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Trophic state changes of semi-arid reservoirs as a function of the hydro-climatic variability

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ABSTRACT

In semi-arid areas, such as the Northeast Region of Brazil (NRB), droughts lead to reduction of reservoir volumes and to increase of nutrient concentrations. The goal was to evaluate the trophic state index (TSI) of semi-arid reservoirs due to interannual variations of precipitation and stored volume. The study included 65 reservoirs in 8 NRB-based watersheds for 2008–2017. From 2013, NRB faced a severe drought that induced a significant reservoir volume reduction. Although the trophic state was already high before the drought (mostly eutrophic and hypereutrophic), the TSI of 91% of the reservoirs increased in the dry period. However, differently from the other watersheds, in which 100% TSI increase was observed for all reservoirs, the groundwater-rich and the lowest-water demand watersheds presented TSI decreases in 30 and 50% of the reservoirs, respectively. Thus, the impact of droughts on these two watersheds was less pronounced, as a potential result of groundwater flow with low-phosphorus concentration into the reservoirs of the former watershed, and lower nutrient loads/higher stored reservoir volumes of the latter one. Simple empirical equations, which are capable to estimate the mean TSI based solely on precipitation and reservoir volume, showed to be potential tools for integrated water management.

1. Introduction

The Northeast Region of Brazil (NRB) is home for more than 50 million people and is the third most important economic area of the country. However, it faces both a natural water deficit due to its semi-arid climate and recurrent droughts. In order to overcome water scarcity, the construction of surface reservoirs fed by the streamflow originating from the rainfall was the main water management practice for farms, industry, municipalities and state and federal governments over the last century. Those reservoirs, in fact, helped minimize the impact of dry seasons and meteorological droughts, improving locally the water availability and making up to approximately 90% of the total water supply in NRB (Araújo et al., 2006; Moura et al., 2012). However, the large number of reservoirs has reduced the total water availability at catchment scale (Malveira et al., 2012), amplified the intensity of hydrological droughts (Van Oel et al., 2018) and deteriorated the water quality for human consumption by silting and eutrophication (Lima Neto et al., 2011; Pacheco and Lima Neto, 2017; Lima et al., 2018; Araújo et al., 2019).

The NRB-based reservoirs are generally prone to eutrophication (Barbosa et al., 2012). Their water quality may be affected by many factors, such as: reservoir accumulated volume (Braga et al., 2015; Rocha Junior et al., 2018; Lira et al., 2020), precipitation (Chaves et al., 2013), external load of nutrients (Lopes et al., 2014; Araújo et al., 2019), internal enrichment due to aquaculture (Santos et al., 2017), sediment and phosphorus resuspension (Mesquita et al., 2020), and internal phosphorus loadings (Moura et al., 2019).

Chaves et al. (2013), for example, evaluated the trophic conditions of a medium-sized semi-arid reservoir for a period of two years. The authors found that the trophic state was directly related to the seasonal rainfall variability. Jeppesen et al. (2015) also showed that the irregular rainfall distribution, which drives the hydrological regime of water and nutrient sources in NRB, may increase the reservoir turbidity and algae biomass, changing reservoir trophic state, consequently. On the other

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hand, Brasil et al. (2016) and Rocha Júnior et al. (2018) pointed out that the decrease of reservoir volume leads to a rise of nutrient and chlorophyll-a concentrations during the dry season. However, the drop of reservoir volume and depth may also trigger the reservoir sediment resuspension due to the wind action, which may limit the growth of phytoplankton (Costa et al., 2016).

Although providing some insights on the eutrophication process and its relationship with hydro-climate variables in some Brazilian semi-arid reservoirs, those studies are, however, site-specific that undermines any attempt to extrapolate their findings to poorly gauged or ungauged reservoirs, which are normally in need of water management. Also, catchment heterogeneity, including land use, is a quite important driver of reservoir water quality (Yamashiki et al., 2003; Krol et al., 2011; Liu et al., 2012; Rattan et al., 2019), which has not been properly investigated yet. Moreover, it is unknown so far how a persistent drought alters the magnitude and the variability of the aforementioned eutrophication features. Hence, two main questions remain open:

(1) How droughts and land use affect the trophic state of semi-arid reservoirs?
(2) Can hydro-climatic variables such as rainfall and reservoir volume describe the changes in the physical, chemical and biological properties of the water?

To deal with such issues, this study aims to analyze the trophic state changes of 65 NRB-based reservoirs as a function of the hydro-climatic variability, including a long period of drought. First, a characterization of the inter-annual hydro-climatic variability in the last decade will be carried out, considering meteorological and hydrological droughts (Wilhite and Glantz, 1985). Second, the reservoir limnological variables (total phosphorus, chlorophyll-a and transparency) will be evaluated, as well as the trophic state index (TSI), together with the hydro-climatic variability and the general watershed characteristics. Then, the annual TSI of each reservoir will be fitted by simple empirical equations using only hydrological variables, to assess both the hydrological influence on the eutrophication process and the possibility of prediction of TSI in reservoirs with poorly or no water quality monitoring system. Finally, we will show how our findings may help improve the current reservoir water allocation framework in NRB, which is based on the hydro-climatic variability, and predict the effects of climate changes on the reservoir water quality.

Instead of applying mechanistic models to predict the total phosphorus concentration in each reservoir (Araújo et al., 2019; Moura et al., 2019; Lira et al., 2020; Mesquita et al., 2020), which requires a large amount of data that is barely available, the goal of the present study is to propose a simple tool, based only on rainfall and reservoir volume, to predict TSI and potentially improve integrated water resources management in NRB-reservoir networks.

2. Material and methods

2.1. Study area

The present study covers 65 reservoirs located in eight watersheds of the State of Ceará in the NRB, namely, Banabuiú, Upper Jaguaribe, Middle Jaguaribe, Lower Jaguaribe, Crateús, Salgado, Litoral and Metropolitan (see Fig. 1). These reservoirs were selected because since 2008 they have been monitored by the Ceará Water Resources Management Company (COGERH), presenting consistent time series of hydrological and water quality parameters. The state of Ceará has 90% of its area located in a hot semi-arid climate (BSw'h', according to Koppen's classification) (SUDENE, 2017). The vegetation is mainly formed by a xerophytic thorn-bearing woodland, the Brazilian Dryland Forest. The soil is shallow and much of its basement is formed by crystalline bedrocks (80%) with low density of fractures, making groundwater resources predominantly concentrated and scarce (Araújo, 2011). However, there is regional groundwater flow, occurring on the state borders and in a large sedimentary basin in the state Southeast, called *Araripe* basin (Ceará, 2010; 2011). Note that the Salgado watershed is located within this sedimentary basin (see Fig. 1).

The Brazilian semi-arid region basically has two synoptic systems that drive rainfall: (1) the upper air cyclonic vortices (UACV) and (2) the intertropical convergence zone (ITCZ). The UACV system generates rains from January to February, while the ITCZ drives rainfall mainly from March to June. The UACV rains are usually insufficient to produce streamflow, however, they moisten the landscape, allowing favorable catchment moisture conditions to trigger river flows by ITCZ rains. Normally, 70% of the annual rainfall occurs from February to May. However, the temporal and spatial rainfall variability is highly significant on interannual, seasonal and event-based scales (Campos, 2011).

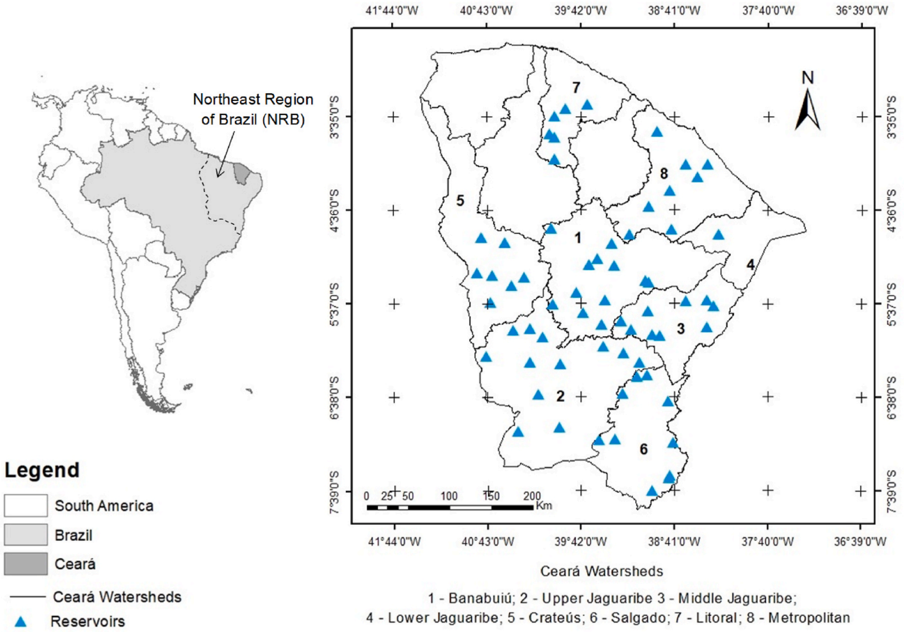

Fig. 1. Location of 65 studied reservoirs in eight watersheds of the State of Ceará in the Northeast Region of Brazil (NRB).

The annual rainfall ranges from 550 to 850 mm. In contrast, the potential evaporation can be up to four times higher, with an annual value of 2550 mm (Araújo and Piedra, 2009; Araújo, 2011). Not only because of the rainfall regime and the high evaporation rates, but also because of the shallow soil and the rugged topography, few rivers are able to withstand some weeks or even some days after the rainy season. Thus, there are two main surface water regimes: lotic waters in the rainy season and lentic ones in the dry season. The lotic ecosystem is formed by ephemeral and intermittent rivers, which are dominantly endogenous. The lentic ecosystem is predominantly based on about 7000 man-made reservoirs with a flooded area larger than 5 ha (FUNCEME, 2008). Such unmonitored reservoirs were not always planned at larger scale but rather made by farmers, normally with financial help of government bodies, according to their local needs of water supply (Mamede et al., 2012).

2.2. Data source

In this study, the rainfall data were obtained from the Foundation of Meteorology and Water Resources of Ceará (FUNCEME). The reservoir volume and water quality data, including Secchi disk depth (SD), total phosphorus concentration (TP) and chlorophyll-a concentration (Chl-a), were made available by the Ceará Hydrological Portal (http://www.hidro.ce.gov.br/), which was jointly developed by the Water Resources of the State of Ceará Secretary (SRH), FUNCEME, and the Ceará Water Resources Management Company (COGERH). The technical reservoir characteristics (Table 1) were obtained from the ATLAS/SRH (http://atlas.cogerh.com.br/). All data comprise a period from 2008 to 2017. Although many factors such as salinity, pH, dissolved oxygen concentration, sediment composition, reservoir age, wind speed, thermal stratification, among others, potentially affect the trophic state of the reservoirs (Araújo et al., 2019; Moura et al., 2019; Lira et al., 2020; Mesquita et al., 2020), these data were not available as they are not included in the monitoring program of COGERH.

2.3. Trophic state index (TSI)

The trophic state index (TSI) of each reservoir was calculated by using the equations described by Carlson (1977):

$$TSI(SD) = 10\left[6 - \ln SD / \ln 2\right] \tag{1}$$

$$TSI(Chl-a) = 10\left[6 - (2.04 - 0.68 \ln Chl - a) / \ln 2\right] \tag{2}$$

$$TSI(TP) = 10\left(6 - \ln\left(48/TP\right) \Big/ \ln 2\right) \tag{3}$$

Where: SD = Secchi disk depth (m); TP = total phosphorus concentration (μg.L^{-1}); and Chl-*a* = chlorophyll-a concentration (μg.L^{-1}).

Hence, the average TSI was calculated by:

$$TSI(\text{Average}) = [TSI(SD) + TSI(Chl - a) + TSI(TP)]/3 \tag{4}$$

According to the classification of TSI (Carlson, 1977; Carlson and Simpson, 1996), the following trophic states were considered: oligotrophic (TSI $\leq$ 40), mesotrophic (40.1 $\leq$ TSI $\leq$ 50.0), eutrophic (50.1 $\leq$ TSI $\leq$ 70.0), and hypereutrophic (TSI $\geq$ 70.1).

Table 1
General characteristics of the evaluated 65 reservoirs.

	Range	Average
Age (years)	4–101	36
Watershed area (km^2)	16–44,800	2131
Flooded area (ha)	13–32,500	2250
Reservoir capacity (hm^3)	2.4–6700	212

2.4. Empirical equations

Spearman's correlations from 2008 to 2017 were calculated between the average annual TSI and a function of the accumulated volume and precipitation of each reservoir, represented by a dimensionless parameter Φ (Pacheco et al., 2016):

$$\Phi = 1 - [V(\%)]^a + [P(\%)]^b \tag{5}$$

where: Φ = dimensionless parameter adjusted for V (%) and P (%), V = accumulated volume percentage related to the reservoir capacity, P = precipitation percentage related to the maximum observed precipitation, and "a" and "b" = adjustment coefficients.

The accumulated volume percentage of each reservoir was calculated from the ratio between the average annual volume and reservoir capacity. The precipitation percentage of each reservoir was determined by the ratio between the annual precipitation and the maximum observed precipitation in the municipality, where the reservoir is located, within the evaluation period (2008–2017).

2.5. Basic statistics

The Mann-Whitney test was used to compare the median of precipitation, accumulated volume, total phosphorus, chlorophyll-a, Secchi transparency and average TSI, adopting a significance level (α) of 5%.

3. Results and discussion

3.1. Hydrological variables and drought definition

As an example, Fig. 2 shows the Monsenhor-Tabosa reservoir time series of water volume, rainfall, limnologic variables and the average TSI for 2008–2017. The state of Ceará faced a long and severe period of drought triggered in 2012 (see Fig. 2). From that year on, the annual precipitation was normally below the average for all eight watersheds. Mean precipitation in 2012 was, for example, 259 mm in the Banabuiú watershed and 374 mm in the Middle Jaguaribe watershed. Araújo and Bronstert (2015) already reported that meteorological droughts were identified for most of Ceará reservoir catchments in 2012.

However, the reservoirs still had a good accumulation conditions in 2012, with an average volume of about 50% among the watersheds, i.e. the hydrological drought, which lasted until the end of the provided time series, had not started yet. Therefore, two distinct periods were assumed according to the occurrence or not of the hydrological drought: from 2013 to 2017 (dry) and from 2008 to 2012 (moist), respectively. During the former period the average reservoir volume was only 15%, while during the latter period it was 65%. Moreover, 33 out of the studied reservoirs were completely empty (accumulated volume < 1% of total) by the end of the dry period. Fig. 3 presents the variations in precipitation and reservoir volume between the two periods. The statistical Mann-Whitney test showed a significant difference ($p < 0.05$) between the moist and the dry periods.

3.2. Limnological variables and drought impact

The average total phosphorus concentration for the evaluated reservoirs was 0.16 (±0.21) mg.L^{-1}. The average value for the period from 2008 to 2012 (moist) was 0.12 (±0.14) mg.L^{-1}, with a minimum of 0.01 mg.L^{-1} and a maximum of 1.46 mg.L^{-1}. The period from 2013 to 2017 (dry) had a mean of 0.18 (±0.22) mg.L^{-1} with a minimum concentration of 0.01 mg.L^{-1} and a maximum of 3.45 mg.L^{-1}. Regarding the concentration of chlorophyll-a, the average value found was 72.74 (±128.27) μg.L^{-1}. The period from 2008 to 2012 showed an average

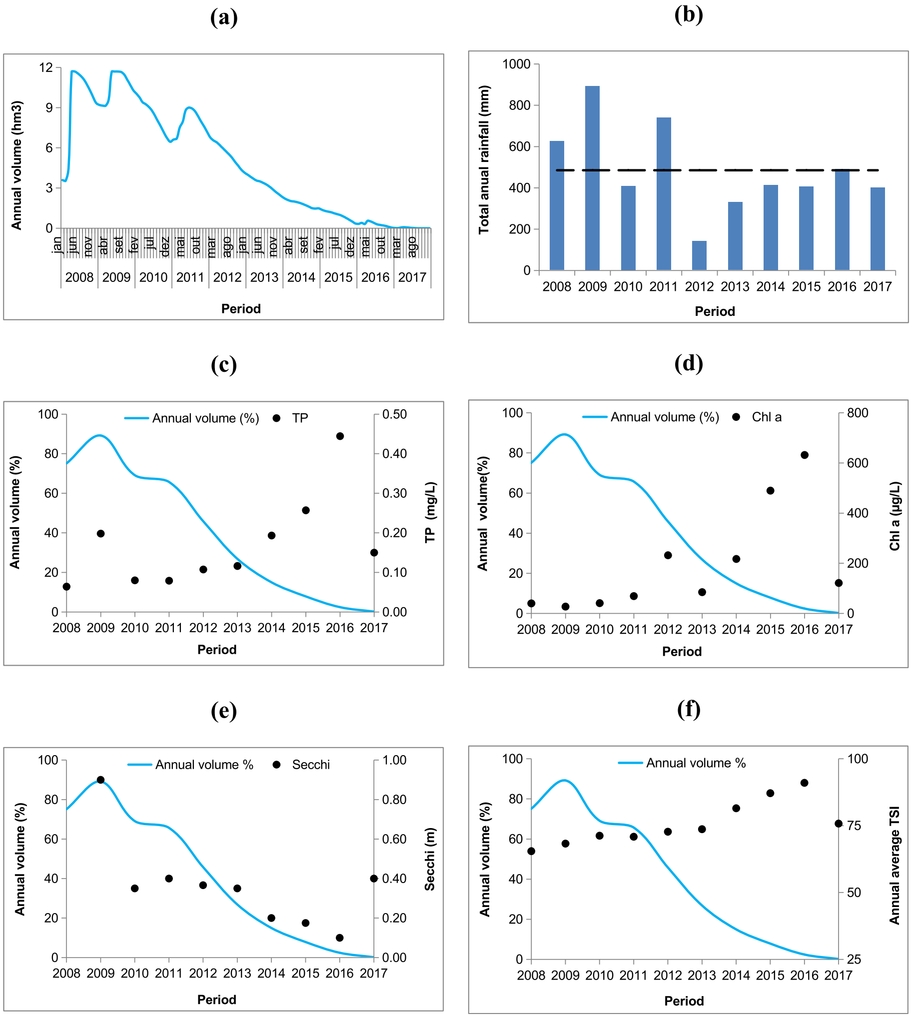

Fig. 2. Reservoir volume, precipitation and limnological variables in Monsenhor-Tabosa reservoir from 2008 to 2017. (a) annual volume, (b) annual rainfall (dashed line represents the average during the period: 585.5 mm), (c) annual volume in percentage versus annual average concentration of total phosphorus, (d) annual volume in percentage versus average annual concentration of chlorophyll-a, (e) annual volume in percentage versus Secchi transparency, and (f) annual volume in percentage versus average TSI.

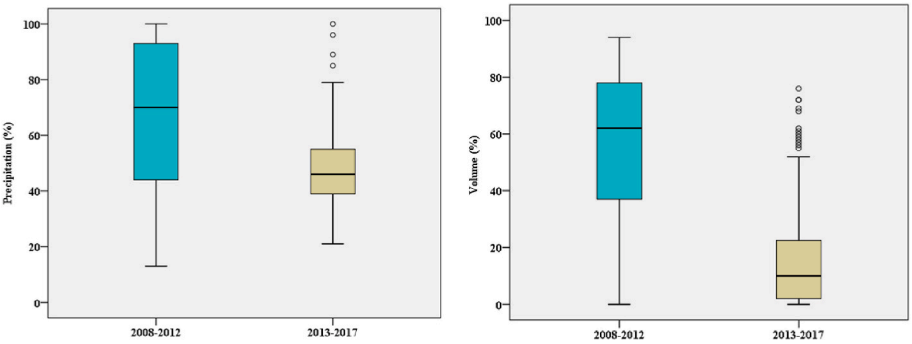

Fig. 3. Box plots of variations in precipitation ($N_{2008\text{-}2012} = 321$; $N_{2013\text{-}2017} = 325$) and accumulated volumes ($N_{2008\text{-}2012} = 309$; $N_{2013\text{-}2017} = 325$) in 65 reservoirs of Ceará. The statistical Mann-Whitney test showed a significant difference ($p < 0.05$) between the periods. Horizontal lines indicate the median and the limits of the graphs indicate the P25 and P75 percentiles. The above and below lines indicate the P90 and P10 percentiles. Circles and stars are outliers and extreme points, respectively.

concentration of 32.26 (±56.67) µg.L^{-1} with minimum and maximum of 0.51 µg.L^{-1} and 539.30 µg.L^{-1}, respectively. In the period from 2013 to 2017, the average concentration was 88.99 (±144.41) µg.L^{-1}. The minimum concentration was 0.20 µg.L^{-1} and the maximum concentration was 1384.93 µg.L^{-1}. The average Secchi transparency was 0.75 (±0.60) m. The period from 2008 to 2012 showed an average transparency of 0.95 (±0.67) m, with minimum and maximum values of 0.10 and 3.70 m, respectively. Regarding the period from 2013 to 2017, the average transparency observed was 0.67 (±0.55) m. The minimum and maximum values were 0.05 m and 4.20 m, respectively. The overall TSI for the 65 reservoirs was 67.7 ± 6.7, which is considered as eutrophic (Carlson and Simpson, 1996). However, one reservoir (1.5%) was characterized as mesotrophic, 39 (60.0%) as eutrophic, and 25 (38.5%) as hypereutrophic. The period from 2008 to 2012 showed a TSI of 62.0 ± 6.6 (eutrophic), with a maximum value of 76.0 (hypereutrophic) and minimum value of 44.3 (mesotrophic). In the period from 2013 to 2017, the TSI increased to 70.0 ± 7.7 (upper limit of eutrophic range), with a maximum value of 83.0 (hypereutrophic) and a minimum value of 46.8 (mesotrophic). Fig. 4 presents the variation of limnological variables and the TSI. The statistical Mann-Whitney test showed a significant difference ($p < 0.05$) between the moist and the dry periods.

Our analyses are supported by last site-specific studies. For example, Santos et al. (2017) found relevant changes in the physical and chemical parameters of water and in the trophic state of the Castanhão reservoir

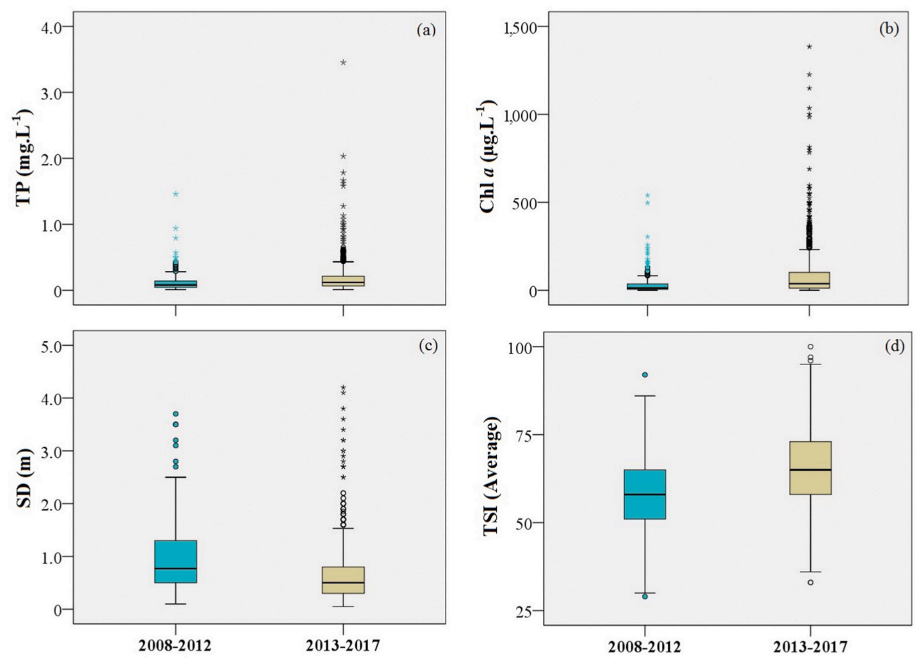

Fig. 4. Box plots of variations in the concentrations of total phosphorus ($N_{2008\text{-}2012} = 319$; $N_{2013\text{-}2017} = 910$; in a), chlorophyll-a ($N_{2008\text{-}2012} = 344$; $N_{2013\text{-}2017} = 857$; in b), Secchi transparency ($N_{2008\text{-}2012} = 308$; $N_{2013\text{-}2017} = 782$; in c), and average TSI ($N_{2008\text{-}2012} = 62$; $N_{2013\text{-}2017} = 70$; in d), for 65 reservoirs of Ceará, from 2008 to 2012, and from 2013 to 2017. The statistical Mann-Whitney test showed a significant difference ($p < 0.05$) between the periods. Horizontal lines indicate the median and the limits of the graphs indicate the P25 and P75 percentiles. The above and below lines indicate the P90 and P10 percentiles. Circles and stars are outliers and extreme points, respectively.

in the Middle Jaguaribe watershed, the largest reservoir in the state of Ceará, after four consecutive years of below-average rainfall. Lacerda et al. (2018) pointed out how nutrient concentration, water column mixing and sediment resuspension contributed to the Castanhão reservoir TSI increase during a dry period. Braga et al. (2015) investigated water quality patterns of two medium-sized semi-arid reservoirs in Brazil after two years of rainfall scarcity. In both water bodies, the reservoir volume was considerably reduced, contributing to the water quality degradation due to increase in algae biomass and turbidity. Similar findings can be related to the Orós reservoir, the second largest reservoir in the state of Ceará and located in the Upper Jaguaribe watershed, according to Santos et al. (2014).

3.3. *Influence of the watershed heterogeneity*

Summarily, 91% of the reservoirs presented an increase in the average TSI from the moist (2008–2012) to the drought (2013–2017) periods, due to the reservoir volume reduction, followed by the increase of nutrient and chlorophyll-a concentration, and by the decrease in transparency. However, those changes in trophic level did not necessarily lead to changes in trophic state. Moreover, we found out that the trophic state dynamics was not uniform among the studied watersheds. One can group up six watersheds, namely Metropolitan, Banabuiú, Middle Jaguaribe, Lower Jaguaribe, Upper Jaguaribe and Crateús in terms of similar behaviours, in which TSI increased in all reservoirs. While the Salgado and Litoral watersheds together showed a rather different dynamics, with TSI decreasing in 30 and 50% of the reservoirs, respectively, some questions arise. First, although the Litoral and the Metropolitan (coastal) watersheds had similar hydro-climatic patterns, why did their reservoir TSI behave so distinctly? Second, why did the Salgado watershed not resemble the other inland watersheds?

The differences of the reservoir TSI changes between the Litoral and the Metropolitan watersheds shown in Fig. 5(a) may be explained by their land and water use characteristics, which can be potentially represented by their water demands [Fig. 5(b)]. Note that the total water demand for the eight watersheds is 35 m^3/s, and includes domestic, industrial and agricultural uses, according to the State Plan of Water Resources (PERH, 2005). The Metropolitan watershed has the highest population density and is the most industrialized area of the state, producing a large nutrient load into the water bodies by significant discharges of domestic sewage and industrial wastes. This is reflected by the highest water demand (37%) shown in Fig. 5(b). On the other hand, the Litoral watershed, excluding the festive dates, has a much lower population density and very low industrial and agricultural activities that leads to a lower nutrient contribution to the aquatic ecosystems. Moreover, the average volume of reservoirs in the Litoral watershed remained quite high, around 65% during the entire period. Consistently, the lowest water demand (1%) shown in Fig. 5(b) belongs to the Litoral

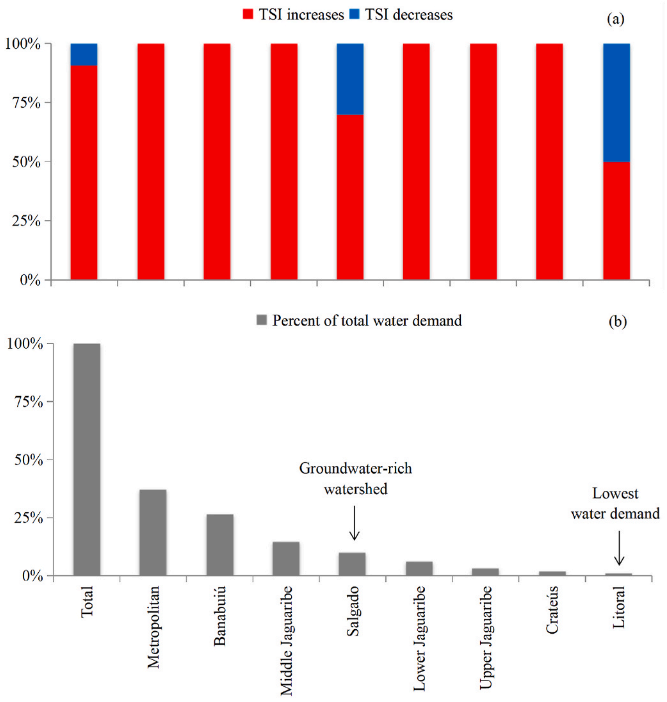

Fig. 5. Percentage of (a) trophic state index (TSI) changes from 2008 to 2012 (moist) to 2013–2017 (dry) among the studied watersheds, and (b) water demand (including domestic, industrial and agricultural uses) obtained from the State Plan of Water Resources.

watershed. This trend is in agreement with the results of Lira et al. (2020), who showed that the TSI is a strong function of the volume of NRB-based reservoirs. The Salgado watershed has the best sedimentary geological formations, which are found in the *Araripe* basin, for groundwater storage and release, providing significant groundwater reserves, whose wells are up to 1000 m deep and have discharges reaching 300 m^3/h (Ceará, 2011). Machado et al. (2004) showed hydraulic connectivity between the different *Araripe* aquifer systems. Mendonça et al. (2004) found isotopic similarities between wells and small reservoirs, supporting the hypothesis of interaction between surface waters and groundwater flow. In fact, the relatively good quality of the Salgado watershed waters may be associated with its connection to the regional groundwater flow. Lewandowski et al. (2015) showed many possibilities of large decreases of total phosphorus at aquifer-lake interface, for example, due to water recharge and increased oxygen availability. Moura et al. (2019) confirmed that increased oxygen concentration can significantly reduce internal phosphorus loadings in NRB-based reservoirs.

3.4. Modelling of the trophic state index (TSI)

Fig. 6 illustrates linear regressions between the average TSI and the Φ parameter (a function of precipitation and accumulated volume, both in percentage) from four reservoirs, being three out of them (Castanhão, Orós and Banabuiú reservoirs) the main water reserves of the state of Ceará. Table A1 in appendix lists the linear regressions for the 65 evaluated reservoirs. Although the simplicity of the linear regressions, the calculated Spearman's correlations were worthwhile (ρ = 0.41–0.99), confirming the strong hydrological influence on the eutrophication process in NRB-based water bodies. The underlying processes behind these high correlations are (1) the higher precipitation increases the nutrient loads into the reservoirs (Chaves et al., 2013), and (2) the reservoir volume reduction increases the nutrient concentration (Lira et al., 2020), which lead to the increase of TSI. Similarly, Gelca et al. (2016) also showed consistent correlations between water quality variables and climate predictors for 57 reservoirs in Texas, US.

Due to the shortness of the time series per reservoir, it was not possible to apply a more robust assessment of the fitted empirical equations, such as the selection of a specific dataset for validation. Thus, in a simplified manner, we compared the measured and modeled TSI for the whole study period (Table A1). In general, the average measured and modeled TSI were very close, with an average difference of about 7%. In addition, the measured and modeled trophic levels were equal in 44 (about 70%) from the 65 reservoirs during the period studied.

It is interesting to stress, however, that five reservoirs located in the Salgado watershed (in bold in Table A1) had a different best-fitted linear regression: the TSI increases with an increasing accumulated volume and decreasing precipitation. This rather different behavior can be explained for the Tatajuba reservoir, because it had an average accumulated volume of 77% in the wet period and 54% in the dry one, which are much higher than 15% of average volume found for all reservoirs during 2013–2017. For the other four reservoirs (Prazeres, Manoel Balbino, Gomes and Thomas Osterne), the reason may be the interaction between the surface waters and groundwater flow in the *Araripe* Basin, where these reservoirs are located, because large decreases of total phosphorus may take place at aquifer-lake interface, as already discussed in section 3.3.

3.5. How could the reservoir water allocation be improved?

In the studied watersheds, the allocation of the reservoir waters is negotiated among the users and the COGERH mediates this negotiation. The allocation is planned for a period of 6–18 months ahead after the natural recharge of the reservoirs by the end of the rainy season. Assuming average lake evaporation and negligible inflow to the reservoir (worst-case scenario), reservoir emptying is simulated with different scenarios of water release. After analyzing the reservoir emptying simulations, the watershed committee decides on the total reservoir release and the user water amounts. In this process, an estimation of the TSI could be carried out, since we showed that it is just a function of the cumulative volume and precipitation. Including the reservoir trophic state dimension, one could improve water allocation plans or trigger measures of water conservation, such as: the non-use of high eutrophic reservoirs for human supply or the improvement of water treatment plant efficiency, respectively.

In further work, examples of including a projection of reservoir trophic state changes in the reservoir water allocation framework will be investigated. Also, a sustainability index could be developed in order to

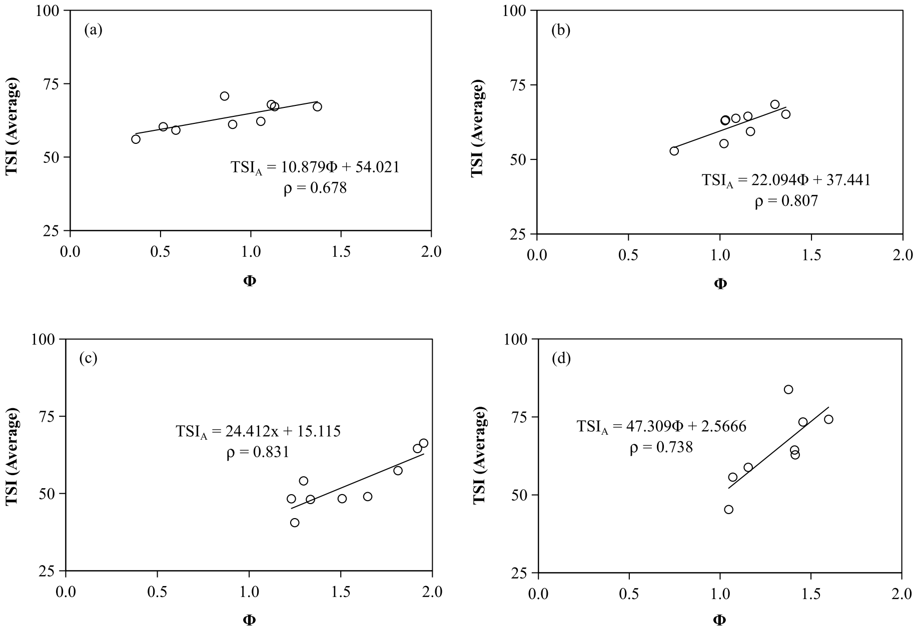

Fig. 6. Spearman's correlations (ρ) between the average TSI and the Φ parameter (function of precipitation and accumulation volume, both as a percentage) for four reservoirs: (a) Banabuiú, (b) Orós, (c) Castanhão, and (d) S. Ant. de Russas.

evaluate the water availability and supply in the region, considering measures of vulnerability, resilience and drought (see e.g. Vieira and Sandoval-Solis, 2019).

3.6. *How could the climate changes affect the reservoir water quality?*

Marengo et al. (2012) showed that, in addition to rising temperatures causing a warmer climate, precipitation in the Brazilian semi-arid region could be reduced up to 40% by 2100 due to global climate change. Taking into account precipitation and temperature projections from CMIP5 global models, Silveira et al. (2016) found positive trend for temperature and precipitation anomalies between −20% and 20% for the São Francisco River Basin, the most important NRB watershed. According to Brasil et al. (2016), the future warmer, drier climate projected by different climate scenarios will reduce the quantity and quality of water in 40 tropical shallow man-made lakes in Brazil, increasing the risks of salinization, anoxia and eutrophication, considering the present-day relationships between water quality and atmospheric variables (see also Gelca et al., 2016).

Thus, considering no relevant changes of land and water use patterns on the long-term, the possible warmer, drier climate in NRB may drive even higher trophic levels due to the decrease of surface water availability. The most vulnerable watershed is the Metropolitan one, where the main socio-economic activities are concentrated, followed by the inland watersheds (Middle Jaguaribe, Upper Jaguaribe, Crateús and Banabuiú). Also, it is questionable whether the Litoral and Salgado watersheds will keep with the relatively good water quality conditions in the future.

In further work, the fitted linear regressions could be used to specifically assess the impact of global climate changes on the eutrophication of the studied water bodies. The atmospheric model(s) can project the precipitation over the reservoir lake and its evaporation, a hydrological model coupled with the atmospheric one(s) can be used to simulate reservoir inflows and one can prognose the future reservoir abstractions. The result accumulated volume from the projected water balance components and the projected precipitation can provide future trophic state changes, using the proposed empirical equations.

4. Conclusions

The development of a persistent hydrological drought drove the TSI increase of about 90% of 65 reservoirs (2.4–6700 hm^3) in the Northeast Region of Brazil, home for more than 50 million people. The reservoir volume reduction was followed by an increase in phosphorus and chlorophyll-a concentrations and decrease in transparency. The minimum TSI (44.3–46.8), the average TSI (62.0 ± 6.6 to 70.0 ± 7.7) and the maximum TSI (76.0–83.0) increased from the wet period (2008–2012) to the hydrological drought (2013–2017), respectively. The trophic state rose for 36 reservoirs (55.4%), normally from mesotrophic to eutrophic, and dropped for 1 reservoir (1.5%), during the hydrological drought. For 28 reservoirs (43.1%), the trophic state remained the same, although most of them showed an increase in their TSI. This confirmed that droughts have an important effect on the trophic state of semi-arid reservoirs.

Although more humid than the inland semi-arid watersheds, the Metropolitan watershed, where the main socio-economic activities of the state of Ceará take place, had a major drought impact on the surface water quality. All Metropolitan reservoirs had an increase in TSI because large amount of nutrients from domestic sewage and industrial wastes are discharged into the water bodies. Also, it is probably the most vulnerable watershed to climate change effects, followed by the inland watersheds (Banabuiú, Middle Jaguaribe, Lower Jaguaribe, Upper Jaguaribe and Crateús), since a warmer, drier climate in NRB has been projected by the end of this century. On the other hand, the groundwater-rich watershed (Salgado) and the lowest-water demand watershed (Litoral) had 30 and 50% of the reservoirs decreasing their TSI, respectively. This was attributed to decreases of total phosphorus at aquifer-lake interface and lower nutrient loads/higher stored volumes, respectively. These results suggest that land use has a relevant impact on the trophic state of semi-arid reservoirs.

Simple empirical equations based solely on rainfall and reservoir volume were obtained for prediction of the TSI in each reservoir. The measured and modeled TSI were very close, with an average difference of about 7%. Additionally, the measured and modeled trophic levels were equal in 44 (about 70%) from the 65 reservoirs in the period from 2008 to 2017. Although their simplicity, the developed empirical equations are promising tools for the inclusion of the eutrophication process dimension in the negotiated allocation of Ceará-based reservoir waters, as they are only a function of accumulated volume and precipitation, which can be easily projected in different reservoir emptying scenarios. In addition, the empirical equations can be used to specifically assess the impact of global climate changes on the eutrophication of the studied water bodies by coupling atmospheric and hydrological models: the first can project precipitation and the latter reservoir volume.

CRediT authorship contribution statement

Mário César Wiegand: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization. **Antônia Tatiana Pinheiro do Nascimento:** Software, Validation, Formal analysis, Resources, Data curation, Visualization. **Alexandre Cunha Costa:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **Iran Eduardo Lima Neto:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A.1Measured and modeled average TSI (TS_e and TS_o, respectively) of the 65 evaluated reservoirs; equations for estimating the average TSI depending on the percentage of accumulated volume and precipitation ($\Phi = 1 - [V(\%)]^a + [P(\%)]^b$); Spearman's correlation (ρ); standard deviation (σ) and adjusted coefficients “a" and “b". Watershed (WS): 1. Banabuiú; 2. Upper Jaguaribe; 3. Middle Jaguaribe; 4. Lower Jaguaribe; 5. Crateús; 6. Salgado; 7. Litoral; 8. Metropolitan.

WS	Reservoir	Vol. (hm^3)	TS_e	TS_o	Equation	ρ	σ (%)	a	B
1	Banabuiú	1600.0	64.0	59.6	$TSI_A = 10.879\Phi + 54.021$	0.678*	6.69	1.0	2.0
	Fogareiro	118.0	72.0	69.1	$TSI_A = 9.9408\Phi + 56.778$	0.624	5.96	1.0	0.0
	Pirabibu	74.0	78.0	73.0	$TSI_A = 20.754\Phi + 39.383$	0.559	7.16	1.0	0.0
	Patu	65.1	66.0	58.8	$TSI_A = 27.680\Phi + 31.003$	0.824**	8.16	1.0	0.0
	São José I	7.7	65.0	57.2	$TSI_A = 29.510\Phi + 24.984$	0.667	12.62	1.0	0.0
	Quixeramobim	8.0	70.0	65.8	$TSI_A = 28.212\Phi + 21.247$	0.664	10.71	3.0	0.0
	Trapiá II	18.0	69.0	63.7	$TSI_A = 13.127\Phi + 52.845$	0.829*	6.21	1.0	1.0
	Serafim Dias	40.9	72.0	68.6	$TSI_A = 12.355\Phi + 53.291$	0.679	8.96	1.0	0.0
	São José II	21.0	63.0	59.7	$TSI_A = 26.377\Phi + 40.039$	0.857*	7.62	1.0	3.0
	Capitão Mor	6.0	75.0	66.7	$TSI_A = 22.880\Phi + 57.094$	0.886*	8.90	1.0	3.0
	Mons.Tabosa	12.1	79.0	81.4	$TSI_A = 20.541\Phi + 42.838$	0.912**	8.01	1.0	0.0
2	Quincoê	4.3	70.8	65.7	$TSI_A = 16.446\Phi + 40.467$	0.479	7.90	3.0	0.0
	Faé	19.2	68.7	61.7	$TSI_A = 42.931\Phi - 6.4453$	0.999**	9.81	1.0	0.0
	Orós	1940.0	62.5	58.2	$TSI_A = 22.094\Phi + 37.441$	0.807**	5.91	1.0	1.0
	Canoas	69.3	70.3	63.3	$TSI_A = 14.847\Phi + 45.706$	0.659*	10.54	1.0	0.0
	Poço da Pedra	52.0	74.2	71.0	$TSI_A = 62.024\Phi - 14.411$	0.695	6.68	1.0	1.0
	Benguê	18.0	70.1	62.9	$TSI_A = 14.874\Phi + 46.028$	0.539	7.92	1.0	0.0
	Arneiroz II	187.7	71.1	63.9	$TSI_A = 19.476\Phi + 37.678$	0.790*	6.89	1.0	0.0
	Parambu	8.6	72.8	58.9	$TSI_A = 45.193\Phi + 12.742$	0.821*	16.22	1.0	1.0
	Várzea do Boi	51.9	76.9	72.0	$TSI_A = -38.092\Phi + 134.32$	0.800	7.40	3.0	1.0
	Trici	13.0	65.1	64.9	$TSI_A = 45.807\Phi - 17.600$	0.595	14.31	2.0	0.0
	Favelas	30.1	78.8	73.3	$TSI_A = 40.147\Phi + 10.378$	0.771	15.10	1.0	0.0
	R. Carvalho	20.1	77.2	69.2	$TSI_A = 22.374\Phi + 38.661$	0.750	8.95	1.0	0.0
3	Castanhão	6700.0	57.0	48.8	$TSI_A = 24.412\Phi + 15.115$	0.831**	8.03	1.0	0.0
	R. da Serra	23.5	67.7	67.4	$TSI_A = 21.041\Phi + 45.229$	0.754	9.07	1.0	2.0
	Figueiredo	509.7	68.0	61.0	$TSI_A = 541.44\Phi - 1012.3$	0.999**	8.15	1.0	0.0
	Canafístula	13.1	66.5	65.1	$TSI_A = 34.311\Phi + 39.675$	0.410	13.63	1.0	3.0
	Santa Maria	6.7	67.1	62.1	$TSI_A = 43.593\Phi + 28.313$	0.695*	14.29	1.0	3.0
	Joaq. Távora	26.8	57.0	53.8	$TSI_A = 26.522\Phi + 35.805$	0.717*	11.58	2.0	3.0
	R. do Sangue	58.4	77.7	66.5	$TSI_A = 42.429\Phi + 24.117$	0.874**	8.95	1.0	1.0
	Jenipapeiro	14.6	70.8	62.5	$TSI_A = 39.171\Phi + 18.349$	0.695*	11.51	1.0	1.0
	Tigre	3.5	56.8	49.2	$TSI_A = 25.527\Phi + 11.078$	0.857**	8.39	1.0	0.0
	Nova Floresta	5.2	52.2	50.0	$TSI_A = 33.615\Phi + 16.680$	0.750	13.11	1.0	1.0
4	S. Ant. de Russas	24.0	65.1	61.7	$TSI_A = 47.309\Phi + 2.5666$	0.738*	8.59	2.0	1.0
5	São José III	8.0	75.5	69.8	$TSI_A = 27.753\Phi + 25.512$	0.905**	6.51	1.0	0.0
	Sucesso	6.6	68.6	64.1	$TSI_A = 43.206\Phi + 12.296$	0.883**	7.89	0.5	0.5
	Realejo	31.6	73.9	65.6	$TSI_A = 28.457\Phi + 26.501$	0.892**	7.53	0.5	0.0
	Carnaúbal	73.2	62.5	68.2	$TSI_A = 24.315\Phi + 31.755$	0.841*	9.73	1.0	1.0
	Barra Velha	99.6	60.7	56.4	$TSI_A = 24.457\Phi + 22.604$	0.886*	7.29	0.5	0.0
	Jaburu II	101.6	74.8	62.3	$TSI_A = 47.133\Phi - 13.124$	0.946**	9.19	1.0	0.0
	Flor Campo	105.0	68.4	61.2	$TSI_A = 25.900\Phi + 26.269$	0.738*	10.81	0.5	0.0
6	Lima Campos	66.4	67.7	61.1	$TSI_A = 36.095\Phi + 2.0744$	0.905**	6.94	2.0	0.0
	Tatajuba	2.72	**49.4**	50.1	$\mathbf{TSI_A = -22.462\Phi + 67.383}$	0.464	6.26	2.0	3.0
	Ubaldinho	31.8	59.8	54.7	$TSI_A = 9.2394\Phi + 44.164$	0.450	9.00	3.0	0.0
	Jenipapeiro II	41.4	68.1	68.4	$TSI_A = 336.59\Phi - 595.94$	0.900*	6.53	1.0	0.0
	Prazeres	32.5	54.2	53.5	$\mathbf{TSI_A = -10.783\Phi + 72.215}$	0.533	8.10	1.0	0.0
	Manoel Balbino	37.2	54.5	52.5	$\mathbf{TSI_A = -15.991\Phi + 72.033}$	0.619	4.52	1.0	3.0
	Quixabinha	31.8	66.3	57.9	$TSI_A = 56.551\Phi - 42.537$	0.843**	6.56	1.0	0.0
	Gomes	2.39	65.9	61.3	$\mathbf{TSI_A = -23.343\Phi + 85.999}$	0.671	7.05	1.0	3.0
	Atalho	72.6	67.4	57.3	$TSI_A = 37.227\Phi - 0.0353$	0.714*	5.93	1.0	0.0
	Thomas Osterne	28.8	53.9	54.2	$\mathbf{TSI_A = -41.180\Phi + 104.18}$	0.766*	7.51	2.0	3.0
7	Santa Maria	8.2	71.2	68.4	$TSI_A = 12.327\Phi + 53.227$	0.655	4.41	0.5	0.0
	G. Atimbore	4.0	69.8	66.0	$TSI_A = 59.584\Phi - 51.630$	0.400	8.46	3.0	0.0
	Patos	7.6	73.9	73.9	$TSI_A = 21.616\Phi + 45.871$	0.378	6.76	0.5	0.0
	S P Timbaúba	15.8	67.3	62.9	$TSI_A = 8.9879\Phi + 57.341$	0.800**	6.75	2.0	1.0
	Missi	65.3	69.7	68.3	$TSI_A = 22.880\Phi + 26.371$	0.754	3.30	2.0	0.0
	Poço Verde	12.4	72.0	61.9	$TSI_A = 65.832\Phi - 19.110$	0.563	11.36	2.0	1.0
8	Cauhipe	12.0	65.4	65.0	$TSI_A = 20.060\Phi + 50.760$	0.510	8.66	1.0	3.0
	Aracoiaba	162.0	65.3	62.1	$TSI_A = 8.6820\Phi + 50.228$	0.729*	3.51	1.0	0.0
	P. Sobrinho	143.0	67.7	69.2	$TSI_A = 40.504\Phi - 7.1040$	0.721*	13.58	1.0	0.0
	Macacos	10.3	71.4	69.6	$TSI_A = 9.6295\Phi + 61.132$	0.412	3.85	0.5	1.0
	Pacajus	232.0	63.7	59.5	$TSI_A = 8.7446\Phi + 49.037$	0.723*	4.79	1.0	0.0
	Castro	62.3	75.2	71.4	$TSI_A = 18.907\Phi + 43.265$	0.933**	4.91	1.0	0.0
	Pacoti	380.0	65.5	61.7	$TSI_A = 20.962\Phi + 46.411$	0.661*	6.22	1.0	2.0
	Malcozinhado	36.6	73.6	68.2	$TSI_A = 18.758\Phi + 38.133$	0.620	5.76	3.0	0.0

*Correlation is significant at the 0.05 level.

**Correlation is significant at the 0.01 level.

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