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Water quality and eutrophication in the Curuçá estuary in northern Brazil

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ABSTRACT

Under natural conditions, estuarine environments exhibit temporal and spatial variability in response to intense physical oscillations of tides and freshwater discharge. Various interactions occur between these physical forces, the resident biota, and surrounding human populations. Therefore, the study of estuaries must consider multiple factors, from aesthetic and sanitary to trophic. To reduce anthropogenic impacts on an estuary, measures must be taken to evaluate its trophic state and to describe its biotic and abiotic relationships. This study applied the Trophic State Index (TSI) and Trophic Index (TRIX) to identify alterations and their possible origins in the waters of the Muriá creek, Curuçá municipality, Pará, Brazil in 2015. The results reflect the typical seasonality of the region. The TSI and TRIX indexes show that Muriá creek is naturally susceptible to eutrophication due to its hydrologic characteristics and diffuse sources of pollution. The combined indexes approach is considered satisfactory because each index provides unique and complementary information. Both indexes use simple methodology and are easy to apply, which allows for efficient monitoring with a rapid response time.

1. Introduction

Estuaries are important coastal ecosystems that support a diverse food web and are important nursery habitats for fish. However, estuaries are increasingly impacted by freshwater flow diversions for human use and nutrient inputs from agriculture and wastewater sources (McNaughton, 2019).

In tropical areas, high volume river flow resulting from the increase in precipitation rates during rainy periods is considered one of the main factors controlling the seasonal dynamics of estuarine productivity, resulting from increased turbidity, low salinity, and increased concentrations and retention time of nutrients (Noriega et al., 2013; Saeck et al., 2013; Barroso et al., 2016). However, nutrient retention time can cause negative processes (Paerl and Justić, 2011; Burford et al., 2016), such as eutrophication, which results from large volumes of domestic and industrial sewage discharged to the estuarine ecosystem (Xu, 2013).

In recent decades, the estuaries of Brazil have been affected by rapid population growth, discharge of domestic wastewater, and aquaculture activities, which significantly alter superficial and sub-superficial estuarine flow (Richi, 2010; Barletta et al., 2019). In Brazil, the National Environment Council created Resolution 357/2005 (BRASIL, 2005) which classifies hydraulic bodies and delimits maximum permitted values of water quality parameters and serves to identify possible changes that have occurred as a result of anthropogenic activities (Pereira et al., 2010; Alves et al., 2013).

Measures are being progressively adopted to reduce anthropogenic impacts on estuarine environments. Such measures include obtaining the knowledge necessary to describe biotic and abiotic relationships in the ecosystem and adopting techniques to evaluate trophic state (Greening and Janicki, 2006; Farage et al., 2010), which are strongly associated with environmental conditions (hydrological and seasonal fluctuations), as seen in the Rio de la Plata (Brugnoli et al., 2019). The Trophic State Index (TSI) and Trophic Index (TRIX) have been used in several water

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environments to assess trophic status, including in Europe (Salas et al., 2008), North America (Anguiano-Cuevas et al., 2015), and South America (Pereira et al., 2010; Alves et al., 2013).

Assessment of the trophic state of water quality is very important for the sustainable management of water resources. The indexes used—called trophic state indexes (EIT)—were developed in order to enable the classification of water from water bodies, providing information to decision-makers and the public regarding the state or nature in which such systems are found (Oliveira et al., 2007).

In Muriá creek, in the municipality of Curuçá (Northeastern Pará, Brazil), trophic state and water quality are important for the survival of regional biota and of the local community. However, these water parameters are affected by the presence of mangroves, domestic effluents, boat traffic, and the inflow of water from the Mocajuba and Curuçá rivers. The focus of this study is to determine seasonal differences in trophic indexes, TSI and TRIX, and relate the indexes to hydrological, physical, and chemical parameters of the waters of Muriá creek.

2. Material and methods

2.1. Study area

Muriá creek is located in the estuary of the Curuçá River, which lies within the municipality of Curuçá (Fig. 1) in the northeast of the state of Pará (PA). Pará is bordered in the north by the Atlantic Ocean, in the east and south by the municipalities of Marapanim and Terra Alta, respectively, and in the west by the municipalities of São Caetano de Odivelas and São João da Ponta (CCS, 2004).

The coastline of the urban center faces the Curuçá River, creating a geographical space typical of riverside locations in the Amazon Rainforest, which are enriched by coastal areas occupied by mangroves (Souza, 2010).

Muriá creek is a hydrographic accident that allows a connection between the waters of the study area and the Mocajuba and Curuçá rivers. The waters of Muriá creek are both economically and socially important for the survival of the local community. For example, there is an extensive mangrove area that provides a food source for residents of the surrounding communities and has wide sections that allow the circulation of boats and other vessels (Souza, 2010).

Muriá creek receives fluvial contributions of effluents from population centers located upstream along its banks and from communities along the section monitored in this study.

The municipality exhibits the Amazon Rainforest equatorial climate-type Am, according to the Köppen classification. It is characterized by high temperatures with an annual average of 27 oC, low thermal amplitude, and abundant total precipitation of over 2000 mm per year. The period with greatest precipitation is from January to June, while the least precipitation occurs from July to December (ANA, 2015).

Muriá creek is influenced by the Curuçá River, the Mocajuba River and the Atlantic Ocean. It has semidiurnal tides that are dominated by a meso- to macro-tidal regimen. The maximum tidal height in the Mocajuba River is approximately 4 m. Currents reach great speeds ranging from 1.9 to 2.1 knots (Mácola and EL-Robrini, 2004).

2.2. Sample collection

Surface water was collected along the Muriá creek, at 21 points distributed in transects, with collection points in the middle of the creek and on the banks. The collections occurred during low tide and high tide (Fig. 1), in the months of January to March, May to July, and September to November in 2015, in order to obtain data from the rainy (January to June) and dry (July to December) seasons in the region (Fig. 2).

Table 1
Trophic state index (TSI) scale according to Carlson (1977).

TSI	Trophic state
$TSI \leq 47$	Ultraoligotrophic (very low eutrophication level)
$47 < TSI \leq 52$	Oligotrophic low eutrophication level)
$52 < TSI \leq 59$	Mesotrophic (medium eutrophication level)
$59 < TSI \leq 63$	Eutrophic (moderate eutrophication level)
$< TSI \leq 67$	Supereutrophic (elevated eutrophication level)
$TSI > 67$	Hypertrophic (very high eutrophication level)

Samples were collected with a Van-Dorn bottle, at a depth of 30 cm in the water column. The packaging, preservation, and transport of the water samples followed the protocol described in the Standard Methods for the Examination of Water and Wastewater (1995).

At the time of water collection, temperature and salinity were measured with a multiparameter probe (Hanna HI 9829). The water samples were sent to the Laboratory of Environmental Chemistry at the Federal Rural University of the Amazon for duplicate analysis.

The analytical methods are: temperature and salinity (multiparameter meter, HANNA model HI 9829), dissolved oxygen (DO; Winkler titration as per Strickland and Parsons, 1972), DO saturation level (%; International Oceanographic Tables UNESCO, 1973), nitrite and nitrate (Grasshoff et al., 1983), N-ammoniacal (Nessler method, adapted from APHA, 1995), total phosphorus (oxidation with potassium persulfate, Grasshoff et al., 1983) and chlorophyll-*a* (spectrophotometric method described by APHA, 1995).

2.3. Trophic indexes

The Trophic State Index (TSI) used in this study was adopted from Carlson (1977) and is further described in CETESB (2008). The TSI was calculated as follows. First,

$$\text{TSI (Chl a)} = 10\times(6-((-0.7-0.6\cdot(\ln \text{Chl a}))/\ln 2))-20 \text{ and} \quad (1)$$

$$\text{TSI (TP)} = 10\times(6-((0.42-0.36\cdot(\ln \text{PT}))/\ln 2))-20 \quad (2)$$

where: TP and Chl a are the total phosphorus concentration (mg m^{-3}) and chlorophyll-*a* concentration (mg m^{-3}), respectively, measured at the water surface. The total phosphorous and chlorophyll-*a* concentrations yielded by Eqs. (1) and (2) were then combined via the following equation, described in CETESB (2008), to yield the final TSI index value:

$$\text{TSI} = [\text{TSI (PT)} + \text{TSI (Chl a)}]/2 \quad (3)$$

The TSI index value is interpreted according to the following classification from Carlson (1977), further described in CETESB (2008), and is classified according to Table 1.

The TRIX index was calculated according to the following equation:

$$\text{TRIX} = (\log_{10}[\text{Chl} - a\cdot(\text{DO}_2\%)\cdot\text{DIN} \,.\, \text{DIP}] + \text{k})/\text{m} \quad (4)$$

where DIN is dissolved inorganic nitrogen (ammoniacal-N plus nitrate plus nitrite), DIP is dissolved inorganic phosphate, and k and m are constants with values of 1.5 and 1.2 respectively, according to Vollenweider et al. (1998).

The TRIX value is interpreted and classified according to Table 2.

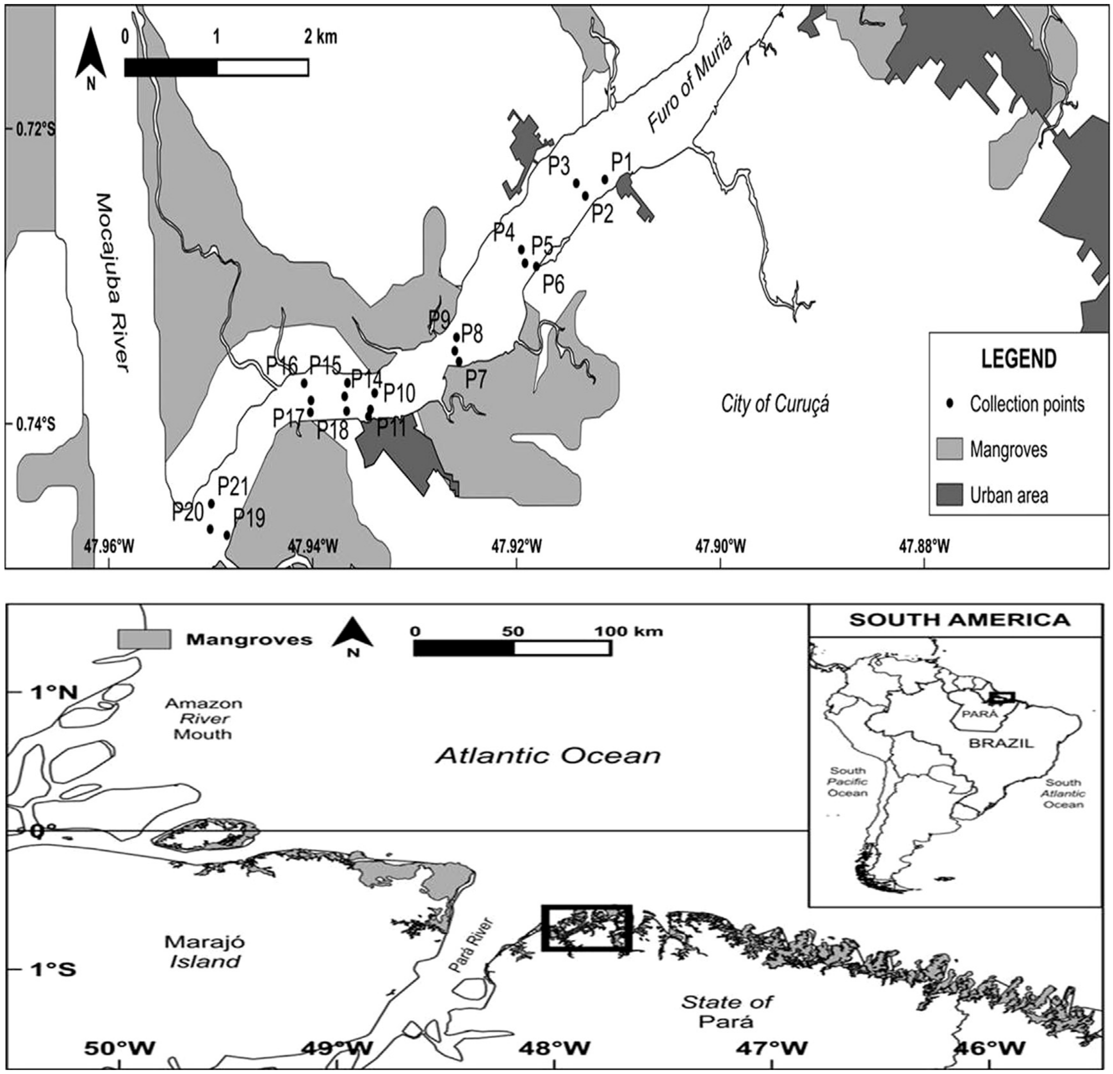

Fig. 1. Study area and sampling sites on Muriá creek, Pará, Brazil.

Table 2
Index TRIX values, condition system and trophic state (Vollenweider et al., 1998).

TRIX	Trophic state
0–4	Low eutrophication level and good water quality
4–5	Medium eutrophication level and good water quality
5–6	High eutrophication level and poor water quality
6–10	Very high eutrophication level and poor water quality

2.4. Statistical analysis

Statistical analysis was carried out via descriptive statistics and multivariate analysis. The significance of the association between pairs of variables was assessed using the Pearson correlation test ($p < 0.05$). Spatial trends were analyzed by simple linear regression. Principal Component Analysis (PCA) was used to adjust the index parameters.

3. Results

3.1. Physical and chemical variables

In 2015, annual cumulative precipitation reached 2428 mm, which is comparable with normal conditions for the Northeast Mesoregion of the state of Pará and for the Microregion of Salgado, where precipitation exceeds 2000 mm per year (ANA, 2015). The historical average precipitation (1982–2015) defines the typical climatic seasonality of the region, with two well-defined seasons (CCS, 2004): dry and rainy (Fig. 2). The period with the lowest precipitation was from August to December, with an average total of 65.1 mm. The rainy season (January to July) presented an average total of 2111.6 mm of rainfall, with the highest levels occurring in March and April.

The minimum, maximum, mean, and standard deviation values of the 2015 dataset obtained along the Muriá creek were calculated by season and by tidal stage (ebb and flow) (Table 3). The salinity measurements follow typical regional seasonality, with the lowest values occurring during the rainy period when water is diluted by rainfall. In this period, the waters from the Curuçá and Mocajuba rivers also exhibited higher nitrate concentrations, which in turn increased chlorophyll-*a* levels.

Conversely, during the period with the least rain, the highest salinity, nitrite, ammoniacal-N, total phosphorus, and dissolved oxygen (DO) saturation levels were found.

With respect to tides, the greatest variations in all water parameters were observed during the dry period and the largest magnitudes were detected during ebb tides, with the exception of DO saturation. These high magnitudes during ebb tides are evidence of diffuse pollution sources. During an ebb tide, there is less

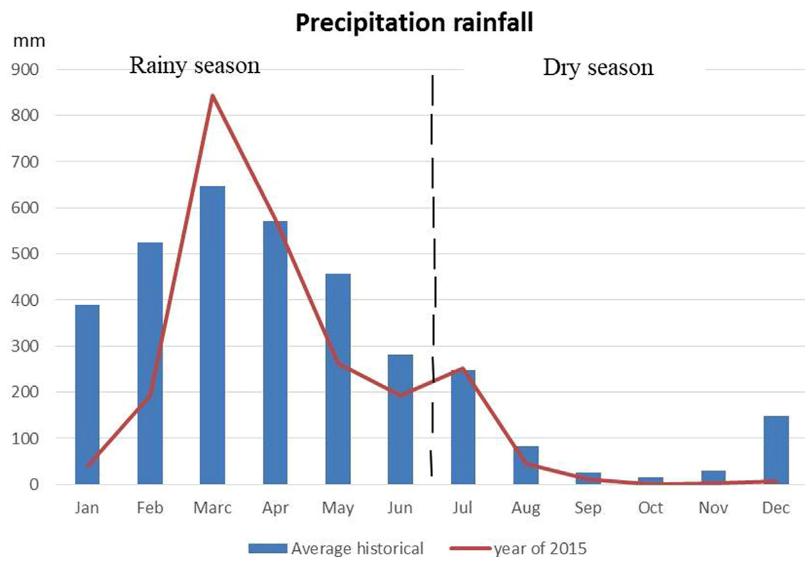

Fig. 2. Pluviometric precipitation in Curuçá municipality: historical averages from 1982 to 2015. *Source:* National Water Agency (Agência Nacional das Águas - ANA, 2015).

Table 3
Mean and standard deviation (Std. Dev.), minimum (Min.), maximum (Max.), number values (n) of the water analysis data obtained along Muriá creek, categorized by season and tidal state.

Parameters	Dry season	
	Ebb tide	Flood tide
	Mean ± Std. Dev. (Min; Max; n)	Mean ± Std. Dev. (Min; Max; 84)
Salinity	30.4 ± 2.8 (24.6; 35.0; 84)	25.8 ± 13.0 (28.3; 36.8; 84)
Nitrate (mg m^3)	151.4 ± 73.4 (10.0; 310.0; 84)	51.2 ± 133.0 (0.0; 910.0; 84)
Nitrite (mg m^3)	11.0 ± 4.4 (0.0; 20.0; 84)	0.9 ± 3.0 (0.0; 10.0; 84)
N-ammoniacal (mg m^3)	1177.2 ± 926.5 (2800.0; 130.0; 84)	948.2 ± 748.6 (100.0; 2800; 84)
Total phosphorus (mg m^3)	250.6 ± 99.7 (50.0; 470.0; 84)	206.5 ± 131.6 (70.0; 680.0; 84)
Chlorophyll- *a* (mg m^3)	9.5 ± 12.7 (0.14; 49.5; 84)	3.2 ± 2.7 (0.0; 12.1; 84)
OD	82.2 ± 7.0 (59.0; 105.0; 84)	89.2 ± 7.5 (61.0; 107.0; 84)
	Rainy season	
Salinity	17.5 ± 6.7 (7.0; 28.0; 105)	20.4 ± 6.3 (8.4; 36.1; 105)
Nitrate (mg m^3)	331.1 ± 281.1 (0.0; 930.0; 105)	223.7 ± 234.2 (0.0; 810.0; 105)
Nitrite (mg m^3)	7.4 ± 6.8 (0.0; 30.0; 105)	7.0 ± 7.0 (0.0; 30.0; 105)
N-ammoniacal (mg m^3)	549.7 ± 712.4 (20.0; 2730.0; 105)	511.8 ± 657.2 (40.0; 2730.0; 105)
Total phosphorus (mg m^3)	150.8 ± 83.0 (40.0; 410.0; 105)	184.5 ± 88.3 (26.0; 460.0;105)
Chlorophyll- *a* (mg m^3)	13.1 ± 18.1 (0.05; 101.5; 105)	8.8 ± 12.7 (0.04; 94.6; 105)
OD	70.0 ± 20.0 (48.0; 135.0; 105)	80.7 ± 20.2 (46.0; 186.0; 105)

dilution of effluents discharged into the creek. The phenomenon for DO saturation is the inverse, with the flood tide providing an influx of water with higher salinity, and therefore higher oxygen saturation.

3.2. Trophic indexes (TSI, TRIX)

Fig. 3a and b show the distributions of TSI values as a function of season and tidal stage. During the rainy period in ebb and flood tides, the TSI means indicate a eutrophic environment and the maximum values indicate a hypereutrophic environment.

In the least rainy season, differences are observed between tidal stages. During the ebb tide, the TSI minimum value is oligotrophic, the medium value is eutrophic, and the maximum value is hypereutrophic.

The TSI values continued to oscillate widely with seasons and tides. Between the two variables used to form the TSI (chlorophyll-*a* and phosphorus concentration), chlorophyll-*a* concentration contributed most to the variation in TSI values, as verified in TSI-Chl a correlation analysis (0.52, $p < 0.05$).

The distribution of TRIX values mirrored the spatial and temporal patterns of the TSI, i.e., during the rainy period (Fig. 4a), there are no differences between tidal stages, and in the dry period there were differences between tidal stages (Fig. 4b). The mean values indicated an environment of high and very high eutrophication levels, due to the diffuse pollution sources that affected the environment.

3.3. Water quality and eutrophication

Pearson's correlation was verified between TRIX and the TSI (0.86, $p < 0.05$), indicating that both indexes are able to demonstrate local environmental conditions. The TSI has a positive correlation with chlorophyll-*a* (0.52, $p < 0.05$), demonstrating the influence of productivity on the trophic state of Muriá creek. Dissolved oxygen is positively related to salinity (0.64, $p < 0.05$), indicated that saline water inputs favor the oxygenation of water. On the other hand, DO is inversely related to nitrate concentrations (−0.56, $p < 0.05$), which indicates the consumption of oxygen in the transformation from nitrite to nitrate in the nitrogen cycle.

Analysis of principal components using all data, and during set periods and tides, was used to identify the highlighted variables

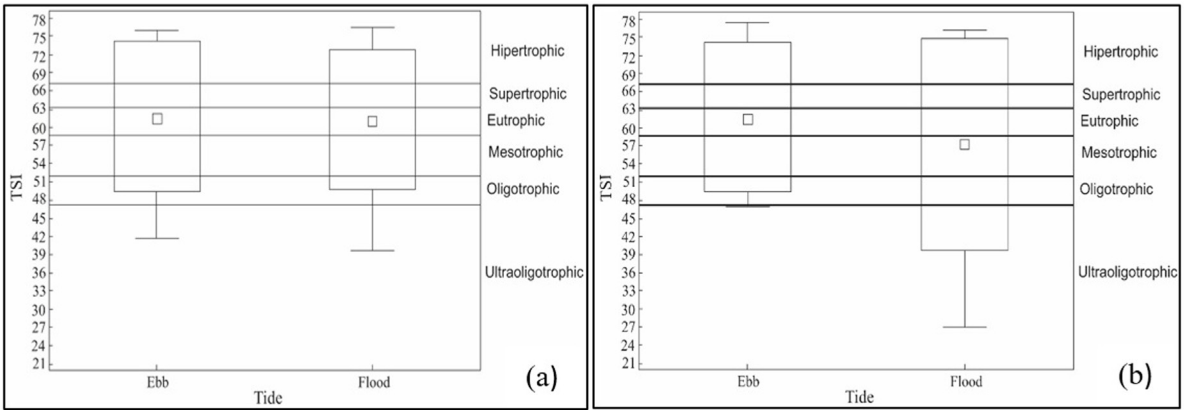

Fig. 3. Distribution of trophic state index (TSI) values in ebb and flood tides during (a) the rainy period, and (b) the dry period.

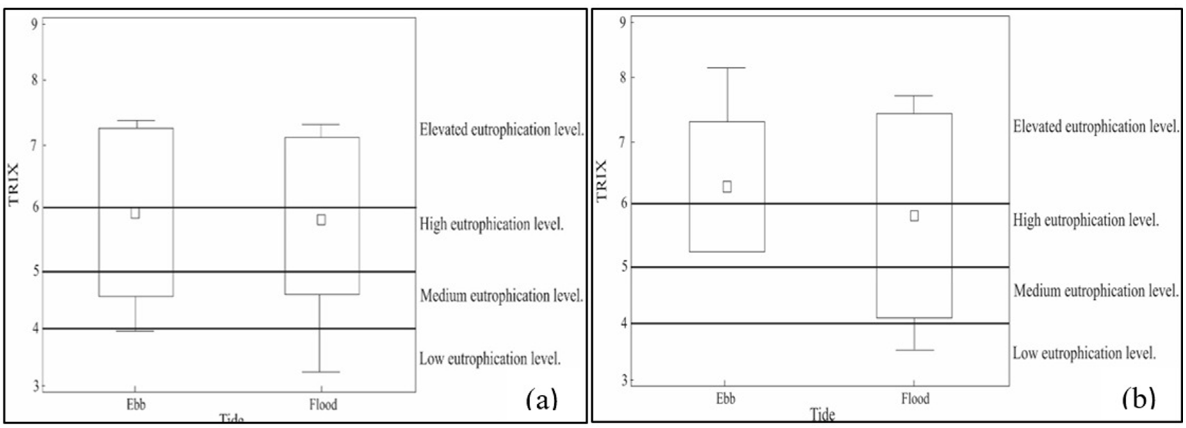

Fig. 4. Distribution of trophic index (TRIX) values in ebb and flood tidal stages during (a) the rainy period, and (b) the dry period (b) in the ebb and flood tidal stages.

of water quality (Table 4). Three components were extracted based on eigenvalues, together explaining about 74% of the original variation in the data. The first component (PC1) explained 35% of the total variance and showed positive correlation between TSI, TRIX, and Chl a, indicating that chlorophyll-*a* has a strong influence on index values. The second component (PC2) explained about 24% of the total variance and presents TRIX, salinity, and total phosphorus as the main elements; positive correlation indicates that, even with increases in salinity, TRIX values are influenced by high total phosphorus. The third component (PC3) explained about 15% of the total variation and highlights N-ammoniacal and total phosphorus, in contrast to chlorophyll-*a*. The negative correlation between these variables indicates that these nutrients influence local productivity and influence water quality in the Muriá creek.

Table 4
Weights and variance explained by the first three main components of the analysis of data obtained in the Muriá creek waters. The most significant values are in bold (>0, 40).

Variable	PC1	PC2	PC3
TSI	**0, 44**	0, 29	−0, 33
TRIX	**0, 42**	**0, 41**	−0, 01
Salinity	−0, 30	**0, 48**	−0, 02
Nitrate	0, 37	−0, 32	0, 27
Nitrite	0, 28	−0, 01	0, 32
Ammonium-N	0, 09	0, 36	**0, 51**
TP	0, 01	**0, 40**	**0, 41**
Chl a	**0, 43**	0, 11	**−0, 45**
OD%	−0, 36	0, 33	−0,29
Explained variance (%)	**35**	**24**	**15**

4. Discussion

In 2015, cumulative precipitation in the municipality of Curuçá reached 2428 mm, which is the same order of magnitude as the normal conditions for the Mesoregion of the Northeast of Pará and for the Microregion of Salgado, where abundant rainfall exceeds 2000 mm per year (ANA, 2015).

In view of seasonal characteristics, rainfall has a strong influence on the availability of nutrients in the water column, increases concentration of chlorophyll-*a*, reduces dissolved salts content, and lowers salinity (Pereira et al., 2010; Gomes et al., 2013). On the other hand, the flooding of adjacent mangroves contributes to increased sediment load, nutrients, and particulate and dissolved organic matter, which is transported through tidal channels to the estuary, thus increasing phytoplanktonic biomass, expressed in chlorophyll-*a* (Pardal et al., 2011; Pamplona et al., 2013).

Due to these factors, increased chlorophyll-*a* concentrations are seen in Muriá creek during the rainy season, as well as lower salinity, which was caused by freshwater inflow. Also during this period, water from the Curuçá and Mocajuba rivers favors higher turbidity, and higher concentrations of nitrate and phosphate. The influence and importance of rainfall on physico-chemical and biological parameters in the aquatic environment has been reported since the 1950s. In estuarine regions, seasonal variations in parameters are evident (Pereira et al., 2010; Alves et al., 2012); similar to patterns observed at Muriá creek, salinity decreases during the rainy season (Almeida, 2009; Silva et al., 2011; Lima et al., 2015).

The highest concentrations of salinity, electrical conductivity, pH, and DO in the dry season are favored by coastal waters that influence estuarine water quality (Moura and Nunes, 2016). Seasonal reductions between the rainy and dry season and longitudinal variations in nutrient concentrations are expected, as this estuary is subject to intense influence from vegetation and coastal waters.

N-ammonia was the predominant species among nitrogenous compounds. This may be related to the nitrification process, with N-ammoniacal resulting from the conversion of nitrate or nitrite, thereby reducing the concentrations of nitrate and nitrite. N-ammoniacal is positively correlated with TRIX (0.46, $p < 0.05$).

High turbidity in the rainy season and at low tide in Muriá creek is similar to that found in estuarine regions of the northeast region of Pará in the Curuçá estuary (PA) (Palheta et al., 2012), in the Caeté estuarine system (Bragança, PA) (Moura and Nunes, 2016), and in the Cachoeira river estuary, Northeastern Brazil (Souza et al., 2009).

In addition to turbidity, tidal movement is responsible for variations in salinity, electrical conductivity, phosphate, and chlorophyll-*a*. At high tide, the waters of Muriá creek are oxygenated, with a slightly alkaline pH due to the supply of coastal water. These waters are clearer, with lower concentrations of organic matter, and are more oxygenated, due to circulation and mixing, (Moura and Nunes, 2016).

The development and improvement of indexes using a reduced number of variables is of great importance, especially for developing countries and regions where the costs involved in analysis of certain parameters may limit assessments of water quality (Filho et al., 2020).

Marreto et al. (2017) they observed spatial variation in the trophic state index, which reflected the presence of point pollution sources in the marginal waters of the Patos Lagoon estuary. Palheta et al. (2012) obtained results in their seasonal and tidal analysis of trophic indexes in the Curuçá Estuary, reporting the influence of excess nutrients from effluent discharge of shrimp farms and aquaculture, which are very common in the region. Concentrations of these nutrients tend to increase as cultivation develops, due to increasing inputs of animal food and, consequently, of phosphorus and chlorophyll-*a* (Simões et al., 2008). These inputs are associated with inadequate handling of food and wastes before, during, and after the aquaculture cycle. In addition to the nutrient contribution of excess animal food, 77.5% of the nitrogen and 84% of the phosphorus content of ingested food are discharged through excretion, which becomes deposited in benthic areas close to the farms (Simões et al., 2008; Ferreira et al., 2011).

In the present study, ebb tide caused higher concentrations of the nutrients that drove chlorophyll-*a* production. Conversely, the flood tide offered an influx of seawater to dilute nutrient levels. During the flood tide, the environment oscillated between a low value of ultraoligotrophic, a medium value of mesotrophic, and a maximum value of hypereutrophic.

Because of seasonal variability in environmental processes that influence the eutrophication level of a water body, water quality will vary throughout the year. However, a lack of basic sanitation has directly affected the estuaries of Brazil. The negative impact of wastewater on water quality is visible in estuaries of the Cachoeira River in the northeast region of Brazil (Souza et al., 2009), the Ipojuca and Merepe rivers in Pernambuco (Batista and Flores Montes, 2014), the Paraíba River in Cabedelo, Paraíba (Correia et al., 2015), and the Caeté River in Pará (Monteiro et al., 2016). However, in Muriá creek, negative impacts on water quality appear to be mitigated by hydrodynamics. Despite the trophic indexes indicating unfavorable water quality, aquatic macrophytes and algal blooms were not observed. This could be a result of the high flow rate and the daily tidal amplitude of the region, as well as the short flooding duration in mangrove areas.

5. Conclusions

In the municipality of Curuçá, historical average precipitation (1982–2015) defines the typical climatic seasonality of the region, with two well-defined seasons: dry and rainy. This seasonality directly affects the physical, chemical, and biological variables of Muriá creek.

The TSI and TRIX indexes show that Muriá creek is naturally susceptible to eutrophication due to its hydrological characteristics and diffuse pollution sources, with emphasis on chlorophyll-*a*, total phosphorus, and N-ammoniacal. The combined use of these indexes is considered satisfactory because each index contributed unique and complementary information. Both offer the advantage of a simple methodology and are easy to apply, enabling efficient monitoring with a rapid response time.

The environmental conditions and underlying mechanisms in Muriá creek identified by the application of these indexes support their relevance to estuarine monitoring and their applicability in understanding the environment. These indexes may be used as tools to implement local public policies toward the improvement of basic sanitation for the population.

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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