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Analysis of total phosphorus and chlorophyll a correlations in Ceará reservoirs, Brazil

Análise das correlações entre fósforo total e clorofila a em reservatórios do Ceará, Brasil

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ABSTRACT

Reservoirs worldwide are prone to water quality degradation caused by increased primary production. Therefore, it is essential to comprehend the factors that influence this phenomenon as it plays a fundamental role in controlling eutrophication. The aim of this study was to analyze the correlation between total phosphorus (TP) and chlorophyll a (Chla) in 155 reservoirs located in the state of Ceará, Brazil. This analysis was conducted through a comprehensive examination of historical data (2008–2021) obtained from the water resource management company of the state, which monitors these parameters. The correlation between TP and Chla was examined through simple adjustments, utilizing the coefficient of determination (R^2) as an evaluation metric. Afterward, the study investigated the potential influences on the dynamics of these adjustments based on factors such as the hydrographic basin, reservoir size, trophic state (as for Chla and TP concentrations), and the volumetric variability coefficient. In general, the adjustments yielded unsatisfactory models ($R^2 < 0.4$) for the majority of reservoirs (n = 115). Despite their inadequacy, these models align with classic literature models, indicating that in most basins, higher availability of TP in the water column contributes to increased Chla concentration. The analysis of factors influencing the pattern and dispersion of adjustments between Chla and TP revealed that the performance of R^2 is associated with various factors, such as different watersheds, volumetric variability, and Chla concentrations. The variance in R^2 between reservoirs of varying sizes and trophic states based on TP concentration was considered insignificant.

Keywords: nutrients; semiarid; eutrophication; water quality.

RESUMO

Reservatórios em todo o mundo são susceptíveis à degradação da qualidade da água em razão do aumento da produção primária, e a necessidade de entender os fatores que a influenciam é questão fundamental para o controle da eutrofização. O objetivo deste estudo foi analisar a correlação entre fósforo total (PT) e clorofila a (Cla) em 155 reservatórios localizados no estado do Ceará, Brasil. Esta análise foi realizada por meio do levantamento de dados históricos (2008–2021) monitorados e divulgados pela companhia de gestão de recursos hídricos do estado. A relação entre PT e Cla foi analisada por meio de ajustes simples, utilizando como métrica de avaliação o desempenho do coeficiente de determinação (R^2). Posteriormente, investigou-se como a dinâmica desses ajustes pode ser influenciada com relação à bacia hidrográfica, ao porte do reservatório, ao estado trófico (quanto à concentração de Cla e PT) e ao coeficiente de variabilidade volumétrica. De forma geral, os ajustes resultaram em modelos insatisfatórios ($R^2 < 0{,}4$) para a maioria dos reservatórios (n = 115). Esses modelos, apesar de insatisfatórios, seguem as tendências de modelos literários clássicos, mostrando que na maioria das bacias a disponibilidade de PT na coluna d'água favorece o aumento da concentração de Cla. A análise dos fatores que influenciam o padrão e a dispersão dos ajustes entre Cla e PT demonstrou que a *performance* dos R^2 está relacionada às diferentes bacias hidrográficas, à variabilidade volumétrica e às concentrações de Cla. A variância entre os R^2 de reservatórios de diferentes portes e estados tróficos conforme a concentração de PT não foi significativa.

Palavras-chave: nutrientes; semiárido; eutrofização; qualidade da água.

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Introduction

Artificial eutrophication is considered one of the most widespread water quality problems in the world (Cruz et al., 2019; Shuvo et al., 2021). This phenomenon arises from the excessive accumulation of nutrients, leading to a range of detrimental outcomes such as heightened primary productivity, progressive degradation of aquatic ecosystems, oxygen depletion, reduced water transparency, increased turbidity, and disruption of aquatic equilibrium (Santos et al., 2021; Bao et al., 2022). In Brazil, accelerated eutrophication processes are observed in multipurpose reservoirs, where several factors contribute to their exacerbation, namely the release of nutrients into water bodies, urbanization, and water volume fluctuations resulting from periods of water scarcity, particularly in the semiarid region (Pacheco and Lima Neto, 2017; Figueiredo et al., 2020).

Phosphorus and nitrogen are widely acknowledged as key nutrients with a significant impact on water quality, particularly with regard to phytoplankton growth and chlorophyll a (Chla) concentration in lakes (Shuvo et al., 2021; Mendes et al., 2022). Among these nutrients, total phosphorus (TP) is generally recognized as the primary limiting factor for phytoplankton growth and Chla concentration. Consequently, empirical relationships between TP and Chla have been extensively used to establish a foundation for managing TP concentrations and regulating trophic states (Rocha et al., 2020; Yuan and Jones, 2020; Quinlan et al., 2021).

Historically, empirical models describing the relationship between Chla and TP were primarily established through linear regression models applied to a diverse range of temperate lakes (Dillon and Rigler, 1974; Jones and Bachmann, 1976; Carlson, 1977). These studies consistently reported similar coefficients and observed that the relationship between TP and Chla intensified as the trophic state of the lakes increased. However, as time progressed, numerous investigations assessed the applicability limitation of these findings to different regions, lake types, and reservoirs, verifying that the variability in the TP-Chla relationship can be influenced by a multitude of morphological and ecological factors (Wiegand et al., 2020; Yuan and Jones, 2020; Kim and Ahn, 2022).

In their study, Quinlan et al. (2021) investigated the dynamics between TP and Chla by analyzing a comprehensive dataset comprising 3,874 lakes from 47 countries across different regions and exploring the most influential variables, including landscape morphometric characteristics, lake attributes, nutrient limitations, and temperature effects. Similarly, Rocha et al. (2020) examined the relationship between TP, total nitrogen (TN), and Chla in 35 reservoirs in Ceará, providing models with satisfactory predictive capabilities for TP. Furthermore, several studies were widely employed to predict Chla based on TP in various scenarios: spatial variation (Filazzola et al., 2020; Yuan and Jones, 2020; Siswanto et al., 2022), seasonal fluctuations (Rocha Junior et al., 2018; Shuvo et al., 2021; Mandal et al., 2022), morphometric characteristics (Qin et al., 2020; Janssen et al., 2021), among other parameters (Mamun et al., 2019; Kupssinskü et al., 2020; Shin et al., 2020).

Although there are extensive investigations into the TP input load and the impacts of climate change on water quality in tropical reservoirs (Mesquita et al., 2020; Raulino et al., 2021; Rocha and Lima Neto, 2021, 2022), studies evaluating the TP predictive capacity using large-scale simple regression models are still scarce. Consequently, given the significance of understanding the role of phosphorus, particularly in the context of current environmental changes and decline in water quality associated with increased eutrophication, the primary objective of this study was to assess the correlations between TP and Chla in 155 reservoirs in Ceará, identifying the factors that influence the predictability of Chla and its relationship with TP in these places.

Methodology

Place of study and data collection

For this study, a total of 155 reservoirs located across the state of Ceará, northeast of Brazil were selected (Figure 1). Encompassing a territorial area of 150 km², Ceará holds the highest proportion of its territory within the semiarid region compared to other states, with 95% (175 out of 184) of its municipalities situated within this region (Brasil, 2021). The area exhibits notable temporal and spatial variability in precipitation patterns and experiences high rates of evaporation. Due to the semiarid climate, the primary source of water supply for the approximately 9 million inhabitants of Ceará relies heavily on the stored water accumulated in surface reservoirs (Souza et al., 2017). At present, the state manages a network of reservoirs with a combined storage capacity of 18,674 hm³ (FUNCEME, 2021).

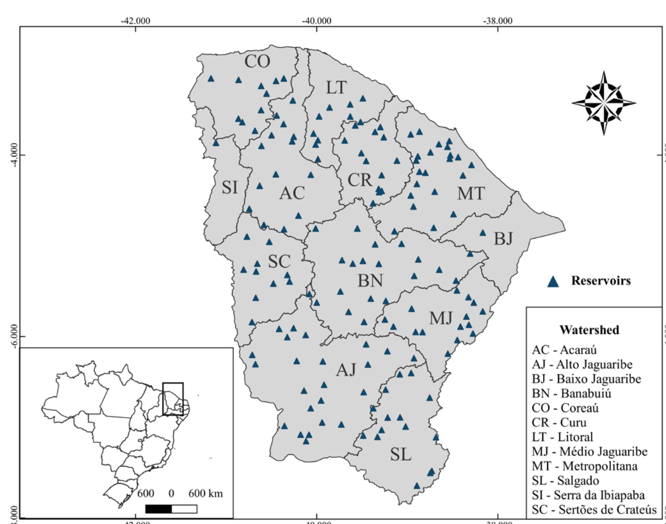

Figure 1 – Distribution of monitored reservoirs.

The Chla, TP, and volume data utilized in this study were obtained from the Ceará Hydrological Portal, a collaborative effort involving the Secretary of Water Resources of the State of Ceará (SRH), the Cearense Foundation of Meteorology and Water Resources (FUNCEME), and the Water Resources Management Company of the State of Ceará (COGERH), which provides data on water quality monitoring and reservoir volume measurements in the state (Ceará, 2021). The selection process involved choosing reservoirs that had available data for Chla, TP, and volume simultaneously, with a minimum of 10 data collections. This selection yielded a total of 4,596 sample sets from 155 reservoirs distributed across the 12 hydrographic basins of the state of Ceará during the period from 2008 to 2021 (Appendix 1). In cases where parameter values were reported as below the detection limits, the respective minimum values were adopted as concentration values for analysis in this study.

Data analysis

For the limnological evaluation of data, descriptive statistics were employed, including measures as mean, standard deviation, minimum, and maximum values of TP, Chla, and volume percentage. To assess the variability of TP and Chla, limnological analysis was conducted considering the dataset as a whole, grouped by reservoir, and assessing the temporal variation of the average concentrations by hydrographic basin. To capture the effects of hydrological drought, the data were divided into two distinct periods reflecting the impact of reduced precipitation and the associated hydrological conditions: The years 2008 to 2012 were classified as a wet period, characterized by relatively higher rainfall and The years from 2013 to 2021, were considered as a dry period, since the state experienced below-average rainfall, resulting in most reservoirs reaching volumetric percentages below 50% (Wiegand et al., 2021).

To determine the correlation between TP and Chla, the R^2 was calculated using simple linear regression for the entire dataset as well as for each watershed and individual reservoir under investigation. This analysis was performed using the Microsoft Excel™ software. The obtained results were then classified based on the statistical performance evaluation criteria for TP correlations, as recommended by Moriasi et al. (2015) into four groups: Very Good ($R^2 > 0.8$), Good ($0.65 < R^2 \leq 0.8$), Satisfactory ($0.4 < R^2 \leq 0.65$), and Unsatisfactory ($R^2 \leq 0.4$).

The variability of the correlation performance among the reservoirs was analyzed in relation to various factors, including hydrographic basin, reservoir size, coefficient of variation (CV) of the reservoir volume, and trophic state indices. To assess this variability, the Shapiro-Wilk test was applied to examine the normality of the data within each classification group. However, since most tests conducted on the subgroups did not exhibit a normal distribution, non-parametric variance analysis was employed using the Kruskal-Wallis test. Dunn's individual significance test was conducted as a post hoc analysis, considering statistical significance when $p < 0.05$.

Regarding the hydrographic basin classification, the reservoirs were categorized according to the specific hydrographic basin to which they belong. Regarding reservoir size, they were divided into four groups as stated by Ceará (2018): Strategic (> 500 hm^3), Large Size (100–500 hm^3), Medium Size (10–100 hm^3), and Small Size (1–10 hm^3). This categorization helps assess the correlation performance based on the size of the reservoir. Furthermore, the reservoirs were classified according to the CV of the annual volumetric percentage. This coefficient was determined by calculating the ratio of the standard deviation to the average of the annual percentage volumes observed for each reservoir over the monitoring period. The observed variability ranges were classified as follows: Very High ($CV > 1.2$), High ($0.8 < CV \leq 1.2$), Medium ($0.4 < CV \leq 1.2$), and Small ($CV \leq 0.4$).

To assess the impact of the trophic state index on the correlations between TP and Chla, the study investigated whether significant differences existed in the R^2 values among reservoirs with different trophic levels. In this study, the trophic level classification of the reservoirs was conducted using two methods based on the classification limits proposed by Cunha et al. (2013) for mean Chla concentration and TP intervals (Table 1).

Results and Discussion

The study collected Chla and TP concentration data for all observed samples from 155 monitored reservoirs across 12 hydrographic basins in the state of Ceará. The mean TP concentration across all reservoirs was 0.125 mg/L ± 0.188 (mean ± standard deviation). The TP concentrations ranged from 0.002 mg/L (observed in Forquilha/Acaraú and Angicos/Coreaú reservoirs) to 5,062 mg/L (found in Acarapé do Meio/Metropolitana reservoir). Regarding Chla concentrations, the average was 50.933 µg/L ± 92.548, with a minimum value of 0.2 µg/L (recorded in 58 reservoirs) and a maximum of 1671.4 µg/L (observed in Colina/Sertões de Crateús reservoir). The annual percentage volume showed an average of 40.81% ± 30%, ranging from a minimum of 0.01% to a maximum of 100%. Figure 2 visually represents the variations in TP (A) and Chla (B) concentrations across the Ceará basins using a box diagram.

Table 1 – Intervals for trophic state classification adopted.

Trophic State	Total Phosphorus (mg/L^{-1})	Chlorophyll a ($\mu g/L^{-1}$)
Ultra-oligotrophic	TP ≤ 0.0159	Chla ≤ 2.0
Oligotrophic	0.016 < TP < 0.0238	2.1 < Chla ≤ 3.9
Mesotrophic	0.0239 < TP ≤ 0.0367	4.0 < Chla ≤ 10
Eutrophic	0.0368 < TP ≤ 0.0637	10.1 < Chla ≤ 20.2
Super eutrophic	0.0638< TP ≤ 0.0776	20.3 < Chla < 27.1
Hyper-eutrophic	TP > 0.0776	Chla > 27.2

Source: Cunha et al. (2013).

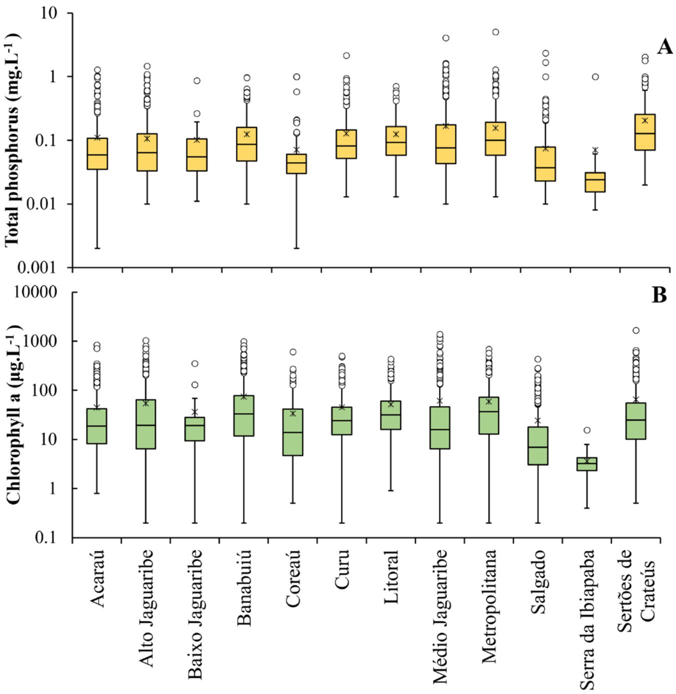

Figure 2 – Variation of total phosphorus (A) and chlorophyll a (B) in the twelve hydrographic basins of Ceará, on a linear-log scale. The bottom and top of the box represent, respectively, the first (25%) and third quartile (75%) of the sample, the lower and upper limits, the minimum and maximum values. The circles in the graph indicate the outliers, the inner lines identify the medians and, the asterisks, the means.

The study analyzed the variability of Chla in relation to the percentage of available volume in the reservoirs, considering the wet period from 2008 to 2012 and the dry period from 2013 to 2021. As indicated by Wiegand et al. (2021), the state of Ceará experienced a prolonged period of drought starting in 2012, characterized by below-average rainfall and volumetric percentages below 50% in most watersheds. In line with their findings, the average volume for all basins during the wet period exceeded 50% (65.9%), whereas during the dry period, the average dropped to 30.9%. Figure 3 illustrates the concentrations of TP and Chla in relation to volumetric variability in each basin during the wet and dry periods. Regarding TP, when considering the entire dataset, the mean TP concentration was similar for both periods, at approximately 0.121 mg/L. However, an increase in phosphorus concentration was observed in most basins, with the exception of Coreaú, Curu, Litoral, Metropolitana, and Serra da Ibiapaba.

It is important to note that while the decrease in reservoir volume generally leads to an increase in nutrient concentrations, the absence of rain during drought periods can result in a reduction of nutrient input loads into the reservoirs. This is because the main sources of pollutants in tropical reservoirs are typically associated with the transport of sediments from both point and non-point sources of pollution in the watershed (Cavalcante et al., 2018; Saha et al., 2022). Furthermore, Dutra et al. (2022), in their study on water quality in the Paraibuna river, observed significant changes in variable concentrations during different periods due to seasonality, highlighting the influence of temporal variability on water quality parameters. These findings emphasize the complex dynamics of nutrient concentrations in reservoirs, which can be influenced by factors such as rainfall patterns, sediment transport, and seasonal variations.

The analysis of Chla concentration revealed an overall increase in the mean concentration from 28.542 to 49.728 µg/L^{-1} between the wet and dry periods, indicating higher biomass during the dry period. This trend was observed in most basins, except for Serra da Ibiapaba and the Litoral, where no significant increase in Chla concentration was observed. These findings corroborate previous studies (Rocha Junior et al., 2018; Leite and Becker, 2019; Soares et al., 2019) that demonstrated the influence of volume changes on biomass concentration in reservoirs, indicating that the fluctuations in water volume, driven by the region's climatic characteristics, impact the stability of the water column and the composition of the cyanobacterial community and biomass (Ding et al., 2018; Rocha Junior et al., 2018).

Simple linear regression models

The results of the simple linear regression analysis for the entire dataset presented a statistically insignificant model, indicating a weak relationship between TP and Chla ($R^2 = 0.137$; n = 4,596). Similarly, the correlations between TP and Chla obtained for each watershed yielded unsatisfactory determination coefficients, with the highest value found in the Baixo Jaguaribe watershed ($R^2 = 0.85$). The observed trends in the basin-specific models, although not highly significant, generally align with the curves proposed by Bartsch and Gakstatter (1978) and Rast and Lee (1978) (Figure 4), indicating that excessive phosphorus input can stimulate algal proliferation. However, the Curu basin showed an inverse trend, with Chla decreasing as TP concentration increased.

This may be attributed to factors such as reduced light permeability and low oxygen levels, which can limit algal production even under high nutrient conditions (Yu et al., 2022). It is important to note that the observed curves differ from those proposed by Dillon and Rigler (1974). This discrepancy can be attributed to the fact that the models suggested by Dillon and Rigler (1974) were derived from data from lakes with much lower TP concentrations than those observed in this study. Therefore, their applicability may be limited to aquatic environments with characteristics similar to the lakes used in the modeling process.

The analysis of the correlations between TP and Chla for each individual reservoir revealed that the majority of reservoirs (74.19%; n = 115) had unsatisfactory correlations according to the statistical performance criterion proposed by Moriasi et al. (2015) (Appendix 2). For the remaining classificatory limits, 20% (n = 31) of the reservoirs had correlations classified as satisfactory, only a small percentage of reservoirs (3.87%; n = 6) showed correlations classified as good, and an even smaller percentage (1.94%; n = 3) had correlations classified as very good.

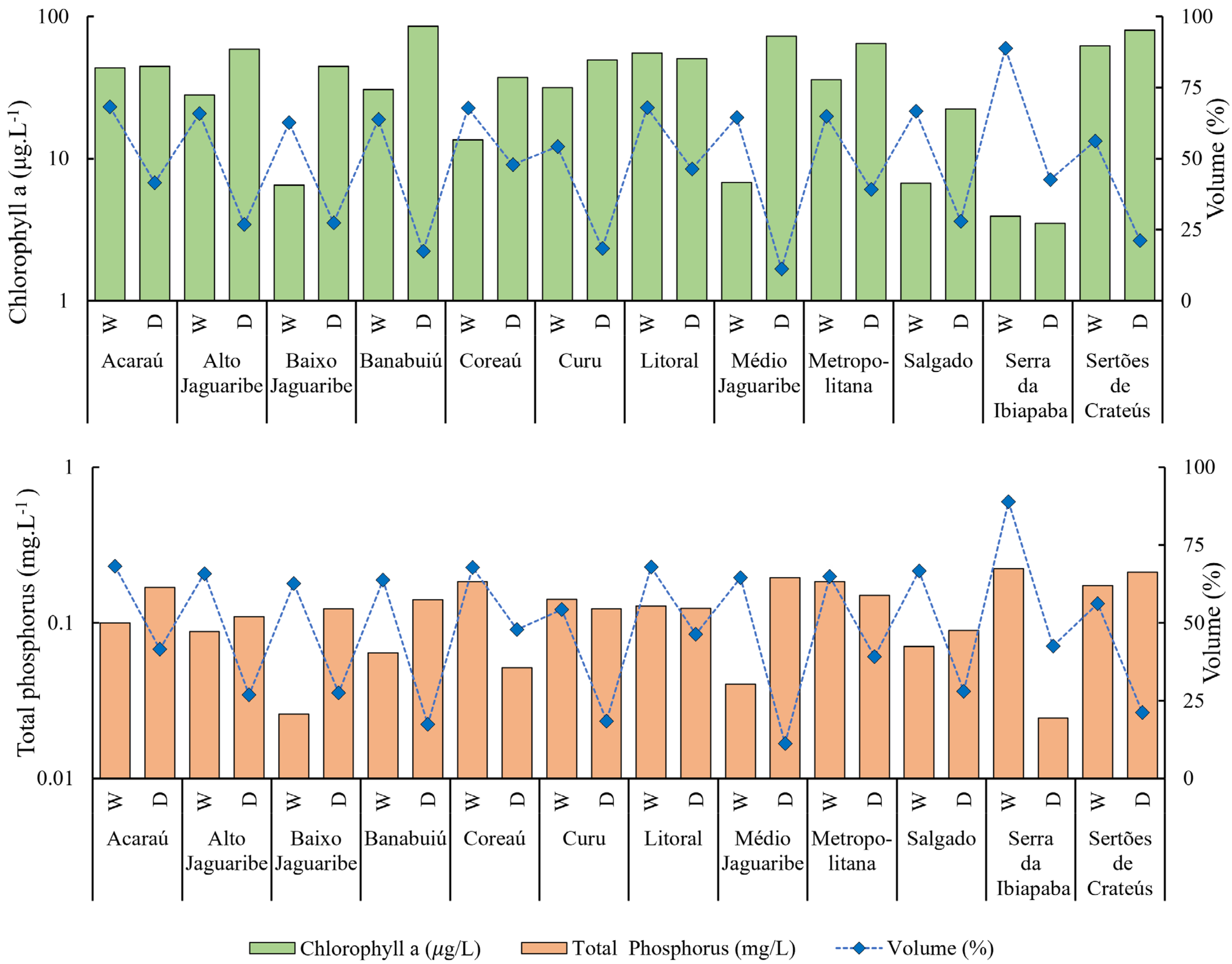

Figure 3 – Variation of the average concentration of chlorophyll a, total phosphorus and volumetric percentage during the wet (W) and dry (D) periods.

In general, it is worth noting that despise the predominance of unsatisfactory models, the correlations based on the dataset from each individual reservoir were more significant compared to those considering the basin as a whole. This suggests that the relationship between Chla and TP can vary even among reservoirs within the same ecoregion and under similar trophic conditions (Wilkinson et al., 2021), highlighting the limitations of applying models based on combined data from multiple reservoirs to predict results in individual reservoirs.

The findings of other studies in reservoirs with similar regions support the results obtained in the present study, showing positive correlations between TP and Chla, but with limited statistical significance. Rocha et al. (2020) reported a $R^2 = 0.34$ in their evaluation of 35 reservoirs monitored by COGERH, and Carneiro et al. (2014) found a $R^2 = 0.39$ in their study of 21 reservoirs in the state of Goiás. Similarly, Menezes et al. (2019), in their investigation into the influence of climate change on the trophic state of semiarid lakes, obtained positive correlations between TP and Chla but also classified them as unsatisfactory. The limited statistical significance of the models can be attributed to the complexity of the processes involved in predicting algal biomass in reservoirs with high climate variability. Studies such as Wiegand et al. (2020) indicated that TP may not be the primary nutrient affecting eutrophication in Ceará reservoirs, since TN, besides being the most representative nutrient, was also the most important predictor of algal growth. According to Raulino et al. (2021) and Shuvo et al. (2021), although TP is often the most influential nutrient on Chla concentrations, in many cases, the combined impact of other factors such as hydroclimatic variables are equally important. Therefore, the inclusion of additional factors beyond TP input is crucial in predicting Chla, which explains the predominance of unsatisfactory correlations observed in the studied Ceará reservoirs.

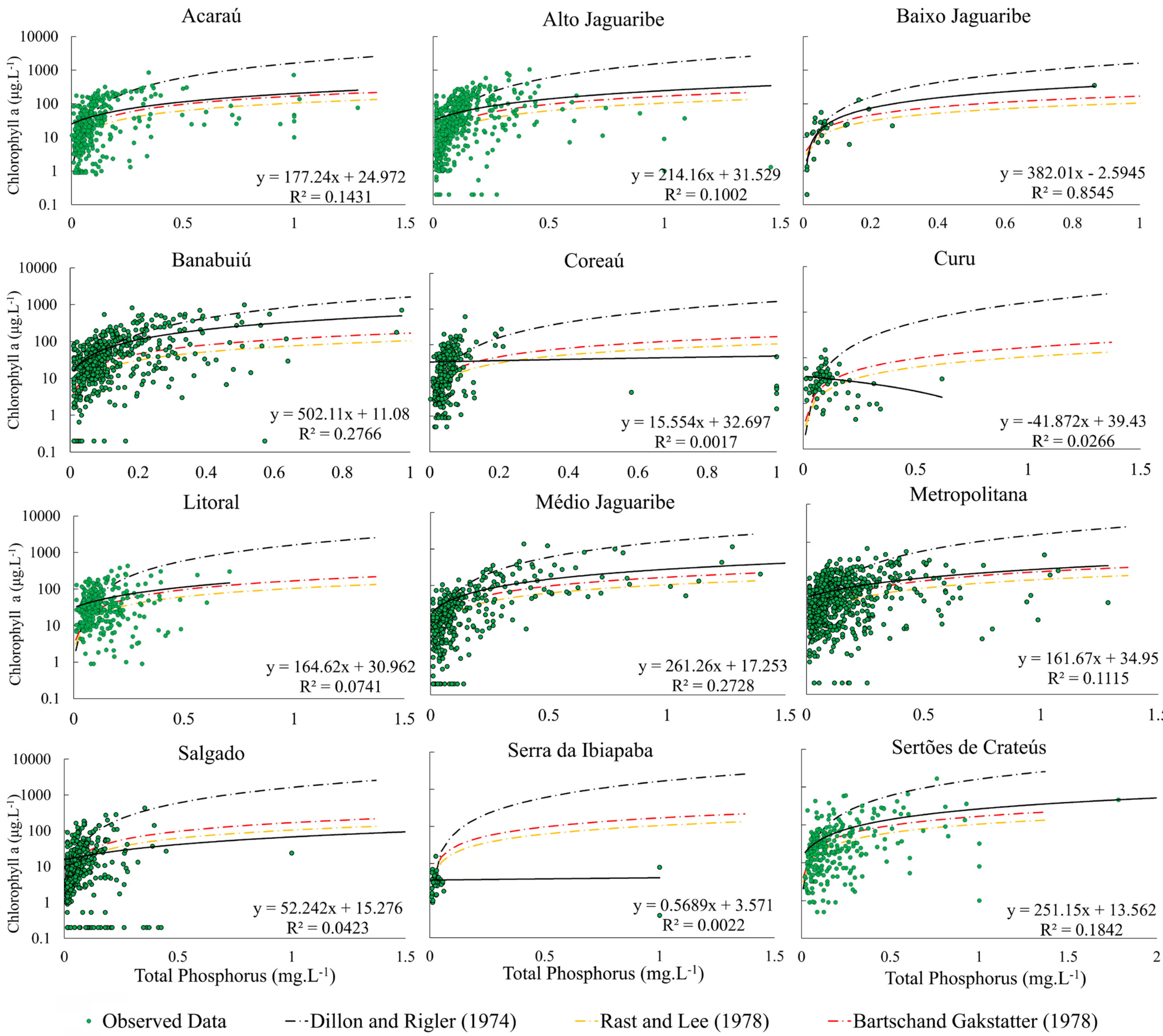

Figure 4 – Correlations between total phosphorus and chlorophyll a in the studied watersheds and comparison with classic literature models.
Y: adjusted model; R^2: coefficient of determination.

The distribution of correlations obtained for the reservoirs among the studied basins, as shown in Figure 5, reveals that the Médio and Alto Jaguaribe basins exhibited the best statistical performance, with respectively 60 (n = 9) and 41.8% (n = 10) of the reservoirs achieving a satisfactory or higher rating (Appendix 3). It is important to note that the Baixo Jaguaribe basin had a 100% rating, but this is based on only one reservoir. The average correlations observed in the reservoirs of these basins were 0.463 and 0.342 for the Médio and Alto Jaguaribe basins, respectively.

The Metropolitana and Salgado basins exhibited the highest percentages classified as unsatisfactory, with respectively, 90.9 (n = 22) and 93.3% (n = 15) of their reservoirs falling into this category, and an average R^2 of 0.159 and 0.109. The Kruskal-Wallis test further confirmed the influence of the watershed on the correlations between TP and Chla (H(9) = 40.651; p = 2.77e-05). The Middle Jaguaribe and Lower Jaguaribe basins showed significant differences compared to six other basins, suggesting that these two have distinct patterns of nutrient dynamics and algal biomass response. Reservoirs are strongly connected to their watersheds, as they receive sediment transport from surface runoff and groundwater recharge (Goyette et al., 2019; Lira et al., 2020; Melo et al., 2022). Once each hydrographic basin has different sources of predominant pollution (agriculture, urbanization, fish farming, livestock, etc.), phosphorus loads input in each reservoir are inherent to the land use and land cover characteristics of each basin, leading to differences in the predictive capacity of TP–Chla correlations among the basins.

The analysis of the correlations between TP and Chla with respect to reservoir size revealed that there was no significant impact of size on Chla prediction. The unsatisfactory correlations were evenly distributed among the different size classes, with similar percentages of unsatisfactory correlations observed for Small (71.7%), Medium (75.9%), Large (75%) and Macro (75%) size reservoirs. Additionally, the mean correlations between the groups were also similar (0.216 ± 0.234; 0.236 ± 0.224; 0.233 ± 0.236 and 0.234 ± 0.252, respectively) (Appendix 5), further supporting the finding that reservoir size did not have a significant influence on Chla prediction. This observation was also confirmed by Kruskal-Wallis test (H(3) = 0.636; p = 0.887) and Dunn's post hoc test, which did not indicate any significant differences between the correlations of reservoirs of different sizes.

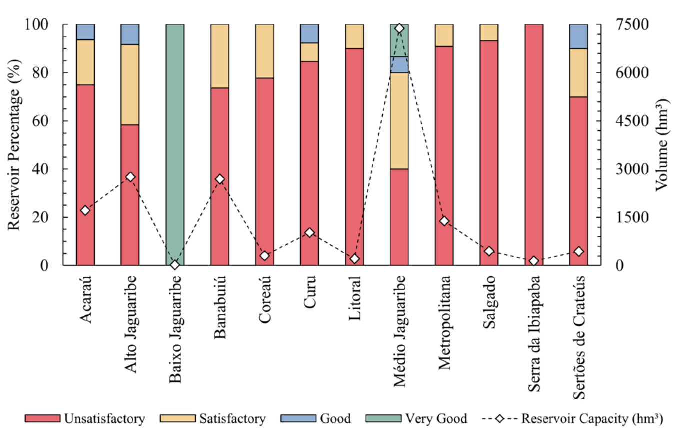

Figure 5 – Reservoir percentage in each coefficient of determination classified by watershed.

The statistical performance classifications were also compared with respect to the annual variability of the reservoir's estimated volumetric percentage based on the CV (Appendix 6). The results showed that the percentage of unsatisfactory correlations varied among the different CV groups. Among the reservoirs with small variability, 83.3% (n = 6) were classified as unsatisfactory. For the medium CV group, 91.42% (n = 35) had unsatisfactory correlations. In the High CV group, 67.41% (n = 89) were unsatisfactory, and in the very high CV group, 72% (n = 25) were unsatisfactory. The Kruskal-Wallis variance test indicated a significant effect of the volumetric variability coefficient on the correlations between TP and Chla (H(3) = 22.944; p = 5.66e-05). The Dunn's post hoc test further revealed significant differences, particularly between the very high and the medium CV groups (p = 0.0005), as well as between the high and the medium CV groups (p = 0.000005).

In fact, the mean correlations between TP and Chla observed in reservoirs classified as very high (0.297 ± 0.258) and high (0.287 ± 0.221) were found to be higher compared to those in the medium (0.111 ± 0.168) and low (0.171 ± 0.215) variability coefficient groups. The higher coefficients of variability in these groups indicate greater dispersion between the samples, suggesting extreme events of both increase and decrease in the water level during the study period. This dispersion can be attributed to the complex processes involved in increasing nutrient concentrations in each reservoir. For instance, the rise in water level in reservoirs can, in certain cases, improve water quality by increasing dilution capacity due to elevated runoff (Ding et al., 2018). However, in other cases, the increase in volume can lead to the release of phosphorus that is adsorbed to oxides, thereby increasing the risk of phosphorus release from bottom sediments into the water column, which results in elevated concentrations (Wu et al., 2021; Rocha and Lima Neto, 2022).

To assess the variations in correlations among different concentration ranges of TP and Chla, the trophic state classification was employed, utilizing the limits proposed by Cunha et al. (2013). Based on the classification scheme that employs phosphorus as an indicator of trophic status (Figure 6A), most reservoirs exhibited an average classified as hypereutrophic (107).

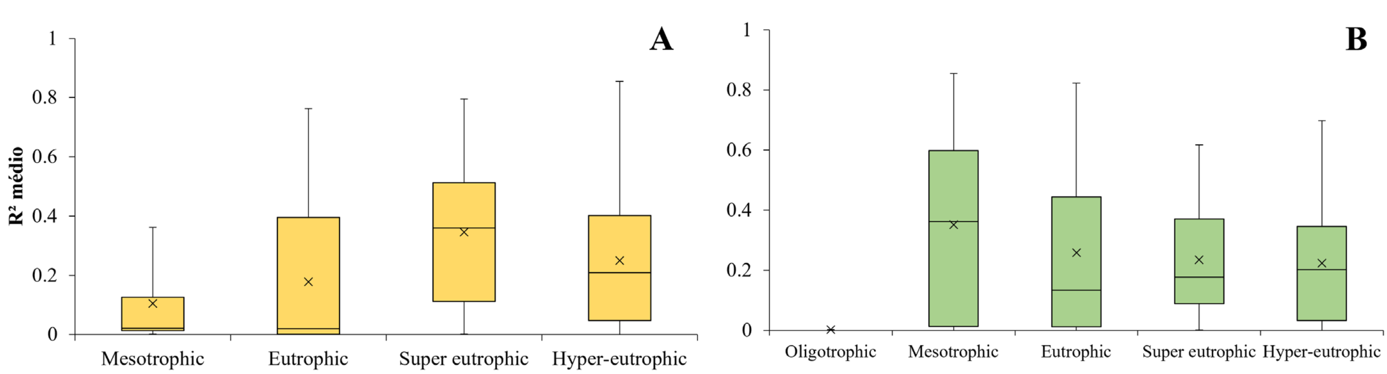

Figure 6 – Dynamics of the correlations between total phosphorus and chlorophyll a according to the trophic state classified through (A) total phosphorus and (B) chlorophyll a. The bottom and top of the box represent, respectively, the first (25%) and third quartile (75%) of the sample. The lower and upper limits, the minimum and maximum values. The circles in the graph indicate the outliers, the inner lines identify the median and, the asterisk, the mean.

The percentage of reservoirs with unsatisfactory classification was relatively consistent among all classes, including Mesotrophic (80%), Eutrophic (71%), Supereutrophic (47%), and Hypereutrophic (63%). When examining the adjustments made for the reservoirs, no significant variation was observed among the groups (H(3) = 1.952; p = 0.288). The means for all intervals were found to be similar (Appendix 4).

The lack of influence of phosphorus on the correlations' dynamics may be attributed to the necessity of investigating TP as a limiting nutrient in the studied reservoirs. Additionally, the insignificant predictive models identified provide further evidence that the TP alone cannot fully elucidate the complex processes underlying Chla concentrations and the occurrence of algal blooms in these reservoirs. While phosphorus is known to regulate primary biological production in oligotrophic lakes and is considered the primary limiting nutrient in freshwater ecosystems, several studies have demonstrated co-limitation by multiple factors, which is often the rule (Qin et al., 2020; Wiegand et al., 2020; Mamun et al., 2021).

Regarding the influence of Chla concentrations (Figure 6B), the suggested thresholds for Chla concentration identified 100 reservoirs as hypereutrophic. Among these reservoirs, 67% exhibited unsatisfactory adjustments between TP and Chla. Similarly, for the eutrophic and supereutrophic classes, the percentages were 64 and 63%, respectively. Notably, the average values of R^2 decreased with the intensification of the trophic state. This analysis is further supported by significant differences identified in the Kruskal-Wallis test (H(3) = 8.28; p = 0.04).

In oligotrophic aquatic environments, it is common to observe the occurrence of undesired blooms of certain phytoplankton species. These species have the ability to regulate their metabolism to adapt to low levels of dissolved inorganic phosphorus. Simultaneously, the decomposition of phytoplankton contributes to an increase in total organic carbon, leading to nitrogen denitrification. This process results in a faster rise in TP compared to nitrogen levels. Consequently, TP becomes the dominant predictor, indicating a higher predictive capacity in reservoirs with lower concentrations of Chla (Chen et al., 2018; Liang et al., 2020).

Conclusion

This work evaluated the correlations between TP and Chla in 155 reservoirs located in Ceará, identifying the ability of TP to predict chlorophyll a, and the factors that influence the dynamics of correlations. The concentrations of TP and Chla exhibited spatial and temporal variability, with variations observed between different basins and observation periods. Regarding the variability of Chla and TP in relation to reservoir volume, it was found that the average concentrations of Chla increased in all basins during the dry period. Similarly, approximately 58.3% of the basins exhibited a similar trend of increased phosphorus concentrations during the dry period.

The correlation models between TP and Chla observed for each basin, while not highly significant, aligned with the patterns described in classical literature models. This suggests that, in most basins, the availability of TP in the water column contributes to an increase in Chla concentration. Additionally, when assessing these correlations within the context of each reservoir, it was found that most reservoirs (n = 115) was unsatisfactory with an average R^2 of 0.133. Although these correlations were lower than the values reported in the literature for tropical reservoirs, they were still higher than those obtained when considering the data sets on a basin level. This underscores the importance of accounting for the intrinsic characteristics of each individual reservoir when evaluating TP-Chla correlations.

Regarding the factors that can influence the pattern and dispersion of chlorophyll and TP correlations, the study found significant differences based on the type of watershed, volumetric variability, and trophicity of the reservoir in relation to Chla. However, the influence of reservoir size and phosphorus concentration was not found to be significant in the observed reservoirs. Thus, the current analysis suggests that, considering the highly variable and often statistically unsatisfactory TP-Chla correlation models obtained in this study, there is a need to incorporate additional variables (nitrogen, transparency, turbidity, volume, precipitation, temperature, etc.) in the development of a more robust Chla prediction model in tropical reservoirs.

Contribution of authors:

GUIMARÃES, B. M. D. M.: Conceptualization; Formal analysis; Investigation; Methodology, Writing – original draft. LIMA NETO, I. E.: Conceptualization; Formal analysis; Writing – review & editing; Supervision; Project administration.

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Appendix

Appendix 1 – Description of monitored reservoirs and quantity of samples per watershed.

Watershed	Reservoirs	Capac. (hm^3)	n
Acaraú	Acaraú Mirim, Araras, Arrebita, Ayres de Sousa, Bonito, Carão, Carmina, Diamantino II, Edson Queiroz, Farias de Sousa, Forquilha, Jatobá II, Jenipapo, São Vicente, Sobral, Taquara.	1,737.46	465
Alto Jaguaribe	Arneiroz II, Benguê, Broco, Caldeirões, Canoas, Do Coronel, Facundo, Faé, Favelas, Forquilha II, João Luís, Mamoeiro, Monte Belo, Muquém, Orós, Parambu, Pau Preto, Poço da Pedra, Quincoé, Rivaldo de Carvalho, Trici, Trussu, Valério, Várzea do Boi.	2,768.58	639
Baixo Jaguaribe	Santo Antônio de Russas	24	27
Banabuiú	Banabuiú, Capitão Mor, Cedro, Cipoada, Curral Velho, Fogareiro, Jatobá, Mons. Tabosa, Patu, Pedras Brancas, Pirabibu, Poço do Barro, Quixeramobim, São José I, São José II, Serafim Dias, Trapiá II, Umari, Vieirão.	2,755.32	531
Coreaú	Angicos, Diamante, Gangorra, Itaúna, Martinópole, Premuoca, Trapiá III, Tucunduba, Várzea da Volta.	283.64	288
Curu	Caxitoré, Desterro, Escuridão, Frios, General Sampaio, Itapajé, Jerimum, Pentencoste, São Domingos, Salão, São Mateus, Sousa, Tejuçuoca	1,056.17	368
Médio Jaguaribe	Adauto Bezerra, Canafístula, Castanhão, Ema , Figueiredo, Jenipapeiro, Joaquim Távora, Madeiro, Nova Floresta, Potiretama, Riacho da Serra, Riacho do Sangue, Santa Maria, Santo Antônio, Tigre.	7,373.99	379
Metropolitana	Acarape do Meio, Amanary, Aracoiaba, Batente, Castro, Catucinzenta, Cauhipe, Cocó, Gavião, Germinal, Itapebussu, Macacos, Malcozinhado, Maranguapinho, Pacajus, Pacoti, Penedo, Pesqueiro, Pompeu Sobrinho, Riachão, Sítios Novos, Tijuquinha.	1,383.75	732
Salgado	Atalho, Cachoeira, Gomes, Jenipapeiro II, Junco, Lima Campos, Manoel Balbino, Olho d'Água, Prazeres, Quixabinha, Rosário, São Domingos II, Tatajuba, Thomás Osterne, Ubaldinho.	452.312	207
Serra da Ibiapaba	Jaburu I	140.33	43
Sertão de Crateús	Flor do Campo, Jaburu II, Realejo, São José III e Sucesso.	436.04	281
Total		18,599.122	4596

Appendix 2 – Statistical performance of the studied reservoirs

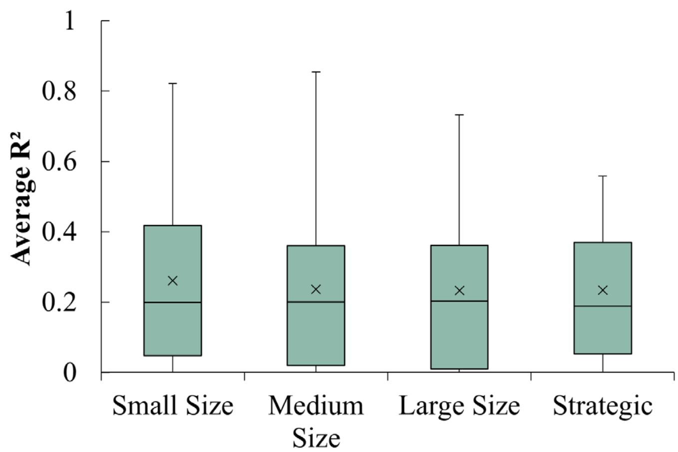
Performance criteria	*n*-reservoirs	Mean ± SD	Range
Unsatisfactory ($R^2 \leq 0,4$)	115	0.133 ± 0.126	2.49E-05–0.399
Satisfactory ($0,4 < R^2 \leq 0,65$)	31	0.504 ± 0.069	0.627–0.404
Good ($0,65 < R^2 \leq 0,8$)	6	0.744 ± 0.041	0.795–0.691
Very Good ($R^2 > 0,8$)	3	0.831 ± 0.020	0.85–0.818

Appendix 3 – Statistical analysis of correlations by watershed.

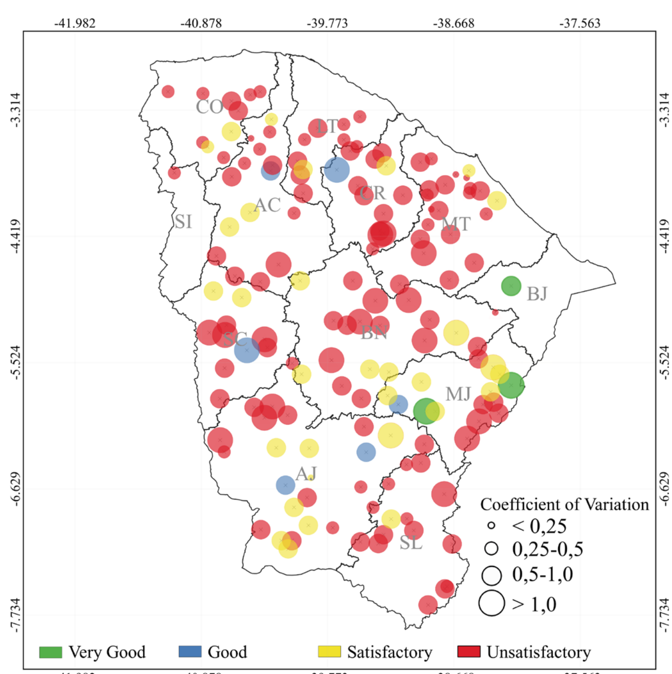
Watershed	*n*-reservoirs	Mean ± SD	Range
Acaraú	16	0.195 ± 0.064	0.000–0.796
Alto Jaguaribe	24	0.342 ± 0.044	0.009–0.770
Baixo Jaguaribe	1	0.855	0.855–0.855
Banabuiú	19	0.279 ± 0.042	0.001–0.617
Coreaú	9	0.129 ± 0.072	0.001–0.552
Curu	13	0.228 ± 0.058	0.009–0.698
Litoral	10	0.121 ± 0.055	0.000–0.515
Médio Jaguaribe	15	0.463 ± 0.060	0.017–0.822
Metropolitana	22	0.159 ± 0.031	0.000–0.479
Salgado	15	0.109 ± 0.035	0.000–0.419
Serra da Ibiapaba	1	0.002	0.002–0.002
Sertões de Crateús	10	0.303 ± 0.079	0.001–0.692

Appendix 4 – Statistics of the correlations between TP and Chla according to the trophic state.

Trophic state	Chlorophyll a (µg.L^-1^)			Total Phosphorus (mg.L^-1^)		
	n	Mean ± SD	Range	*n*	Mean ± SD	Range
Ultra-oligotrophic	0	-	-	0	-	-
Oligotrophic	1	0.002 ±	0.002	0	-	-
Mesotrophic	21	0.351 ± 0.325	0.0001–0.468	5	0.104 ± 0.151	0.002–0.361
Eutrophic	19	0.257 ± 0.286	0.0001–0.438	21	0.178 ± 0.251	2.5e-05–0.762
Super eutrophic	14	0.234 ± 0.200	0.008–0.762	15	0.346 ± 0.282	0.002–0.795
Hyper-eutrophic	100	0.223 ± 0.189	2.5e-05-0.854	107	0.249 ± 0.282	8.3e-05-0.854



Appendix 5 – Variation of average correlations according to reservoir size.



Appendix 6 – Distribution of mean correlations between TP and Chla according to the coefficient of variation.