Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252024v3712405rc

Scientific Article

Proposal for a trophic status index for brazilian semi-arid reservoirs

Proposta de índice de estado trófico para reservatórios semiáridos brasileiros

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ABSTRACT - The Brazilian semi-arid region, which is characterized by high climate vulnerability, intense and frequent droughts, and irregular rainfall, has a restricted quantity of water in its reservoirs and low quality at several points. Regarding quality, the literature presents indexes that evaluate eutrophication in different conditions, using specific expressions that may not be applied universally. To assist in decision-making and minimize this problem in the semi-arid region, the present work proposes a new trophic state index (TSI) taking into account data and conditions of reservoirs in the semi-arid region of Ceará. In total, 18 variables and the correlations between them were evaluated. In the years 2014-2022, data was made available by COGERH for 25 reservoirs managed by the company. Descriptive statistics were performed for each variable data set, removing outlier values to analyze trends. An exploratory investigation was also carried out, studying correlations between variables and transparency. Phosphorus, nitrogen, chlorophyll *a*, and turbidity presented the most significant correlations for the composition of the proposed TSI. An adaptation was made in the base expression of the TSI, which is associated with the values obtained in the semi-arid region of Ceará. Trophic classes were suggested for this new TSI along with their respective expressions. The proposed index yielded comparable results in certain classifications when compared with other established indexes. High concentrations of cyanobacteria occurred in reservoirs classified as eutrophic. To enhance the robustness of this novel index, it is recommended to extend its application to additional reservoirs within the semi-arid region.

Keywords: Trophic level. Monitoring. Ceará reservoirs. Correlation.

RESUMO - O Semiárido brasileiro, caracterizado por alta vulnerabilidade climática, secas intensas e frequentes e chuvas irregulares, possui quantidade restrita de água em seus reservatórios e baixa qualidade em diversos pontos. Quanto a qualidade, literatura apresenta índices que avaliam a eutrofização em condições distintas, por meio de expressões próprias, que podem não ser aplicadas universalmente. Para auxiliar na tomada de decisão, a fim de minimizar esse problema na região semiárida, o presente trabalho propõe um novo índice de estado trófico (IET) levando em consideração dados e condições de reservatórios do semiárido cearense, avaliando 18 variáveis e as correlações entre eles. Os dados foram disponibilizados pela COGERH, nos anos de 2014 - 2022, para 25 reservatórios administrados pela companhia. Foi feita estatística descritiva para cada conjunto de dados das variáveis, com remoção de valores *outliers* para avaliação das tendências de variação destes nos reservatórios. Estudo exploratório também foi realizado, no estudo de correlações para as variáveis *versus* transparência. Fósforo, nitrogênio, clorofila e turbidez apresentaram as correlações mais significativas para a composição do IET proposto. Foi feita uma adaptação na expressão base do IET, para estar associada aos valores obtidos no semiárido cearense. Foram sugeridas classes tróficas para esse novo IET, com suas respectivas expressões. O índice proposto apresentou resultado similares em algumas classificações, quando comparado a outros índices consolidados. A ocorrência de alta concentração de cianobactérias se deu em reservatórios classificados como eutróficos. Sugere-se aplicação deste índice em mais reservatórios da região semiárida para lhe conferir robustez.

Palavras-chave: Nível trófico. Monitoramento. Reservatórios cearenses. Correlação.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: December 18, 2023.
Accepted in: April 1, 2024.

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INTRODUCTION

Eutrophication is a natural phenomenon associated with the productivity of species present in water bodies. High levels of nutrients in water (mainly nitrogen and phosphorus) favor the occurrence of this process. However, the various human activities in these water bodies and their surroundings leads to the acceleration of eutrophication, resulting from the excessive availability of nutrients at a greater rate than water body can assimilate.

The main consequences of eutrophic environments are fish mortality, high proliferation of aquatic plants, dominance of cyanobacteria, reduced transparency and reduced biodiversity (GLIBERT et al., 2010; SMITH; SCHINDLER, 2009). Therefore, the various possible uses for these waters are compromised, including recreation, irrigation, animal watering, navigation, and industrial and residential supply (VON SPERLING, 2014).

The development of indexes, particularly the trophic state index (TSI), presents a practical method of evaluating the situation of rivers and reservoirs. This is achieved through the measurement of some variables that are associated with microbiological productivity and the presence of nutrients. These indexes facilitate the understanding of the qualitative aspects of water bodies by both experts and laypeople.

The different indexes for assessing trophic status have different expressions, generally composed of correlations between physical, chemical, and biological variables. The total concentration of phosphorus (TP) and chlorophyll *a* (CHL) are the main indicators used in previous studies (CARLSON, 1977; CUNHA; CALIJURI; LAMPARELLI, 2013; ROLIM, 2016; TOLEDO JR., 1990). Due to methodological differences between the research cited, particularly different climatic conditions that can affect physical, chemical, and biological balances in the water body, the use of a single trophic state index as “universal” may not be representative of the conditions for other bodies of water from where they were not originally prepared (SALAS; MARTINO, 2001). When determining the trophic state index, it is also important to evaluate the existence of other relevant factors that may be significant in evaluating the eutrophication process in water bodies, as turbidity, dissolved oxygen content, and cyanobacteria count in the water (ESTEVES, 2011; LIMA et al., 2020).

Dams represent the main source of water in the semi-arid region (SAMIMI et al., 2020). During extended periods of drought, there is a significant reduction in reservoir volumes, leading to changes in physical and chemical conditions, such as light availability, mixing regimes, and nutrient concentrations (BRAGA et al., 2015). Studies carried out in the semi-arid region frequently classified reservoir waters as eutrophic or hypereutrophic (CAVALCANTE et al., 2019; ROLIM, 2016; SANTOS et al., 2020).

The volume variability in Ceará’s reservoirs resulting from the influence of typical characteristics of a semi-arid region, i.e., an evaporation rate between 1200 and 3200 mm year^{-1}, average annual precipitation of less than 800 mm, and high average annual temperatures ranging from 24 to 28 °C (MOURA et al., 2019), presents a major problem. Additionally, high levels of nutrients recorded in water bodies in Ceará pose another risk factor (VIDAL; CAPELO NETO, 2014). To attain the requisite quality standards for different uses of dams in Ceará, a systematic and ongoing assessment, tailored to local conditions, is imperative. Such assessments will facilitate the implementation of public and environmental policies aimed at enhancing water quality. In this context, a trophic state index is proposed based on data from semi-arid reservoirs in Ceará, aiming to contribute to the evaluation of eutrophication levels in reservoirs within the semi-arid region.

MATERIAL AND METHODS

Description of the study area

Ceará belongs to the Brazilian semi-arid region, with 95% of the state’s municipalities located in the region. The management of water resources in the State of Ceará is the function of the water resources management company (COGERH), which controls the supply of underground and surface water under the State’s control.

From a hydrological perspective, the state of Ceará is subdivided into 12 river basins, comprising 157 reservoirs monitored by COGERH. It has average annual temperatures between 27 and 30 °C and a prominent rainy season between January and April, while September to December is the dry season. For this study, we selected 25 reservoirs with the greatest water capacity according to the volume of reservoirs indicated in the Technical Data Sheet for Reservoirs (COGERH, 2023), ensuring representation from at least one reservoir in each river basin. The water bodies under study have quarterly monitoring. The location of each selected reservoir is shown in Figure 1.

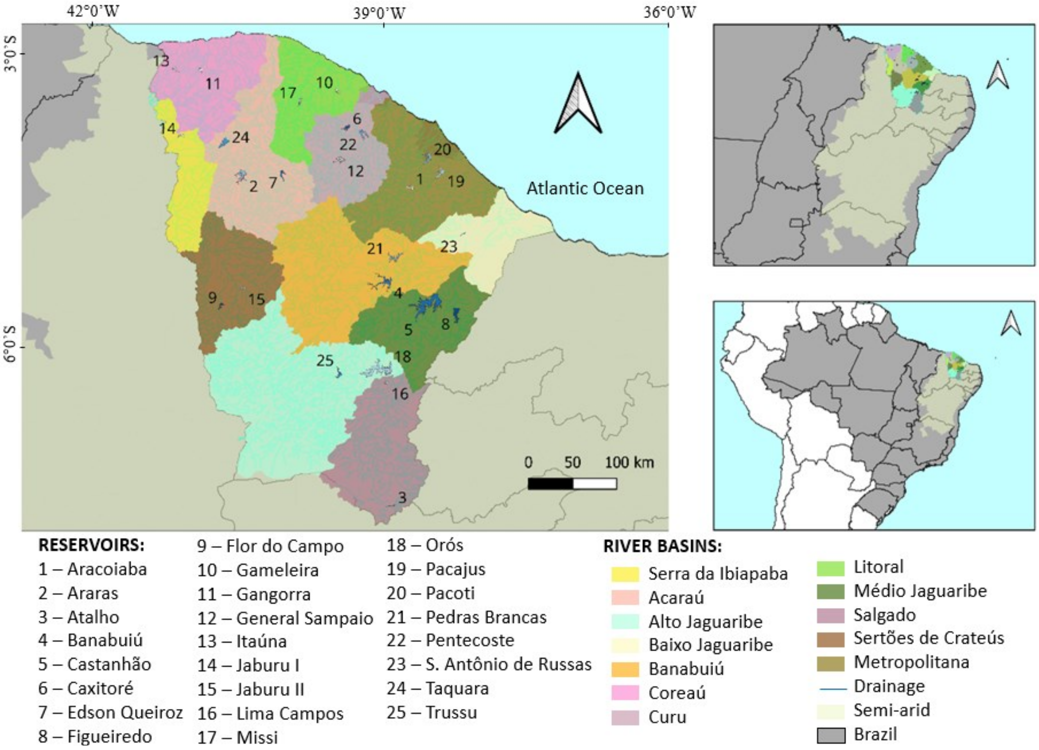


Figure 1. Map of the State of Ceará (highlighting the selected reservoirs).

The chosen reservoirs serve various purposes, including animal watering, primary and secondary contact recreation, and artisanal fishing. These uses are prevalent across nearly all selected reservoirs. As a result of these uses, the reservoirs are impacted by the discharge of domestic sewage, agricultural waste, animal waste, and other pollutants associated with human and agricultural activities (FONSECA; AMARAL; NAVONI, 2024).

Sample collection and analysis of variables

The samples were collected in dark plastic bottles, identified and labeled, and stored in a refrigerated environment until analysis at the laboratories. The water sample was collected at a depth of 0.3 meters, 50-60 meters from the bank of each reservoir. Throughout the study period (2014-2022), 36 samplings were conducted for each reservoir, occurring quarterly and amounting to 900 collections in total.

The physicochemical parameters of the samples were analyzed by the Ceará Water and Sewage Company (Cagece), while the biological analyses (cyanobacteria count) were carried out by the Pernambuco Institute of Technology (ITEP) (2014-2019) and Conágua Environmental (2020-2022).

In total, 18 parameters were analyzed. The cyanobacteria count was analyzed using the Utermöhl method (KARLSON et al., 2010); transparency was measured with a Secchi disk (DS); and electrical conductivity, dissolved oxygen, pH, and temperature were measured using a multiparametric probe. The remaining 12 variables (total alkalinity, calcium, chloride, chlorophyll *a*, true color, iron, total phosphorus, magnesium, total nitrogen, sodium, total dissolved solids, turbidity) were analyzed using standard methodologies, as outlined by APHA (2017) and indicated in Table 1.

Table 1. Parameters evaluated with respective units and analysis methods.

Parameter	Unit	Analysis method
Total alkalinity	mg L^{-1}	Titrimetry (2320 B)
Calcium	mg L^{-1}	Titrimetry with EDTA (3500-Ca B)
Chloride	mg L^{-1}	Argentimetric (4500-Cl B)
Chlorophyll *a* (CHL)	µg L^{-1}	Spectrophotometric (10200 H)
True color	mg L^{-1}	Visual comparison method (2120 B)
Iron	mg L^{-1}	Phenanthroline (3500-Fe B)
Total phosphorus (TP)	mg L^{-1}	Persulfate Method for Simultaneous Determination (4500-P J) and Ascorbic Acid Method (4500-P E)
Magnesium	mg L^{-1}	Calculation method (3500-Mg B)
Total nitrogen (TN)	mg L^{-1}	Persulfate method for simultaneous determination (4500-P J) and Cadmium Reduction Method (4500-NO3- E)
Sodium	mg L^{-1}	Flame Emission Photometry (3500-Na B)
Total Dissolved Solids (TDS)	mg L^{-1}	Gravimetry (2540 D) and calculation
Turbidity (TURB)	NTU	Nephelometric (2130 B)

Statistical analysis of data

Microsoft Excel and GraphPad Prism (10.1.1) were used to organize the data and perform the descriptive statistics of the study. Different normality tests were performed for the analysis of the results: Anderson-Darling, Shapiro-Wilk, and Kolmogorov-Smirnov. For the exploratory analysis, principal component analysis (PCA) was used. This statistical analysis model enables the comprehensive evaluation of extensive data sets, minimizing information loss by processing the provided data and identifying potential clusters of samples exhibiting similarities (MARCHETTI et al., 2015). Pre-processing was applied to the autoscaling data, which considers all parameters as important in the initial analysis, regardless of the unit of measurement and the amplitude of the data (CORREIA; FERREIRA, 2007).

In correlation studies, the behavior of the data was evaluated in terms of normality (for parameter x transparency correlations). Data was only used if there was a pair of results (parameter/transparency) to be compared in the same analysis period. The correlation coefficient value for the data set was used when evaluating the correlations obtained in this study. The “strength” of these associations between the parameters was defined by ranges of r value, with values greater than 0.3 indicating a moderate correlation, while values greater than 0.5 indicate a strong correlation (XIAO et al., 2016).

Construction of the trophic state index

The literature already includes different indexes of trophic status based on studies in different places and climates around the world. The equations developed by some of these researchers, which are taken as references, are compiled in Table 2.

Salas and Martino (2001) advocate for the advancement of methodologies in evaluating the trophic state of water bodies. Souza et al. (2018) state that the evaluation criteria in humid regions must differ from the eutrophication evaluation criteria in regions with a semi-arid climate. There are some studies in semi-arid climatic conditions, such as those carried out by Rolim (2016) and Lima et al. (2020).

Table 2. TSI equations for different authors.

Authors	Climatic condition	Equations
Carlson (1977)	Seasoned	$\mathrm{TSI(TP)}=10\left\{6-\left[\frac{\ln\left({}^{48}/_{\mathrm{TP}}\right)}{\ln 2}\right]\right\}$ $\mathrm{TSI(CHL)}=10\left\{6-\left[\frac{(2.04-0.68\times\ln \mathrm{CHL})}{\ln 2}\right]\right\}$ $\mathrm{TSI(Mean)}=\frac{\mathrm{TSI\ (TP)+TSI\ (CHL)}}{2}$
Toledo Jr. (1990)	Tropical	$\mathrm{TSI(TP)}=10\left\{6-\left[\frac{\ln\left({}^{80.32}/_{\mathrm{TP}}\right)}{\ln 2}\right]\right\}$ $\mathrm{TSI(CHL)}=10\left\{6-\left[\frac{(2.04-0.695\times\ln \mathrm{CHL})}{\ln 2}\right]\right\}$ $\mathrm{TSI(Mean)}=\frac{\mathrm{TSI\ (TP)+TSI\ (CHL)}}{2}$
Lamparelli (2004)	Subtropical	$\mathrm{TSI(TP)}=10\left\{6-\left[\frac{(1.77-0.42\times\ln \mathrm{TP})}{\ln 2}\right]\right\}$ $\mathrm{TSI(CHL)}=10\left\{6-\left[\frac{(0.92-0.34\times\ln \mathrm{CHL})}{\ln 2}\right]\right\}$ $\mathrm{TSI(Mean)}=\frac{\mathrm{TSI\ (TP)+TSI\ (CHL)}}{2}$
Cunha, Calijuri and Lamparelli (2013)	Tropical/Subtropical	$\mathrm{TSI(TP)}=10\left\{6-\left[\frac{(1.33-0.28\times\ln \mathrm{TP})}{\ln 2}\right]\right\}$ $\mathrm{TSI(CHL)}=10\left\{6-\left[\frac{(0.84-0.25\times\ln \mathrm{CHL})}{\ln 2}\right]\right\}$ $\mathrm{TSI(Mean)}=\frac{\mathrm{TSI\ (TP)+TSI\ (CHL)}}{2}$

Given each distinct climate, with different temperatures and rainfall characteristics, it is necessary to make adaptations to the equations that make up the TSI for the semi-arid climate condition.

The extensions of the expressions that make up the TSI in this work are based on the study by Carlson (1977). In their study, the initial expression for determining the trophic state is presented in Equation (1):

$$\mathrm{TSI\ (DS)} = 10(6 - \log_2 \mathrm{DS}) \qquad (1)$$

where TSI (DS) is the trophic state index due to transparency and DS is the transparency measured by the Secchi Disk (m). In this equation, the value 10 is a multiplicative term to ensure the values range from 0–100, while the value of six is associated with the maximum transparency measurement recorded in the study by Carlson (1977), i.e., 41.6 meters in Lake Masyuko (Japan). The other expressions of TSI as a function of total phosphorus and chlorophyll *a* come from the correlations of these parameters with transparency.

In constructing the TSI based on semi-arid findings, the maximum transparency measurement was utilized, substituting the value of six. This value was then transformed into a logarithmic scale with a base of 2 and incorporated into the revised expression.

RESULTS AND DISCUSSION

Multivariate data evaluation principal component analysis

By utilizing the PCA statistical tool, the number of parameters needed for a large set of data can be reduced, depending on the intensity expressed in the eigenvalues and the main component that they relate to. It is also possible to observe and identify some groups of samples depending on the parameters analyzed by this tool. Figure 2 presents the loadings (variables) graph prepared in this work.

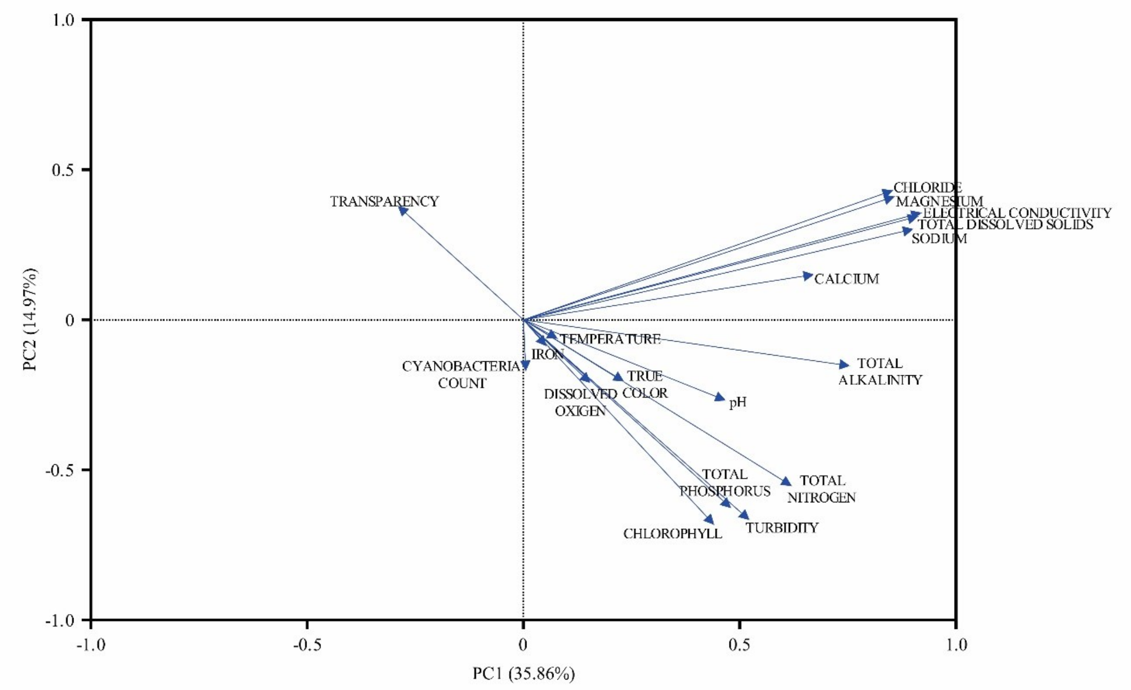


Figure 2. Chart of loadings for the 18 variables studied.

The data is organized and visualized in a segmented manner on the graph, with samples and parameters depicted within distinct ‘sectors’ delineated by vertical lines (main component 1-PC1) and horizontal lines (main component 2-PC2). Each component expresses a response factor regarding the behavior observed in the samples. For the data set, PC1 explains 35.86% of the data behavior, while PC2 explains 14.97%. Together, these components indicate 50.83% of the sample distribution.

Certain parameters exhibited analogous trends and proximity to each other on the graph. Total phosphorus, total nitrogen, chlorophyll *a*, and turbidity demonstrate a positive aspect in PC1 and a negative aspect in PC2, each with comparable magnitudes. The parameters representing the contents of chloride, magnesium, sodium, and calcium, as well as TDS and electrical conductivity, have a positive aspect in both PC1 and PC2.

Multiparametric correlation

All parameters - except for the pH parameter - did not show normality in their distribution (non-parametric data), an aspect frequently observed in the analysis of varied environmental data with high amplitudes. Given this test, the Spearman coefficient (rs) appears as the most appropriate correlation indicator for the study of these parameters, with its multiple correlations depicted in Figure 3.

The transparency parameter presented significantly negative correlation values with other variables. Figure 4 presents the generated equations and the correlation coefficients observed between the transparency parameter and the total nitrogen, total phosphorus, chlorophyll *a*, and turbidity parameters for the period of study for all basins.

From the observed correlations, the Equations (2), (3), (4) and (5) were obtained:

$$\ln(DS) = -0.2092\times\ln(TN) - 0.1969 \qquad (2)$$

$$\ln(DS) = -0.4017\times\ln(TP) + 1.458 \qquad (3)$$

$$\ln(DS) = -0.2187\times\ln(CHL) + 0.4781 \qquad (4)$$

$$\ln(DS) = -0.4764\times\ln(TURB) + 0.8120 \qquad (5)$$

Transparency and STI

The highest water transparency value recorded in the period under study was 4.8 meters, which occurred in the Pentecoste reservoir (maximum depth = 29.4 m) located in the Curu Basin, in October 2015. Following the sequence of actions described in the methodology, we obtained the Equation (6) – relationship between transparency and STI:

$$\mathrm{TSI}\ (\mathrm{DS}) = 10\ (3 - \log_2 \mathrm{DS}) \qquad (6)$$

To construct the expressions, Equation (6) is modified to Neperian logarithm form to produce Equation (7):

$$\mathrm{TSI(DS)} = 10[(3 - \left(\frac{\ln \mathrm{D\,S}}{\ln 2}\right)] \qquad (7)$$

Although transparency data is used in the determination of correlations and equations for the TSI, it is not directly applied to determine the trophic state of water. Instead, equations based on the total phosphorus content (often associated with the limiting nutrient) and chlorophyll *a* (often associated with phytoplankton biomass) are commonly used (BARROS, 2013; FEITOSA, 2011; WANG et al., 2008).

By substituting Equations (2), (3), (4) and (5) into Equation (7), individual expressions for the trophic state index are obtained – in Equations (8), (9), (10) and (11) – depending on each parameter:

$$\mathrm{TSI(TN)} = 10(3 - \frac{[-0.2092\ln(\mathrm{TN}) - 0.1969]}{\ln(2)}) \qquad (8)$$

$$\mathrm{TSI(TP)} = 10(3 - \frac{[-0.4017\ln(\mathrm{TP}) + 1.458]}{\ln(2)}) \qquad (9)$$

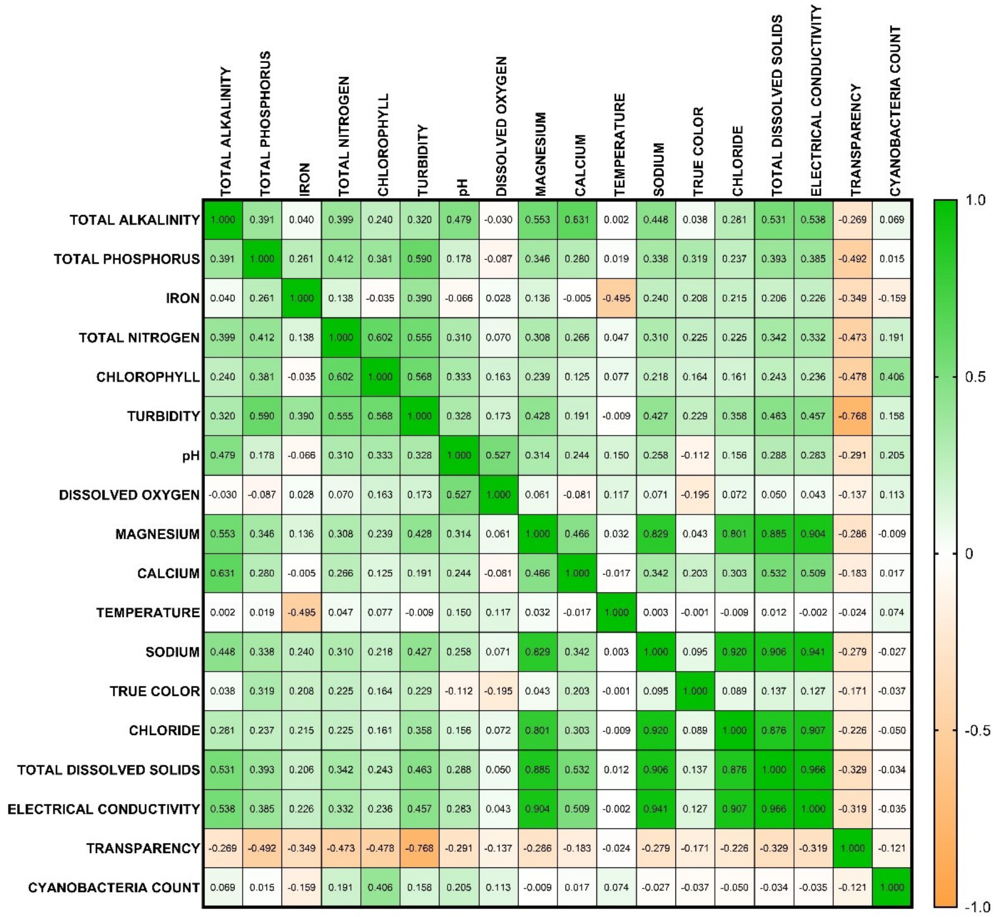
$$\mathrm{TSI(CHL)} = 10(3 - \frac{[-0.2187\ln(\mathrm{CHL}) + 0.4781]}{\ln(2)}) \qquad (10)$$

$$\mathrm{TSI(TURB)} = 10(3 - \frac{[-0.4764\ln(\mathrm{TURB}) + 0.8120]}{\ln(2)}) \qquad (11)$$

Where TN is the total nitrogen concentration (mg L^{-1}); TP is the total phosphorus concentration (μg L^{-1}); CHL is the chlorophyll *a* concentration (μg L^{-1}); TURB is the turbidity measurement (NTU).

For the trophic classification of reservoirs, it is recommended to utilize the average TSI to consider the contribution of each parameter in this classification definition. These parameters showed the same direction and similar amplitude according to the loadings graph (Figure 2), indicating that they contribute in the same proportion. Therefore, it is not necessary to assign a weighting to either parameter. The average TSI is indicated by Equation (12).

$$\mathrm{TSI_{Average}} = \frac{[\mathrm{TSI(TN)} + \mathrm{TSI(TP)} + \mathrm{TSI(CHL)} + \mathrm{TSI(TURB)}]}{4} \qquad (12)$$



	TOTAL ALKALINITY	TOTAL PHOSPHORUS	IRON	TOTAL NITROGEN	CHLOROPHYLL	TURBIDITY	pH	DISSOLVED OXYGEN	MAGNESIUM	CALCIUM	TEMPERATURE	SODIUM	TRUE COLOR	CHLORIDE	TOTAL DISSOLVED SOLIDS	ELECTRICAL CONDUCTIVITY	TRANSPARENCY	CYANOBACTERIA COUNT
TOTAL ALKALINITY	1.000	0.391	0.040	0.399	0.240	0.320	0.479	-0.030	0.553	0.631	0.002	0.448	0.038	0.281	0.531	0.538	-0.269	0.069
TOTAL PHOSPHORUS	0.391	1.000	0.261	0.412	0.381	0.590	0.178	-0.087	0.346	0.280	0.019	0.338	0.319	0.237	0.393	0.385	-0.492	0.015
IRON	0.040	0.261	1.000	0.138	-0.035	0.390	-0.066	0.028	0.136	-0.005	-0.495	0.240	0.208	0.215	0.206	0.226	-0.349	-0.159
TOTAL NITROGEN	0.399	0.412	0.138	1.000	0.602	0.555	0.310	0.070	0.308	0.266	0.047	0.310	0.225	0.225	0.342	0.332	-0.473	0.191
CHLOROPHYLL	0.240	0.381	-0.035	0.602	1.000	0.568	0.333	0.163	0.239	0.125	0.077	0.218	0.164	0.161	0.243	0.236	-0.478	0.406
TURBIDITY	0.320	0.590	0.390	0.555	0.568	1.000	0.328	0.173	0.428	0.191	-0.009	0.427	0.229	0.358	0.463	0.457	-0.768	0.158
pH	0.479	0.178	-0.066	0.310	0.333	0.328	1.000	0.527	0.314	0.244	0.150	0.258	-0.112	0.156	0.288	0.283	-0.291	0.205
DISSOLVED OXYGEN	-0.030	-0.087	0.028	0.070	0.163	0.173	0.527	1.000	0.061	-0.081	0.117	0.071	-0.195	0.072	0.050	0.043	-0.137	0.113
MAGNESIUM	0.553	0.346	0.136	0.308	0.239	0.428	0.314	0.061	1.000	0.466	0.032	0.829	0.043	0.801	0.885	0.904	-0.286	-0.009
CALCIUM	0.631	0.280	-0.005	0.266	0.125	0.191	0.244	-0.081	0.466	1.000	-0.017	0.342	0.203	0.303	0.532	0.509	-0.183	0.017
TEMPERATURE	0.002	0.019	-0.495	0.047	0.077	-0.009	0.150	0.117	0.032	-0.017	1.000	0.003	-0.001	-0.009	0.012	-0.002	-0.024	0.074
SODIUM	0.448	0.338	0.240	0.310	0.218	0.427	0.258	0.071	0.829	0.342	0.003	1.000	0.095	0.920	0.906	0.941	-0.279	-0.027
TRUE COLOR	0.038	0.319	0.208	0.225	0.164	0.229	-0.112	-0.195	0.043	0.203	-0.001	0.095	1.000	0.089	0.137	0.127	-0.171	-0.037
CHLORIDE	0.281	0.237	0.215	0.225	0.161	0.358	0.156	0.072	0.801	0.303	-0.009	0.920	0.089	1.000	0.876	0.907	-0.226	-0.050
TOTAL DISSOLVED SOLIDS	0.531	0.393	0.206	0.342	0.243	0.463	0.288	0.050	0.885	0.532	0.012	0.906	0.137	0.876	1.000	0.966	-0.329	-0.034
ELECTRICAL CONDUCTIVITY	0.538	0.385	0.226	0.332	0.236	0.457	0.283	0.043	0.904	0.509	-0.002	0.941	0.127	0.907	0.966	1.000	-0.319	-0.035
TRANSPARENCY	-0.269	-0.492	-0.349	-0.473	-0.478	-0.768	-0.291	-0.137	-0.286	-0.183	-0.024	-0.279	-0.171	-0.226	-0.329	-0.319	1.000	-0.121
CYANOBACTERIA COUNT	0.069	0.015	-0.159	0.191	0.406	0.158	0.205	0.113	-0.009	0.017	0.074	-0.027	-0.037	-0.050	-0.034	-0.035	-0.121	1.000

Figure 3. Correlation matrix (heat map) for the parameters.

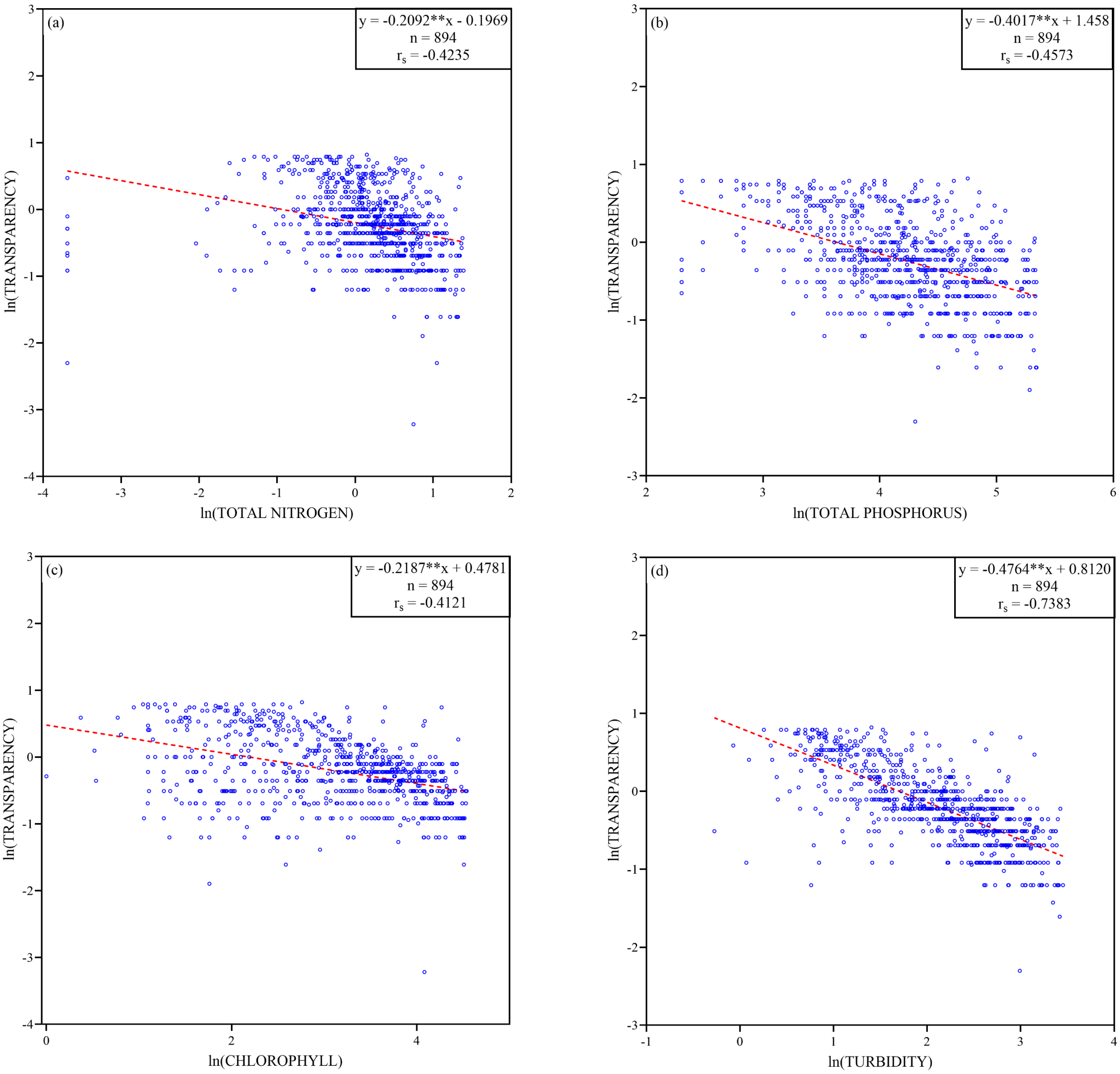


Figure 4. Correlations between the transparency parameter and (a) nitrogen, (b) phosphorus, (c) chlorophyll *a*, and (d) turbidity.

Table 3 includes the values corresponding to each trophic state, together with the indicative concentration ranges for each parameter analyzed. The concentration ranges were determined by percentiles derived from the dataset for each parameter.

Table 3. TSI classification proposal and reference values for each parameter.

Trophic state	Average TSI value	TN ($mg\ L^{-1}$)	TP ($\mu g\ L^{-1}$)	CHL ($\mu g\ L^{-1}$)	TURB (NTU)
Oligotrophic	$TSI \leq 29.7$	$TN \leq 0.74$	$TP \leq 39$	$Chl \leq 8.33$	$Turb \leq 3.54$
Mesotrophic	$29.7 < TSI \leq 32.4$	$0.74 < TN \leq 1.10$	$39 < TP \leq 57$	$8.33 < Chl \leq 18.82$	$3.54 < Turb \leq 6.88$
Eutrophic	$32.4 < TSI \leq 34.4$	$1.10 < TN \leq 1.54$	$57 < TP \leq 79$	$18.82 < Chl \leq 33.65$	$6.88 < Turb \leq 11.29$
Supereutrophic	$34.4 < TSI \leq 36.3$	$1.54 < TN \leq 2.10$	$79 < TP \leq 116$	$33.65 < Chl \leq 56.21$	$11.29 < Turb \leq 17.10$
Hypereutrophic	$TSI > 36.3$	$TN > 2.10$	$TP > 116$	$Chl > 56.21$	$Turb > 17.10$

The proposed index differs from others in the literature as it uses total nitrogen and turbidity, which have proven to be significant contributors to the index. This inclusion reflects a consideration of the intrinsic characteristics of semi-arid reservoirs. In situations where a measurement of these variables cannot be obtained, the TSI is calculated excluding them.

To understand the other differences and similarities between the proposed methodology in this study and other indexes for assessing the eutrophication process, trophic classification ranges were collated for each TSI model along with their corresponding parameters and concentrations (see Table 4). The concentration ranges for nitrogen and turbidity were removed because they cannot be compared with existing models as they do not consider these parameters.

Table 4. Parameter concentration ranges and average TSI in each model.

	Authors	Average TSI	TP (µg L^{-1})	Chl (µg L^{-1})
Ultraoligotrophic	Toledo Jr. (1990)	$TSI \leq 24$	-	-
	Lamparelli (2004)	$TSI \leq 47$	$TP \leq 8$	$Chl \leq 1.17$
	Cunha, Calijuri and Lamparelli (2013)	$TSI \leq 51.1$	$TP \leq 15.9$	$Chl \leq 2$
	This work	-	-	-
Oligotrophic	Toledo Jr. (1990)	$24 < TSI \leq 44$	$6.6 < TP \leq 26.5$	$0.5 < Chl \leq 3.8$
	Lamparelli (2004)	$27 < TSI \leq 52$	$8 < TP \leq 19$	$1.17 < Chl \leq 3.24$
	Cunha, Calijuri and Lamparelli (2013)	$51.1 < TSI \leq 53.1$	$15.9 < TP \leq 23.8$	$2 < Chl \leq 3.9$
	This work	$TSI \leq 29.7$	$TP \leq 39$	$Chl \leq 8.33$
Mesotrophic	Toledo Jr. (1990)	$44 < TSI \leq 54$	$26.5 < TP \leq 53$	$3.8 < Chl \leq 10.3$
	Lamparelli (2004)	$52 < TSI \leq 59$	$19 < TP \leq 52$	$3.24 < Chl \leq 11.03$
	Cunha, Calijuri and Lamparelli (2013)	$53.1 < TSI \leq 55.7$	$23.8 < TP \leq 36.7$	$3.9 < Chl \leq 10$
	This work	$29.7 < TSI \leq 32.4$	$39 < TP \leq 57$	$8.33 < Chl \leq 18.82$
Eutrophic	Toledo Jr. (1990)	$54 < TSI \leq 74$	$53 < TP \leq 211.9$	$10.3 < Chl \leq 76.1$
	Lamparelli (2004)	$59 < TSI \leq 63$	$52 < TP \leq 120$	$11.03 < Chl \leq 30.55$
	Cunha, Calijuri and Lamparelli (2013)	$55.7 < TSI \leq 58.1$	$36.7 < TP \leq 63.7$	$10 < Chl \leq 20.2$
	This work	$32.4 < TSI \leq 34.4$	$57 < TP \leq 79$	$18.82 < Chl \leq 33.65$
Supereutrophic	Toledo Jr. (1990)	-	-	-
	Lamparelli (2004)	$63 < TSI \leq 67$	$120 < TP \leq 233$	$30.55 < Chl \leq 69.05$
	Cunha, Calijuri and Lamparelli (2013)	$TSI > 58.1$	$TP > 63.7$	$Chl > 20.2$
	This work	$34.4 < TSI \leq 36.3$	$79 < TP \leq 116$	$33.65 < Chl \leq 56.21$
Hypereutrophic	Toledo Jr. (1990)	$TSI > 74$	$TP > 211.9$	$Chl > 76.1$
	Lamparelli (2004)	$TSI > 67$	$TP > 233$	$Chl > 69.5$
	Cunha, Calijuri and Lamparelli (2013)	-	-	-
	This work	$TSI > 36.3$	$TP > 116$	$Chl > 56.11$

(-) Non-existent data.

The new proposed index presents a total phosphorus concentration range of 39–116 µg L^{-1} for changing trophic classifications. The minimum value for this class change (oligo/ meso) is higher than the other indexes, being more than three times higher than the minimum indicated by Lamparelli (2004). The upper concentration of this nutrient in the working range is much less than that of other models, being approximately half the value indicated by Toledo Jr. (1990), Lamparelli (2004), and Cunha, Calijuri and Lamparelli (2013). As for the chlorophyll *a* concentration range (8.33–56.11 µg L^{-1}), the lower limit is higher than the others for the oligotrophic class, with variations being slightly more permissive for this classification. The upper limit of the range presents a concentration similar to that recorded by

Toledo Jr. (1990) and Lamparelli (2004).

In 2022, the TSI was calculated for the 25 reservoirs studied (Table 5), using the expressions developed in this research compared with the expressions proposed by Toledo Jr. (1990), Lamparelli (2004), and Cunha, Calijuri and Lamparelli (2013).

Table 5. Comparison of the trophic classifications of the different trophic state indexes for the April 2022 collection (TSI_T = average TSI value according to Toledo Jr. (1990); TSI_L = average TSI value according to Lamparelli (2004); TSI_C = average TSI value according to Cunha, Calijuri and Lamparelli (2013); and TSI_P = average TSI value according to the present work).

Reservoir	TP (µg L^{-1})	Chl (µg L^{-1})	TN (mg L^{-1})	Turb (NTU)	TSI_T	TSI_L	TSI_C	TSI_P
Aracoiaba	50	20.12	0.963	8.42	56.9 E	59.8 E	57.7 E	32.5 E
Araras	55	5.56	0.688	1.48	51.2 M	56.9 M	55.5 M	28.3 O
Atalho	12	3	0.15	1.7	37.1 O	50.8 O	51.3 O	24.7 O
Banabuiú	127	58.68	1,613	23.3	69.0 E	65.3 S	61.5 S	36.8 H
Castanhão	141	16.18	0.913	8.81	63.3 E	62.4 E	59.4 S	33.8 E
Caxitoré	80	10.2	1.1	3.53	56.9 E	59.6 E	57.4 E	31.2 M
Edson Queiroz	61	18.55	1.25	4.11	57.9 E	60.2 E	57.9 E	31.7 M
Figueiredo	55	14.09	0.938	3.09	55.8 E	59.2 E	57.2 E	30.6 M
Flor do Campo	64	18.14	1,275	4.62	58.2 E	60.3 E	58.0 E	31.9 M
Gameleira	120	21.08	0.82	7.03	63.5 E	62.6 E	59.5 S	33.3 E
Gangorra	73	68.77	2,513	20.27	65.8 E	64.0 S	60.6 S	36.2 S
General Sampaio	50	9.07	0.59	3.84	52.9 M	57.9 M	56.2 E	30.1 M
Itaúna	34	3.24	0.588	1.91	45.0 M	54.2 M	53.6 M	27.5 O
Jaburu I	200	43.02	2.15	17.7	70.7 E	65.9 S	61.8 S	37.0 H
Jaburu II	34	15.02	0.963	4.21	52.7 M	57.9 M	56.4 E	30.5 M
Lima Campos	64	79.89	2	11.07	65.6 E	63.9 S	60.6 S	34.9 S
Missi	82	12.54	0.9	4.03	58.1 E	60.1 E	57.8 E	31.5 M
Orós	57	13.91	0.788	6.33	56.0 E	59.3 E	57.3 E	31.7 M
Pacajus	86	23.93	0.825	5.99	61.7 E	61.9 E	59.1 S	32.7 E
Pacoti	88	18.53	2,575	5.45	60.6 E	61.3 E	58.7 S	33.2 E
Pedras Brancas	127	41.76	2,063	12.67	67.3 E	64.4 S	60.9 S	35.7 S
Pentecoste	128	103.3	2,375	12.3	71.9 E	66.7 S	62.5 S	36.5 H
Snt.Ant. de Russas	36	7.17	0.638	5.32	49.4 M	56.3 M	55.1 M	30.1 M
Taquara	70	14.18	0.938	4.81	57.6 E	60.0 E	57.7 E	31.7 M
Trussu	64	40.29	1.8	18	62.2 E	62.3 E	59.4 S	35.1 S

U = Ultraoligotrophic; O = Oligotrophic; M = Mesotrophic; E = Eutrophic; S = Supereutrophic; H = Hypereutrophic.

The three existing indexes applied yielded highly comparable trophic classifications. Specifically, the index developed in this study produced similar results in trophic classification compared to the others, differing by only one trophic level in some instances, either higher (as in Pentecoste) or lower (as in Itaúna).

While approximately 37.34% of classifications align identically, the presence of different outcomes highlights a favorable attribute of the proposed index. If classifications were overwhelmingly similar, the necessity for this index would diminish, as existing ones could adequately perform the task. Conversely, if a marked differentiation existed, it might suggest a flaw in the index's creation, rendering it non-representative of the studied region.

Concurrently with the classifications derived from the index, reservoirs categorized as eutrophic, supereutrophic, and hypereutrophic exhibit a pronounced prevalence of cyanobacteria. Cell counts ranging from 38,000 to 612,000 cells mL^{-1} were recorded, with the majority exceeding 50,000 cells mL^{-1} (the maximum permissible value for class II waters according to National Environment Council – CONAMA – Resolution 357/2005) (BRASIL, 2005). The excessive presence of cyanobacteria is a recognized issue in eutrophicated water bodies (GLIBERT et al., 2010).

CONCLUSION

The statistical analyses carried out helped to identify correlations between the variables of this work, using tools such as PCA and Spearman's coefficient (r_s), presenting important results for understanding the relationships between the variables. A trophic state index was created based on statistical correlations, composed of variables already frequently used in the literature (phosphorus and chlorophyll *a*) together with others that are comparatively novel and less explored in eutrophication studies (nitrogen and turbidity). The comparison made between the application of the proposed index and other existing indexes showed similarity in parts of the classifications and concentration ranges of each trophic class, as well as the occurrence of a few cases with very different classifications. Data on cyanobacteria occurring in some studied reservoirs corroborates the trophic classification given to the water bodies. It is suggested that this proposed TSI can be applied to more reservoirs in Ceará and other states, providing increased index reliability and robustness.

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