Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Assessing the drought in the state of Ceará - Brazil: the relationship between drought, trophic state index, and anthropogenic pressure

Avaliação da seca no Estado do Ceará – Brasil: relações entre a seca, o índice do estado trófico e a pressão antropogênica

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ABSTRACT

The present study addressed the effects of water scarcity on the deterioration of water quality in 155 reservoirs located in the state of Ceará, Brazil, using the drought index SPI (standardized precipitation index) calculated for the accumulation time scales of 3, 6, and 12 months. Based on this, a comparison was made with the variations in the trophic state index of these reservoirs, between 2008 and 2021. The study pointed to the occurrence of an intense series of dry events between 2012 and 2018, highlighting the year 2013, when the SPI assumed a value of -2.43 identifying an extremely dry year. Also, during this period, the amount of water stored by the state's reservoirs achieved only 8% of the total storage capacity, with the existence of eutrophic and hyper-eutrophic dams accounting for 68% of the total in 2016. In this context, it was observed that, during the transition from a dry to a wet period, the average trophic state index of the reservoirs tended to increase, rising from 62.1 (2008–2012) to 65.1 (2013–2017), before decreasing to 61.5 with the return of the wet period (2018–2021). In addition, to assess the influence of human activities on water quality, land use and occupation data from three basins in Ceará were analyzed. It was observed that the basin with the largest area occupied by agriculture experienced the most significant increases in total phosphorus and chlorophyll-a concentrations.

Keywords: drought index; water quality; land use and occupation; water demand.

RESUMO

O presente estudo abordou os efeitos da escassez hídrica na deterioração da qualidade da água em 155 reservatórios localizados no Estado do Ceará – Brasil, utilizando o Índice de Seca (SPI, *standardized precipitation index*) calculado para escalas temporais de acumulação de 3, 6, e 12 meses. Com base nisso, foi realizada uma comparação com as variações no índice do estado trófico desses reservatórios entre 2008 e 2021. O estudo apontou a ocorrência de uma intensa sequência de eventos de seca entre 2012 e 2018, destacando o ano de 2013, quando o SPI assumiu um valor de -2.43, caracterizando um ano extremamente seco. Além disso, nesse período, a quantidade de água armazenada pelos reservatórios do estado atingiu apenas 8% da capacidade total de armazenamento, com a existência de barragens eutróficas e hiper-eutróficas passando a compor 68% do total em 2016. Nesse contexto, observou-se que, durante a transição de um período seco para um período úmido, o índice do estado trófico médio dos reservatórios tendeu a aumentar, passando de 62,1 (2008–2012) para 65,1 (2013–2017), antes de reduzir para 61,5 com o retorno do período úmido (2018–2021). Adicionalmente, para avaliar a influência das atividades humanas na qualidade da água, foram analisados dados de uso e ocupação do solo de três bacias hidrográficas do Ceará. Observou-se que a bacia com a maior área ocupada por atividades agrícolas apresentou os aumentos mais significativos nas concentrações de fósforo total e clorofila-a.

Palavras-chave: índice de seca; qualidade da água; uso e ocupação do solo; demanda hídrica.

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Funding: this study was financed by the Coordination for the Improvement of Higher Education Personnel (CAPES), grant number 88887.827342/2023-00.

Conflicts of interest: the authors declare no conflicts of interest.

Received on: 05/07/2024. Accepted on: 03/16/2025.

https://doi.org/10.5327/Z2176-94782111

Introduction

Access to water in an adequate quantity and quality for human consumption is one of the factors that most affect the health of a population. In this context, the effects of climate change are seen as one of the major threats to public health globally in the 21st century (Dejarnett et al., 2018). By enabling changes in precipitation regimes, temperature, and sea level rise, such climate changes end up directly affecting the availability of drinking water, therefore, with negative impacts, mainly, on human health (Abedin et al., 2019), since safe and accessible water supply is essential for the survival and wellbeing of the population.

It is fundamental to highlight that climate change is responsible for increasing the number and intensity of extreme weather events, especially drought, which often results in episodes associated with outbreaks and sporadic cases of water and foodborne diseases (Cissé, 2019). It is expected that global climate change will disproportionately affect semi-arid regions, especially in the Brazilian Northeast (NEB), since increases in average air temperatures may be responsible for causing greater degradation of natural resources and human quality of life through prolonged droughts that will consequently trigger the scarcity of water resources (Elliott et al., 2014; Marengo et al., 2017).

Thus, the future scenario of the NEB is even more worrisome due to the estimates of air temperature increase predicted by the assessment report AR5 climate projections of the Intergovernmental Panel on Climate Change (IPCC) for the region (Torres et al., 2018). The estimates point to an increase in the recurrence of droughts (Santos et al., 2019) and changes in land use (Silva et al., 2019), with a forecast for increased desertification due to the exploitation of the region's vegetation and the lack of conservation practices, which harm diversity and water resources (Fernandez et al., 2019).

The impacts of drought on NEB have been registered since the 16th century, so that the consequences of water scarcity vary according to the intensity, duration, and spatial extent of the phenomenon (Dantas et al., 2020), consequently causing, throughout history, negative effects on activities such as agriculture, tourism and recreation, electricity generation, urban water supply, and transport (Medeiros et al., 2020). In that regard, drought in NEB not only affects people's food and water security but also leads to a change in landscapes, in the production processes of runoff and flow concentration and, in turn, to ecological and environmental problems.

In parallel, the water quality of freshwater systems is controlled not only by hydrological, biogeochemical, and anthropogenic influences that operate at various temporal and spatial scales but also by climate variability (Mosley, 2015). From the perspective of climatic events, considering drought phenomena for example, when a reduction in water flows and levels occurs, there is an increase in residence time and a decrease in the discharge of water bodies that, when associated with high temperatures, can alter the rates of ecosystem processes such as productivity, respiration, and reaeration (Ahmadi and Moradkhani, 2019).

In the case of semi-arid regions, such as the NEB, there is a huge dependence on artificial reservoirs for human supply and agricultural irrigation in periods of water scarcity. Given the enormous spatial-temporal variability of rainfall in the region, the high evaporation rates, the longer residence time of water during drought events, and the trophic status of reservoirs in semi-arid regions may vary according to the reservoir volume (Braga et al., 2015), precipitation (Chaves et al., 2013), inputs of external nutrient loads from surrounding soils (Lopes et al., 2014), and internal processes such as aquaculture (Bezerra et al., 2014).

In this context, it can be observed that NEB reservoirs are highly susceptible to eutrophication processes, which result in increased turbidity, conductivity, salinity, nutrient concentrations, and phytoplankton biomass, including the occurrence of cyanobacterial blooms (Braga et al., 2015). At the same time, the low water level can allow the phosphorus stored in the sediment to be resuspended by various processes, such as the action of the wind, intensifying internal fertilization and, consequently, eutrophication (Araújo et al., 2016).

The NEB region, characterized by a semi-arid climate, faces significant water scarcity, which has prompted the construction of dams as a key strategy. This approach has resulted in a dense reservoir network. However, this network represents potential threats to the sustainability of the water system (Araújo et al., 2023) as the presence of numerous reservoirs increases evaporation rates and complicates management (Araújo and Medeiros, 2013). On the other hand, reservoirs promote more equitable water distribution and enhance energy efficiency by improving the spatial distribution of water resources (Araújo and Medeiros, 2013).

The state of Ceará faces challenges due to frequent droughts that affect both the quantity and quality of water in its reservoirs (Martins et al., 2018; Raulino et al., 2021). It has also been a target of the reservoir construction strategy aimed at democratizing water access and mitigating drought impacts. Additionally, Ceará stands out for its significant agricultural production and strong livestock sector (IPECE, 2022), leading to notable anthropogenic impacts on watersheds subjected to these economic activities.

In order to evaluate the effects of water scarcity on the deterioration of water quality in reservoirs located in semi-arid regions, the state of Ceará was used for this work as the study object as it represents a significant area of the NEB and provides an updated database of precipitation and quantitative and qualitative aspects of the water in its reservoirs, made possible by the Water Resources Management Company (COGERH, *Companhia de Gestão dos Recursos Hídricos*).

Material and Methods

To evaluate the hypothesis in question, the study sought to identify and characterize, in the region, periods of drought and flood through the standardized precipitation index (SPI) for accumulation periods of 3, 6, and 12 months. The results of this drought index were then compared with the classification given by the trophic state index (TSI) obtained for 155 reservoirs located in the study area, thus allowing the establishment of a relationship between extreme weather events and their effects on the availability of water in quantity and quality. In addition, the contributions of different land use and occupation, as well as multiple uses of water to the aggravation of water stress in the region were also evaluated, in order to have a view of the anthropogenic pressure on the water quality of the region's reservoirs, comparing for this the TSI of three basins characterized by different types of land use. Figure 1 presents a methodological flowchart that illustrates the steps and procedures adopted in the research.

Study area

The study object of this work was the state of Ceará, located in the North of the semi-arid region of NEB (Figure 2), between 3rd and 7th of South latitude, with total area of approximately 146,000 km^2 and 560 km of coastline.

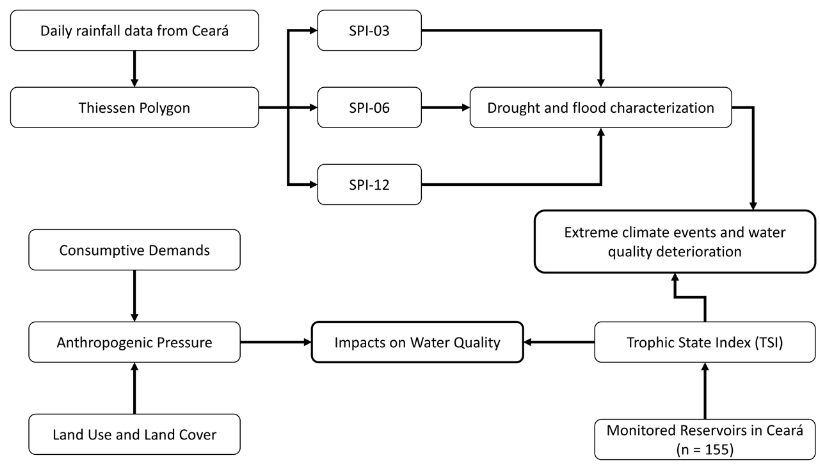

Figure 1 – Steps and procedures of the research: methodological flowchart.
SPI: standardized precipitation index in time scales 3, 6, and 12 months.

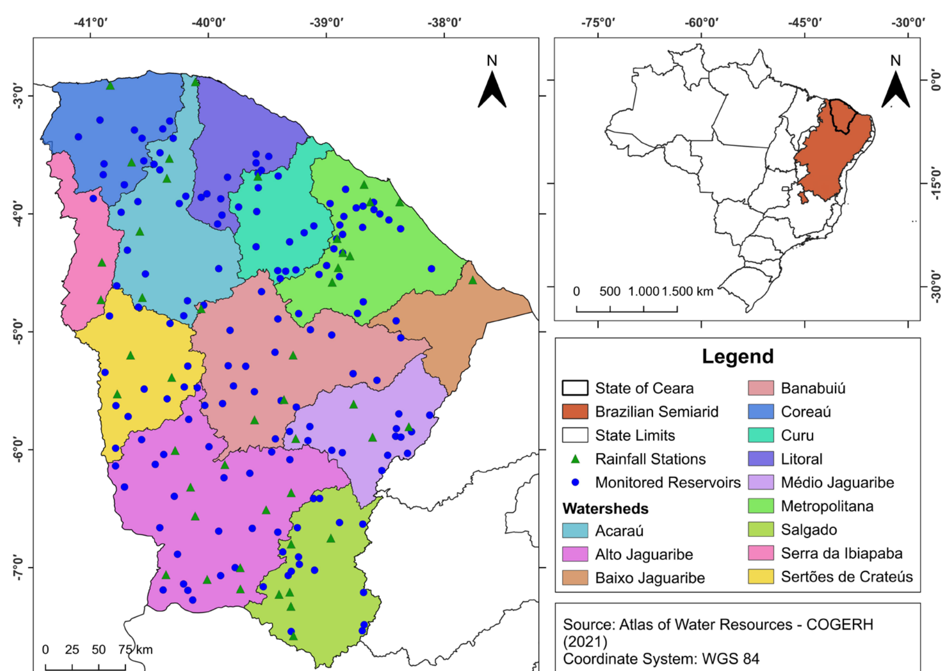

Figure 2 – Locations of 155 COGERH monitored reservoirs and 47 FUNCEME rainfall stations in the state of Ceará, located in the Brazilian semi-arid region.
COGERH: Brazilian Water Resources Management Company; FUNCEME: Foundation Cearense for Meteorology and Water Resources.

The region is characterized by a short rainy season, with precipitation ranging from 400 mm in the interior to 1,200 mm along the coast, primarily occurring between March and May. In terms of potential annual evaporation, it exceeds 2,000 mm (Souza Filho, 2018; Gonçalves et al., 2023).

The regional climate of Ceará is also characterized by prolonged periods of drought, which causes the hydrological regime to be marked by the intermittence of most of the state's watercourses. As a result, the flow rates observed in these watercourses are derived from the release of water from reservoirs (artificial perennialization). Thus, water supply is provided through stocks accumulated in surface reservoirs, which are highly vulnerable to the effects of evaporation (Souza Filho, 2018).

Calculation of standardized precipitation index

To identify and assess wet and dry periods, as well as the severity of these phenomena in the study area, the SPI—already implemented in several researches aimed at identifying droughts in Brazil (Nascimento et al., 2017; Gonçalves et al., 2023; Fernandes et al., 2024)—was used in this study.

SPI is a statistical indicator that correlates the rainfall accumulated over months with the distribution of rainfall accumulated in the same period. First introduced by McKee et al. (1993), the index in question is currently recommended for operational monitoring purposes by the World Meteorological Organization (WMO) (Hayes et al., 2011), having, as its main advantage, the multi-scale calculation that allows the identification of extreme conditions in different periods of accumulation and that can affect different components of the hydrological cycle.

The SPI calculation procedure is based on long-term rainfall records adjusted to a probability function, with the gamma probability density function being more commonly used (McKee et al. 1993; Silva et al., 2020), according to Equation 1:

$$g(x) = \frac{x^{a-1} e^{-\frac{x}{\beta}}}{\beta^{\alpha} \Gamma(a)} \tag{1}$$

Where:
a = shape parameter;
β = scale parameter;
x = precipitation value; and
Γ = gamma function.

Furthermore, it is considered: a>0; β>0; and x>0.

The SPI values are the result of applying the inverse of the standardized normal distribution (Ψ) of the cumulative function G(x), obtained by integrating Equation 1, according to Equation 2, and assuming the new parameters $\hat{\alpha}$, β and A, calculated, respectively, by Equations 3, 4, and 5:

$$G(x) = \int_0^x \frac{x^{\hat{\alpha}-1} e^{-\frac{x}{\beta}}}{\hat{\beta}^{\hat{\alpha}} \Gamma(\hat{\alpha})} \tag{2}$$

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{3}$$

$$\hat{\beta} = \frac{\hat{x}}{\hat{\alpha}} \tag{4}$$

$$A = \ln(\bar{x}) - \frac{\sum ln\,(x)}{n} \tag{5}$$

Where:
n = number of precipitation observations;
x = mean of the data sample; and
Ψ-1 = inverse of the normal probability function with zero mean and variance one.

From this, there is the categorization of SPI values into classes, namely: extremely dry (SPI<-2); severely dry (-2≤SPI<-1.5); moderately dry (-1.5≤SPI<-1.0); close to normality (-1.0≤SPI<1); moderately wet (1.0≤SPI<1.5); very wet (1.5≤SPI<2); and extremely wet (SPI≥2) (Mckee et al., 1993).

As discussed, SPI can be calculated for different time scales. For the present study, time scales of 3 months (SPI-3), 6 months (SPI-6), and 12 months (SPI-12) were chosen. These time scales were selected because SPI-3 reflects medium and short-term conditions, with a greater application in soil moisture analysis. SPI-6, in turn, indicates medium-term trends in soil moisture patterns and precipitation, serving as a good indicator of drought impacts on agriculture (Silva et al., 2021). SPI-12 reflects long-term precipitation patterns, typically linked to average flows, reservoir water levels, and groundwater levels (Zargar et al., 2011).

Data acquisition

The daily rainfall data obtained for this work were accessed from the Foundation Cearense for Meteorology and Water Resources (FUNCEME, *Fundação Cearense de Meteorologia e Recursos Hídricos*), comprising all rainfall stations within the state of Ceará, Brazil. FUNCEME presented constant data series for the period between 1980 and 2021, allowing a maximum of one week of failure for the dry season (May–November) and three failures in the pre-season and in the rainy season, i.e., 10% failure. Thus, there were a total of 47 stations, arranged in Figure 2, with their area of influence calculated using the Thiessen method (Lee et al., 2018).

Trophic state of reservoirs

To establish a link between extreme weather events, especially drought, and the deterioration of the quality of water stored in reservoirs dedicated to human supply, the data referring to 155 reservoirs monitored by COGERH (Figure 2) was accessed from the platform of the Ceará Hydrological Portal, in its Water Quality System (COGERH, 2021). It is noteworthy that the information collected includes data on transparency, stored volume, and concentration of phosphorus, nitrogen, chlorophyll-a, and cyanobacteria in the reservoirs over the period from 2008 to 2021. These data are updated by COGERH itself, through quarterly monitoring campaigns and, in order to present updated and synthetic information on the physical, chemical, and biological properties of the reservoir, the TSI is adopted, which classifies water bodies according to their condition: oligotrophic (TSI≤40), mesotrophic (40.1≤TSI≤50.0), eutrophic (50.1≤TSI≤70.0), and hypereutrophic (TSI≥70.1) (Carlson, 1977).

The methodology applied to classify the trophic status of monitored reservoirs by COGERH is based on that presented by Paulino et al. (2013) that, by definition, the TSI is not limited only to physicochemical, bacteriological, and phytoplankton analyses, as these factors often do not reflect the real conditions of the reservoirs. The TSI was initially created for temperate climates and later adapted for tropical climates, and it also provided a conservative approach, with lower limits anticipating an increasing trophic state classification as found by Cunha et al. (2021).

To validate the results, COGERH considers the following aspects: Carlson's TSI, adapted by Toledo Jr. (1990); limiting nutrient; cyanobacteria count; intensity of aquatic plants present in the water mirror; volume stored in the weir; and observations from regional management. Therefore, the TSI models provided by Carlson (1977) and adapted for tropical environments by Toledo Jr. (1990) are based on the concentrations of total phosphorus (IET_{TP}), chlorophyll-a (IET_{Cla}), and Secchi transparency (IET_{S}), according to Equations 6, 7 and 8:

$$IET_S = 10 \times \left(6 - \frac{0{,}64 + ln\ (Sd)}{ln\ 2}\right) \quad (6)$$

$$IET_{Cla} = 10 \times \left(6 - \frac{2{,}04 - 0{,}695 \times ln\ (Cla)}{ln\ 2}\right) \quad (7)$$

$$IET_{TP} = 10 \times \left(6 - \frac{ln\ \frac{(80{,}32)}{TP}}{ln\ (2)}\right) \quad (8)$$

Where:
Sd = transparency (m);
Cla = chlorophyll-a concentration (µg/L); and
TP = total phosphorus concentration.

From this, the TSI result is given by the arithmetic mean of IET_{TP}, IET_{Cla}, and IET_{S}.

It is important to emphasize that, in this study, the calculation of standard deviations of the sample's values of each limnological variable was performed by removing the values outside the dispersion range, and proceeding with the calculation of the TSI from there. This procedure was performed seeking greater homogeneity (Ngouna et al., 2020) of the obtained data for transparency, phosphorus concentration, and chlorophyll-a of the evaluated reservoirs.

The results obtained using Equations 6–8 were then compared with the cyanobacteria count information and, especially, with the knowledge of the environmental conditions of each reservoir held by the regional managements, since, from the sample collection period, technicians and institutions end up obtaining, with greater proximity, a better idea of the real conditions of the reservoir in question.

Land use and occupation

Seeking to assess the likely risks that changes in land use and occupation (LUO) can bring to the water quality of reservoirs, information about LUO were obtained from the historical series of maps of LUO in Brazil from Collection 5 of the Mapbiomas project (Mapbiomas, 2020) for the state of Ceará in raster format, with a resolution of 30 meters for latitude and longitude, available on its platform.

The Mapbiomas project provides a historical series of annual maps with the LUO classification for the period from 1985 to 2019. The classification in question follows a division into classes that is based on a hierarchical system containing four levels, which are further distinguished into: anthropic, natural, and mosaic; the latter occurs when it is not possible to differentiate between the natural and anthropic types. Table 1 presents the Mapbiomas hierarchical classification system, listing the different classification levels and type of use.

The overall accuracy of Collection 5 in its LUO classification is 91.2, 89.8, and 87.7%, respectively, for level 1, 2, and 3 classes (Mapbiomas, 2020). Therefore, the percentage evolution of the area of each LUO class for the years 1985, 1995, 2005, and 2019 was analyzed. It is also important to highlight that for this analysis, the percentage area was chosen due to a discrepancy in the order of magnitude of the absolute values of the areas between some classes.

In this analysis, only the classes of level 1 of the Mapbiomas classification system were considered, with two differences. First, the forest formation class (level 1) was divided into the natural forest (level 2) and planted forest (level 2) classes. Second, the urban infrastructure class (level 2) was separated from the non-vegetated area class (level 1).

Consumptive water use

In order to evaluate how different consumptive water uses affect reservoir volumes in the study area, monthly discharge data for consumptive uses from municipalities in the state of Ceará were obtained from the National Water and Sanitation Agency (ANA, *Agência Nacional de Água e Saneamento Básico*) database. This database takes into account a survey carried out in 2019, which categorizes the multiple uses of water into: human (urban and rural), animal supply, industry, mining, thermoelectricity, and irrigation for the period between 1931 and 2019 (ANA, 2019). As done for the LUO, water demands for 2000, 2005, 2010, 2015, and 2019 were also analyzed.

Table 1 – Hierarchical classification used by Mapbiomas for land use and coverage.

Level 1	Level 2	Level 3	Level 4	Type of use
Forest	Natural Forest	Forest Formation		Natural
		Savannah Formation		Natural
		Mangrove		Natural
	Planted Forest			Anthropic
Non-Forest Natural Formation	Flooded Field and Swampy Area			Natural
	Country Formation			Natural
	Apicum			Natural
	Rocky Outcrop			Natural
	Other Non-Forest Formations			Natural
Agriculture	Pasture			Anthropic
	Agriculture	Temporary Farming	Soy	Anthropic
			Cane	Anthropic
			Other Temporary Crops	Anthropic
		Perennial Crop		Anthropic
	Agricultura and Pasture Mosaic			Anthropic
Non-Vegetated Area	Beach and Dune			Natural
	Urban Infrastructure			Anthropic
	Mining			Anthropic
	Other Non-Vegetated Areas			Mosaic
Water Bodies	River, Lake and Ocean			Natural
	Aquaculture			Anthropic
Not Observed				-

Source: adapted from Mapbiomas (2020).

Results and Discussion

Standardized Precipitation Index

Figure 3 shows the average time series of SPI-3 (Figure 3A), SPI-6 (Figure 3B), and SPI-12 (Figure 3C)—standardized precipitation index for 3, 6, and 12 months—over the state of Ceará from the monthly rainfall obtained from the 47 analyzed posts of FUNCEME for the period 1980–2018. Data show a great interannual and decadal variability, noting that the main drought events occurred in 1981–1984, 1987, 1990–1994, 1997–1999, 2001, 2005, 2007, 2010, and 2012–2018 for the three time scales. Some of these years were likewise highlighted in the study by Santos et al. (2019), which sought to characterize and monitor drought events in the NEB, also using the SPI on 3, 6, and 12-month time scales, for the period 1988–2017. It is also important to emphasize the SPI values recorded in the early 1980s, when the NEB experienced multi-year droughts that had significant effects on agriculture and livestock, impacting approximately 40% of the region (Carmo and Lima, 2020).

In this context, for SPI-12, the period between 2012–2018 draws attention to an intense drought event, in which the index remained negative throughout the period in question, reaching a peak of -2.43 in March 2013, thus being classified as extremely dry. This observation is similar to the result obtained in the study carried out by Silva et al. (2021) who evaluated the spatial-temporal variability of the SPI in the sub-basin Choró located in Ceará, noting that in March 2013, the SPI-12 recorded an event of -2.7.

Still, regarding the period 2012–2018, it is important to point out that this period is presented by several studies in the literature as the period of occurrence of the most severe drought in NEB in the last 30 years (Marengo et al., 2020; Pontes Filho et al., 2020). In parallel, some studies try to associate the worsening water scarcity in the region throughout this period with the strong El Niño events between 2015–2016 (Marengo et al., 2017).

This time, analyzing the occurrence of rainy events, it is highlighted that the main ones occurred in 1985–1986, 1988–1989, 1995–1996, 2000, 2002–2004, 2008–2009, and 2011, with a maximum value of 1.40

for the SPI-12 in December 2009. Santos et al. (2019) found in their study for the state of Ceará, a maximum value for SPI-12 in October 2009, attributing the increase in rainfall that year to the influence of the La Niña event, as well as the persistence of negative anomalies in the sea surface temperature (SST) in the North Atlantic and positive anomalies in SST in the South Atlantic.

Trophic state

Figure 4 shows the time series of the TSI classification of 155 reservoirs monitored by COGERH in the state of Ceará, as well as the percentage volume of water stored by them in relation to the total capacity of the state, for the period 2008–2021. It is possible to observe that in the years 2008–2012—the period that preceded the series of severe drought events demonstrated by the SPI in its different temporal scales (Figure 3)—, the volume stored by the reservoirs was above average, reaching almost 80% of the total storage capacity in 2009. Furthermore, although there was already an expressive number of eutrophicated reservoirs, water bodies classified as oligotrophic were still expressive.

It is important to highlight that during the rainy season, the inflow of water into reservoirs increases, typically carrying high levels of nutrients, which consequently raises sediment concentrations (Lira et al., 2020).

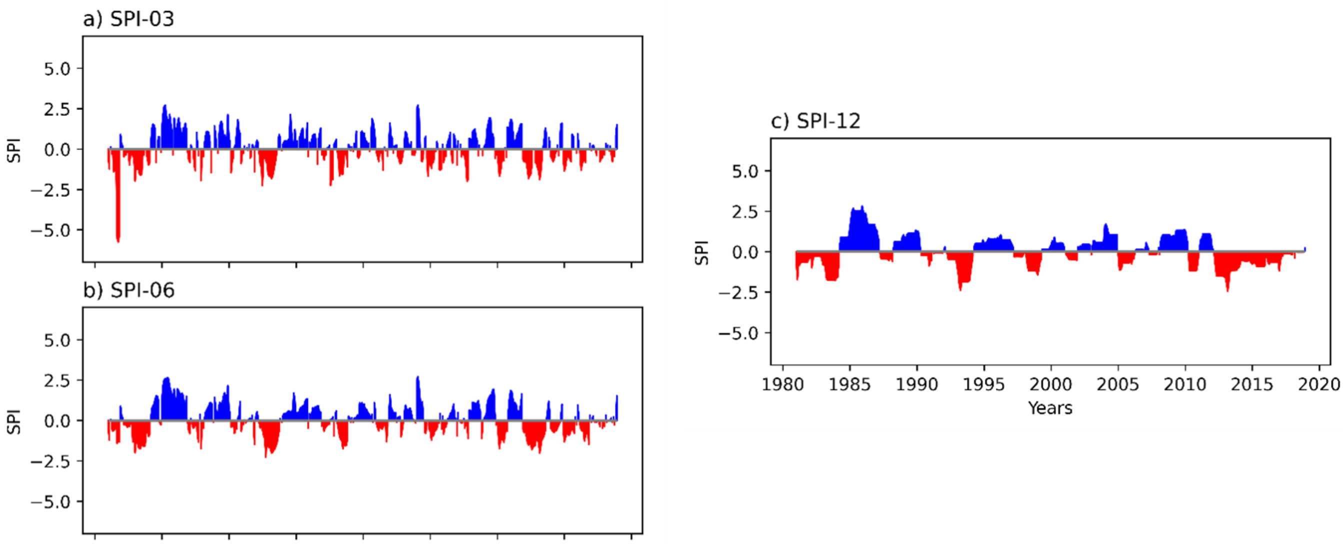

Figure 3 – Standardized precipitation index (SPI) for the state of Ceará in the scales of (A) 3 months (SPI-3), (B) 6 months (SPI-6), and (C) 12 months (SPI-12).

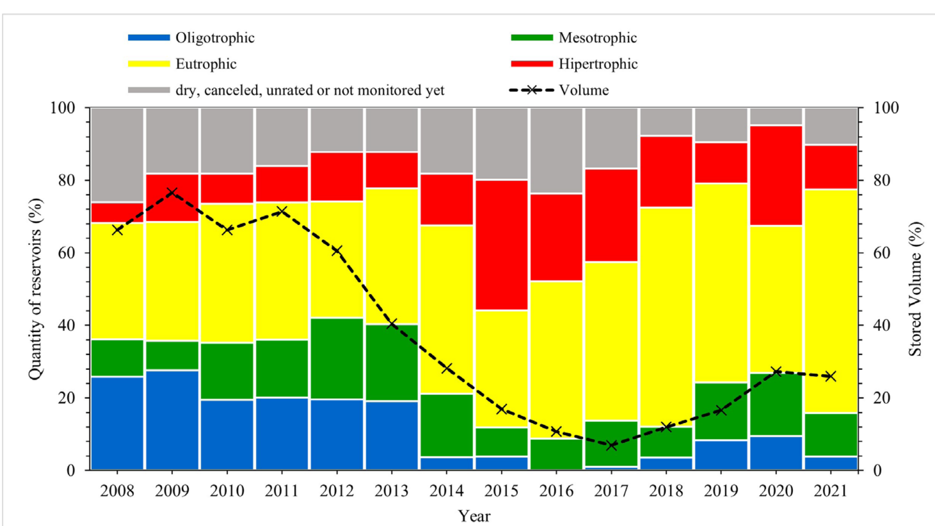

Figure 4 – Time series of the trophic state index classification for the 155 reservoirs monitored by COGERH in the state of Ceará and the percentage volume of water stored by these in relation to the total capacity of the state, for the period between 2008 and 2021.

These changes also affect water transparency and influence the structure of phytoplankton communities (Znachor et al., 2020).

This situation began to change between 2013–2017, a period during which the SPI-12 remained persistently negative, highlighting the severity of the drought. During this time, the reservoir's stored water volume declined significantly, reaching only 8% of its total capacity. Following the same trend, the TSI classification also showed an increase in the number of eutrophic and hypereutrophic dams, so that together they represented 68% of the dams assessed in 2016, with oligotrophic dams having an almost inexpressive representation in that same year.

Accordingly, the change in the TSI during this period can be explained by the fact that tropical reservoirs in dry conditions are more prone to eutrophication than those in humid environments, as the accumulation of nutrients is favored by low and highly variable flows, thus contributing to algal blooms (Wiegand et al., 2016). High temperatures and high evaporation rates during extreme droughts can also influence reservoir respiration and reaeration rates (Mishra et al., 2021). Parallel to this, the force of the wind acting on water bodies with low water levels produces a rapid mixing of water and the resuspension of sediments, changing the properties of the water column and bringing accumulated nutrients from the deeper layers of the weir (Araújo et al., 2016).

Works aimed at studying the trophic state of reservoirs, such as those carried out by Lima et al. (2015) and Santos et al. (2017), respectively, in the Pereira de Miranda and Castanhão reservoirs—both located in Ceará—have concluded that the drought that began in 2012 introduced hydraulic and morphometric characteristics in the reservoirs that allowed the wind to become a disturbance factor. According to the authors, this condition is capable of breaking the stability of the water column, allowing the remobilization of nutrients and sediments accumulated at the bottom of the reservoirs.

The study conducted by Wiegand et al. (2021) evaluated the TSI of 65 reservoirs located in Ceará for the period 2008–2017, and divided the time series in a wet period (2008–2012) and a dry period (2013–2017). The authors reported that, although a significant portion of the reservoirs already presented high TSI (eutrophic and hypereutrophic), it was observed, from 2013, when the NEB suffered a severe drought, that the TSI of at least 91% of the reservoirs increased even more. This phenomenon was mainly associated with the reduction in the volume of the reservoirs, followed by the increase in the concentration of nutrients and chlorophyll-a.

Looking now at the period between 2018–2021, in turn, there is an improvement in weather conditions, demonstrated by the occurrence of rainy events, as best represented by the SPI-3 and SPI-6 (Figures 3A and 3B). During the last years, therefore, an increase in the volume stored by the reservoirs has been noted, reaching 25% of the total capacity at the end of the period analyzed.

Simultaneously, however, the increase in volume was not accompanied by a reversal of the TSI in the monitored reservoirs. Despite the increase in the number of reservoirs, classified as oligotrophic and mesotrophic, eutrophic and hypereutrophic reservoirs, still constituted around 76% of the water bodies assessed in 2021. Raulino et al. (2021) assessed the eutrophication of reservoirs in the semi-arid region under the effects of climate change scenarios. According to the authors, a reduction in reservoir volume generally increases their trophic state and eutrophication process, which, as mentioned, was not observed in the period analyzed.

The hypothesis that water renewal in a reservoir would lead to an expected improvement in the trophic indices of the water body was also tested by Cortez et al. (2022). The authors assessed the variation in the trophic conditions of Cruzeta Reservoir, located in the semi-arid region of NEB, from 2012 to 2019, which was marked by a severe drought. While similar studies in semi-arid regions of Ethiopia have suggested scenarios of improved water quality following drought periods (Teferi et al., 2014), by the end of the study period, Cruzeta Reservoir had shifted from an eutrophic to a hypertrophic state, a transition that was aggravated by the prolonged drought.

Wiegand et al. (2021), in turn, demonstrated a direct correlation between the reduction in reservoir volume due to drought events and the increase in nutrient concentrations and, consequently, the TSI of these reservoirs.

Continuing with the methodology adopted by Wiegand et al. (2021), of dividing the periods studied into 2008–2012 (wet) and 2013–2017 (dry), Figure 5 shows the variation of the limnological variables and the TSI of the reservoirs studied, this time, adding the period 2018–2021 in the analysis, when the SPI began to point out a higher occurrence of rainy weather events.

Therefore, the mean total phosphorus (TP) concentrations ranged from 0.13 mg/L in the period 2008–2012, to 0.14 mg/L during 2013–2017, reaching the average, for the last four years, with 0.11 mg/L. Observing, this time, the concentrations of chlorophyll-a (Chl-a), the period 2008–2012 had an average concentration of 73.9 μg/L, in 2013–2017, the average rose to 85.57 μg/L, and for 2018–2021, the concentration was 79.15 μg/L. Regarding Secchi's average transparency (SD), this had an average value in 2008–2012 of 0.78 m, falling to 0.65 m in 2013–2017, and presenting an average for the period 2018–2021 of 0.79 m.

Table 2 presents a summary of the values obtained in this work for the limnological and TSI variables across different periods, comparing them with the values found by Wiegand et al. (2021) in their assessment of TSI in reservoirs in semi-arid regions. Therefore, it is evidenced that for the periods in which it is possible to make a comparison of values, the limnological variables were in great agreement between the two studies, with an increase in the concentrations of TP and Chl-a and a reduction in SD with the passage of the humid period to the dry period being noticed.

This scenario was also observed by Guimarães and Lima Neto (2023). The authors analyzed the concentrations of Chl-a and total nitrogen in 155 reservoirs distributed across 12 hydrographic regions in the state of Ceará. With the exception of one hydrographic region, an increase in Chl-a concentration was observed from the wet to the dry period, rising from 29.649 to 55.420 µg/L (an increase of approximately 87%). The authors also found that parameter concentrations varied across basins, with higher average concentrations of Chl-a and total nitrogen in basins with denser reservoir networks. Additionally, the seasonal dynamics of Chl-a and total nitrogen were influenced by fluctuations in the volumetric water percentage in the reservoirs. During the dry period, which has a lower average water volume than the wet period, most basins exhibited increased pollutant concentrations.

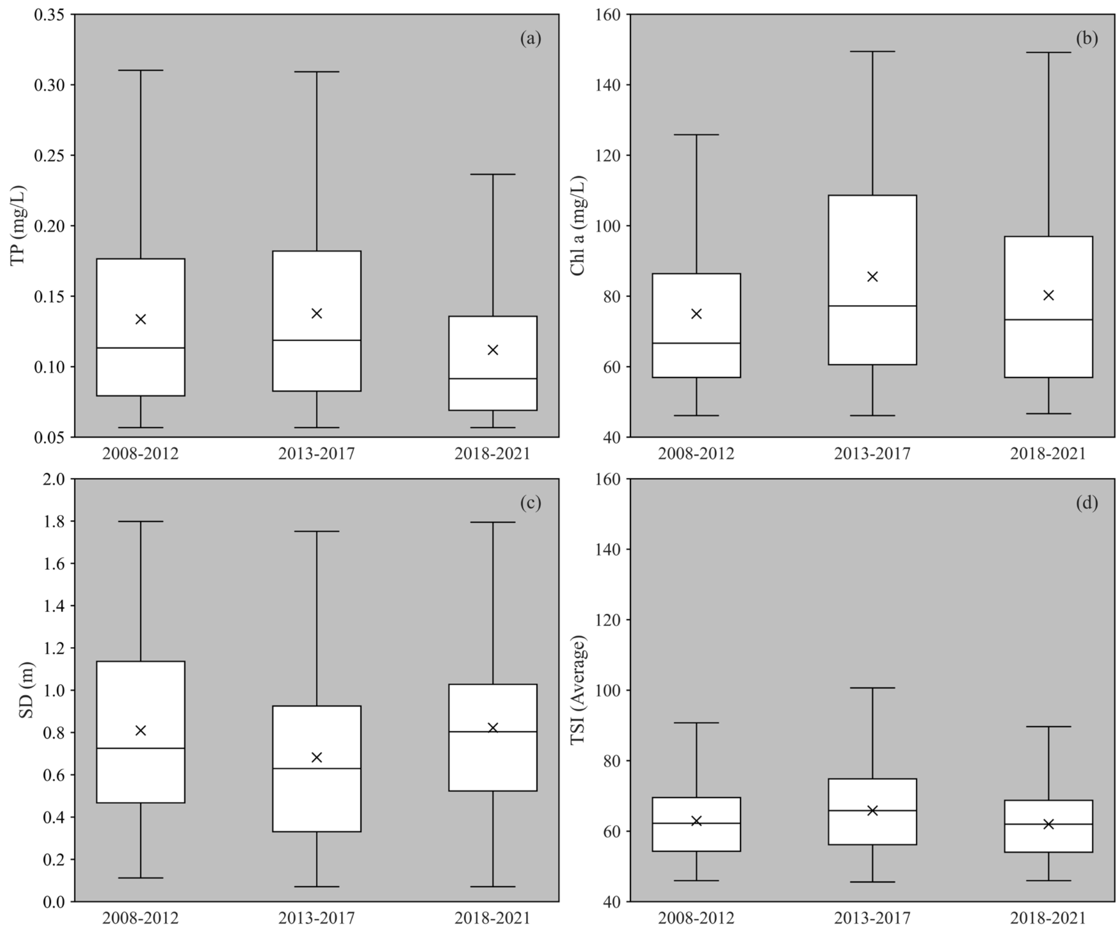

Figure 5 – Box plots of variations in the concentrations of total phosphorus (A), chlorophyll-a (B), Secchi transparency (C), and average trophic state index (D), for 155 reservoirs in the state of Ceará between 2008–2012, 2013–2017, and 2018–2021.

Table 2 - Comparison between the values of the limnological and standardized trophic index variables found by Wiegand et al. (2021) and the present study for the periods 2008–2012 (wet), 2013–2017 (dry), and 2018–2021.

	2008–2012		2013–2017		2018–2021		Mean	
	Wiegand et al. (2021)	Observed	Wiegand et al. (2021)	Observed	Wiegand et al. (2021)	Observed	Wiegand et al. (2021)	Observed
TP (mg/L)	0.12	0.13	0.18	0.14	-	0.11	0.16	0.13
Chl-a (µg/L)	32.26	73.90	88.99	85.57	-	79.15	72.74	79.54
SD (m)	0.95	0.78	0.67	0.65	-	0.79	0.75	0.74
TSI	62.00	62.10	70.00	65.10	-	61.50	67.70	62.90

TP: total phosphorus; Chl-a: chlorophyll-a; SD: transparency; TSI: trophic state index.

However, when the values for the years 2018–2021 are inserted, it can be seen that the mean concentrations of TP and Chl-a fall, respectively, in the order of 0.03 mg/L and 6.42 μg/L, while the SD increases around 0.14, revealing, therefore, an improvement in the water quality standards of the reservoirs with the return of the rainy season.

When analyzing the values found for the TSI, it is noticed, again, a similarity between the results of the two studies. Therefore, both agree with an increase in TSI values with the passage from the dry to the wet period. However, the study by Wiegand et al. (2021) indicates a TSI average of 70 between 2013–2017, while the present study, in the same period, defined an average of 65.1 with a tendency to fall to 61.5 in the subsequent period, when it had a higher frequency of rainy events. The discrepancy found between the studies, however, may be associated with the difference in the number of reservoirs used in the study. It is also noteworthy that, observing the general average of the TSI of the three periods evaluated, it appears that both works classify the set of reservoirs as eutrophic (Carlson, 1977), with an average value of 67.7 in the work by Wiegand et al. (2021) and 62.9 in this study.

Land use and water demands

Despite the importance of studying the influence of climatic and hydrological factors on water quality, these alone are not enough to control changes in the property of water in space and time, being also relevant to assess them, together with anthropogenic factors (Badruzzaman et al., 2012). Changes in LUO and in water demand between its multiple usages are some examples of how anthropogenic pressure can influence the water quality of water bodies.

One of the main factors that compromise the ecological integrity and water quality of different ecosystems around the world refers to the changes in land use patterns, mainly related to urbanization, agriculture, deforestation, and pasture conversion (Miserendino et al., 2011).

Although at the regional scale, climate variability and anthropogenic factors may interact with each other, at the basin scale, these two factors can be considered independent (Li et al., 2016). Figure 6 illustrates the distribution of LUO across the study area, highlighting the predominant characteristics of each basin: Metropolitana (greater influence of urban infrastructure), Médio Jaguaribe (greater influence of agricultural areas), and Acaraú (greater coverage of natural forests). To observe the influence of LUO on the limnological parameters of water in reservoirs at the basin level, Figure 7 compares the values of TP, Chl-a, SD, and TSI among these basins, providing insights into how these factors vary according to the dominant land use.

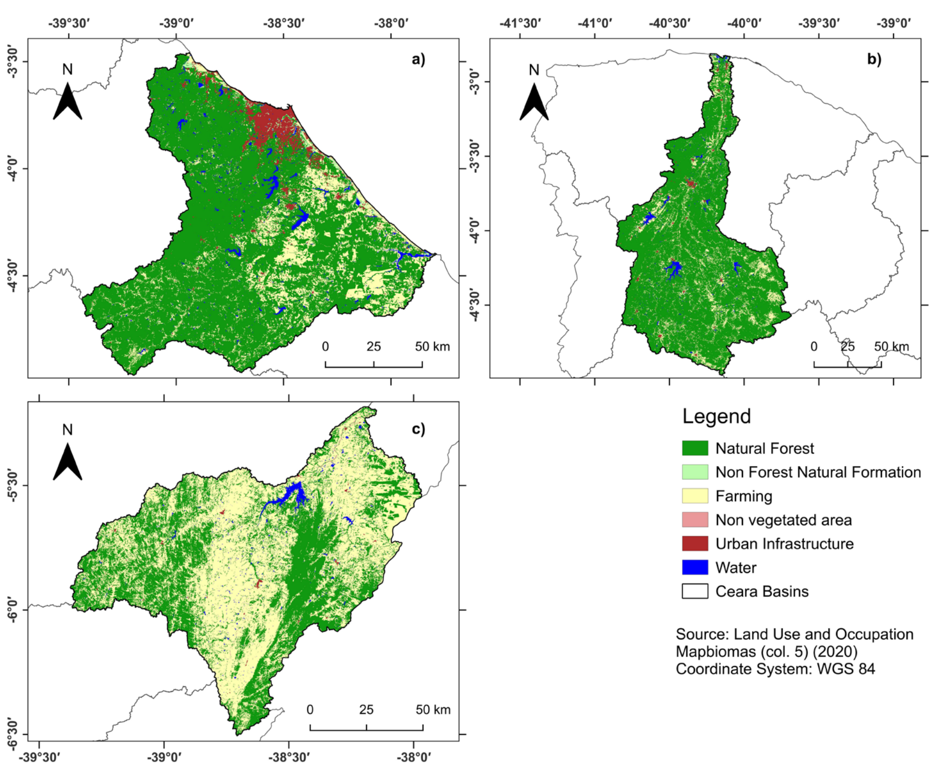

Figure 6 – Land use and occupation maps of the (A) Metropolitana, (B) Acaraú, and (C) Médio Jaguaribe basins for 2019.

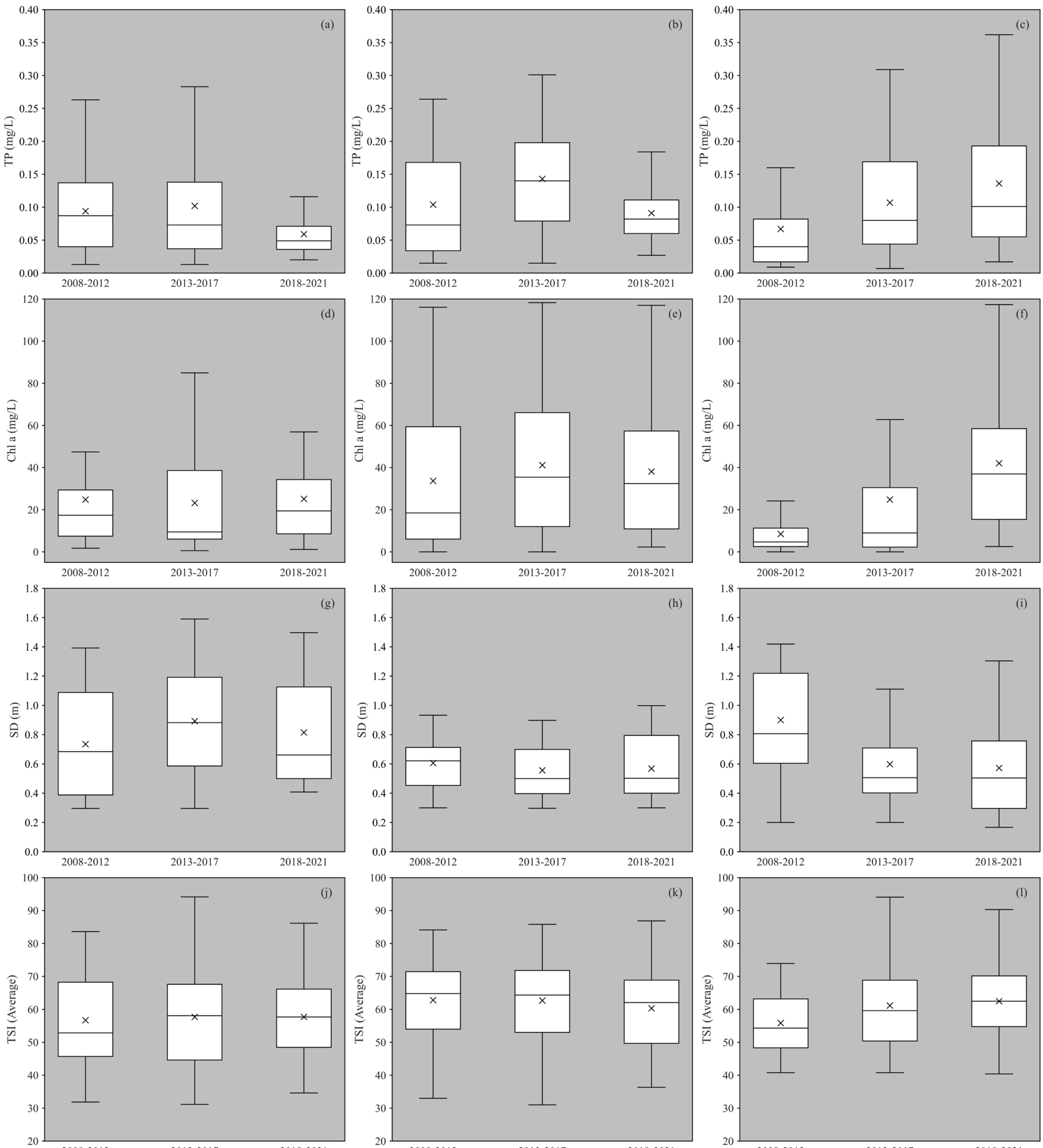

Figure 7 – Boxplots of variations, respectively, for the reservoirs of the Acaraú, Metropolitana, and Médio Jaguaribe basins, in the concentrations of total phosphorus (a, b, c), chlorophyll-a (d, e, f), Secchi transparency (g, h, i) and average trophic state index (j, k, l).

Figure 7 reveals that the reservoirs in the three regions evaluated exhibit similar behavior during the transition from the wet (2008–2012) to the dry period (2013–2017). During this transition, the TSI values increased, primarily due to the rise in the average concentrations of TP and Chl-a. However, this increase was less pronounced in the Acaraú and Metropolitana basins, where the TSI rose from an average of 56.4 and 62.6 during the wet period to 57.6 and 62.7, respectively. Despite these variations, the reservoirs consistently remained in a state of eutrophication throughout both periods, as indicated by the mean TSI values (Carlson, 1977).

In this context, the effect of drought on reservoir water quality was more accentuated in the Médio Jaguaribe basin for which the TSI increased, between the first two periods studied, from an average of 55.4 (eutotrophic) to 60.7 (eutotrophic). In parallel, while this basin had an increase in its average TSI with the return of the wet period—reaching a value of 61.9 (eutotrophic)—, the other two basins had a reduction in their average TSI for the same interval of time. It is pointed out, therefore, that the phenomenon in question was mainly caused by the drastically increase in average concentrations of TP and Chl-a in recent years, probably associated with land use in the Médio Jaguaribe basin that turned to agriculture, since the Metropolitana (more urbanized) and Acaraú (with more areas of forest cover) basins had a reduction in the average concentration of these limnological variables.

This phenomenon can be explained by the tendency of agricultural and urban areas to release nutrients into aquatic ecosystems, triggering eutrophication processes (Le Moal et al., 2019). In support of this, Cortez et al. (2022) also emphasized that eutrophication can be linked to the low water volume in reservoirs and the inflows of nutrient-rich water due to runoff. Semi-arid shallow soils are naturally prone to erosion, leading to nutrient loss that enters the reservoir with rainfall (Mosley, 2015). The nutrients' load is also linked to organic matter in the sediment, considering the reservoir's lack of management before water inflow and the surrounding agricultural activities (Araújo, Lima Neto, and Becker, 2019). Together, these factors contribute to the exacerbation of nutrient loading in aquatic systems, reinforcing the critical role of both water volume and external nutrient sources in driving eutrophic conditions.

Wiegand et al. (2021) observed a discrepancy in TSI values between reservoirs in Ceará's coastal and metropolitan regions. The study attributes this difference to LUO and water demand. Reservoirs in the Metropolitana basin were more eutrophic due to higher population density and industrialization, resulting in significant nutrient loads from domestic sewage and industrial waste. In contrast, the Litoral basin, except during festive periods, experiences lower nutrient input due to its smaller population and less intensive agricultural and industrial activities.

Conclusions

This study addressed drought in Ceará, focusing on its effects on reservoir water quality and emphasizing the roles of climatic extremes and anthropogenic factors. It was observed that the transition from dry to wet periods influenced the average TSI, which increased from 62.1 (2008–2012) to 65.1 (2013–2017) during the dry period and decreased to 61.5 with the return of wet conditions (2018–2021). Despite the increased reservoir volume during the wet period (25% capacity in 2021), the number of eutrophic and hypereutrophic reservoirs rose significantly, representing 76% of the evaluated water bodies. This highlights that greater water availability did not equate to improved water quality.

The reservoirs of the three regions evaluated had similar behavior in the transition from the wet period (2008–2012) to the dry period (2013–2017) since the TSI values showed an increase in this transition, mainly influenced by the increase in concentration average of TP and Chl-a.

The impact of drought on reservoir water quality was most pronounced in the Médio Jaguaribe basin, where the TSI rose significantly from an average of 55.4 (mesotrophic) to 60.7 (eutrophic) during the transition from wet to dry period. Unlike other regions, this basin also experienced a further increase in TSI during the subsequent wet period, reaching 61.9 (eutrophic). This trend is likely linked to rising concentrations of TP and Chl-a, driven by intensified agricultural and livestock activities, as evidenced by the region's land use patterns (Figure 6).

Acknowledgement

The authors sincerely acknowledge the financial support provided by the Coordination for the Improvement of Higher Education Personnel (CAPES).

Authors' Contributions

Magalhães, J.H.F.: conceptualization, data curation, formal analysis, funding, acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing – original draft, writing – review & editing. **Sousa**, F.J.C.: formal analysis, investigation, methodology, software, validation, visualization, writing – review & editing. **Lima**, C.E.S.: conceptualization, data curation, formal analysis, acquisition, investigation, methodology, software, validation, visualization, writing – review & editing. **Silveira**, C.S.: conceptualization, funding, methodology, project administration, resources, supervision, validation, writing – review & editing.

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