



Understanding the Water Quality Dynamics in a Large Tropical Reservoir Under Hydrological Drought Conditions

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Abstract Severe drought is widely recognized for its impact on water quantity, but its equally consequential role in degrading water quality often goes understudied. This issue significantly complicates reservoir management, especially in multi-purpose reservoirs, which face potential conflicts between the water users during periods of reduced water availability. Despite numerous studies addressing water quality, there is limited data availability regarding the unique dynamics observed in semiarid regions. To address this research gap, an extensive data collection effort was conducted in a semiarid region reservoir serving multiple functions, including human

consumption, irrigation, and fish farming. The primary objective was to establish a comprehensive database encompassing critical water quality parameters, facilitating an in-depth exploration of spatio-temporal water quality dynamics during a hydrological drought. The findings are expected to provide a solid scientific foundation for informed water management practices during severe droughts. Notably, the study reveals distinctive water quality dynamics in semi-arid regions. Monthly assessments confirm complete nutrient mixing within the studied reservoir, with temporal variations surpassing spatial ones, suggesting the applicability of complete-mixing models in future investigations. Additionally, the research underscores the prevalence of chemical stratification in dissolved oxygen levels over thermal stratification, with dissolved oxygen declining downstream, particularly during the rainy season. In summary, this study offers a comprehensive understanding of water quality dynamics in a reservoir experiencing significant degradation during a hydrological drought, highlighting the vulnerability of semiarid reservoirs to water quality decline during such periods. These insights hold substantial importance for enhancing management strategies and mitigating water conflicts in similar tropical reservoirs, thereby contributing to the sustainable utilization of this critical resource.

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1 Introduction

There are several factors that contribute to water quality deterioration. Pollutant discharges in water bodies can render the water unsuitable for direct use in human consumption or other industrial applications (Barçante et al., 2020; de Lacerda et al., 2018; de Rocha & Lima Neto, 2021, 2022; Panagopoulos, 2022). Droughts are another factor that has been widely recognized for their direct impacts on water quality deterioration (Li et al., 2018; Leite & Becker, 2019). This deterioration, marked by eutrophication and harmful algae blooms (de Oliveira et al., 2020; Zhang et al., 2021), not only escalates water treatment costs (Carmichael et al., 2016; Pontes Filho, 2020) but also triggers critical consequences such as fish kills due to hypoxia, especially during the rainy season (Carneiro et al., 2023).

Understanding water quality dynamics can be complex, as it is the result of interactions between numerous physical and environmental factors (Park et al., 2021). Furthermore, the impacts of drought on water quality exhibit significant variation depending on the specific characteristics of each water body and its surrounding catchments (Li et al., 2017). Therefore, effective reservoir management necessitates a comprehensive understanding of regional differences, as well as temporal and spatial patterns of nutrients and other physical, chemical, and biological parameters (Hudson & Vandergucht, 2015; Huo et al., 2019).

Several studies have explored the dynamics of water quality in semiarid and tropical region reservoirs. However, these studies have predominantly focused on studying one water quality parameter within various reservoirs (Carneiro et al., 2023; Germán et al., 2021; Wiegand et al., 2021; Zhong et al., 2022), or have been conducted outside drought periods, often lacking more than a year's worth of data (dos Santos et al., 2016; Molisani et al., 2013, 2015), whereas in the present study, we incorporated a 5-year profiling monitoring of several important water quality parameters in six different sampling points in a large and deep reservoir during and after a drought period. This extensive monitoring allows us to comprehend the spatio-temporal variation and the many interactions within the water quality dynamics of a reservoir that were not observed in previous studies.

In addition, while the findings of previous studies provide important contributions, they do not

provide an in-depth perspective of the water quality dynamics of the reservoir to support management programs in tropical semiarid reservoirs. These programs have to approach solutions for water allocation decisions that minimize conflicts and for the many fish kills that occur in the reservoir. In order to find the solutions, a high availability of multiparameter water quality data is required, which is usually the main difficulty encountered by previous studies and that the present study seeks to overcome it through its in-depth monitoring.

Thus, this study aims to address this knowledge gap by utilizing a newly established, comprehensive water quality monitoring system to unravel the intricacies of water quality dynamics in a semiarid reservoir. We investigate the spatial and temporal patterns and interactions among key water quality parameters essential for environmental management, including nutrients, algae, cyanobacteria, dissolved oxygen, and temperature.

Our focal point is the Castanhão reservoir, a vital water body situated in the Brazilian semiarid region, serving purposes ranging from irrigation and fish farming to water supply (Raulino et al., 2021). Notably, this reservoir supplies water to the metropolitan region of the State of Ceará (about 5 million inhabitants) through water transfer. The severe and prolonged drought that has afflicted the region since 2012 (Sousa Estácio et al., 2022) has led to a substantial reduction in the reservoir's volume, pushing it into a state of eutrophication/hypereutrophication (Ceará, 2022a). Consequently, in-depth field monitoring efforts commenced in 2016, incorporating various sampling points and profiling analyses, rendering the reservoir exceptionally suited for the extensive investigation proposed in this study.

Our dataset spans from 2016 to early 2022, during which the reservoir's volume consistently remained below 20% of its capacity, representing a prolonged hydrological drought period. This study not only enhances our comprehension of the spatio-temporal dynamics of water quality within a tropical reservoir during hydrological drought conditions but also provides a valuable reference for state-based water agencies seeking scientifically grounded decisions in water management. These decisions aim to alleviate water conflicts related to allocation and utilization processes, and the findings are anticipated to

benefit reservoir management in similar semiarid regions worldwide.

2 Materials and Methods

2.1 Study Area

This study was conducted in Castanhão. A reservoir built in 2002 in the Brazilian semiarid (Fig. 1). It has a storage capacity of 6.7 billion m³, a dam crest elevation of 111 m, and a maximum height of 71 m (Ceará, 2022a). The catchment area of Castanhão reservoir is 45,309 km², which is characterized by mild slopes varying normally from 0 to 15° (Ceará, 2022a). The main uses of Castanhão's water are for human consumption, agriculture, and fish farming. This reservoir is part of a water transfer system that supplies water to the capital of the State Ceará and its metropolitan region, with 4.1 million inhabitants (Sousa Estácio et al., 2022).

The predominant soil types are argisols, luvisols, neosols, chernosols, latosols, and planosols, in which shrubby Caatinga vegetation develops (Ceará, 2022b). In addition, the reservoir is in a region of shallow soils located in the crystalline geological formation (Ceará, 2022b). This type of soil, associated with the semiarid climate, results in intermittent rivers and usually negligible baseflow. The annual rainfall in the reservoir's catchment is 836 mm/year (de Rocha & Lima Neto, 2021, 2022). The rainfall is usually concentrated from January to May, resulting in a strong seasonal variation.

During the dry months, the reservoir's inflow is practically null. Then, because of the high evaporation rates, the volume severely decreases. From 2012 to 2019, this region was affected by a severe meteorological drought event, which resulted in a Castanhão's volume decrease from 75% of its volume to around 2% (Sousa Estácio et al., 2022).

Those changes associated with pollution and internal phosphorus recharge triggered the eutrophication of the reservoir (de Rocha & Lima Neto, 2021), which

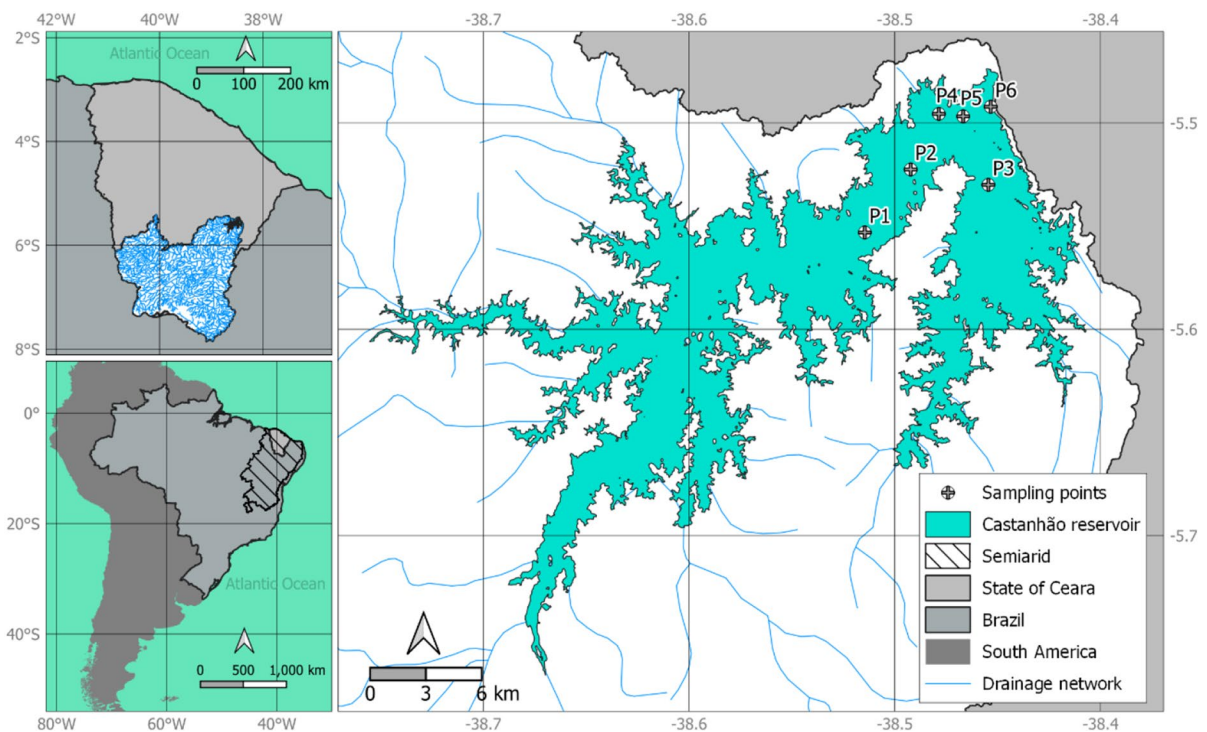


Fig. 1 Map of the study area: the location of Brazil within South America and the state of Ceará within Brazil, with an indication of the Brazilian semiarid region, Castanhão reser-

voir, and its drainage network (left panels). Representation of Castanhão reservoir and its sampling points (right panel)

caused cyanobacteria blooms that make water treatment more expensive (Zhai et al., 2022), and oxygen depletion, which caused fish kill in the fish farming areas (Molisani et al., 2015). In addition, due to its multiple uses, and its location in a semiarid region, the water allocation of Castanhão is a potential source of conflicts. For instance, depending on the amount of fish farming allowed in the reservoir, there are different impacts on the water quality of this reservoir, which can negatively interfere with the other uses.

2.2 Data and Analyses

2.2.1 Data Acquisition

Since Castanhão is one of the most important reservoirs of the State of Ceará, a more detailed water quality monitoring was initiated in 2016. Instead of surface analysis in one sampling point, other sampling points and more water quality parameters with a profiling analysis were added to the monitoring campaigns. The main purpose of this monitoring was to consider not only the water quantity but also the water quality in the water allocation. In order to closely monitor the water quality, the acquisition of more consistent water quality data was essential.

The sampling campaigns were divided into two: profiling and water quality (Fig. S1). Profiling was performed using a YSI EXO 2 probe that measures dissolved oxygen (DO), temperature, total dissolved solids (TDS), salinity, and pH. These physicochemical parameters were measured in all six sampling points from the surface (0.3 m depth) every 0.5 m until reaching 8 m depth, then the measurements were made each 1 m until reaching the depth 0.5 m above the sediment layer.

Water samples were taken in points P3, P4, and P6, in five different calculated depths (Table S2) within the water column. Then, the samples were taken to a laboratory to quantify the following parameters: total phosphorus (TP), total nitrogen (TN), chlorophyll a (Chl-a), pheophytin, orthophosphate, nitrate, nitrite, ammoniacal nitrogen, true color, biochemical oxygen demand, and cyanobacteria cell density. All those analyses were performed according to Apha (2017).

The profiling parameters were measured monthly from January 2016 to February 2022. The water

quality parameters analyzed in the laboratory were from samples taken in each trimester from May 2016 to September 2020 and monthly from October 2020 to January 2022.

2.2.2 Data Processing

The data was processed using R Core Team (2022). In order to assess the spatial variation of the parameters, the data distribution, boxplot, and correlation analysis between the sampling points were used. Then, since droughts are known to highly influence the water quality of a reservoir (Wiegand et al., 2021), inter-annual and intra-annual variations for each parameter were assessed. This allowed us to assess both the impact of a long-range negative trend of water level and wet and dry rainfall seasons on the water quality of Castanhão.

The strength and persistence of thermal and chemical stratification (for DO) were also analyzed since those factors highly influence the water quality dynamics of a reservoir (Nong et al., 2023). The strength of chemical stratification for DO (SCS-DO) was calculated according to the equation below (Noori et al., 2021; Yu et al., 2010):

$$SCS - DO = \frac{DO_s - DO_B}{0.5 \times (DO_s + DO_B)} \quad (1)$$

where DO_s and DO_B are DO concentrations at the surface (0.3 m depth) and at the bottom (0.5 m above sediment layer) of the reservoir, respectively. A null SCS-DO indicates that the DO is not stratified.

Thermal stratification was evaluated using two different indexes. First, the thermocline strength index (TSI) was calculated using the following equation (Yu et al., 2010):

$$TSI = \Delta T / \Delta h \text{ (}^\circ\text{C/m)} \quad (2)$$

where ΔT is the temperature difference between the surface (0.3 m depth) and the bottom (0.5 m above sediment layer) of the reservoir, respectively. Δh is the depth of the water column in meters. Thermocline is recognized to exist when $TSI > 1$ ($^\circ\text{C/m}$) and the higher the value of TSI, the stronger the thermal stratification (Yu et al., 2010).

Then, the relative water column stability (RWCS) coefficient was also calculated to evaluate thermal stratification in Castanhão (Cui, Wang, et al., 2021).

$$RWCS = (\rho_B - \rho_s) / (\rho_4 - \rho_5) \quad (3)$$

where ρ_B and ρ_s represent the water density (g/L) at the bottom and surface of the water column, respectively. ρ_4 and ρ_5 represent the water densities at 4 and 5 °C, respectively.

Water densities were calculated using Eq. 4, considering normal atmospheric pressure and disregarding the salinity of the water (Carneiro et al., 2023).

$$\rho = a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4 + a_5T^5 \quad (4)$$

In which the coefficients are $a_0 = 999.842594$, $a_1 = 6.793953 \times 10^{-2}$, $a_2 = -9.095290 \times 10^{-3}$, $a_3 = 1.001685 \times 10^{-4}$, $a_4 = -1.120083 \times 10^{-6}$, and $a_5 = 6.536332 \times 10^{-9}$. An RWCS ≥ 50 was considered a reference to confirm thermal stratification in the water column.

3 Results and Discussion

3.1 Reservoir Hydrology

Figure 2 shows the variations of volume, inflow, outflow, and evaporation in the Castanhão reservoir during the analyzed period in the present study. It is important to highlight that from 2016 to 2017, the reservoir volume drastically decreased (Fig. 2A) due to the drought period. Between 2016 and 2022, the average monthly inflow during the rainy season was 66.62 Mm³, with a maximum value of around 500 Mm³/month. Even with the increase in volume observed in March 2020 (Fig. 2B), the reservoir volume is still much lower than the one observed in the pre-drought period. Drought periods can have high negative impacts on the water quality of a reservoir, e.g., higher salinity, less DO concentration leading to hypoxia of the hypolimnion, increase in Chl-a concentrations, and eutrophication (de Lacerda et al., 2018).

3.2 Spatial Variation of TP and TN

Pearson's correlation analysis was performed to assess the spatial variation of water quality parameters

within the sampling points (Fig. S6). Points P3, P4, and P6 were selected among the six sampling points to optimize the use of laboratory resources and expedite the monitoring process. These three sampling points have considerably different characteristics, where P3 is on the right branch of the reservoir, P4 is on the left branch and it is the point where fish farming is more concentrated, and P6 is the closest point to the dam.

Since Castanhão is a large and deep reservoir, it would be expected that the water quality variables would present significant spatial variation. However, TP and TN concentration correlation between the three sampling points was significantly high ($p < 0.001$) (Fig. S6A and B, respectively). All the correlation coefficients for TP can be considered perfectly positive ($r > 0.8$), and all the coefficients for TN can be considered strongly positive (Yu et al., 2020). This makes it evident that those parameters follow similar variation patterns through time in the surface (0.3 m) within the sampling points. A pattern is also confirmed by the time series of TP and TN (Fig. S25 and S26, respectively), which show that the variation of these parameters is similar through each month.

Fig. 3A and B shows that the median values of TP and TN concentration for each sampling point are similar, corroborating that there is no significant variation in the horizontal distribution of TP and TN. Similar homogeneous horizontal TP distribution was found in a tropical shallow reservoir located in Ethiopia, where there was a lack of thermal stratification, and consequently a frequent mixing of water column (Tibebe et al., 2019).

However, Castanhão could present significant variation in the vertical nutrient distribution (de Oliveira et al., 2021). Figure 3C and D show that there is no pattern of TP (median 0.07–0.1 mg/L) and TN (median 1–1.3 mg/L) concentrations within the water column of P6, which is the deepest sampling point. Those results associated with the strong correlation of TP and TN between points (Fig. S6A and B) indicate that the nutrient spatial distribution for the Castanhão reservoir can be approximated to a complete mixing. Even though the median values within the vertical profile of TP and TN are similar, it is notable that in the deepest section of the water column, there are more outliers than in the other depth sections (Fig. 3C and D). This could be associated with the release of nitrogen and phosphorus from the sediment layer due

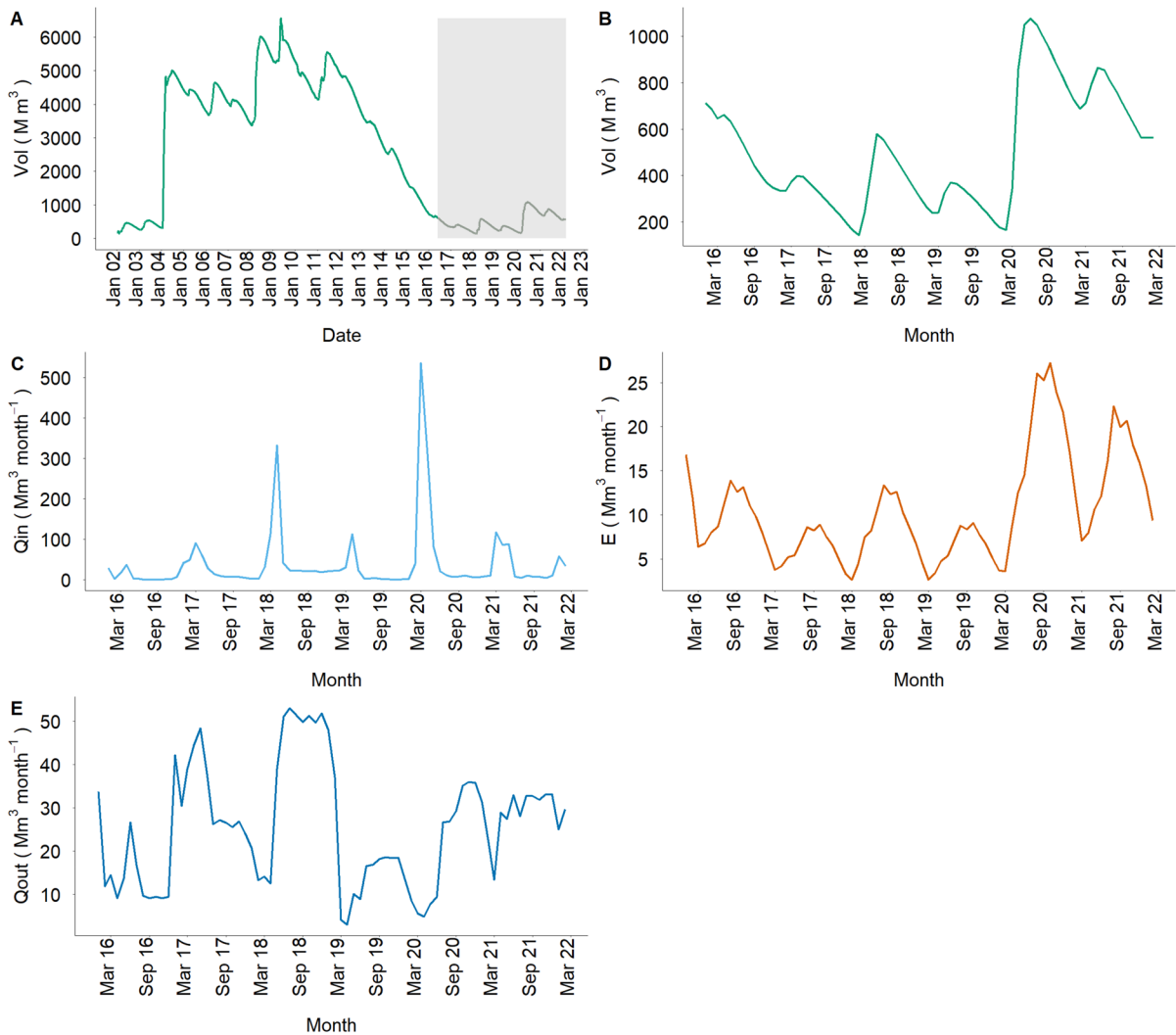


Fig. 2 **A** Daily volume of the Castanhão reservoir, the shaded area corresponds to the period during which monitoring for the present study was conducted. Mm^{-3} stands for million cubic meters. **B** Detail of the average monthly volume of Castan-

hão reservoir from January 2016 to January 2022. **C** Monthly inflow of Castanhão reservoir. **D** Monthly evaporated volume of Castanhão reservoir. **E** Monthly controlled reservoir release

to variations on the redox conditions, thermal stratification, pH, and the hydrodynamics of the reservoir (Kwak et al., 2018). These effects are more pronounced in areas where the water column is deeper and in reservoirs with caged aquaculture activity (Zhang et al., 2022) such as the Castanhão reservoir.

Nutrient distribution in reservoirs may vary widely from one reservoir to another. For instance, de Oliveira et al. (2021) conducted a study in a deep reservoir located in a semiarid climate, while Pearce et al. (2017) examined a shallow reservoir in a temperate

climate. Both studies reported a spatially uniform distribution of nutrient concentration within their respective studied reservoir. However, it is worth noting that there was an exception to this uniform distribution: the point closest to the dam in both cases. They were probably influenced by the mixture associated with the water intake of the reservoir (de Oliveira et al., 2021) and due to higher TP concentration in the sediment of the point closest to the dam (Pearce et al., 2017). The distribution of nutrients in reservoirs can be influenced by anthropogenic activities, leading to variations in

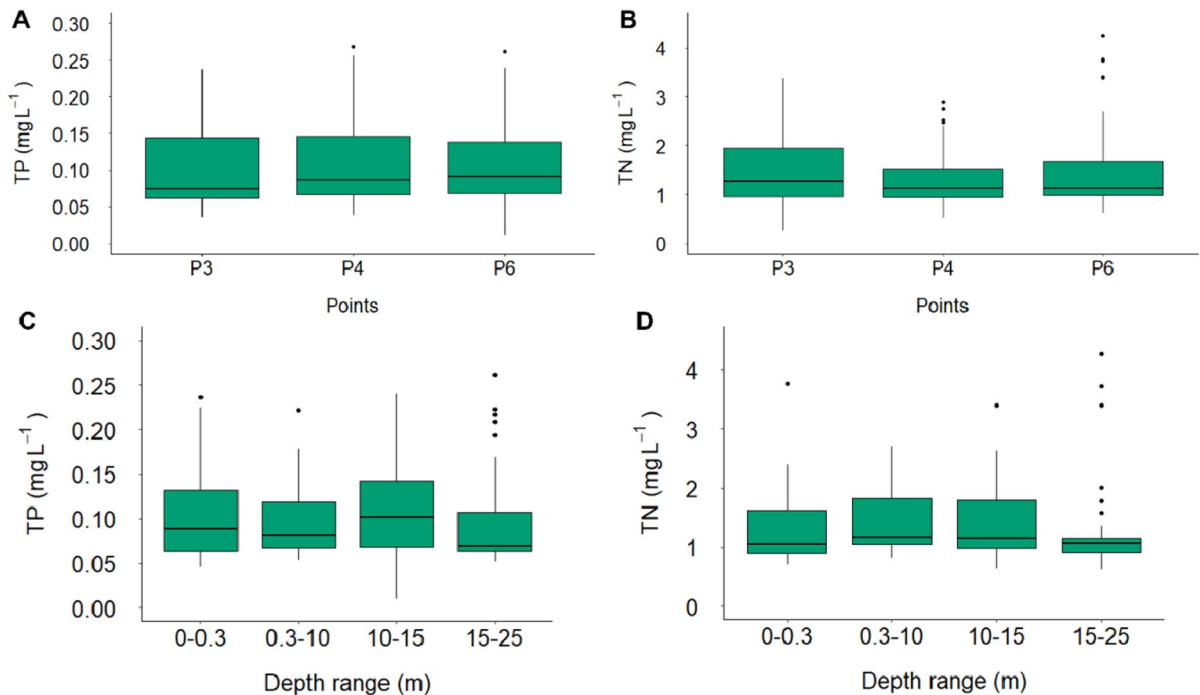


Fig. 3 Boxplots comparing the values of nutrient concentrations among the sampling points. **A** Concentration values for total phosphorus (depth sampling ranging from 0.3 to 25 m), **B** for total nitrogen (depth sampling ranging from 0.3 to 25 m).

Boxplots comparing nutrient concentration within different depths of P6 at the water column: **C** Concentration values for total phosphorus and **D** for total nitrogen. The horizontal line in each boxplot represents the median value

both TP and TN concentrations within the reservoir (López-Doval et al., 2017). Additionally, it has been observed that TP concentrations may vary while TN concentrations remain relatively stable in response to these anthropogenic impacts (Varol, 2020).

Other important factors that can influence the nutrient distribution are thermal and chemical stratification (Sun et al., 2022; Yang et al., 2021). So, to understand the complete mixing of nutrients in the Castanhão reservoir and its water quality dynamics, it is essential to evaluate physicochemical parameters such as DO, temperature, and TDS (Section 3.3).

In addition, to be more certain of the homogeneous spatial distribution of TP and TN concentration in Castanhão, sampling points located more upstream should be analyzed. For instance, Molisani et al. (2015) analyzed nutrient variation in the Castanhão reservoir for 1 year, and the TP concentration did not vary much within the sampling points located at the middle of the reservoir, at the cage area, and at the dam (which are close to the sampling points in the present study). However, the authors also analyzed

a sampling point that is not present in our study: the inlet sampling point. This is a sampling point close to the reservoir entrance, which presented a significantly higher TP concentration in the study conducted by Molisani et al. (2015). The authors suggested that higher values of TP in the inlet point indicated that upstream nutrient sources had a greater impact on water quality conditions in the reservoir than the fish farming area. However, their study was conducted when the reservoir was at 60% capacity, whereas during the present study, the reservoir's level was much lower (below 20%). Therefore, the potential impact of fish farming on nutrient input can be greater.

3.3 Spatial Variation of Temperature, DO, and TDS

Figure S22 compares the physicochemical water quality parameters of the sampling points. P1, P2, P4, and P5 are in the left branch of the reservoir; P3 is in the right branch of the reservoir; P6 is the closest point to the dam retaining wall. The temperature values of P1, P2, P3, and P4 have similar median values

(around 28.5 °C), but P5 and P6 presented slightly lower median values (around 28 and 27.5 °C, respectively) (Fig. S22B).

The spatial distribution of TDS appears to be among three groups: P1 and P3, P2 and P4, and P5 and P6 (Fig. S22 C). The highest values were observed in P5 and P6, and the lowest data dispersion is at P1 and P3. In the present study, conductivity, salinity, and TDS are perfectly positively correlated; therefore, the highest values of TDS in P5 and P6 indicate that salinity was also higher in those points. P5 and P6 are also the sampling points with the lowest DO concentrations, which is expected since higher salinity values lead to the water holding less oxygen (Chapra, 2008; Ahmed & Lin, 2021). In addition, higher concentrations of TDS can promote the formation and deposition of calcium-bound phosphorus to the sediment, which is a fraction of phosphorus that can later be released to the water column under low pH conditions (Wen et al., 2020).

The observed spatial variation of TDS and temperature can be determining factors for the spatial distribution of phytoplankton, considering that no significant spatial variation of nutrients was observed on a monthly time scale (Chen et al., 2023; Xue et al., 2018). This observation can be further used as a tool for predicting cyanobacteria blooms, which is a recurrent challenge in reservoir management.

The TSI values for Castanhão reservoir are all < 1 °C/m (Fig. S4), which according to Yu et al. (2010) means that there is no significative presence of thermocline. Another index used to estimate the occurrence of thermal stratification is the RWCS; when its value is above 50, it is possible to characterize thermal stratification in the water column (Cui, Li, et al., 2021). Figure S5 shows that there are periods in the Castanhão reservoir where RWCS is higher than 50, with P2 being the sampling point, and where thermal stratification is the strongest. This analysis confirms that Castanhão does not exhibit as strong or frequent thermal stratification as other reservoirs (Carneiro et al., 2023; Noori et al., 2021; Yu et al., 2010), but the peaks of thermal stratification strength usually occur during the wet season (Figs. S4 and S5). This weak and not frequent thermal stratification can be the main reason of the complete mixing of nutrients in the Castanhão reservoir observed in the monthly time scale.

Since the present study was conducted mainly during a drought period, the thermal stratification may be stronger when the reservoir reaches higher capacity, which can cause the absence of complete mixing of nutrients. However, even with its low water volume during drought period, the mean hydraulic residence time (HRT) of Castanhão is around 30 months (Fig. S2), which can be considered a long HRT. For instance, this value is already higher than the 1-month limit mentioned by Elçi et al. (2007), who state that reservoirs with high water volumes flowing through them (HRT < 1 month) would tend not to present thermal stratification. This can indicate that nutrient distribution in Castanhão has a particular behavior not observed in other studies.

The dynamics of DO can be more complex in reservoirs than in lakes due to the different factors that can affect its dynamics, e.g., gradients in flow velocity, thermal stratification, nutrient concentration, organic matter decomposition, and phytoplankton growth (Hudson & Vandergucht, 2015; Yu et al., 2010). DO is clearly decreasing from upstream to downstream, where the median values go from around 6.3 mg/L in P1 to around 3 mg/L in P6 (Fig. S22A). The point where DO concentration varies the least is P1, which is the sampling point with the higher median value of DO during the studied period, and with the lowest values of SCS-DO (Fig. S3).

DO concentration decreasing from upstream to downstream can be due to the weak thermal stratification at Castanhão reservoir (Figs. S4 and S5) when compared to the chemical stratification of DO (SCS-DO Fig. S3). When thermal stratification is not strong, there is a much thicker layer of water moving in the downwind direction, which results of sediments reaching further within the reservoir (Elçi et al., 2007). Therefore, the sediments can be deposited within greater distances and probably can accumulate more in the most downstream sampling point (P6—the closest to the dam) of Castanhão reservoir. This sedimentation will later result in organic particle decomposition which can lead to oxygen metalimnetic or hypolimnetic depletion (Gelder et al., 2003; Hudson & Vandergucht, 2015). Another important parameter that influences DO dynamics in a reservoir is the phytoplankton activity since photosynthesis can increase DO concentration (Conceição et al., 2021; Li et al., 2015); therefore, this interaction should also

be taken into consideration when analyzing the water quality dynamics in a reservoir.

3.4 Spatial Variation of Chl-a and Cyanobacteria Cell Density

Similar to TP and TN, Chl-a concentration presented a uniform spatial distribution, with a significantly high ($p < 0.001$) and strongly positive correlation between the concentrations within the sampling points (Fig. S6C).

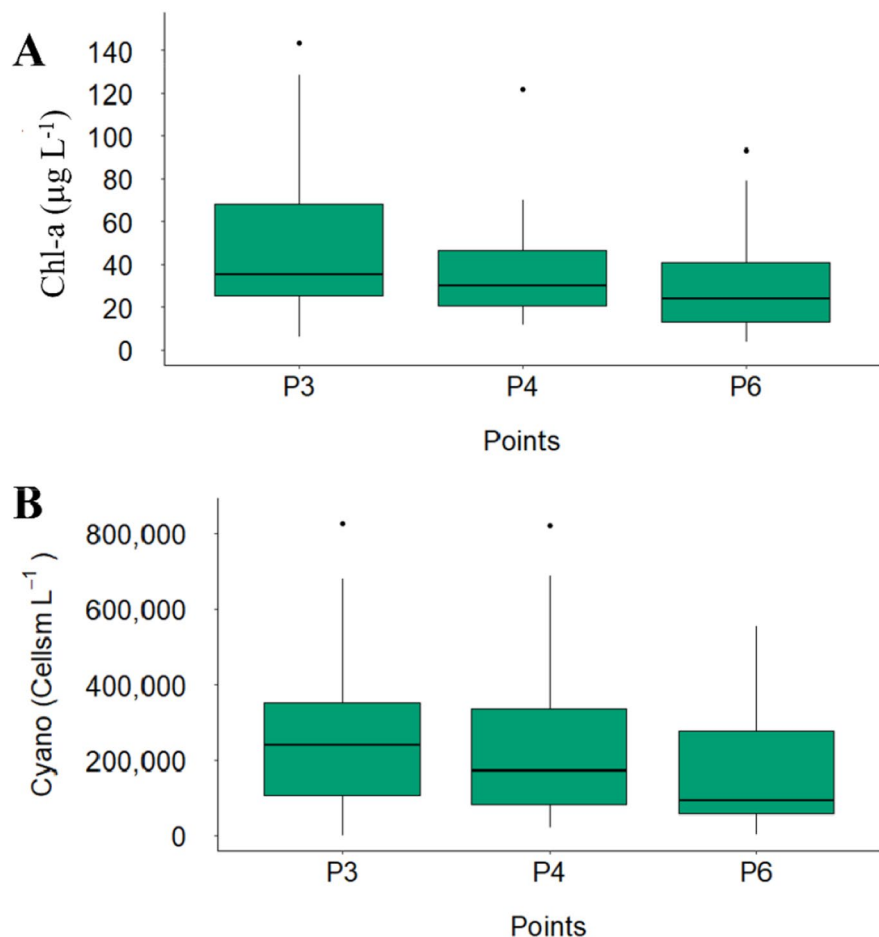
This was not strongly observed for the cyanobacteria cell density (Fig. S6D) where the correlation coefficients were moderately positive ($0.2 < r < 0.5$). The significance of correlation between P4 and P6 was not significant ($p > 0.05$). In contrast, the correlation between points P3 and P4 and P3 with P6 can be considered significant ($p < 0.01$ and $p < 0.05$, respectively).

Even though Chl-a correlation between the sampling points was strongly positive (Fig. S6C), Fig. 4A shows that P3 has a slightly higher median Chl-a concentration than P6, whereas P3 and P4 present similar median Chl-a concentration (Fig. 4A).

Cyanobacteria cell density appeared to follow the same spatial variation pattern as Chl-a (Fig. 4B), with higher median values in P3 and P4 and lower median value in P6. However, the spatial differences between the median values of cyanobacteria are higher than the ones for Chl-a. This is corroborated by the lower correlation values for cyanobacteria cell density between the sampling points P3, P4, and P6 (Fig. S6D).

The fact that the spatial distribution differences of cyanobacteria are higher than the ones observed for Chl-a and that there is no significant correlation between those two parameters (Figs. S19, S20, and S21) indicates that Chl-a is not following cyanobacteria cell density variation, which is not the case in

Fig. 4 Boxplots comparing the values of concentrations among the sampling points. **A** for chlorophyll a concentration (depth sampling of 0.3 m) and **B** for cyanobacteria cell density (depth sampling of 0.3 m). The horizontal line in each boxplot represents the median value



other studies, where Chl-a is found as one of the most important variables for cyanobacterial blooms prediction (Lunetta et al., 2015; Park et al., 2021; Su et al., 2018).

This may be because Chl-a serves as a proxy for estimating overall algae biomass, encompassing both eukaryotic algae and cyanobacteria (Li et al., 2022). Therefore, it is expected that those organisms would respond differently to an environmental stressor. For instance, cyanobacteria are highly susceptible to competition with algae when there is a limitation of nutrient supply where cyanobacteria dominate at low N:P ratios (Grover et al., 2022). In order to confirm this non-significant association between those organisms, water samples should be collected from different water depths, since there could be uncertainties associated with assuming that phytoplankton distribution is uniform and with sampling Chl-a only from the surface (Li et al., 2022).

Regarding the influence of phytoplankton on the DO concentrations, P4 was the only point that presented a significant correlation between cyanobacteria cell density and DO concentration ($r = 0.58$, $p < 0.01$). P4 is also a sampling point with higher DO concentration and cyanobacteria cell density than P6 (Fig. S22A and 4b), which is an indicator that photosynthetic activity in P4 is leading to an increase on the cyanobacteria biomass and contributing to an increase in DO concentration (Conceição et al., 2021; Li et al., 2015).

The spatial variation of phytoplankton cell density and DO concentration indicates that the water intake could be benefited by a selective withdrawal. For instance, this technique could enable epilimnetic water releases, where there is more DO available when comparing with the hypolimnion layer (Duka et al., 2021). In addition, the release of warmer waters can contribute to decrease the thermal stability during the rainy season (Wang et al., 2024), which is when the peaks of thermal stratification usually occur (Fig. S5).

3.5 Temporal Variations of Water Quality Parameters

3.5.1 Total Phosphorus, Total Nitrogen, and Phytoplankton

TP median values clearly increased from 2017 to 2019, then decreased from 2020 to the beginning of 2022. This decrease was probably due to a dilution effect since the reservoir volume presented a

significant intake in 2020 (Fig. 2B). The years that presented the highest data dispersion were 2017 and 2020, with values going from around 0.075 to 0.2 mg/L (Fig. S23A). The year 2017 was the one where the hydrological drought was intense, and the reservoir volume was significantly decreasing; therefore, the nutrient variation was more susceptible to internal phosphorus loading. As for the year 2020, the reservoir volume substantially increased, and the non-point pollution sources were possibly the main factors responsible for the high variation in TP concentration (Lu et al., 2021).

As for the intra-annual changes of TP concentration, Fig. 5A shows that the month with the highest concentration values was May, which is at the end of the rainy season. This shows that the water inflow of the reservoir is one of the main contributors for the increase of TP in the reservoir. In addition, the data dispersion for this month is lower when compared to the months of January, April, and July, which were the months with the highest data dispersion, indicating that the TP concentration at the end of the rainy season was consistently high. Finally, the months with the lowest TP concentration were March, September, November, and December. Among these, September, November, and December are months within the dry season when the TP load from reservoir inflow is practically null.

Between 2016 and 2019, TN median concentration values remained similar until it decreased in 2020, the median going from around 1.6 to around 0.8 mg/L in 2020, slightly increasing to 1 mg/L in 2021, and 1.2 mg/L in the beginning of 2022 (Fig. S23B). This decrease in 2020 was possibly due to the significant increase in the reservoir volume, which caused a dilution effect to dominate the effects on TN concentrations.

Concerning the intra-annual variation of TN, the month with the highest median value was April (around 2.1 mg/L) (Fig. 5B). It is possible to observe an increase from March to April (rainy season) and then a decrease pattern from April to July (from around 2.1 to 1 mg/L). Confirming that, like TP, the TN load from the reservoir inflow is an important contributor to the increase in TN concentrations in the reservoir. However, the variation in TP concentration is more pronounced than the one observed in TN concentration (Fig. 5).

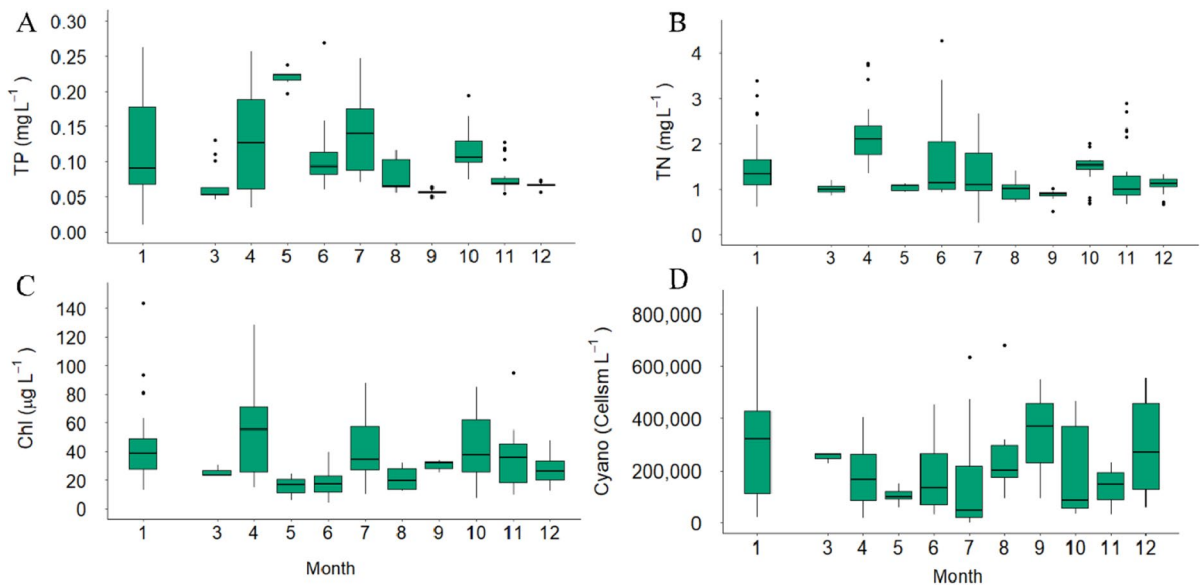


Fig. 5 Boxplots comparing water quality changes within the months, with sampling depths ranging from 0.3 to 24.6 m. **A** total phosphorus, **B** total nitrogen, **C** chlorophyll a, and **D**

cyanobacteria cell density. The horizontal line in each boxplot represents the median value

Chl-a concentration presented a clear increase pattern in the same years that TP also increased (from 2018 to 2019), with median values going from 50 to 80 µg/L (Fig. S23C). Then, in 2020, it decreased to a median of 20 µg/L and then increased to 40 µg/L in 2022. The variation of Chl-a following the one observed for TP concentration is expected since the increase on nutrient concentration causes an increase on phytoplankton productivity (de Oliveira et al., 2020; Guimarães & Neto, 2023).

The month where the median Chl-a concentration was the highest was April (around 60 µg/L) (Fig. 5C), which is also the month where TP and TN concentrations start to increase. During the dry period (July to December), the variation pattern of Chl-a (Fig. 5C) seems to be similar to the one observed for TP (Fig. 5A): increase from June to July, a decrease from July to August, and a clear decrease from October and December. However, during the rainy period, those parameters did not present similar variations. For instance, TP increased significantly from April to May, and Chl-a concentration decreased. This may be caused by Chl-a dilution from high inflow and because the increase in sediment loads can limit primary production rates (Dalu et al., 2015).

Cyanobacteria cell density increased from 2020 to 2022 (Fig. S23D). In addition, the intra-annual variation did not present any clear patterns between the rainy and dry seasons (Fig. 5D). This may have happened because cyanobacteria are organisms that can regulate buoyancy in the water column throughout the day in order to find the best environment conditions (Barçante et al., 2020). Since the data analyzed in the present study was taken only at the surface (0.3 m depth), it may not have captured in-depth information on the behavior of cyanobacteria.

3.5.2 Dissolved Oxygen, Temperature, and Total Dissolved Solids

The median values of DO throughout the years remained around 5 mg/L with higher data dispersion during the years 2017 and 2022 (Fig. S24A), but a clear pattern of DO concentration variation was observed between the rainy and dry seasons (Fig. 6A). During the rainy season (January to June), the median DO concentration decreases, and the data dispersion increases. In contrast, during the dry season (July to December), the median DO concentration increases from June to August and remains similar from August to December. In addition, the data dispersion during

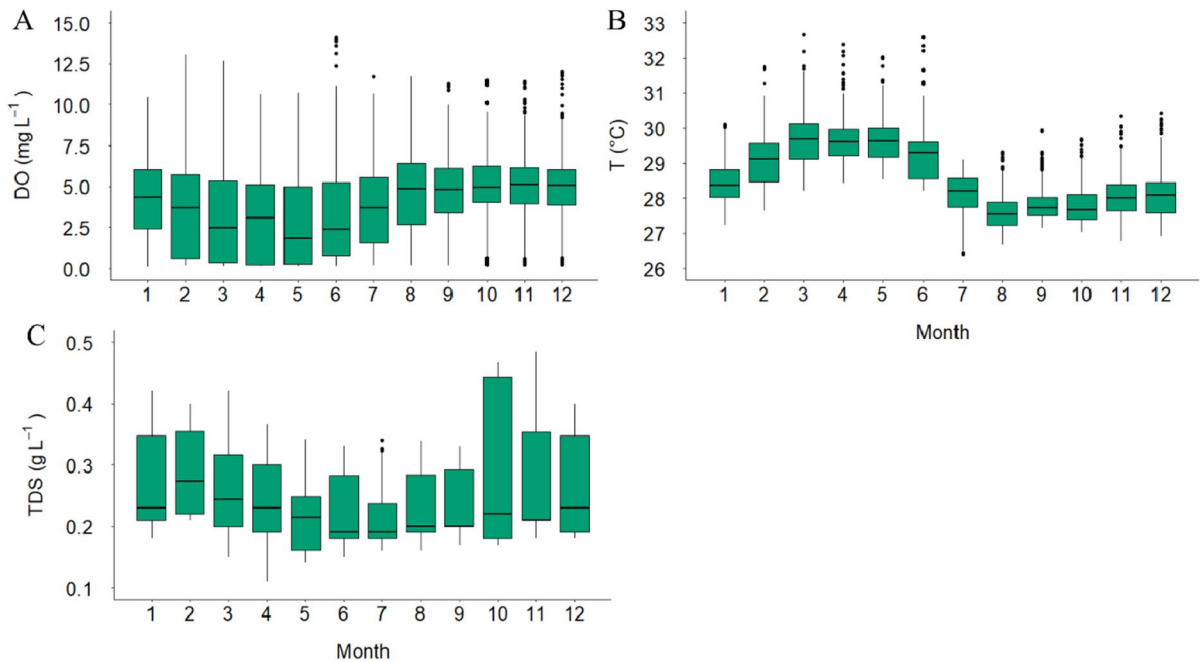


Fig. 6 Boxplots comparing profiling monitoring variable changes within the months, with sampling depths ranging from 0.3 m under the water surface to 0.5 m above the sediment

layer. **A** presents dissolved oxygen concentrations, **B** temperatures, and **C** total dissolved solids. The horizontal line in each boxplot represents the median value

the dry season considerably decreases when compared to the rainy season.

The high impact of the rainy period on worsening the water quality that was observed in the present study is not observed in all regions. For instance, in the reservoir studied by Li et al. (2015), located in a temperate monsoon climate, the heavy rainfall events disturb stratification and causes an increase of DO at the bottom of the reservoir. In contrast, the reservoir studied by Dalu and Wasserman (2018), located in a tropical region, presented better water quality, including higher DO concentration, during dry seasons and the opposite during wet seasons. This is caused by the heavy rainfall which leads to high nutrient input and increase water temperature, both effects observed in the present study (Fig. 6A and B), which contribute to the formation of an anoxic zone at the bottom of the reservoir (Li et al., 2015).

At the beginning of the rainy period (January), the temperature starts to increase and the median values remained similar from March to May (Fig. 6B). Then, it starts to decrease from June to August, and the median remained similar until December, the end of the dry season. In addition, the median values

increased from 2016 to 2022 (around 27.5 to 29 $^{\circ}\text{C}$) (Fig. S24B). The increase in the water temperature starts in 2020, which is also the year where the reservoir volume significantly increased (Fig. 2A). The temperature increase in 2020 and during the rainy period may be due to a different temperature in the water inflow (Chung et al., 2008; Li et al., 2020), which could be confirmed by studying the inflow upstream, the reservoir. The fact that water temperature decreases from upstream to downstream of Castanhao reservoir (Fig. S22B) also corroborates the hypothesis that the water temperature from the inflow of the reservoir is higher than the water temperature of the reservoir.

In general, TDS concentration decreased from the years 2016 to 2020 (Fig. S22C). However, there was a slight increase from 2020 to 2022 but not returning to the same levels as 2016. Between the months of February and June, the median values of TDS also decreased but remained similar during the other months of the year (Fig. 6C). This decrease during rainy season could be due to a dilution effect, and the high TDS concentration values in 2016 and 2017 could be due to the decrease in the reservoir volume,

which associated with evaporation contributed to a concentration of dissolved material (Jones & van Vliet, 2018; Li et al., 2017).

3.6 Pearson's Correlation Analyses

Pearson's correlation analysis was performed to verify if there is a pattern on the correlation between the physicochemical parameters (DO, pH, salinity, and temperature) at the top and at the bottom of the reservoir (Figs. S7 to S18).

The main pattern observed was that DO concentration was strongly or perfectly positively correlated to the pH at the top and at the bottom of the reservoir ($p < 0.001$). Even though pH does not have a direct effect on DO (Banerjee et al., 2019), changes in pH can be an important mechanism for nutrient precipitation or release from sediments, which affect the DO concentration (Zhang et al., 2014), therefore, this positive correlation would be expected.

The correlation between DO and temperature had three main groups. In P1 and P2, DO was moderately positive ($r = 0.29$ and $r = 0.45$; $p < 0.05$ and $p < 0.001$, respectively) correlated to the temperature only at the surface of the reservoir (Figs. S7 and S9). However, at the bottom of the reservoir, DO in P5 and P6 presented a moderately negative correlation with temperature ($r = -0.46$; $p < 0.001$, Figs. S16 and S18). This may be due to higher photosynthetic activity in P1 and P2 than in P5 and P6, which leads to higher surface DO concentrations. In addition, the higher upstream temperatures can contribute to increase phytoplankton biomass and DO concentration (He et al., 2019; Li et al., 2021; Pečić et al., 2023). As for P5 and P6, the ones with the lowest DO concentration (Fig. S22A) and more persistent chemical stratification of DO (Fig. S3), the negative correlation between DO and temperature indicates that in those sampling points, temperature can be one of the factors that is contributing to the low DO concentrations; since higher temperature decreases oxygen solubility in the water (Nong et al., 2023; Wei et al., 2022). In contrast, P3 and P4 did not show any significant correlation between DO and temperature both at the bottom and at the top of the reservoir.

Regarding the correlation between Chl-a and nutrients, in P3 (Fig. S19), Chl-a was strongly positively correlated with both TP (0.56, $p < 0.01$) and TN (0.72, $p < 0.001$). In P4 (Fig. S20), which is the

closest point to the fish farming, Chl-a was moderately positive correlated with TP (0.46, $p < 0.05$) and strongly positive correlated to TN (0.60, $p < 0.01$). However, in P6 (Fig. S21), which is closest to the dam retaining wall, Chl-a was not significantly correlated to TP, but it was moderately positive correlated to TN (0.43, $p < 0.05$). Depending on the species composition of the phytoplankton in each sampling point, they respond differently to the same N:P ratio in the water (Huo et al., 2019; Summers & Ryder, 2023), which could explain why the Chl-a correlation with nutrients varies within the sampling points.

In contrast with other studies (Søndergaard et al., 2011), cyanobacteria cell density did not present significant correlation with TP, TN, and Chl-a. This could be because cyanobacteria samples were taken at a depth of 0.3 m; it is possible that there is a significant presence of cyanobacteria deeper into the water column (Rosińska et al., 2017). Another reason is that for Castanhão, the change in the nutrients and Chl-a concentration may not have an immediate effect on cyanobacteria cell density. For instance, Gu et al. (2020) found that phosphorus loads affected only the maximum cyanobacteria biomass but not the growth cycle. They concluded that the growth cycle of cyanobacteria was not related to phosphorus concentration.

4 Conclusions

The spatio-temporal variation of several water quality parameters and their interactions were assessed in the Castanhão reservoir, situated in the Brazilian semiarid region. The results indicate that TP and TN concentrations did not exhibit significant variation among the sampling points. This finding suggests the feasibility of applying a complete-mixing model in a monthly time step for evaluating nutrient dynamics in reservoirs within semiarid regions in future studies. The observed uniform distribution of nutrients can be attributed to the weak thermal stratification observed in the Castanhão reservoir, where the chemical stratification of dissolved oxygen prevails over thermal stratification. It is noteworthy, however, that although thermal stratification is not a frequent occurrence, it typically manifests during the rainy season. This season is characterized by higher water temperatures compared to the dry season, suggesting the possibility of warmer water

entering the reservoir during this period. To confirm this hypothesis, a detailed analysis of the inflow water temperature is essential. During the rainy season, a noticeable degradation in water quality occurred, marked by peak concentrations of TP and TN. This underscores the significance of temporal variation of nutrients which surpassed spatial variation. Additionally, dissolved oxygen concentrations displayed significant spatial and temporal patterns. DO concentration decreased from upstream to downstream, with a notable decline during the rainy season, resulting in hypoxia levels. Given that this condition is favorable to fish mortality events, the rainy season emerges as a critical window for reservoir managers to implement preventive measures.

Chlorophyll a exhibited a uniform distribution across the sampling points and displayed positive correlations with both TP and TN. However, cyanobacteria cell density did not exhibit significant correlations with nutrients and chlorophyll a, contrary to previous studies.

The absence of significant spatial variation in nutrient distribution suggests that the assumption of complete nutrient mixing can be applied to develop models of phosphorus dynamics in order to predict phosphorus concentrations in the reservoir based on the different sources of this nutrient. This can be an important tool for water managers to simulate scenarios and decide on a water allocation plan that minimizes the negative impacts on the water quality of reservoirs within similar regions. However, it is essential to consider the spatial variation of dissolved oxygen when assessing the internal loading of phosphorus. It is worth noting that the analysis of cyanobacteria in this study was limited to the reservoir's surface. Future studies examining the variation of cyanobacteria cell densities and other parameters throughout the water column throughout the day could be valuable for managing and predicting harmful cyanobacteria blooms, as these organisms are known to adjust their depth to optimize photosynthesis.

Furthermore, this study focused on physicochemical and biological data within the reservoir itself. Given the significant deterioration in water quality during the rainy season, future studies could include an assessment of water quality from upstream tributaries to gain a more comprehensive understanding of the system.

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Data Availability Data available on request.

Declarations

Conflict of Interest The authors declare no competing interests.

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