 μg/L, recorded at points Bill 02900 and BIRP 00500 during the rainy season. The maximum TP value was 410 μg/L at Bill 02100, which also had the highest LC concentration at 395 μg/L, while the lowest LC concentration, 0.5 μg/L, was observed at RGDE 02030.

The data in Table 1 show that, despite the variation in the number of collections, Bill 02100 and Bill 02030 maintained trends of high concentrations, exceeding the recommended levels for TP by more than 20 times and those for LC by more than 50 times, according to CONAMA 357/2005. Point RGDE 02900 also showed high TP levels, with a maximum of 130 μg/L in 2020 and 2021, reaching 260 μg/L in 2022.

Figures 3 (A and B) and 4 (A and B) graphically present the studied parameters (Table 1), considering the seasonality of the collections.

The variation in TP concentrations during the rainy season (Figure 3A) suggests that points BILL 02030 [60; 390 μg/L] and BILL 02100 [80; 510 μg/L] receive greater nutrient input during the rainy season. These same points, despite remaining the most critical, showed a decrease in concentrations and a smaller range of TP levels compared to the dry season (Figure 3B).

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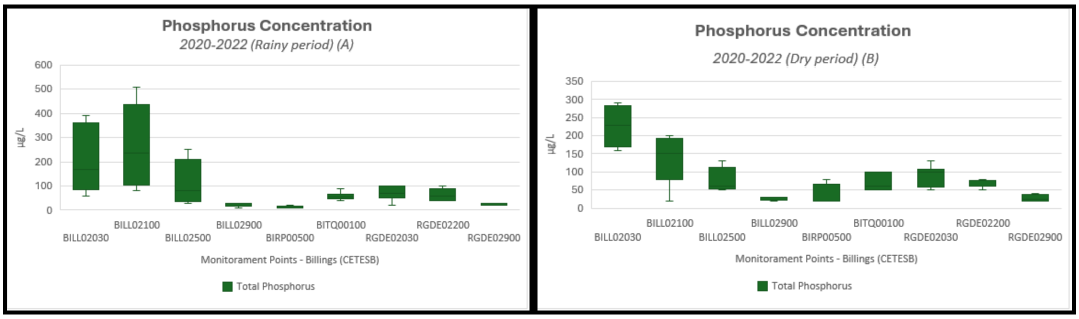
Figure 3 - Variation of TP Concentrations in Billings (A) Rainy and (B) Dry



Source: Infoáguas (CETESB 2020; 2021; 2023); adapted by the authors.

The observed pattern is consistent with the characteristics of the points, as BILL 02030 allows CETESB to monitor water from the Pinheiros River, pumped by the Pedreira Pumping Plant, immediately at its inlet into the Billings Reservoir; that is, it reflects the water conditions without significant mixing with the rest of the reservoir's water. Meanwhile, BILL 02100 allows monitoring of water pumped from the river, but which has already undergone some level of dilution and mixing with other local sources and tributaries, as the point is 7 km away from BILL 02030.

There is no specific period for pumping; however, it occurs more frequently during the rainy season, as a strategy to prevent flooding in the Pinheiros River, increase water reserves in the Billings Reservoir for dry periods, and aid in the dilution of pollutants brought by urban runoff.

Although point BILL02500 also presents greater variability during the rainy season (30–250 µg/L), there is a decreasing trend in TP concentrations, as shown in Figure 3A, possibly related to its position downstream of the inlet points (Figure 2). Another important characteristic is that the point is located under the Imigrantes Highway bridge in São Bernardo do Campo, where a physical narrowing occurs that reduces water velocity. This narrowing creates favorable conditions for the sedimentation of suspended particles and facilitates natural pollutant attenuation processes, such as the decomposition of organic matter by microorganisms. During the dry season, because the inflow of water pumped from the Pinheiros River is less frequent, the influence of nutrient input at BILL02500 is significantly reduced, resulting in lower variability and TP concentration values [50;78 µg/L].

From point BILL02900 to RGDE02900, a decreasing trend in TP concentrations and amplitude is observed at each point, both during the rainy and dry seasons (Figures 3A and 3B). This behavior suggests that the reservoir has a self-purification capacity relative to the initial TP load, regardless of seasonal variations between the rainy and dry seasons.

The variation in CL concentrations between the rainy and dry seasons (Figures 4A and 4B) reflects a similar trend to that observed for TP, with critical points showing an increase in biomass during the rainy season. Points BILL02030 [43; 271 µg/L] and BILL02100 [57; 511 µg/L] record the highest CL values and greatest amplitude during the rainy season, suggesting that the high input of TP-rich nutrients is the main driver of algal blooms.

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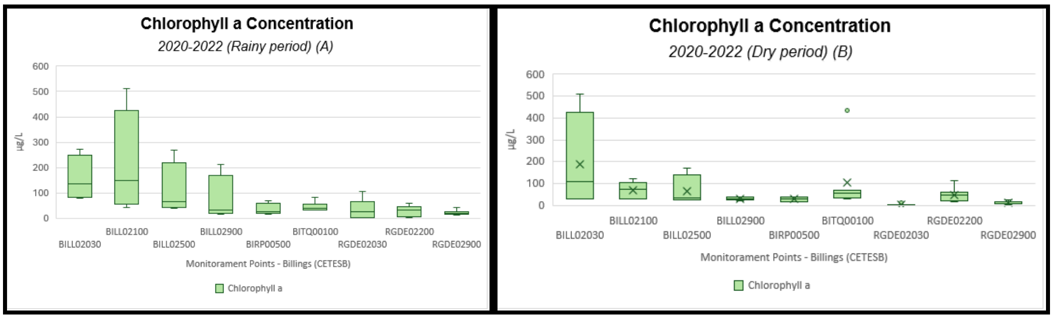
Figure 4 - Variation of CL Concentrations in Billings (A) Rainy and (B) Dry



Source: Infoáguas (CETESB 2020; 2021; 2023); adapted by the authors.

At point BILL02500, CL also exhibits greater variability during the rainy season ([39; 269 µg/L]), with a downward trend in concentrations. This point, located in a narrowing area that promotes the attenuation of particles and organic matter, naturally contributes to lower CL levels. During the dry season, with the reduction in water pumping from the Pinheiros River, CL at BILL02500 stabilizes at lower values [23; 171 µg/L]. From BILL02900 to RGDE02900, a downward trend is observed in both CL concentrations and variability, in line with the stabilization observed at TP.

3.1 Relationship between TP and CL

As shown in Figures 3A and 3B, the variation in TP concentrations over the years presented a distribution pattern similar to that observed for CL concentrations (Figures 4A and 4B), suggesting the potential influence of TP on the presence of biomass. By applying ANCOVA, it was possible to infer that the TP variable maintains a strong relationship with CL levels, as shown in Table 2.

Table 2 – Results of ANCOVA applied to the data set.

Description*	*F*	p-value
Interaction between TP concentrations and Collection Points	1,66	0,11
Differences between Collection Points	22,32	< 0.001
Effect of TP concentrations on CL concentrations	30,65	< 0.001
* Transformed data – natural logarithm		

Source: Elaborated by the authors.

The ANCOVA results indicated a significant relationship between TP and CL concentrations (Table 2). Therefore, it can be inferred that, for the studied period, TP availability is a preponderant factor in CL concentrations, which is directly related to the amount of biomass present in the Billings Reservoir. On the other hand, the F and p values (Table 2) indicated that, although each point has unique characteristics that influence nutrient input, for the dataset (102 observations), without considering seasonality, such singularities did not significantly affect TP input; however, for CL, it was found that the collection points significantly influence its concentration. Finally, the values of α (30.65) and p (<0.001) allow us to infer that the variation in CL is statistically explained, for the most part, by the variation in TP concentrations.

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3.3 Trophic State Indices - TSI

Figures 5A and 5B allow a comparison of the TSI classes for the Billings points, corresponding to the year 2020, between the rainy and dry seasons. Considering that the concentrations of TP and CL frequently exceeded, several times, at all points, the limits defined by CONAMA 357/2005 (Table 1), it was expected that the maps would show TSI values that would classify the Billings Reservoir as a supereutrophic [64;66] and hypereutrophic [68;75] environment. In practice, both indicate a very high level of biomass and primary productivity, which will affect important water quality parameters. Typically, environments with extreme eutrophication classes favor cyanobacterial blooms, which result in a reduction in dissolved oxygen and can release toxins that are harmful to aquatic ecosystems and human health (Ansari, 2011).

Regarding the TSI calculated for 2021, except for RGDE 02900, classified as supereutrophic (Figures 6A and 6B), the hypereutrophic environment remained predominant. However, TSI values were above 160 during the rainy season (Figure 6A). According to CETESB reports (2022), precipitation in October (approximately 150 mm) was above the historical average (110 mm), while in December (130 mm) was slightly below the expected average (150 mm). Therefore, as observed in Figure 3A, the highest TP values are consistent with the water supply, with a high pollutant load that is pumped to the reservoir to prevent flooding of the Pinheiros River.

During the dry season (Figure 6B), point BITQ 00100 attracted attention, as it presented a TSI greater than 170. At the other points, the TSI variation followed the same pattern observed in 2020. BITQ 00100 is located at the turn of the Taquacetuba arm to the Guarapiranga reservoir. Precipitation information in São Bernardo do Campo[3], indicated that in September (the month of collection), there were frequent dry days, with few light rains; however, the typical pattern of transition to the rainy season remained. With little rainfall, the limited water renewal reduces the dilution of accumulated nutrients. Low water flow can also favor the accumulation of suspended solids, which tend to settle to the bottom due to the lack of flow, releasing the TP in future rain events, which would be expected at the end of the dry season.

[3]Weather Spark - Online platform that provides historical weather data and detailed forecasts for locations around the world.

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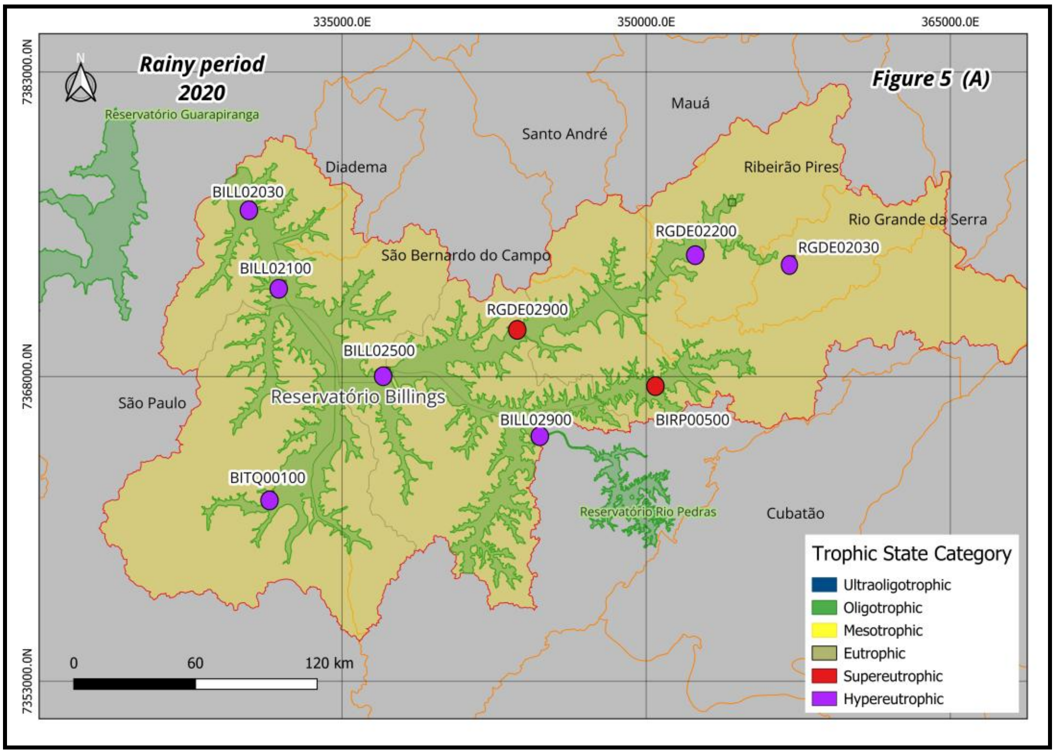
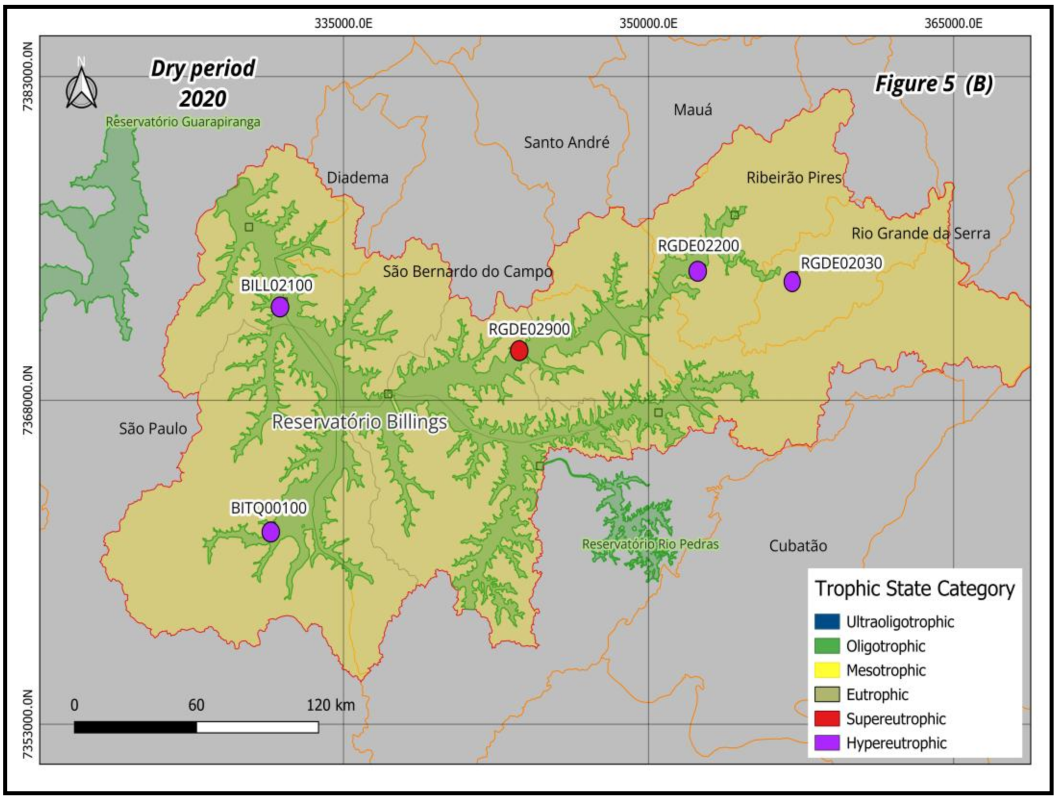
Figure 5 - TSI classes at Billings Reservoir in 2020: (A) Rainy; (B) Dry.





Source: Basin Committee (2021); TSI calculated by the authors from Infoáguas-CETESB.

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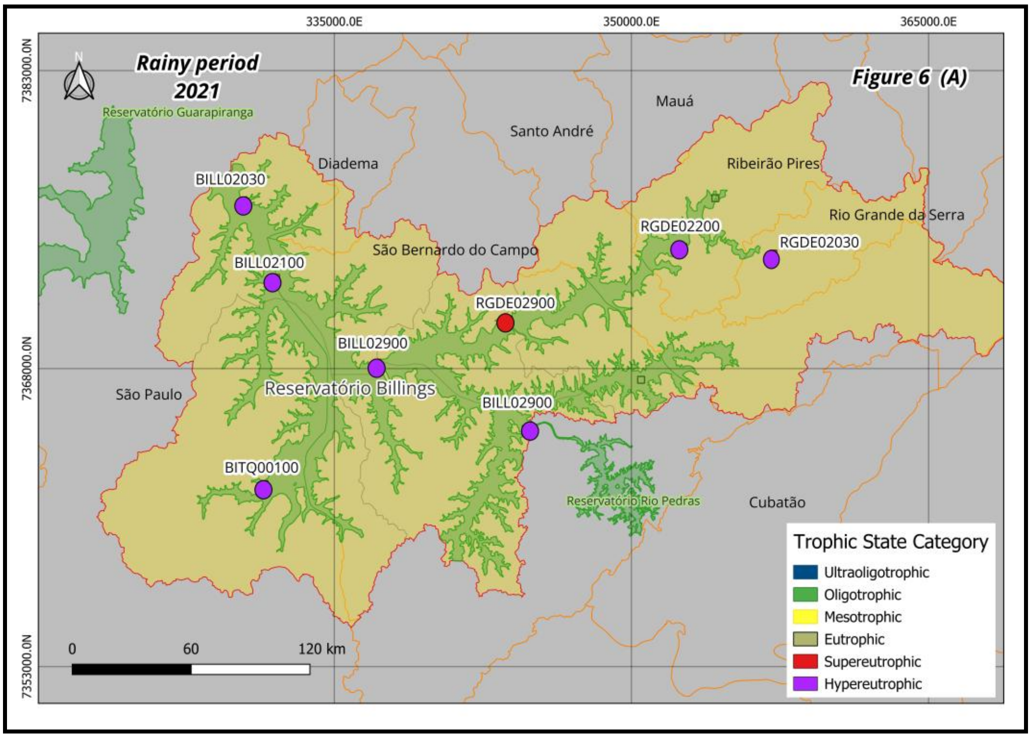
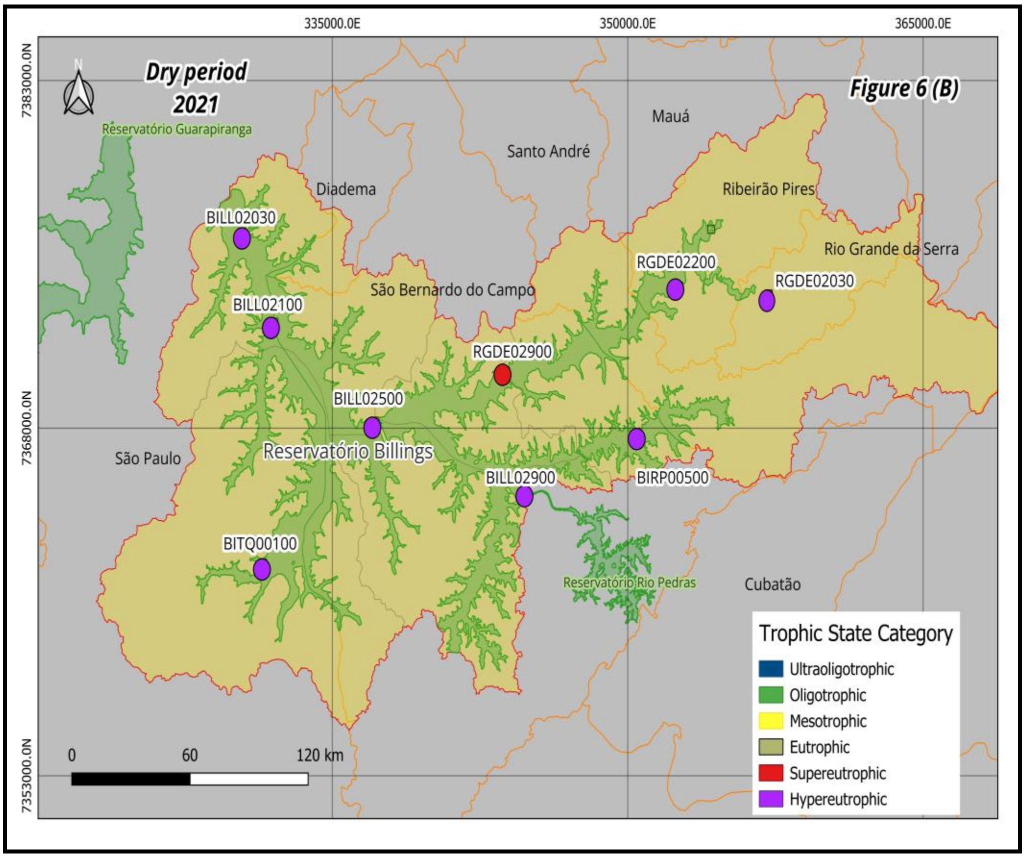
Figure 6 - TSI classes at Billings Reservoir in 2021: (A) Rainy; (B) Dry.





Source: Basin Committee (2021); TSI calculated by the authors from Infoáguas-CETESB.

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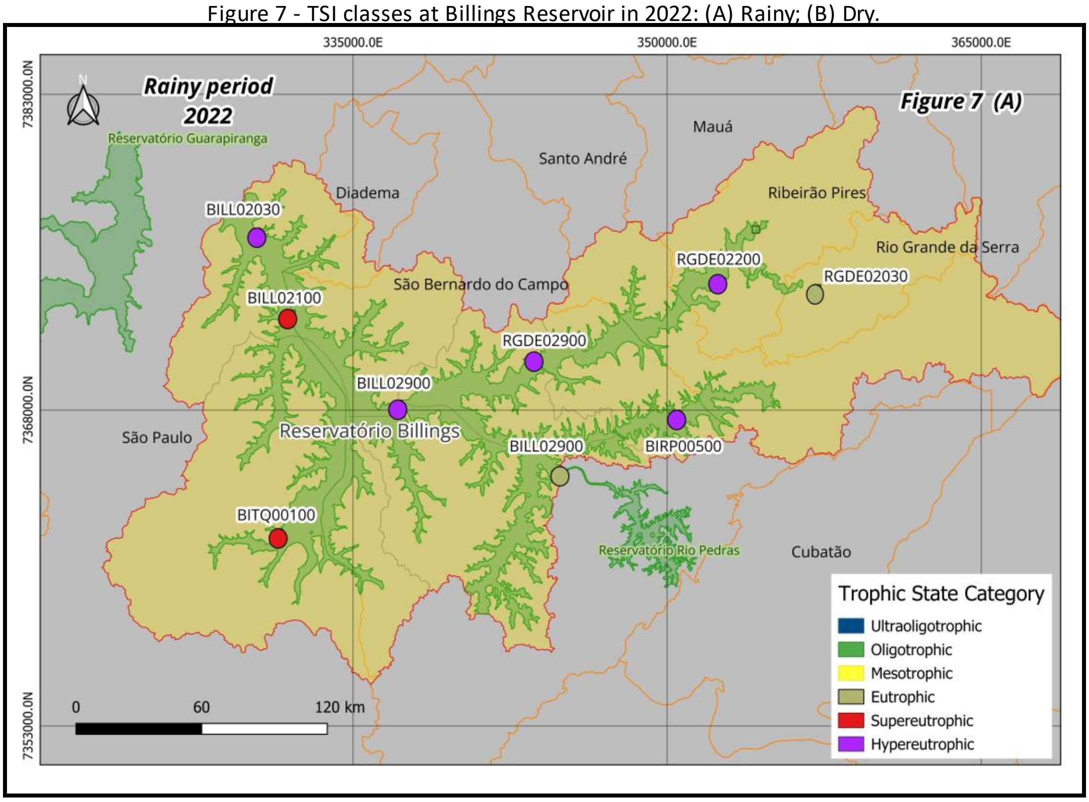
For the 2022 collections, there was greater variability in TSI, with a downward trend; although super- and hyper-eutrophic classes prevailed, both during the rainy and dry seasons (Figures 7A and 7B). Anomalous values, i.e., TSI values above 160, were observed at BIRP 00500 (rainy and dry) and RGDE 02200 (rainy).

BIRP 00500, located in the Braço do Rio Pequeno, is monitored to assess water quality at the transfer point from the Billings Reservoir to the Rio Grande Reservoir, whose waters are, in fact, directed to public supply. Its TSI values (160 in the rainy season; 165 in the dry season) may be due to this point receiving inputs from urban and peri-urban basins, making it susceptible to enrichment by pollutants from surface runoff.

The anomalous TSI value (177) for RGDE 02200 (Figure 7A), which is located in the area of Clube Prainha Tahiti, on the banks of the Billings Reservoir, may be due to the characteristics of its surroundings, with abundant vegetation and recreational areas. This point has been experiencing an increase in the density of cyanobacteria, which may be associated with internal processes within the water body, such as nutrient cycling, intensified by the environmental conditions of the rainy season.

With the information gathered, the complexity of eutrophic processes in urban environments can be verified, in which natural factors intertwine with anthropogenic pressures. It is important to emphasize, however, that overcoming the identified problems does not depend solely on the technical-scientific understanding of environmental variables, but also on systemic and organizational conditions that directly influence the effectiveness of interventions and the integrated management of the dam.

Figure 7 - TSI classes at Billings Reservoir in 2022: (A) Rainy; (B) Dry.



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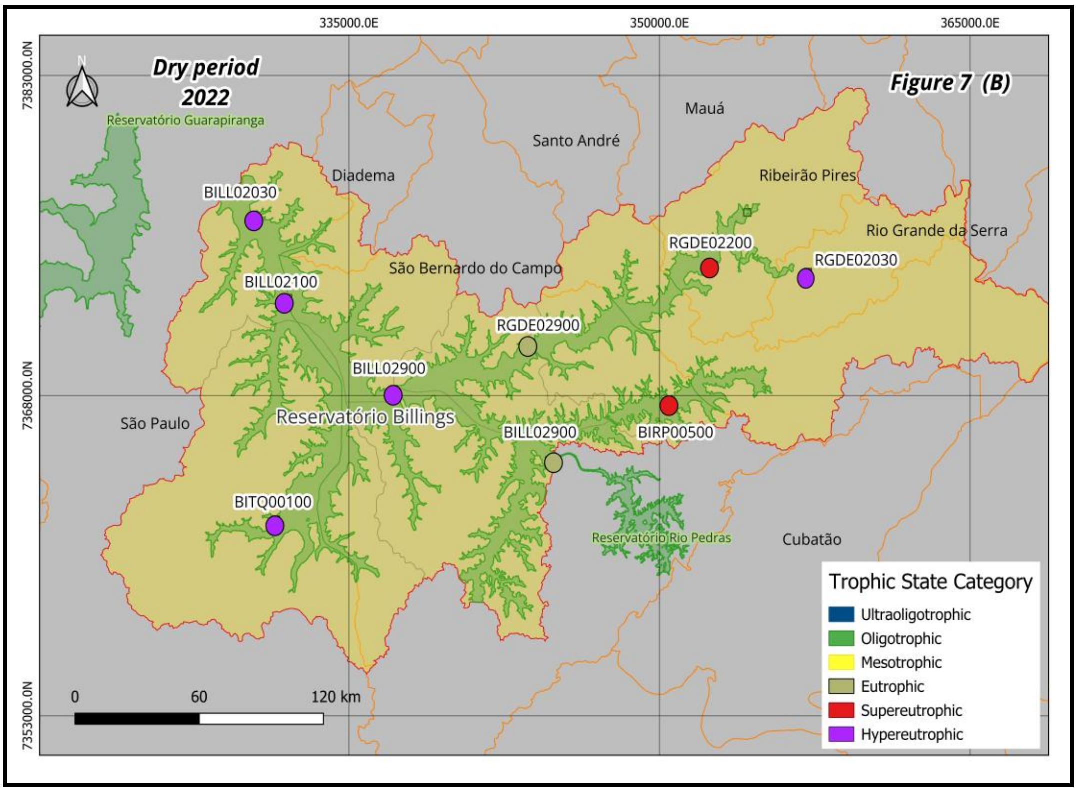

Source: Basin Committee (2021); IET calculated by the authors from Infoáguas-CETESB.

3.4 Structural Limitations to the Management of the Billings Reservoir

The management of the Billings Reservoir involves a multitude of institutional actors—among them, federal, state, and municipal government agencies, concessionary companies, civil society organizations, and the public. This complex configuration, while representing an opportunity for building collaborative governance, also poses significant challenges to coordinating actions, defining responsibilities, and implementing effective public policies.

Specialized literature indicates that water management is, in essence, conflict management (Wolf, 2009). As the uses and users of water resources diversify, the difficulty of building consensual solutions among public, private, and community actors also increases (Raulino, 2024). Despite these tensions, water resources offer the potential for shared benefits—such as improved environmental quality, economic dynamism, tourism, and recreational use—as long as they are properly managed (Sadoff & Grey, 2002). However, the lack of definition of responsibilities among responsible entities compromises effective control over environmental impacts. The 2020–2023 State Water Resources Plan, for example, identifies several conflicts over water use in the region and presents strategies for their management, involving institutions such as DAEE, ANA, SABESP, CETESB, EMAE, among others.

In the economic sphere, budgetary constraints and obstacles to the application of charging instruments hinder the sustainability of management actions. Brazilian legislation has evolved to recognize water as an economic good: the Water Code (Decree No. 24,643/1934)

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already provided for the possibility of repaid use; the National Environmental Policy (Law No. 6,938/1981) introduced the user-pays principle; and the Civil Code (Law No. 10,406/2002) provided for remuneration for the use of public goods in common use. These principles were incorporated into the National Water Resources Policy, which establishes water charges as an instrument to encourage rational use, increase resource value, and finance programs outlined in basin plans.

In the State of São Paulo, water charges are regulated by Law No. 12,183/2005 and also seek to internalize the socio-environmental costs of water use, especially in cases of degradation and conflicts over the resource. However, even with the application of these instruments, the funds collected are not always sufficient to meet structural demands. The SWRP 2020–2023 prognostic report highlights SABESP's investments in WRMU-06 (Alto Tietê), where the Billings Reservoir is located, which have contributed to advances in sanitation coverage. Nevertheless, significant gaps remain regarding effluent collection and treatment, as well as the reduction of pollutant loads that impact water bodies (Nilson, 2013).

Institutional and economic limitations are compounded by social barriers. The presence of precarious settlements and irregular occupations in watershed areas compromises not only water quality but also the effectiveness of monitoring and environmental restoration efforts. Therefore, education and awareness-raising are essential to promoting the sustainable use of water resources. According to Silva (2020), the Hidroanel Program, in conjunction with the Billings Reservoir Basin Development and Environmental Protection Plan, developed initiatives aimed at raising awareness of the region's main environmental and urban problems. These initiatives addressed issues such as the occupation of natural areas, basic sanitation, inadequate solid waste disposal, and impacts on public health, seeking to mobilize the population to share responsibility for watershed conservation (Frias, 2020).

4 CONCLUSION

The study on the Billings Reservoir's water quality revealed a concerning trend of the level of trophicity, with a predominance of supereutrophic and hypereutrophic conditions. The analysis, based on data from CETESB (2020 to 2022), indicated that TP and CL concentrations frequently exceed the limits established by CONAMA Resolution 357/2005, compromising water quality.

Statistically, TP was found to be the predominant factor in algal blooms, especially during rainy months, when water pumping from the Pinheiros River is intensified to prevent flooding. This contributes to the greater input of nutrients, favoring eutrophication. The highest TSI values were also observed during the rainy season.

The research findings highlight the importance of monitoring water bodies to support water management and decision-making. Analysis of parameters such as TP and CL can inform nutrient control strategies and environmental management practices. In the case of Billings Reservoir, such data can guide public policies aimed at preserving water quality and ensuring the sustainability of this vital resource for the SPMR's public water supply.

Another relevant point is the fact that it fosters integration among stakeholders in the use of water as a resource, whether for processing, tourism, leisure, or other purposes. In this context, as previously discussed, the lack of coordination among multiple institutional

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stakeholders and limited financial resources hinder the effectiveness of preservation and restoration efforts for the dam, reinforcing the need for coordinated measures and sustainable investments.

The analysis demonstrates that the problems faced by Billings go beyond technical and environmental aspects. Therefore, it is necessary to prioritize the adoption of structural measures that consider territorial specificities, as well as the role of environmental planning aimed at reducing inequalities and ensuring water security.

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DECLARATIONS

AUTHOR CONTRIBUTIONS

- **Concepção e Design do Estudo**: APR and FSRS.
- **Curadoria de Dados**: APR, FSRS and AO.
- **Análise Formal**: APR, FSRS and AO.
- **Aquisição de Financiamento**: APR.
- **Investigação**: APR, FSRS and AO.
- **Metodologia**: APR, FSRS and AO.
- **Redação - Rascunho Inicial**: APR and FSRS.
- **Redação - Revisão Crítica**: APR, FSRS and JLG.
- **Revisão e Edição Final**: APR, FSRS and JLG.
- **Supervisão**: APR.

CONFLICTS OF INTEREST

We, the authors **Fabiano Sampaio Rodrigues dos Santos; Andreza Portella Ribeiro; Anderson de Oliveira and Jorge L. Gallego**, hereby declare that the manuscript entitled *"Eutrophication Indicators in Billings Reservoir, São Paulo: Support for Urban Planning and Water Resource Management"*:

- Has no financial ties that could influence the results or interpretation of the study.
- Has no professional relationships that could affect the analysis, interpretation, or presentation of the results.
- The authors (APR and JLG) are employed by the respective institutions listed in their affiliations, while the authors PPS, SA, and CDS completed their pós-graduate studies at UNINOVE with full scholarships.

We declare that there are no conflicts of interest with other groups or academic and research institutions.