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Multimodel TSI Evaluation to Characterize Eutrophication in a Tropical Semi-Arid Reservoir: a case study of the Araras Reservoir

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The authors declare that there are no conflicts of interest

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Abstract

Objective: To evaluate different models for characterizing eutrophication in a reservoir located in the semi-arid region of Araras.

Methodology: The assessment of the Trophic Status Index and the risk of eutrophication was carried out using five Trophic Status Index models. The calculation of eutrophication risk using the Probability Density Function was applied to the TSI multi-model assessment to generate the representative value of the Trophic State.

Originality/Relevance: The development of the research and the data processing corroborate the need for monitoring reservoirs, combined with integrated water management as a way to allow multiple uses and clarify the influence of hydrological and water quality parameters of water on the Trophic Status Index.

Results: The results indicated that, in the period from 2009 to 2022, the Reservoir Volume variable influenced water quality, specifically in its levels of nitrogen, total phosphorus, and chlorophyll, indicating an increased risk of eutrophication as the reservoir emptied. All models used showed discrepancies in the classification of the Trophic State; however, the multi-model assessment associated with the calculation of eutrophication risk proved to be a consistent tool for evaluating the eutrophication of the Araras reservoir.

Social/Management Contribuitions: The monitoring of reservoirs and the multi-model assessment provide reliable and consistent information for the adequate management of water quality in reservoirs in the tropical semi-arid region of Brazil.

Keywords: trophic state, limiting nutrient, risk, semi-arid

Avaliação multimodelo IET para a caracterização da eutrofização em um reservatório do semiárido tropical: estudo de caso do Reservatório Araras

Resumo

Objetivo: Avaliar diferentes modelos para a caracterização da eutrofização em um reservatório localizado na região semiárida de Araras.

Metodologia: A avaliação do estado e do risco de eutrofização foi realizada mediante a utilização de cinco modelos de Índice de Estado Trófico. O cálculo de risco de eutrofização pela Função Densidade de Probabilidade foi aplicado à avaliação multimodelo IET para gerar o valor representativo do Estado Trófico.

Originalidade/Relevância: O desenvolvimento da pesquisa e o tratamento de dados corroboram a necessidade de monitorar os reservatórios, aliada à gestão integrada das águas como forma de permitir os usos múltiplos e esclarecer a influência dos parâmetros hidrológicos e de qualidade de água no Índice de Estado Trófico.

Resultados: Os resultados apontaram que, no período de 2009 a 2022, a variável Volume do Reservatório influenciou a qualidade de água, especificamente em seus níveis de nitrogênio total, fósforo total e clorofila, indicando o aumento do risco de eutrofização conforme o esvaziamento do reservatório. Todos os modelos utilizados mostraram divergências quanto à classificação do Estado Trófico, todavia, a avaliação multimodelo associada ao cálculo de risco de eutrofização demonstrou-se uma ferramenta consistente para a avaliação da eutrofização do reservatório Araras.

Contribuições sociais para a gestão: O monitoramento dos reservatórios e a avaliação multimodelo fornecem informações confiáveis e consistentes para o adequado gerenciamento da qualidade da água de reservatórios do semiárido tropical brasileiro.

Palavras-chaves: estado trófico, nutriente limitante, risco, semiárido

Evaluación multimodelo IET para la caracterización de la eutrofización en un embalse tropical semiárido: estudio de caso del Embalse de Araras

Resumen

Objetivo: Evaluar diferentes modelos para la caracterización de la eutrofización en un embalse ubicado en la región semiárida de Araras.

Metodología: La evaluación del estado y del riesgo de eutrofización se realizó mediante cinco modelos de Índice de Estado Trófico. El cálculo del riesgo de eutrofización a través de la

Función de Densidad de Probabilidad se aplicó a la evaluación multimodelo del IET para generar el valor representativo del Estado Trófico.

Originalidad/Relevancia: El desarrollo de la investigación y el tratamiento de datos corroboran la necesidad de monitorear los embalses, combinada con la gestión integrada del agua como una forma de permitir usos múltiples y aclarar la influencia de los parámetros hidrológicos y de calidad del agua en el Índice de Estado Trófico.

Resultados: Los resultados indicaron que, en el periodo 2009 al 2022, la variable Volumen del Embalse influyó en la calidad del agua, específicamente en sus niveles de nitrógeno total, fósforo total y clorofila, lo que indica un aumento del riesgo de eutrofización a medida que el embalse se vaciaba. Todos los modelos utilizados mostraron divergencias en cuanto a la clasificación del Estado Trófico; sin embargo, la evaluación multimodelo asociada con el cálculo del riesgo de eutrofización demostró ser una herramienta consistente para la evaluación de la eutrofización del embalse de Araras.

Contribuciones sociales/ de gestión: El monitoreo de los embalses y la evaluación multimodelo proporcionan información confiable y consistente para la gestión adecuada de la calidad del agua en embalses de la región semiárida tropical brasileña.

Palabras clave: estado trófico, limitar los nutrientes, riesgo, semiárido

Introduction

Eutrophication refers to the enrichment of surface waters with plant nutrients, usually associated with anthropogenic nutrient sources. The trophic state of lakes and reservoirs is the central concept of their management, describing the relationship between the nutritional status and the increase in organic matter in lakes and reservoirs (Misha, 2023).

Eutrophication is a recurring global issue in lakes and reservoirs, being intensified in environments characterized by significant spatial-temporal climate variability, such as the semi-arid region of Brazil. These surface reservoirs serve as the primary water source for most of the year and are more susceptible to eutrophication processes due to substantial water level variations, extended periods of low recharge, and high evaporation rates (Guimarães, 2023).

Some of the many negative effects of eutrophication include degraded water quality for human consumption, depletion of dissolved oxygen, limited recreational use, and promoting proliferation of cyanobacteria that can potentially produce toxins which are harmful to human health. This excessive proliferation increases water treatment costs and consequently puts its various uses at risk (Geletu, 2023). Eutrophication can have drastic environmental impacts, hindering the multipurpose use of aquatic systems, directly altering the biotic component of water resources, significantly increasing the biomass of algae, cyanobacterial blooms, and aquatic macrophytes, and affecting the socioeconomic component. Indirect results of this process include changes in aquatic community structure, reductions in dissolved oxygen concentrations, odor problems, increased turbidity, the formation of hydrogen sulfide, fish death, etc. (Júlio-Júnior, 2005; Sardinha et al., 2018).

The Trophic State Index (TSI) aims to classify water bodies into different trophic levels, evaluating water quality in terms of nutrient enrichment and its effect on excessive algae and cyanobacteria growth (CETESB, 2017). However, the most frequently used TDIs were not specifically developed for tropical waters, and caution is warranted when interpreting data from systems located in the semi-arid region of northeastern Brazil (Rolim et al., 2019).

Better understanding of the trophic classification of reservoirs based on comparative studies and temporal trends can facilitate developing metrics which are easy to calculate and communicate, thereby strengthening eutrophication prediction and management (Klippel, 2020). There is considerable debate among researchers about which index should be used for tropical aquatic systems, in turn leading to the use of multiple indices and consequently resulting in differing classifications for the same aquatic ecosystem (Pomari et al., 2018).

The use of the TSI to characterize the trophic conditions of semi-arid reservoirs has revealed considerable limitations, mainly because the semi-arid climate determines the conditions which control the dynamics of the eutrophication phenomenon, notably due to droughts and dry spells, which are recurrent in this region. The application of a multimodel TSI approach, associated with the probabilistic calculation of eutrophication risk using the Probability Density Function (PDF) concept, is a consistent methodology for characterizing the eutrophication of reservoirs in the Brazilian semi-arid region.

The use of trophic indices enables prioritizing decision-making regarding water resource management, public environmental policies, and the availability of information about water quality and eutrophication to the public. It is easy to apply due to the practicality of the analytical determinations that comprise it, and so it a useful tool for making eutrophication studies more objective, synthesizing information on the physical, chemical, and biological parameters, and facilitating communication with various water user groups in cases of conflict and crisis (Bem et al., 2009; ANA 2017).

In this sense, it is justified to employ the multimodel TSI evaluation to characterize eutrophication in a tropical semi-arid reservoir with the aim of addressing the deficiencies which may affect the applicability of the TSI in reservoirs of the tropical semi-arid region due to the different structures and conditions of models developed for other regions.

The main models for determining the trophic state index used in Brazilian regions are the Carlson model (1977); the Kratzer & Brezonik model (1981); the Toledo Júnior et al. model (1983); the Lamparelli model (2004); and the Cunha et al. model (2013). The trophic state index model developed by Carlson (1977) for temperate environments takes into account the calculation of total phosphorus, chlorophyll-a, and water transparency measured by the Secchi disk. The average of these three parameters constitutes the mean TSI, enabling classification of the reservoir's trophic degree. The TSI based on total nitrogen developed by Kratzer & Brezonik (1981), considers a critical concentration of chlorophyll-a of 10 µg/L as the concentration marking the onset of trophic conditions in water bodies. For this, they used the relationship between total nitrogen and chlorophyll-a.

The model proposed by Toledo Júnior et al. (1983) involved a mathematical modification of Carlson's (1977) model to adapt it to subtropical environments, applying linear regression analysis to the values of total phosphorus concentrations, chlorophyll-a, and Secchi disk transparency in a study conducted at the Barra Bonita-SP reservoir (Moura Filho; Araújo, 2020). On the other hand, considering the TSI of Toledo Júnior et al. (1983), Lamparelli (2004) then made modifications to obtain a TSI based on total phosphorus and chlorophyll-a determinations. Cunha (2012) proposed an index for assessing the trophic state in subtropical reservoirs, using bimonthly data from São Paulo reservoirs from 1996 to 2009. Cunha, Calijuri, and Lamparelli (2013) added the hypereutrophic class to Cunha's (2012) trophic levels, thus expanding the classification range for trophic state (Araújo et al., 2018).

The Araras reservoir, the fourth largest in the state of Ceará and of great strategic importance for the northern region, was selected for this case study and will be characterized in terms of trophic state based on a comparative analysis with the trophic classification of the Companhia de Gestão dos Recursos Hídricos (COGERH), considering data from the last 13 years of monitoring campaigns.

Methodology

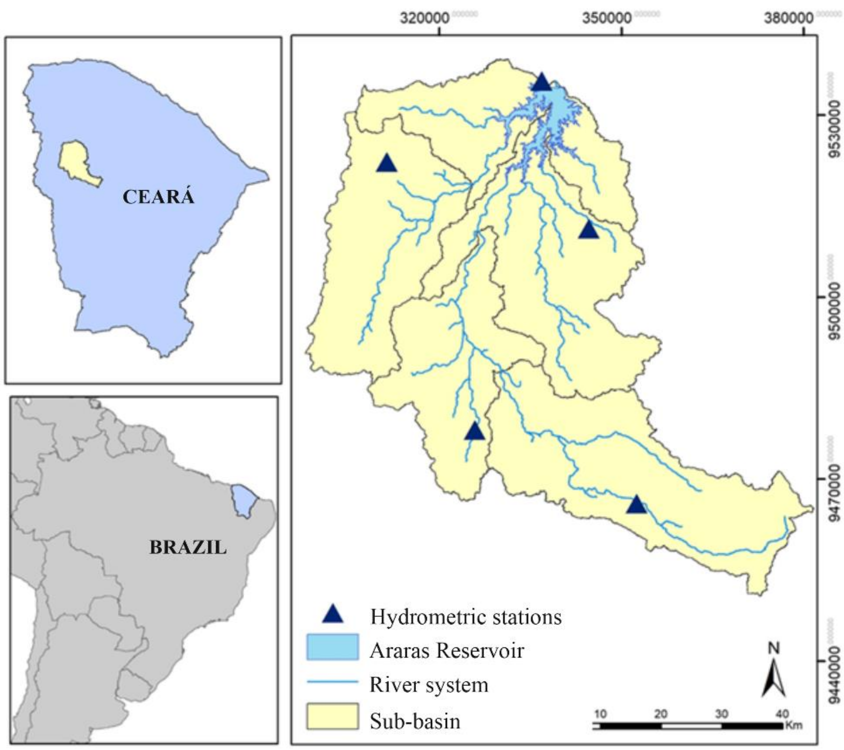
Study area

The Araras Reservoir, located in the Acaraú River sub-basin, was selected to apply the methodology developed in this study due to its numerous relevant aspects (Figure 1). It is the fourth largest federal public reservoir in the State of Ceará and is of significant strategic importance for human water supply, agriculture, irrigation, and industries in the northern part of the state, contributing to the socioeconomic development of this region. The Araras Reservoir aims to ensure the perennial flow and control the flooding of the Acaraú River, irrigate 14,000 hectares of the river's floodplains, and support fish farming and crop utilization in the upstream area (Meireles et al., 2017).

This reservoir is under continuous monitoring by COGERH through its Water Quality Monitoring Network Program, which conducts quarterly sampling campaigns. These campaigns collect and analyze various water quality parameters: Total Phosphorus, Total Nitrogen, Chlorophyll (Chl-a), and Depth (Secchi Disk). Quantitative aspects of the reservoir, such as inflow rate, water level, evaporation, outflow rate, and percentage volume, are also continuously monitored. The physical-chemical data were provided by COGERH, and samples were collected at coordinates UTM, zone 24M, 9533796 mN, and 339926 mE. Sampling is performed at a depth of 0.3 meters, with physical-chemical determinations occurring *in situ* using portable devices or samples being sent to responsible laboratories (Guimarães, 2023).

Figure 01

Araras reservoir location



Trophic State Index (TSI) determination

This study employed five different TSI models to determine the trophic state of the Araras Reservoir, covering the temporal sequence of water quality monitoring data from quarterly sampling campaigns conducted from August 2009 to January 2022. These models were selected based on a review of literature related to the diagnosis and indication of the trophic state of reservoirs in the Brazilian semi-arid region, constituting a multi-model TSI evaluation of the water body's eutrophication degree. The models used include Carlson (1977); Kratzer & Brezonik (1981); Toledo Júnior et al. (1984); Lamparelli (2004); and Cunha et al. (2013).

Determination of limiting nutrient

Three different models were applied to determine the factor responsible for primary production in the Araras Reservoir. The limiting nutrient models used were those of Kratzer & Brezonik (1981); Carlson (1991); and the TN/TP ratio of Redfield (1958).

Multi-Model eutrophication assessment

The combined approach of multi-model TSI assessment and the probabilistic method for calculating eutrophication risk using the PDF concept was developed and applied to characterize eutrophication in a semi-arid tropical reservoir. The Araras Reservoir, located in the Acaraú sub-basin, Ceará, Brazil, was used as a case study. The data base of Total Phosphorus (TP), Total Nitrogen (TN), Chlorophyll-a (Chl-a), and Secchi Disk (SD) measurements, organized and provided by the Companhia de Gestão de Recursos Hídricos (COGERH), was utilized. Samples with simultaneous data of TP, TN, Chl-a, and SD from the quarterly sampling campaigns between August 2009 and January 2022 were selected.

The limiting nutrient for the Araras Reservoir was determined using the three main models from the literature: Kratzer & Brezonik (1981); Carlson (1991); and Redfield (1958). Five different TSI models (Carlson, 1977; Kratzer & Brezonik, 1981; Toledo Júnior et al., 1983; Lamparelli, 2004; Cunha et al., 2013) were used to classify the trophic state of the reservoir. Using the resulting data set from this evaluation, the probabilistic method for risk calculation with PDF was applied to determine the eutrophication risk of the reservoir. Descriptive statistics were used to process limnological and hydroclimatic variables, and correlations between TP, TN, Chl-a, and SD were analyzed along with the coefficient of determination. Additionally, correlations between percentage volume and daily average precipitation with the TSIs calculated in the multi-model methodology were examined.

Uncertainties and eutrophication risk

Although the multi-model TSI assessment can provide a range of actions for managing eutrophication of water bodies (Klippel, 2020), potential discrepancies between final results may lead to inaction by decision-makers. In this regard, the set of TSI model outputs can be used to calculate the risk of eutrophication using the PDF concept. The risk value is more convenient for decision-making, considering the structural uncertainty of TSI models (Chang et al., 2015; Alves et al., 2020; Carneiro et al., 2022).

In this study, it is assumed that failure (eutrophication of the reservoir) occurs when the trophic state exceeds the system's capacity, defined as the threshold for eutrophic state, above which the reservoir is considered eutrophic. Therefore, eutrophication risk is defined as the probability of exceeding the eutrophic level (TSI_eutrophic) (Alves et al., 2020). It is expressed as follows:

$$Eutrophication\ Risk = P\,[TSI > TSI_{eutrophic}]$$

The reference TSI ($TSI_{eutrophic}$) for eutrophication characterization is TSI = 54. Using the set of TSI values generated from the multi-model TSI assessment, the eutrophication risk of the reservoir was determined using PDF with the following equation:

$$P = \frac{x}{N}$$

In which:

- P is the probability associated with the order number of the TSI;

- x is the number of models with TSI values greater than 54;

- N is the total number of TSI models.

It is important to note that when the multi-model TSI assessment consists of a single model, which occurs when the limiting nutrient evaluation points to TN, the result is limited to a probability of either 0 or 100% for eutrophication risk, depending on whether the reference eutrophication value (TSI = 54) is exceeded.

Results and Discussion

Evaluation of limnological variables, percent volume, and daily precipitation

The limnological and hydroclimatic characteristics of the Araras reservoir were assessed through descriptive statistical analysis (mean, minimum, maximum, standard deviation) of historical monitoring data for water quality parameters (TN, TP, Chl-a, and SD) from 2009 to 2022. Table 1 presents a summary of the statistical results for these variables.

It was observed that the average percent volume of the Araras reservoir over the evaluated period was 41.62%; this finding was also noted by Araújo and Bronstert (2016) and Wiegand et al. (2021), who reported that volumetric levels below 50% were recorded for most watersheds during the study period due to the prolonged drought experienced in Ceará.

Table 1

Hydroclimatic and limnological characteristics

	TN (mg/L)	TP (mg/L)	Chl-*a* (µg/L)	Depth. (m)	Volume (%)	Precipitation (mm)
Minimum	0,152	0,023	3,75	0,20	3,40	0,00
Maximun	5,412	0,358	219,62	3,10	100	44,0
Average	1,744	0,103	61,015	1,03	41,62	3,03
Deviation	1,387	0,075	68,235	0,750	33,07	7,89
N	33	33	33	33	33	33

Fonte: Elaboração própria.

The results indicated that when the reservoir had lower percent volumes, the TN, TP, Chl-a, and SD limnological variables exhibited the poorest results. The Chl-a and TP were 42% and 91%, respectively, being out of compliance with the limits established by CONAMA Resolution No. 357/2005, which recommends P < 0.03 mg/L and Chl-a < 30 µg/L for lentic water bodies of class II (Brasil, 2005).

Empirical correlations of water quality parameters in the Araras Reservoir

Figure 2 displays the empirical correlations among the TN, TP, Chl-a, and depth (SD) parameters The correlation values between the parameters are centered in the circle, considering the monitoring period from 2009 to 2022.

Figure 2

Pearson Correlation

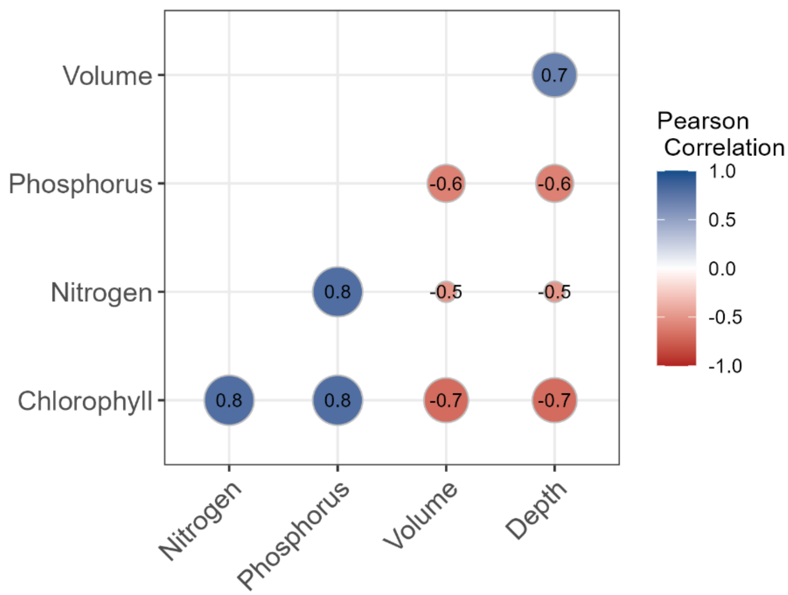


Figure 2 shows that TN and TP have a direct positive correlation, indicating an increasing trend in TN concentration with an increase in TP concentration. Similarly, there is a direct association between TN and Chl-a, as the concentration of the latter tends to increase with higher TN levels. TN concentration shows a negative correlation with SD, meaning that as TN levels increase, SD values decrease, indicating worsening transparency as TN concentration rises. The increase in TP concentration is associated with a rise in Chl-a concentration. The correlation between TP and SD also shows a similar negative trend, as higher TP concentrations lead to decreased SD values, implying reduced water transparency. The results regarding Chl-a and its relationship with TN and TP are consistent with those of Rocha et al. (2019), who analyzed the relationships between TP and TN concentrations and phytoplankton in Ceará reservoirs and found that Chl-a values followed the same variation trend as TP concentrations, though TN did not significantly affect phytoplankton dynamics in the reservoir.

Associating Chl-a concentration with SD values reveals a strong inverse linear correlation, indicating that higher Chl-a concentrations lead to reduced transparency, confirmed by the high correlation coefficient.

Statistical performance criteria for TN correlations classify them into four groups: Very Good ($R^2 > 0.7$), Good ($0.6 < R^2 \leq 0.7$), Satisfactory ($0.3 < R^2 \leq 0.6$), and Unsatisfactory ($R^2 \leq 0.3$). These criteria also apply to TP correlations, classified as Very Good ($R^2 > 0.8$), Good ($0.65 < R^2 \leq 0.8$), Satisfactory ($0.4 < R^2 \leq 0.65$), and Unsatisfactory ($R^2 \leq 0.4$) (MORIASI et al., 2015). Generally, all water quality variables show significant causal relationships among themselves, as demonstrated by the mathematical behavior in the figures, relatively high R^2 values, and strong correlations. These findings also align with Bilgin (2020), who used correlation analysis to examine relationships among TN, TP, DS, and Chl-a, finding a strong positive correlation between TP and SD, while TN showed a comparatively lower correlation with SD.

These findings indicate strong relationships among the variables, consistent with those found by Freire and Sousa Filho (2022), who identified a close relationship between chlorophyll-a, nitrogen, phosphorus, and Secchi disk, especially between chlorophyll-a concentrations and other variables.

Empirical correlations between percent volume and quality parameters

Figure 3 illustrates the temporal evolution of the reservoir's percent storage volume in relation to the concentrations of water quality parameters (TN, TP, Chl-a) in the Araras reservoir.

Figure 3

Temporal evolution of the volume of the reservoir associated with the parameters total nitrogen (a), chlorophyll (b) and total phosphorus (c)

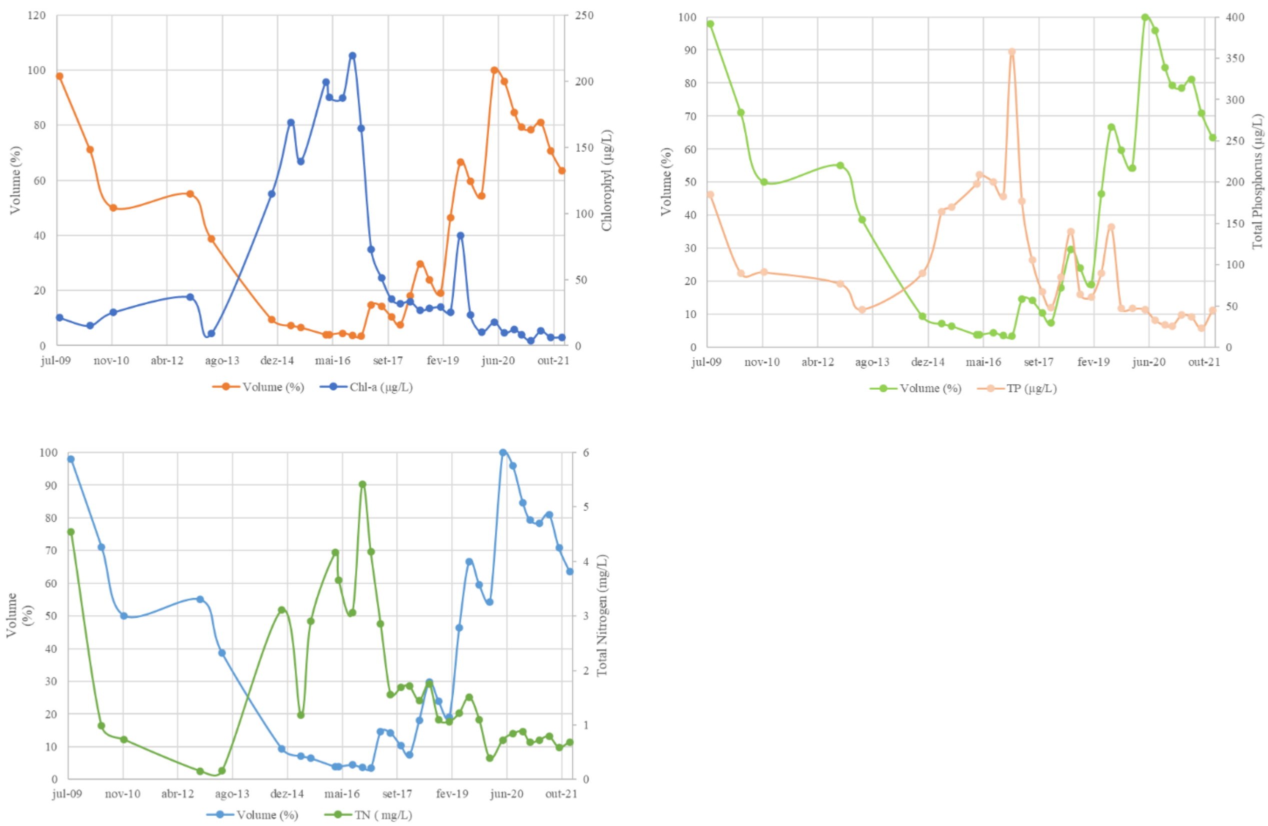


Figure 3 shows an inverse relationship between TN and the reservoir's percent volume. Although there is variability, it is observed that as volume decreases, TN concentration increases, with the lowest percent volumes corresponding to the highest TN concentrations, and vice versa. A similar pattern is seen with total phosphorus (TP), where lower volumes correspond to higher TP concentrations. Notably, the lowest volume percent periods corresponded to the highest TP concentrations, and higher volume percentages generally led to lower TP concentrations, particularly towards the end of the study period. Similarly, an inverse relationship is inferred between Chl-a and percent volume, where decreased volume corresponds to increased Chl-a concentrations, with periods of lower volume corresponding to higher Chl-a levels. This is consistent with Magalhães (2023), who found that seasonal dynamics significantly influenced water quality in Ceará reservoirs, with Chl-a concentrations rising as storage volume decreased, along with increased TN and TP concentrations during drought periods.

These results are similar to those of Markad et al. (2019), who found that as water levels in reservoirs declined, parameters like Chl-a, TP, and SD worsened, with the worst results observed in summer, attributing water quality improvement to dilution effects from increased volume. This study identifies a similar vulnerability as noted by Wiegand et al. (2020, 2021), who reported that prolonged drought in Ceará led to increased nutrient concentrations due to drastically reduced water volumes. TP concentrations may also rise due to internal sediment load and low inflows during drought periods, while TN concentrations could result from activities such as planting and animal watering within the reservoir's watershed (Braga et al., 2019; Rocha; Lima Neto, 2021).

Empirical correlations between percent volume and TSIs calculated

Figure 4 shows the temporal evolution of the reservoir's percent storage volume associated with TSI values from the multimodel assessment based on monitoring data from 2009 to 2022.

Figure 4

Temporal evolution of the volume associated with TSIs

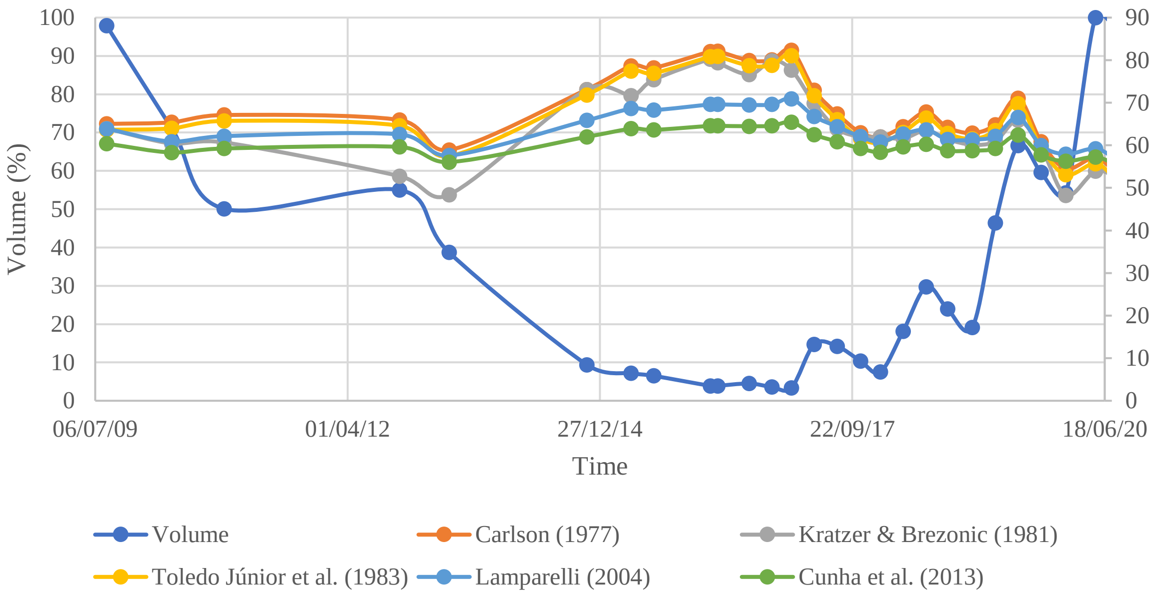


Figure 4 reveals an inverse relationship between TSI values and the reservoir's percent volume. As stored water volume decreases, the trophic conditions of the reservoir intensify, despite divergences among the TSI values. The divergence among models corroborates findings by Araújo et al. (2018), who observed that TSI classes could differ significantly even for the same monitoring point and campaign, varying between oligotrophic and hypereutrophic classifications. The five TSI models show a trophic trend influenced by volume fluctuations over the study period. All models indicate worst values when the percent volume is very low (below 10%) and better values when the percent volume is higher, at the beginning and end of the period studied.

It is noted that the models by Lamparelli (2004) and Cunha et al. (2013) suggest more conservative TSI values, with the former showing higher values than the latter. They follow similar trends over time, reflecting a strong relationship between the results. The TSI calculated using Lamparelli's model (2004) was notably different, being less conservative and showing greater discrepancies from other models. This trend was also observed by Cunha et al. (2021), who compared Lamparelli's model with Carlson's (1977) model, finding the latter more conservative. The model by Cunha et al. (2013) was the most conservative, showing the worst results during the driest periods when the reservoir had the lowest percent volumes. This finding is consistent with Beghelli et al. (2016), who used Cunha et al.'s (2013) classification and observed a eutrophication process during the dry periods.

This study found that percent storage volume impacts water quality, aligning with Santos et al. (2017), who used the TSI from Cunha et al. (2013) for the Castanhão reservoir and demonstrated that prolonged drought intensified eutrophication. They also noted that stratification in the water column occurred during higher volumes, but was disrupted as volumes decreased, altering nutrient dynamics. On the other hand, models by Carlson (1977), Toledo Júnior et al. (1983), and Kratzer & Brezonic (1981) indicated higher TSI values for the Araras reservoir. These models generally showed similar trends, indicating strong convergence in how percent volume affects trophic state during drought periods. Batista et al. (2014) also found that the TSI from Toledo Júnior et al. (1983) indicated more intense eutrophication during droughts, consistent with Chaves et al. (2013), who linked trophic state to seasonal hydrological fluctuations in semi-arid regions.

Determination of limiting nutrient using multimodel technique

Table 2 presents the percentage results of determining the limiting nutrient or factor of eutrophication using the respective models for the Araras reservoir from 2009 to 2022. The Carlson (1991) model predominantly identifies nitrogen as the main limiting factor of eutrophication in the Araras reservoir (about 51%), with phosphorus being the limiting nutrient in 39% of the evaluated period. The remaining 10% suggests other factors, such as abiotic turbidity, might limit eutrophication.

Freire and Souza Filho (2022) noted that reduced reservoir volumes facilitate increased phosphorus and nitrogen concentrations, which can elevate chlorophyll-a levels and reduce the euphotic zone, accelerating eutrophication processes. Similarly, Redfield (1958) identified phosphorus as a limiting factor in most lentic systems. However, models that identify nitrogen as limiting, such as Carlson (1991), align with observations by Rocha and Lima Neto (2021), who found higher nitrogen levels influencing the reservoir's primary productivity and eutrophication processes.

Table 2

Limiting nutrient in the Araras reservoir

Model	Nitrogen	Phosphorus	Other factor
Kratzer & Brezonic (1981)	91%	09%	
Carlson (1991)	51%	39%	10%
Redfield (1958)	09%	91%	

The Redfield (1958) model suggests that the predominant cause of the eutrophication condition of the reservoir under investigation is Phosphorus (91%). In 9% of the period evaluated, this model indicated that Nitrogen would be the limiting nutrient for phytoplankton production. The Kratzer & Brezonic (1981) model, in turn, suggests that the eutrophication of the reservoir is limited in 91% of the period evaluated by the nutrient Nitrogen. In 9% of the period, Phosphorus is the limiting nutrient for primary production in the reservoir.

According to the Redfield (1958) model, TP was mainly identified as the limiting nutrient, which agrees with several similar studies. The research by Paulino, Oliveira, and Avelino (2013), studying 2008 to 2011 several reservoirs monitored by COGERH, found that TP was the limiting nutrient in 65% of the results. Wiegand et al. (2020), when evaluating the limiting nutrient for algal production in reservoirs in the Brazilian semiarid region from 2008 to 2017, identified TP as responsible for primary production in 69% of the results. The work of Rocha Júnior et al. (2018) points to TP as a limiting factor for the production of phytoplankton biomass in reservoirs in regions of the tropical semiarid region in Rio Grande do Norte. Rolim et al. (2019), when determining the limiting nutrient for 18 reservoirs in the semiarid region of Ceará, found, using the Redfield ratio, that the limiting nutrient was Phosphorus in 16 reservoirs and Nitrogen in two. This divergence between the three models regarding the limiting nutrient is in line with what is developed by Liang et al. (2020) when evaluating the trophic conditions of 1382 lakes, state that TP and TN control the trophic state of the lakes, indicating that these nutrients limit algal biomass.

Among the three models, there is considerable divergence of results regarding the indication of which nutrient or limiting factor is conditioning the primary production of the Araras reservoir. The limiting nutrient coincides, in 15% of the results found, with three campaigns, two for Phosphorus and one for Nitrogen. In this sense, Maberly et al. (2020) report that P potentially limits lakes where the Chl-a to TP ratio is higher because the conversion of TP to Chl-a is efficient, thus finding that, of the 17 lakes evaluated in their studies, five were limited by P, 1 was limited by N, 10 presented co-limitation and any nutrient did not limit 1. Regarding this divergence of the limiting nutrient, Tundisi and Tundisi (2008) state that the individuality of the reservoirs is very characteristic. Therefore, Nitrogen and Phosphorus may be the limiting nutrients in phytoplankton production.

Trophic classification via TSIs multimodel

Table 03 shows the TSI results for the Araras reservoir, calculated and classified using the TSI multimodel methodology. It also shows the trophic classification carried out by COGERH for the same period, considering the historical series of water quality monitoring from collection campaigns carried out from August 2009 to January 2022.

In the campaigns of October 2012 and May 2013, in which nitrogen was indicated as the limiting nutrient, only the Kratzer & Brezonic (1958) model was used. Among the models, this is the only one considering nitrogen in determining the limiting nutrient. Therefore, on these dates, the other models that use phosphorus in the calculations of the limiting nutrient were disregarded

(Table 03).

Table 03

Multimodel TSI in Araras reservoir

Period	Carlson (1977)	Kratzer & Brezonic (1981)	Toledo Júnior et al. (1983)	Lamparelli (2004)	Cunha et al. (2013)	COGERH
Aug, 2009	65 (‘HE’)	64 (‘HE’)	64 (‘E’)	64 (‘SE’)	60 (‘HE’)	(‘E’)
May, 2010	65 (‘HE’)	60 (‘HE’)	64 (‘E’)	61 (‘E’)	58 (‘SE)	(‘E’)
Nov, 2010	67 (‘HE’)	61 (‘HE’)	66 (‘E’)	62 (‘E’)	59 (‘HE’)	(‘E’)
Oct, 2012	-	53 (‘E’)	-	-	-	(‘O’)
May, 2013	-	48 (‘M’)	-	-	-	(‘E’)
Nov, 2014	73 (‘HE’)	73 (‘HE’)	72 (‘E’)	66 (‘S’)	62 (‘HE’)	(‘HE')
Apr, 2015	79 (‘HE’)	72 (‘HE’)	77 (‘HE’)	69(‘HE’)	64 (‘HE’)	(‘HE’)
Jul, 2015	78 (‘HE’)	75 (‘HE’)	77 (‘HE’)	68 (‘HE’)	64 (‘HE’)	(‘HE’)
Mar, 2016	82 (‘HE’)	80 (‘HE’)	81 (‘HE’)	70 (‘HE’)	65 (‘HE’)	(‘HE’)
Apr, 2016	82 (‘HE’)	79 (‘HE’)	81 (‘HE’)	70 (‘HE’)	65 (‘HE’)	(‘HE’)
Aug, 2016	80 (‘HE’)	77 (‘HE’)	79 (‘HE’)	69 (‘HE’)	64 (‘HE’)	(‘HE’)
Nov, 2016	80 (‘HE’)	80 (‘HE’)	79 (‘HE’)	70 (‘HE’)	65 (‘HE’)	(‘HE’)
Jan, 2017	82 (‘HE’)	78 (‘HE’)	81 (‘HE’)	71(‘HE’)	65 (‘HE’)	(‘HE’)
Apr, 2017	73 (‘HE’)	70 (‘HE’)	72 (‘E’)	67 (‘HE’)	63 (‘HE’)	(‘E’)
Jul, 2017	67 (‘HE’)	64 (‘HE’)	66 (‘E’)	64 (‘SE’)	61(‘HE’)	(‘E’)
Oct, 2017	63 (‘HE’)	62 (‘HE’)	62 (‘E’)	62 (E’)	59 (‘HE’)	(‘E’)
Jan, 2018	62 (‘HE’)	62 (‘HE’)	61(‘E’)	61(‘E’)	58 (‘SE’)	(‘E’)
Apr, 2018	64 (‘HE’)	62 (‘HE’)	63 (‘E’)	63 (‘S’)	60 (‘HE’)	(‘E’)
Jul, 2018	68 (‘HE’)	63 (‘HE’)	66 (‘E’)	64 (‘S’)	60 (‘HE’)	(‘E’)
Oct, 2018	64 (‘HE’)	61 (‘HE’)	63 (‘E’)	61 (‘E’)	59 (‘HE’)	(‘E’)
Jan, 2019	63 (‘HE’)	60 (‘HE’)	62 (‘E’)	61(‘E’)	59 (‘HE’)	(‘E’)
Apr, 2019	64 (‘HE’)	61 (‘HE’)	63 (‘E’)	62(‘E’)	59 (‘HE’)	(‘E’)
Jul, 2019	71 (‘HE’)	66 (‘HE’)	70 (‘E’)	67 (‘HE’)	62 (‘HE’)	(‘E’)
Oct, 2019	61 (‘HE’)	60 (‘HE’)	59 (‘E’)	60 (‘E’)	58 (‘E’)	(‘E’)
Jan, 2020	55 (‘E’)	48 (‘E’)	53 (‘M’)	58 (‘M’)	56 (‘E’)	(‘E’)
May, 2020	57 (‘E’)	54 (‘E’)	56 (‘E’)	59 (‘E’)	57 (‘E’)	(‘E’)
Aug, 2020	54 (‘E’)	53 (‘E’)	52 (‘M’)	57 (‘M’)	55 (‘M’)	(‘E’)
Nov, 2020	54 (‘E’)	54 (‘E’)	52 (‘M)	57 (‘M’)	56 (‘E’)	(‘E’)
Jan, 2021	50 (‘E’)	49 (‘M’)	49 (‘M’)	56 (‘M’)	55 (‘M’)	(‘M’)
Apr, 2021	48 (‘M’)	46 (‘M’)	47 (‘M’)	55 (‘M’)	54 (‘M’)	(‘E’)
Jul, 2021	53 (‘E’)	52 (‘E’)	52 (‘M’)	57 (‘M’)	56 (‘E’)	(‘E’)
Oct, 2021	49 (‘M’)	48 (‘M’)	48 (‘M’)	55(‘M’)	54 (‘M’)	(‘E’)
Jan, 2022	51 (‘E’)	48 (‘M’)	51 (‘M’)	57 (‘M’)	55 (‘M’)	(‘M’)

(‘O’): Oligotrophic; (‘M’): Mesotrophic; (‘E’): Eutrophic; (‘SE’): Supereutrophic; (‘HE’): Hypereutrophic

The evaluation using the five different TSI models from August 2009 to January 2022 in the Araras reservoir resulted in a trophic state classification with a divergence between the models, as shown in Table 03. The models by Carlson (1977), Kratzer & Brezonic (1981), Toledo Júnior et al. (1983), Lamparelli (2004), and Cunha et al. (2013) indicated trophic states that coincide with the COGERH trophic classification in 45%, 45%, 81%, 61%, and 48%, respectively. The model that came closest to the trophic classification carried out by COGERH, for this reservoir and in the same period was that of Toledo Júnior et al. (1983) (81%), while those of Carlson (1977) and Kratzer & Brezonic (1981) were the ones that coincided the least (45%). The trophic state indicated by the model of Toledo Júnior et al. (1983) corroborates the results of Paulino et al. (2013), in a study from 2008 to 2011 in reservoirs monitored by COGERH, in which they found that TP was the limiting nutrient in 65% of the results. The findings of Kipplel et al. (2020) are also in agreement, who, in a comparative study between different TSI's Carlson (1997), Toledo Júnior et al. (1983), Lamparelli (1983) and Cunha et al. (2013), proved that the model of Toledo Júnior (1983) was the most consistent with the trophic conditions of the evaluated reservoirs.

Another relevant point of the TSI multimodel assessment is that, in 88% of the period assessed, at least one of the models coincided with the trophic state indicated by COGERH, reaffirming the usefulness of the proposed methodology to characterize the degree of eutrophication. From the beginning of 2015 to the start of 2017, the hypereutrophic classification of the Araras reservoir coincides with the five different models used and with the trophic classification established by COGERH's methodology. These results are in line with those of Rosendo (2022), who carried out a study on TP in reservoirs of the Acaraú River basin-CE, between 2016 and 2021, with the Lamparelli index (2004) and found that the Araras reservoir was classified as hypereutrophic in at least five consecutive semesters, from 2016 to 2018, and showed an improvement in its degree of eutrophication after twelve semesters of analysis.

A significant pattern is observed in the TSI multimodel assessment: most converge, indicating the possibility of eutrophication up to 2019. Therefore, the trophic classification of the Araras reservoir was more reliable during this period. On the other hand, from 2020 to the end of the period evaluated, the models presented relevant divergences among themselves since, while some models indicated eutrophication of the water body (eutrophic class), others indicated non-eutrophication (mesotrophic class), according to the respective classification range according to the criteria used by each model. In approximately 78% of the period, at least one of the five TSI models coincided with the trophic classification carried out by COGERH for the same period. The TSI multimodel assessment proved to be a handy tool for the trophic classification of the reservoir, providing reliable and consistent information for the adequate management of the reservoir's water quality in the tropical semiarid region.

Eutrophication risks

Table 04 shows the eutrophication risk for the Araras reservoir from 2009 to 2022, with the values of the multimodel assessment that supported the probabilistic calculation of the eutrophication risk using the PDF approach.

Table 04

Eutrophication risks in Araras Reservoir

Period	Carlson (1977)	Kratzer & Brezonic (1981)	Toledo Júnior et al. (1983)	Lamparelli (2004)	Cunha et al. (2013)	Eutrophication risks (%)
Aug, 2009	65	64	64	64	60	**100%**
May, 2010	65	60	64	61	58	**100%**
Nov, 2010	67	61	66	62	59	**100%**
Oct, 2012	-	53	-	-	-	**0%**
May, 2013	-	48	-	-	-	**0%**
Nov, 2014	73	73	72	66	62	**100%**
Apr, 2015	79	72	77	69	64	**100%**
Jul, 2015	78	75	77	68	64	**100%**
Mar, 2016	82	80	81	70	65	**100%**
Apr, 2016	82	79	81	70	65	**100%**
Aug, 2016	80	77	79	69	64	**100%**
Nov, 2016	80	80	79	70	65	**100%**
Jan, 2017	82	78	81	71	65	**100%**
Apr, 2017	73	70	72	67	63	**100%**
Jul, 2017	67	64	66	64	61	**100%**
Oct, 2017	63	62	62	62	59	**100%**
Jan, 2018	62	62	61	61	58	**100%**
Apr, 2018	64	62	63	63	60	**100%**
Jul, 2018	68	63	66	64	60	**100%**
Oct, 2018	64	61	63	61	59	**100%**
Jan, 2019	63	60	62	61	59	**100%**
Apr, 2019	65	61	63	62	59	**100%**
Jul, 2019	71	66	70	67	62	**100%**
Oct, 2019	61	60	59	60	58	**100%**
Jan, 2020	55	48	53	58	56	**60%**
May, 2020	57	54	56	59	57	**80%**
Aug, 2020	54	53	52	57	55	**40%**
Nov, 2020	54	54	52	57	56	**40%**
Jan, 2021	50	49	49	56	55	**40%**
Apr, 2021	48	46	47	55	54	**20%**
Jul, 2021	53	52	52	57	56	**40%**
Oct, 2021	49	48	48	55	54	**20%**
Jan, 2022	51	48	50	57	55	**40%**

The results of the eutrophication risk calculation follow the trend of the TSI multimodel assessment. Therefore, they present the lowest risks of eutrophic conditions at the end of the period, similar to what was found by the multimodel technique.

The PDF's application mainly indicated the total eutrophication risk (100%) for the Araras reservoir from the beginning of the study period until 2019. During this period, most of the TSI models confirm the eutrophication condition. Two dates investigated present the condition of non-eutrophication (eutrophication risk of 0%) and indicate the concentration of TN as the limiting nutrient. They are, therefore, evaluated only by the Kratzer & Brezonic (1981) model, falling into the condition of total eutrophication risk (100% risk) or non-eutrophication condition (0% risk). From 2020 until the end of the study period 2022, the risk of eutrophication did not reach 100%. At the end of this period, the water body showed a lower chance of severe water quality degradation, but it continues with relatively high values of eutrophication risk (40%). The three models responsible for the results that confirm the reduction in the risk of eutrophication at the end of the period were those of Carlson (1977), Kratzer & Brezonic (1981), and Toledo Júnior et al. (1983).

These results show that the combined approach between the multimodel assessment TSI and PDF was satisfactory and easy to apply. The great advantage of this combination is the provision of a point value (probabilistic risk of eutrophication) from a set of TSI results in which each one can be taken as true (Klippel et al., 2020). Wiegand et al. (2016) compared the risks of eutrophication in reservoirs in the semiarid region of Brazil and the humid tropical region of Cuba and concluded that, due to the longer water and phosphorus retention time, reservoirs in the semiarid region are potentially more susceptible to eutrophication. Using the Probability Density Function, this study finds data that corroborate this thesis.

The point value of the eutrophication risk facilitates water quality management in reservoirs since the decision-maker works with specific information (Chang et al., 2015). It is worth noting that such information is more reliable than the trophic status provided by a particular type of TSI model (Carneiro et al., 2022). In this sense, the combined approach constitutes a significant advance concerning the isolated use of multimodel TSI (Klippel et al., 2020).

Conclusion

The different structures and construction conditions of the TSI models affect their applicability in environments other than those for which they were developed. The TSI multimodel assessment, therefore, can overcome these shortcomings, and it was used to assess the eutrophication of the Araras reservoir.

A series of results were obtained by applying the TSI multimodel assessment to the data from the Araras reservoir. First, the water quality parameters that make up the calculated TSI models have statistical solid relationships with each other, and the percentage volume of the reservoir significantly influences water quality. Furthermore, since calculating the eutrophication risk provides essential information for water quality management, the TSI multimodel assessment is critical, as it creates ranges of trophic states for action, reducing the uncertainties of individual model choices. The validity of the data obtained is ensured by the consistency with those prepared by COGERH's methodology for trophic classification.

The concise and precise information that the multimodel approach provides is essential for managing and monitoring reservoirs. The methodology is, therefore, instrumental in the Basin Committees deliberations for managing water resources. The case of the Araras reservoir is no exception, as it is related to the use and occupation of land by agriculture, livestock, and fish farming, as well as the health issues of its surroundings and the river basin.

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