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Effects of different tidal inlet configurations on the water quality of an estuary lagoon complex in northeastern Brazil

Efeitos de diferentes configurações de embocadura na qualidade da água de um complexo estuarino-lagunar no nordeste do Brasil

Teresa Elane Bezerra Luz[1], Mariana Kummer da Rocha Pinheiro[1], Ada Cristina Scudelari[1] & Cynara de Lourdes da Nóbrega Cunha[2]

[1]Universidade Federal do Rio Grande do Norte, Natal, RN, Brasil
[2]Universidade Federal do Paraná, Curitiba, PR, Brasil
E-mails: elanebluz30@gmail.com (TEBL), marianakummer1@gmail.com (MKRP), adaufrn@gmail.com (ACS), cynara@ufpr.br (CLNC)

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ABSTRACT

The Mundaú-Manguaba Estuary Lagoon Complex (CELMM), located on the coast of Alagoas state in Northeastern Brazil, consists of two choked coastal lagoons connected to the Atlantic Ocean by a series of narrow channels, establishing a single tidal inlet, which dynamically alters their position. This study uses the modeling system SisBaHiA® (in Portuguese, Sistema Hidrodinâmico Ambiental) and Trophic Index (TRIX) to evaluate how morphological changes in the CELMM can influence the water quality of the lagoons. The results showed that water quality is mainly influenced by river discharge regimes, with no major changes in the region of the tidal inlet for the three simulated years (2006, 2014 and 2017). Trophic index showed greater changes in the rainy season, with a decline in values as river discharge increases, mainly in the northwest and central portions of the Mundaú Lagoon. In the Manguaba Lagoon an opposite pattern was found, namely a rise in the Trophic index with increased river discharges.

Keywords: Coastal lagoons; Tidal inlet; SisBaHiA®; TRIX; Water quality.

RESUMO

O Complexo Estuarino Lagunar Mundaú-Manguaba (CELMM) é um sistema composto por duas lagunas costeiras do tipo sufocadas, que estão conectadas por canais estreitos e compartilham uma única embocadura, que muda de posição dinamicamente. Este estudo avalia os efeitos que as alterações morfológicas na embocadura do CELMM provocam na qualidade da água usando o Sistema Hidrodinâmico Ambiental (SisBaHiA®) e o Índice de Estrado Trófico (TRIX). Os resultados mostraram que, no interior das lagunas, as concentrações dos parâmetros avaliados são influenciadas principalmente pelo aporte fluvial, não sendo verificadas grandes alterações nos valores médios das concentrações na região das embocaduras nos três anos simulados (2006, 2014 e 2017). O índice TRIX apresentou maiores alterações no período chuvoso, observando-se redução dos valores de TRIX com o aumento da vazão nas porções noroeste e central da laguna Mundaú e, aumento dos valores de TRIX com o aumento da vazão na laguna Manguaba.

Palavras-chave: Lagunas costeiras; Embocadura; SisBaHiA®; TRIX; Qualidade da água.

INTRODUCTION

Coastal lagoons are highly productive shallow water bodies consisting of interfaces between coastal zones, inland waters and marine coastal waters, which enables the development of characteristic fresh and salt-water communities. Coastal lagoons are socially and economically important and can be used in different human activities, such as fishing, tourism and leisure. However, despite their importance, they are among the ecosystems most subjected to anthropic impacts and several forms of degradation, such as embankment landfills and inadequately treated domestic and industrial waste discharge (Chapman, 2012; Newton et al., 2017; Pérez-Ruzafa et al., 2019).

Coastal lagoon tidal inlets are morphologically complex zones whose equilibrium depends on a balance between ocean currents and river discharge (Fortunato et al., 2008). The temporal evolution of tidal inlets (over decades or centuries) is influenced by sediment transport and the tidal prism; however, changes in the tidal inlet can also be caused by extreme events, such as storms (Cayocca, 2001; Tran et al., 2012).

The closing of a tidal inlet may reduce the water circulation speed, leading to an increase in sedimentation and nutrient accumulation. In addition, water exchange with the ocean will decrease, resulting in higher organic matter concentration. Opening the tidal inlet may increase water exchange with the ocean and decrease nutrient concentration, suspended solids and organic matter, thereby reducing sedimentation rates (Milbrandt et al., 2012).

The Mundaú-Manguaba Estuary Lagoon Complex (CELMM), located on the coast of Alagoas state in Northeastern Brazil (Figure 1), consists of two choked coastal lagoons connected to the Atlantic Ocean by a series of narrow channels, establishing a single tidal inlet, which dynamically alters its position. There are a number of economic activities underway near the CELMM, including agriculture, chemical companies, fishing (predominantly artisanal) and tourism. Despite the economic and social importance of the CELMM, environmental problems have compromised lagoon water quality, affecting the chemical, physical and biological equilibrium of the system and provoking/accelerating the eutrophication process (Agência Nacional das Águas, 2006; Cotovicz Junior et al., 2012; Silva, 2017).

Water quality in the CELMM depends strongly on the volume of water exchanged between the lagoons and adjacent coastal region. Morphological changes were observed in the tidal inlet of the CELMM, between 1986 and 2017. During this period, the access channel to the Manguaba Lagoon was open or closed. These changes affect circulation, water renewal rates inside the lagoon and nutrient and sediment exchanges between the lagoons and adjacent coastal region (Luz et al., 2021; Olabarrieta et al., 2014).

With this purpose, this study employs the hydrodynamic and water quality models of the SisBAHIA® (in Portuguese, Sistema Base de Hidrodinâmica Ambiental) to describe and predict the flow, circulation and concentrations of water quality parameters in a marine environment. The water quality model uses the same grid applied for the hydrodynamics model and allows for the use of different time step lengths in the analyses. The advantage of coupling the two models, as in the current work, appears in the determination of the flow velocities and turbulence coefficients, which is done previously in the hydrodynamic model, that can be used directly in the water quality model.

Thus, the aim of the present study was to assess the influence of different tidal inlet configurations on the water quality of the Mundaú-Manguaba Estuary Lagoon Complex (CELMM), using the SisBaHiA® modeling system and Trophic Index (TRIX) and

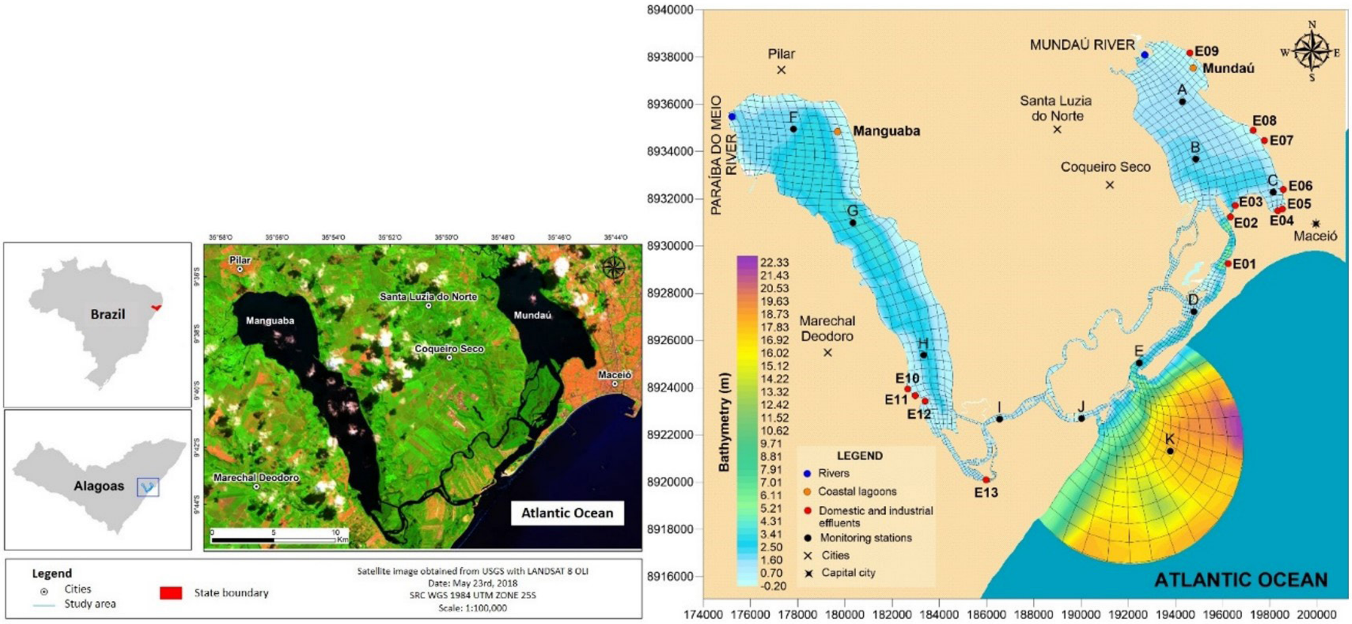

Figure 1. Map of the Mundaú-Manguaba Estuary Lagoon Complex (CELMM) showing the modeling domain of the CELMM with the finite elements grid, bathymetry, location of the stations where the results are presented (A - K), location of sanitary wastewater discharge points (E01 - E13) and the main tributaries.

identify the lagoon regions most affected by tidal inlet changes and the main pollution sources in the lagoons.

METHODOLOGY

Study area

The Mundaú-Manguaba Estuary Lagoon Complex (CELMM) is located in Alagoas state, on the northeastern coast of Brazil (9°35'S to 9°46'S and 35°44'W to 35°58'W), and its contributing watershed encompasses five municipalities: Coqueiro Seco, Marechal Deodoro, Pilar, Santa Luzia do Norte and Maceió, the state capital (Figure 1). According to classification of Köppen-Geiger, the climate of the study area is As, that is, tropical hot. Average annual temperature, rainfall and evaporation are 25.5 °C, 1843 mm and 1073 mm, respectively (Barros et al., 2012; Cunha et al., 2021).

The main tributaries of the CELMM are the Mundaú River, which empties into the Mundaú Lagoon, and Paraíba do Meio river, which flows into the Manguaba Lagoon, with annual river discharges of 33.5 m^3/s and 17.6 m^3/s, respectively (Costa et al., 2010). The tides are semidiurnal, in a regime between micro and mesotidal, with average amplitude of around 1.45 m. The reduced tidal influence in the inner part of the lagoons results from the cushioning provided by the system of channels (Brito Junior et al., 2018; Cunha et al., 2021).

The tidal inlet of the study area exhibits dynamic behavior, changing the configuration over time (Luz et al., 2021). Between 1986 and 1990, the access channel to the Manguaba Lagoon opened due to erosion processes in the southeast region of the tidal inlet. Aeolian transport of sediment from dune fields located northeast of the tidal inlet between 1990 and 1998 closed the access channel. The channel that connects the Manguaba Lagoon to the ocean reopened in June 2010, which may be associated with flooding in the watershed of the tributaries. No closing events were observed after 2010, but the channel broadened between 2014 and 2017, due to intense erosion that may be associated with the extreme flooding that occurred in 2017 (Nunes et al., 2020; Pinheiro, 2020; Luz, 2021).

Computational modeling

The computational model used in this study is the Hydrodynamic Environmental System Database (SisBaHiA®), a system of computational models registered by the Coppetec Foundation, which manages the research agreements and contracts of the Aberto Luiz Coimbra Institute for Graduate Students and Engineering Research (COPPE) at the Federal University of Rio de Janeiro (UFRJ). The most recent version of the SisBaHiA® contains several modules; this study uses hydrodynamic, water quality and eutrophication modules (Rosman, 2021).

The SisBaHiA® hydrodynamic model (HM) uses a second-order numerical system and finite elements for temporal and spatial discretization, respectively. The water quality and eutrophication model (WQEM) follows an Eulerian approach. As such, the same finite elements grid used in the HM is considered, which enables the parameters calculated in the HM, such as wind speed, elevation, flow velocities and geometric characteristics, to be used directly in the WQEM without the need for spatial interpolation (Rosman, 2021).

The WQEM can calculate up to 11 water quality parameters: salinity, temperature, ammonia, nitrate, inorganic phosphorous, zooplankton, biochemical oxygen demand (BOD), dissolved oxygen (DO), organic nitrogen, organic phosphorous and chlorophyll-a, as an indicator of phytoplankton biomass. The model considers the nitrogen, phosphorous and oxygen cycles, which can be simulated jointly or separately (Rosman, 2021). Further details on the SisBaHiA® can be found at: www.sisbahia.coppe.ufrj.br/.

Hydrodynamic (HM) and Water Quality Modeling (WQEM)

Three simulations were performed to assess the effects of different tidal inlet configurations on the water quality of the CELMM for 2006, 2014 and 2017. The year 2006 was before the channel opening, that is, it represents the situation in which there was only one outlet to the ocean; 2017 represents the situation most resembling the present, with two outlets to the sea and 2014, used to calibrate the hydrodynamic model from the water level measured by Brito Junior et al. (2018), and due to the intense erosion in the region, which produced the different configurations of 2014 and 2017. Unfortunately, water quality data are not available to calibrate the water quality model. But once the hydrodynamic model was already calibrated, it is possible to state that consistent results will be presented by the water quality model.

First, hydrodynamic modeling was performed for the three years (2006, 2014 and 2017), followed by simulation of the water quality model for different hydrodynamic scenarios. The two models were simulated for 365 days. The time step used in the hydrodynamic circulation simulation was equal to 30 seconds; for the water quality simulations, the time step was 60 seconds.

The finite elements grid used in the modeling (Figure 1) is composed of quadratic and triangular finite elements. A single mesh was used in the three simulations, given that the SisBaHiA® allows disabling some nodes of the mesh, that is, when defining land borders, some nodes can be disregarded to adapt the mesh to the configuration of the simulated tidal inlet. The use of a single mesh to represent the three tidal inlet configurations was a methodological choice to verify if the strategy to "disable" some nodes was efficient. Pinheiro et al. (2021) used this same strategy, with good results.

Bathymetry of the coastal region was obtained from nautical charts provided by the Brazilian Navy`s Directorate of Hydrography and Navigation (Diretoria de Hidrografia e Navegação, 1977), and bathymetric data from the inner portion of the Mundaú and Manguaba Lagoons obtained from hydrographic surveys conducted by PORTOBRÁS in 1985 and the ANA (National Water Agency) in 2014, respectively (Sant'Ana, 2019). Pinheiro (2020) made a number of changes to the bathymetry of the tidal inlet region, in order to guarantee the formation of access channels. These alterations were also considered in the present study (Figure 2).

The bottom friction coefficient is defined by the Chèzy coefficient, which depends on the equivalent bottom roughness amplitude, stipulated from the composition and distribution of

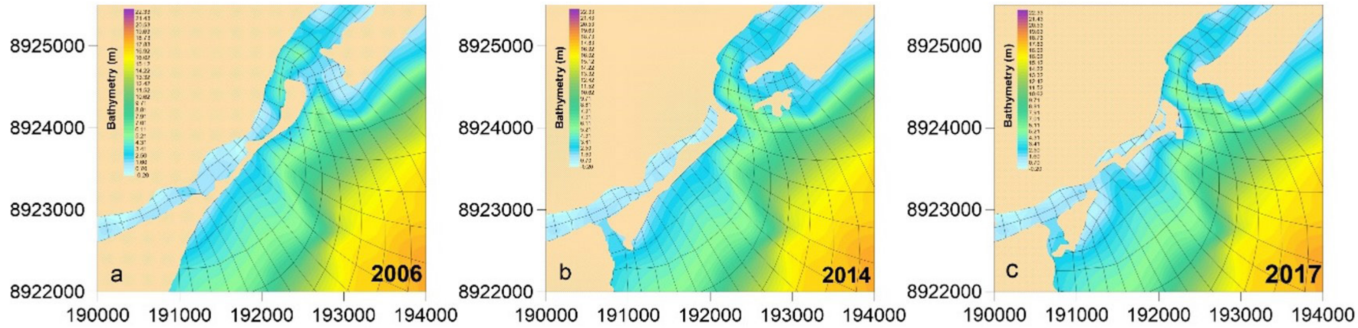

Figure 2. Bathymetry and the grid of different tidal inlet configurations of the CELMM corresponding to the year a) 2006, b) 2014 and c) 2017.

bottom sediments. The bottom roughness amplitudes (ξ) for the CELMM were obtained from Alves (2010). Clays are predominantly found on the bottom of the two lagoons (ξ = 0.005 m), while sands predominate in the channel regions (ξ = 0.022 m) and coarse sandbanks in the adjacent coastal region (ξ = 0.035 m).

In the present study only the effects of astronomical tides were considered, as determined by the SisBaHiA® from 21 harmonic constants established for the port of Maceió (Fundação de Estudos do Mar, 2000). Thus, the tide curves created for 2006, 2014 and 2017 were used in the simulations.

In the modeling domain the wind was considered variable in time and uniform in space. Wind direction and intensity of the simulated years were extracted from the automatic station of Maceió (A303), provided by the National Meteorological Institute (INMET). Intense winds were observed in the E-SE quadrant during the three simulated years, with speeds above 5 m/s (Instituto Nacional de Meteorologia Estações Automáticas, 2020).

The initial condition of the hydrodynamic model was established from previous simulations of the two last days of December before the simulated year. Thus, the results obtained for January 1 were used as the initial condition.

The river discharges of CELMM tributary rivers were obtained from the HidroWeb (ANA) website, which contains the measurements recorded at the hydrometric stations on the rivers. Data from the stations located in the municipalities of Atalaia (ANA 39870000) and Rio Largo (ANA 39770000) were used in the modeling, selected for their location near the outlets of the Paraíba do Meio and Mundaú Rivers, respectively. The daily values of the historical series of 2006, 2014 and 2017 were used in the simulations (Agência Nacional das Águas, 2019).

The sanitary wastewater discharges used in the modeling were obtained using the built-up area method (Kaufmann, 2009), which considers the number of inhabitants and per capita water consumption (Equation 1):

$$Q = k_1 k_2 \frac{CPq}{86400} \tag{1}$$

Where k_1 is the coefficient of highest daily consumption, with a value of 1.2, k_2 the coefficient of highest hourly consumption, with a value of 1.5, C the return coefficient, with a value of 0.8, P the population (inhab) and q average per capita water consumption (L/inhab.day). Three simulations corresponding to 2017 discharges were used. Wastewater discharges from chemical companies and slaughterhouses were not considered due to the lack of data.

A total of 13 domestic wastewater discharge points were found along the CELMM based on the Basic Sanitation Plan of the Municipality of Maceió (Prefeitura de Maceió, 2016), as shown in Figure 1. Average per capita water consumption in the municipalities of Maceió and Marechal Deodoro, where the wastewater discharge points are located, were obtained from the National Sanitation Information System (Sistema Nacional de Informações sobre Saneamento, 2020); the population data for 2017 were estimated using the population projection arithmetic method, applying the data of the last three population censuses (1990, 2000 and 2010) provided by the IBGE (Brazilian Institute of Geography and Statistics) (Instituto Brasileiro de Geografia e Estatística, 2020). The population data of neighborhoods corresponding to the location of these points were used to calculate the discharges of wastewater in Maceió, which cannot be done for points located in Marechal Deodoro, since these data were not available. Table 1 shows the number of inhabitants used in the calculations and the discharges obtained for each wastewater discharge point.

For the water quality model, knowing the concentrations of the variables at the sanitary wastewater discharge points and tributary rivers is essential, as well as information on the concentration of the open border. However, due to the lack of data, some adjustments were made in order to estimate the quality parameter concentrations of the tributary rivers. Thus, DO, BOD and chlorophyll-a concentrations were considered equal in the three simulations.

The seasonal variations of DO concentration in a year in the Mundaú and Manguaba rivers were estimated using a temporal interpolation of the HidroWeb portal data (Agência Nacional das Águas, 2019), which were measured at irregular intervals. The BOD concentration adopted was 5 mg/L, which corresponds to the maximum value for class 2 freshwater bodies, according to CONAMA (National Environmental Council) Resolution 357 (Brasil, 2005). The chlorophyll-a concentration used for the rivers was 15 μg/L. The nitrogen and phosphorous loads of the rivers were estimated from the model developed by Vollenweider et al. (1998), using the exportation coefficients adapted by Salas & Martino (1991) (Table 2), soil use and occupation data (Consultoria Técnica Ltda, 1999; Gama, 2011) and the historical river discharges series of the simulated years (Agência Nacional das Águas, 2019).

Finally, sanitary wastewater was characterized based on per capita contributions of the parameters (Table 3), obtained in Von Sperling (2014), of population and discharges data (Table 1). Thus, BOD, organic nitrogen, ammonia, nitrate, inorganic phosphorous and organic phosphorous concentrations were determined at the 13 discharge points identified. The DO concentration used in all the wastewaters was 2 mg/L, due to the high organic matter load present.

The coefficients used in the water quality model were those established by Rosman (2021) and Cunha et al. (2021). In the WQEM, two types of contour conditions were considered: land borders and open limits. Land borders represent the water body margins and inlet and outlet points, such as rivers and wastewater discharge points, where normal flow are prescribed. The concentrations at the open border are prescribed for influx conditions.

In order to assess the different CELMN compartments, stations were identified along the lagoons and channel zones. Stations A and F characterize the innermost regions of the lagoons, where there is greater influence from the rivers; Stations B and H are near the channels, under more influence from tidal oscillations; Station C is located near the wastewater discharge point of the Mundaú Lagoon; and Station G in the central portion of Manguaba Lagoon. Stations D and I encompass the intermediate region of the access channels to the Mundaú and Manguaba Lagoons and E and J are located near the tidal inlets of the lagoons, respectively. Flow rates are higher at these stations due to the influence of tides.

Table 1. Population data and sanitary wastewater discharges.

Locality	Estimated Number of Inhabitants (2017)	Discharge Point	Q (L/s)
Trapiche da Barra	28,188	E01	40.50
Vergel do Lago	35,133	E02	25.24
		E03	25.24
Levada	12,123	E04	8.71
		E05	8.71
Bom Parto	14,305	E06	20.55
Fernão Velho	6,408	E07	9.21
Bebedouro	11,255	E08	8.08
		E09	8.08
Marechal Deodoro	53,385	E10	33.90
		E11	33.90
		E12	33.90
		E13	33.90

Table 2. Exportation coefficients.

Soil uses	Total phosphorous (g/m^2.year)	Total nitrogen (g/m^2.year)
Urban	0.1	0.05
Agriculture	0.05	0.05
Forest	0.01	0.05

Source: Adapted from Salas & Martino (1991).

Table 3. Per capita contribution for each water quality parameter.

Parameter	Per capita contribution (g/inhab.day)
BOD_5	35.00
Organic nitrogen	2.50
Ammonia	3.50
Nitrate	0.10
Organic phosphorous	0.21
Inorganic phosphorous	0.49

Source: Adapted from Von Sperling (2014).

Trophic Index (TRIX)

With a view to obtaining better spatial and temporal understanding of the trophic state of the CELMM, the multivariate Trophic Index (TRIX) proposed by Vollenweider et al. (1998) was used. This index has been frequently applied to assess the trophic status of Brazilian water bodies (Alves et al., 2013; Cotovicz Junior et al., 2012; Mourão et al., 2020; Paula Filho et al., 2020; Bull et al., 2021), and its calculation considers the chlorophyll-a concentrations, which express the primary production of dissolved inorganic nitrogen (DIN = NO_3 + NH_3) and dissolved inorganic phosphorous (DIP), corresponding to nutritional factors, and the absolute percentage of dissolved oxygen saturation (aD%O), Equation 2:

$$\text{TRIX} = \frac{Log\left(Chlo\ .\ aD\%O\ .\ DIN\ .\ DIP\right) - k}{m} \quad (2)$$

Where *k* and *m* are the constants used to adjust the TRIX scale value, and the concentrations of chlorophyll-a, nitrogen and dissolved inorganic phosphorous are expressed in mg/m^3. In the present study, *k* and *m* were set at 1.5 and 1.2, respectively, according to the values established by Vollenweider et al. (1998). The dissolved oxygen saturation deviation was obtained from the absolute difference between the saturated and dissolved oxygen concentrations available.

The eutrophication level and water quality status can be determined from the TRIX index. According to Vollenweider et al. (1998), TRIX values near zero indicate a low eutrophication level and optimal water quality, while those near 10 show high eutrophication and poor water quality (Table 4).

To identify the relations between water quality, represented by the parameter TRIX, DIN (Dissolved Inorganic Nitrogen), Chlorophyll-a and DIP (Dissolved Inorganic Phosphorous), river discharges and tidal input, an analysis of the Pearson correlation method between the variables was developed for stations in the inner region of the CELMN (Stations A and B, at Mundaú Lagoon, F and H, at Manguaba Lagoon) and in the intermediate region of the access channels to the Mundaú and Manguaba Lagoons(Stations

Table 4. Eutrophication level classification according to the TRIX scale.

TRIX Scale	Eutrophication Level	Water Quality Status
0-4	Low	Optimal
4-5	Medium	Good
5-6	High	Poor
6-10	Elevated	Very Poor

Source: Adapted from Alves et al. (2013).

D and I, respectively) considering the three simulated years (2006, 2014 and 2017). Statistical analysis was carried out using R version 4.1.2 (R Core Team, 2021).

RESULTS AND DISCUSSIONS

Temporal evolution of water quality parameters

Three periods were simulated: 2006, 2014 and 2017. The 2014 dataset was used to calibrate the hydrodynamic circulation model, using water level elevation data reported by Brito Junior et al. (2018). Hydrodynamic modeling results are not presented here, but can be found in Luz, 2021 and Cunha et al., 2021. Measures were taken of the free surface position at Manguaba and Mundaú Lagoons, between 02/16/2014 and 02/25/2014 (Brito Junior et al., 2018). In order to simulate hydrodynamic circulation, tide, wind and freshwater discharge from 2014 data were provided. The results of the free surface position obtained for the model show good agreement with the measured data in relation to the phase, but showed differences in relation to the amplitude. Correlation coefficients (R^2) were 0.84 and 0.65 for the Mundaú and Manguaba lagoons, respectively. One possible cause for obtaining a lower value for R^2 in Manguaba lagoon is that the bathymetry used in the modeling is much older than the period for which these simulations were performed.

Figure 3 present the BOD concentrations for the three simulated years, showing low concentrations in the northeastern and central portion of Mundaú Lagoon (A and B) due to the greater influence of the Mundaú River, which exhibited the lowest BOD concentrations. The highest BOD concentrations are found in the southeastern part of the lagoon (Station C), because of its proximity to wastewater discharge points and the long residence

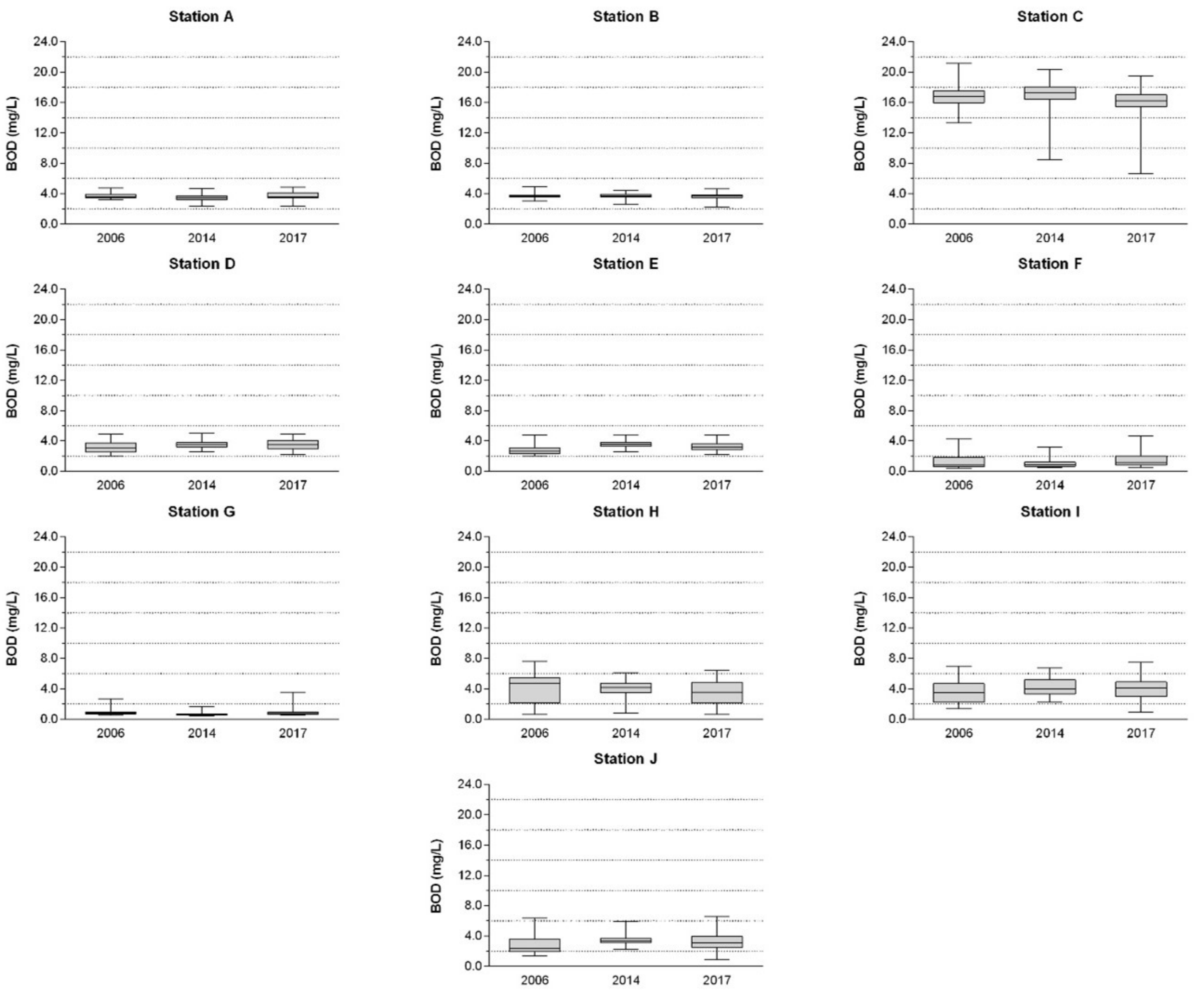

Figure 3. Box plot of BOD concentrations for the three simulated years for the stations located at the Mundaú (A, B and C) and Manguaba (F, G and H) Lagoons, the access channels (D and I) and near the tidal inlet (E and J).

times in the region (Pinheiro et al., 2021). This increase depleted DO concentrations and may compromise aquatic life (Thomann & Mueller, 1987). Stations located in the region of the Mundaú Lagoon channel (D and E) display low BOD concentrations, with values below 4.0 mg/L, which may be related to the shorter residence times in the region (Pinheiro et al., 2021). A slight increase in BOD concentrations was observed near the tidal inlet (Station E) in 2014, compared to those found in 2006 (Figure 3). No significant variations were detected in the BOD concentrations of the other stations, in the three simulated years.

Like the Mundaú Lagoon, the northeastern and central portion of the Manguaba showed low BOD values due to the influence of the Paraíba do Meio River. The different concentrations found in 2006, 2014 and 2017 may be attributed to river discharges variations in the three years. In the southeast portion and the access channel to the Manguaba Lagoon, BOD concentrations and the results obtained rose due to their proximity to wastewater discharge points; however, this increase was insufficient to significantly reduce DO concentrations. In the Manguaba Lagoon, the greatest difference between average simulation values was observed in the station near the tidal inlet (station J), with an increase in the 2014 average compared to 2006, which may be associated with changes in the tidal inlet (Figure 3).

Total nitrogen and total phosphorous concentrations in the northeastern and central regions of the lagoons depend primarily on the nutrient loads in the Mundaú and Paraíba do Meio Rivers, given that the wastewater loads are low because of the low river discharges (Figure 4 and Figure 5). In the channel region of the Mundaú and Manguaba Lagoons, where the tidal influence predominates, no significant variability was observed between average total nitrogen and total phosphorous values between the three simulated years, which remained below 0.15 mg/L and 0.015 mg/L, respectively (Figure 4 and Figure 5).

The total nitrogen and total phosphorous concentrations were used to calculate the average N:P ratios of all the stations, thereby determining the factor that limits primary production

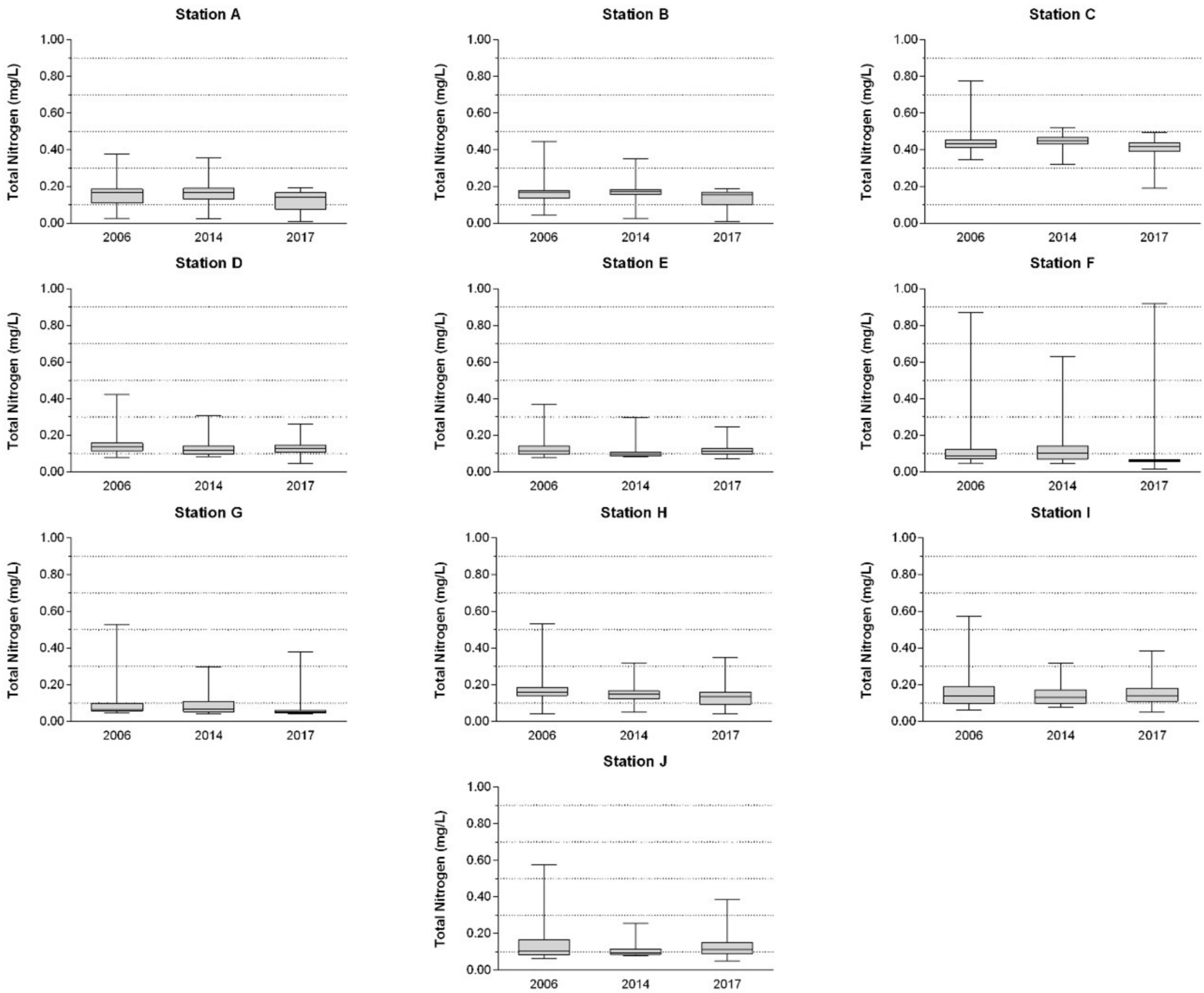

Figure 4. Box plot of total nitrogen concentrations for the three simulated years at the Mundaú (A, B and C) and Manguaba (F, G and H) Lagoons, the access channels (D and I) and near the tidal inlet (E and J).

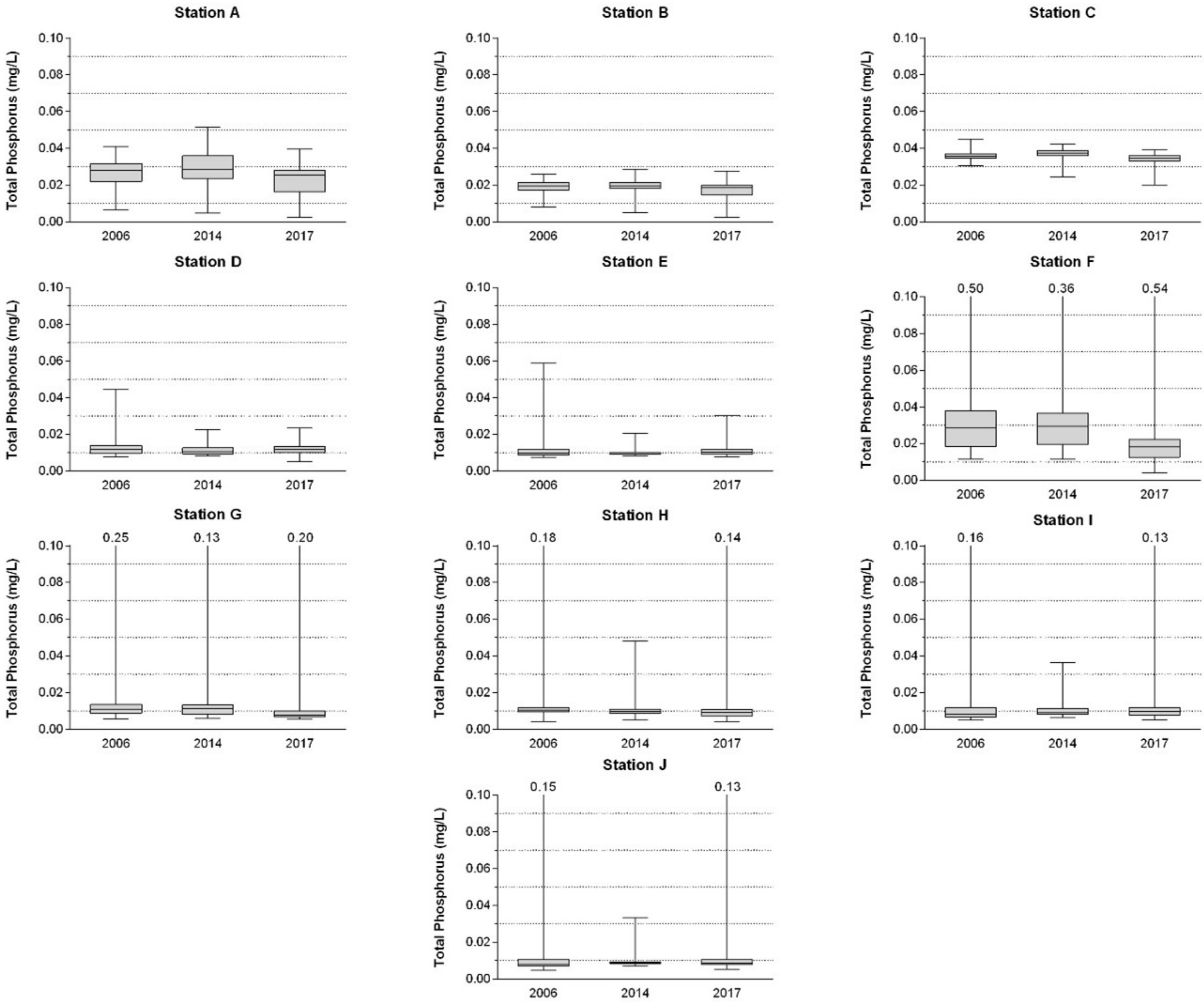

Figure 5. Box plot of total phosphorous concentrations for the three simulated years at the Mundaú (A, B and C) and Manguaba (F, G and H) Lagoons, the access channels (D and I) and near the tidal inlet (E and J).

(Thomann & Mueller, 1987). In the northeastern and central portions of the Mundaú Lagoon (stations A and B), which are under greater fluvial influence, the N:P ratio was below 10 in all three simulations, indicating that in these regions, nitrogen is the “limiting nutrient”, that is, nitrogen availability controls the growth velocity of algae and aquatic plants. In the northeastern and central regions of the Manguaba Lagoon (Stations F and G), nitrogen is also a limiting factor, given that in all the simulations, average N:P ratios were below 10. At the other Mundaú and Manguaba Lagoon stations, phosphorous was a limiting factor in the three simulations (average N:P ratio above 10).

In the Mundaú Lagoon, chlorophyll-a concentrations (Figure 6) were highest in the northeastern and central portions (Stations A and B), with average values varying between 3.5 and 4.6 μg/L and between 1.8 and 2.8 μg/L, respectively. In the southeastern part of the lagoon (Station C), concentrations are lower, and average values were below 1.0 μg/L, which may be associated with the low phosphorous concentrations, since phosphorous is the limiting factor of primary production (Thomann & Mueller, 1987). Greater variability was observed in average chlorophyll-a values in the channel region and near the tidal inlet (Stations D and E).

In the Manguaba Lagoon, the highest average chlorophyll-a concentrations (between 3.3 and 3.8 μg/L) are found in the northeastern portion (Station F), due to its proximity to the Paraíba do Meio River, which supplies a large amount of nutrients. In the central portion of the lagoon (Station G), nutrient concentration is lower, causing a decline in chlorophyll-a concentrations. In the southeastern portion (Station H), despite the high nutrient load, chlorophyll-a concentrations did not increase, remaining below 1.5 μg/L, which may be due to the low total phosphorous concentration, given that in this area it limits primary production (Figure 6). In the channel region and near the tidal inlet (Stations I

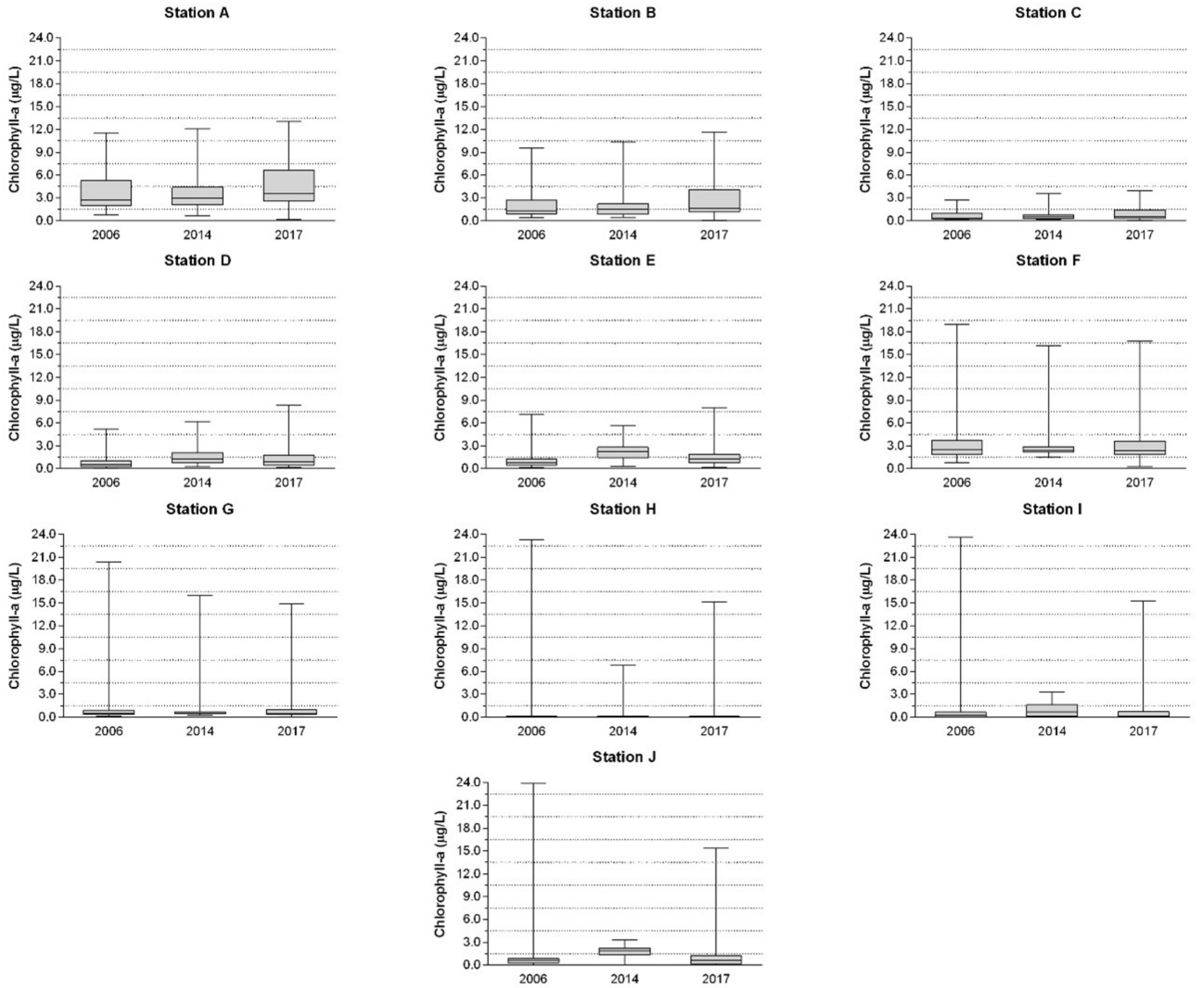

Figure 6. Box plot of chlorophyll-a concentrations for the three simulated years at the Mundaú (A, B and C) and Manguaba (F, G and H) Lagoons, the access channels (D and I) and near the tidal inlet (E and J).

and J) no significant variations were observed between the average simulation values, which ranged from 0.9 to 1.5 μg/L and 1.4 to 1.7 μg/L, respectively (Figure 6).

The highest chlorophyll-a concentrations were observed in the Manguaba Lagoon (Stations G and H) in 2006, with values above 20.0 μg/L, associated with the rainy season. The driest of the three simulated years was 2014 and, as such, exhibited the smallest chlorophyll-a concentration peaks. In the Mundaú Lagoon (Stations A, B and C), the highest chlorophyll-a concentrations were similar for the three years, with values below 12.0 μg/L.

Temporal analysis of the Trophic Index (TRIX)

The temporal evolution of the TRIX throughout the year can be obtained at all the stations established in modeling domain. Figure 7 shows the TRIX values at the Mundaú Lagoon stations. The index varied more in the rainy season (April to September), in the northeastern and central parts of the lagoon (Stations A and B), which are influenced more by the Mundaú River and where the lowest TRIX values are found. When the river discharges in these areas, the TRIX values declined to their lowest levels during peak of the river discharges. The minimum TRIX values found at Station A during the rainy season (3.64, 4.12 and 1.92 in 2006, 2014 and 2017, respectively, correspond to the average (2014) and lowest (2006 and 2017) eutrophication levels.

In the southeastern part of the Mundaú Lagoon (Station C), since the effects of wastewater discharges in these areas, the TRIX values declined to their lowest levels during peak of the discharges predominate, the TRIX behavior at this point was inverse to that found in areas under greater influence of the river. In the Mundaú Lagoon channel and near the tidal inlet (Stations D and E), the TRIX values are influenced primarily by the tidal effects, exhibiting modulation with tidal cycles (Figure 7).

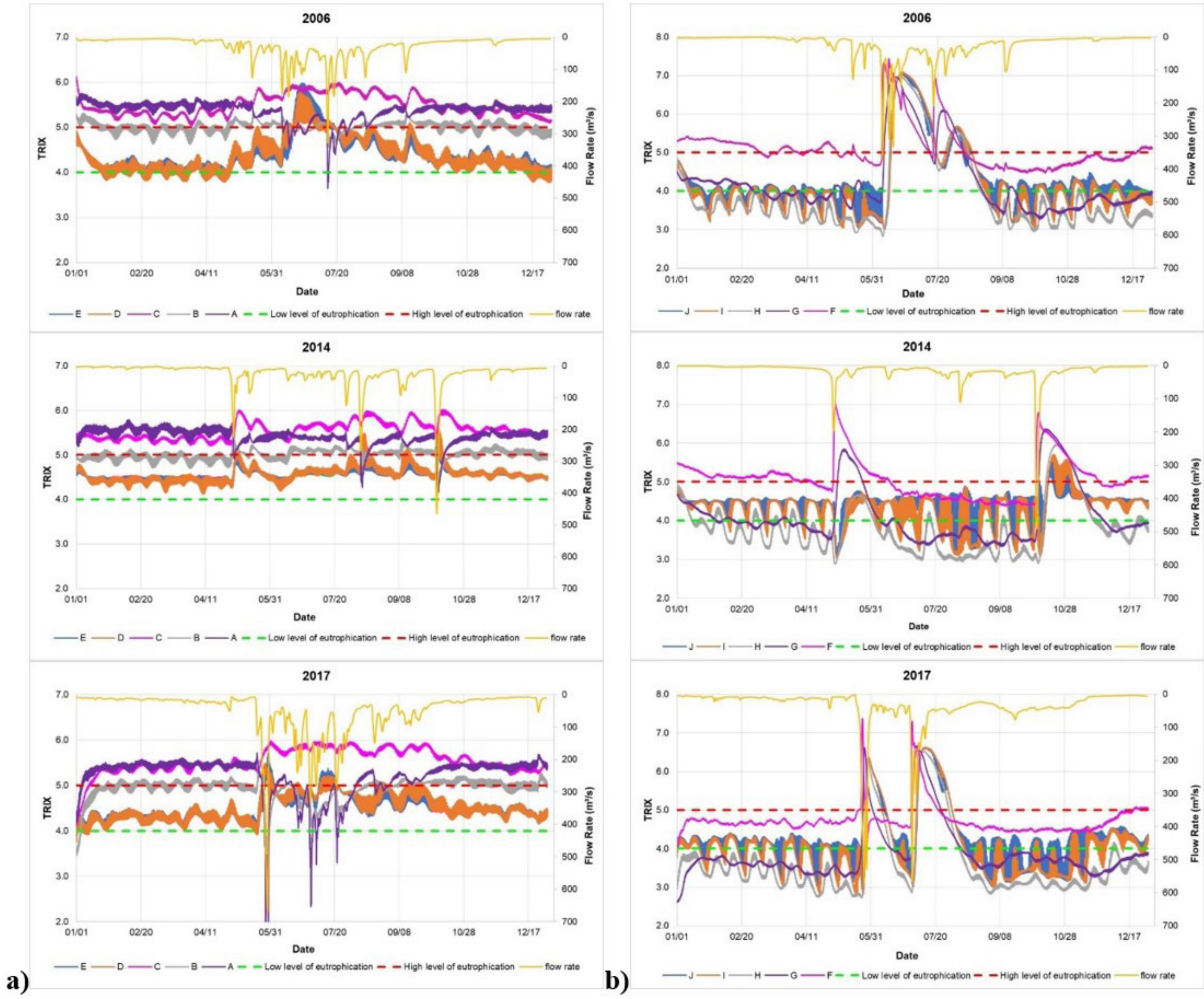

Figure 7. Trophic index (TRIX) a) at the Mundaú Lagoon (Staions A, B and C), the access channel (Station D) and near the tidal inlet (Station E) and Mundaú River discharges for 2006, 2014 and 2017 and b) at the Manguaba Lagoon (Staions F, G and H), the access channel (Station I) and near the tidal inlet (Station J) and and Paraíba do Meio River discharges for 2006, 2014 and 2017.

As in the Mundaú Lagoon, greater oscillations in the TRIX index were observed in the Manguaba Lagoon during the rainy season. In the northeastern and central portions of the lagoon (Stations F and G), the TRIX index rose with an increase in the river discharges in these areas, the TRIX values declined to their lowest levels during peak of the discharges, where maximum values occurred during peak of the discharges. The highest TRIX values during the rainy season were found at Station F, with maximum values of 7.43, 7.02 and 7,37 occurring in 2006, 2014 and 2017, respectively, corresponding to a high eutrophication level and poor water quality (Figure 7).

In the southeastern region of the lagoon (Station H), the wastewater discharge points do not contribute significantly to the variations in the TRIX index, given that in the rainy season the index behaved similarly to those recorded at Stations F and G and in the dry season showed modulation with the tidal cycles, similar to the behavior observed in the channel of the lagoon and near the tidal inlet (Stations I and J). In both lagoons there was a delay in the response of the TRIX index, as the distance between the station and the mouth of the tributary river increased (Figure 7).

A comparison between the dry season TRIX values of 2006, 2014 and 2017 demonstrated significant changes at the stations located in the inner portion of the Mundaú and Manguaba Lagoons, while in the channel region of the lagoons there was a rise in TRIX values in 2014, followed by a decline in 2017, which may be associated with alterations at the tidal inlet. In the rainy season significant changes were observed between the TRIX values of 2006, 2014 and 2017 at all the stations. However, these changes are associated with the variations in tributary river discharges in the three years investigated.

The annual average of the TRIX index in the Mundaú lagoon varied between 4.92 and 5.55, indicating a medium to high variation

Table 5. Correlation between the river discharges with TRIX, DIN (Dissolved Inorganic Nitrogen), Chlo (Chlorophyll-a) and DIP (Dissolved Inorganic Phosphorous) for the years 2005, 2014 and 2017 at various stations.

		Sta_A	Sta_B	Sta_D	Sta_F	Sta_H	Sta_I
2006	TRIX	-0.852	-0.005	0.679	0.625	0.433	0.372
	DIN (mg/L)	-0.669	-0.542	0.191	0.659	0.118	0.317
	Chlo (µg/L)	0.868	-0.840	0.640	0.753	0.402	0.341
	DIP (mg/L)	-0.772	-0.678	0.542	0.662	0.436	0.427
2014	TRIX	-0.783	0.053	0.612	0.290	-0.176	-0.246
	DIN (mg/L)	-0.538	-0.493	0.731	0.467	-0.288	0.055
	Chlo (µg/L)	0.796	0.756	0.381	0.381	0.008	-0.195
	DIP (mg/L)	-0.555	-0.437	0.484	0.568	-0.052	0.089
2017	TRIX	-0.902	-0.606	0.689	0.549	0.307	0.135
	DIN (mg/L)	-0.746	-0.761	0.162	0.562	0.004	0.082
	Chlo (µg/L)	0.837	0.862	0.779	0.812	0.303	0.211
	DIP (mg/L)	-0.769	-0.748	0.095	0.515	0.416	0.358

in the eutrophication level. In the Manguaba lagoon, the annual average varied between 3.61 and 5.11, suggesting eutrophication levels ranging from low to high, with higher values being found near the mouth of the Paraíba do Meio river (Station F). In the region of the channels, the annual average of the TRIX index remained in the range between 4.07 and 4.57, corresponding to an average level of eutrophication.

Cotovicz Junior et al. (2012) obtained TRIX mean values of the 5.34 for Mundaú Lagoon and 5.32 for Manguaba Lagoon, considering each lagoon as a single system, indicating mesotrophic to eutrophic conditions, with high primary productivity. In the channels, the TRIX values were between 4.00 and 4.80, indicating a medium level of eutrophication and moderate primary productivity. TRIX values were calculated from data measured in 7 campaigns, between 2006 and 2009, at 16 stations at Mundaú Lagoon, 20 at Manguaba Lagoon and 10 at channels. The annual mean obtained in this work for the year 2006 were 5.3 and 4.4, in Mundaú and Manguaba Lagoons, respectively. The differences found in Manguaba Lagoon are possibly associated with the number of stations and the time interval used by Cotovicz Junior et al. (2012) for calculating the mean (four years).

The correlation between the river discharge, the TRIX, DIN (Dissolved Inorganic Nitrogen), Chlo (Chlorophyll-a) and DIP (Dissolved Inorganic Phosphorous) for the three years can be seen in Table 5. Among the 72 coefficients, 15 of them (21% of the total) were greater than 0.75, indicating a strong correlation between the variables. It is possible to observe that, in the inner regions of the lagoons (stations A and F), the river discharge is important in defining the water quality in the three years analysed. In the other stations, a less intense correlation is observed between the river discharge and the variables of water quality.

At station A (Mundaú Lagoon) there is a very strong and negative correlation between the river discharge and the TRIX, with r values of -0.85, -0.78 and -0.90 in 2006, 2014 and 2017, respectively, and a very strong and positive correlation between river discharge and Chlo, with r values of 0.87, 0.80 and 0.84 in 2006, 2014 and 2017, respectively. DIN and DIP showed negative correlations with the river discharge, but to a lesser extent, with r values of -0.67, -0.54 and -0.75 in 2006, 2014 and 2017, respectively, for DIN, and with r values of -0.77, -0.56 and -0.77 in 2006, 2014 and 2017, respectively, for DIP. At Station A, the correlation values did not change significantly between the years 2006 and 2017, because the hydrodynamic circulation is strongly influenced by the river discharge. In station B, only the correlations between the river discharge and Chlo were significant, with r values of -0.84, 0.76 and 0.86 in 2006, 2014 and 2017, respectively. Even with a not so significant correlation, it is possible to observe a significant increase in the correlation between the river discharge and the TRIX between the years 2006 and 2017. Station F (Manguaba Lagoon) shows a strong correlation between river discharge and Chlo in 2006 and 2017, with r values of 0.75 and 0.81, respectively, reinforcing the conclusion that the Paraíba do Meio River is responsible for the nutrient load to the lagoon. We can conclude that in the inner region of the Mundaú lagoon, the water quality is strongly influenced by the fluvial flow; in the Manguaba lagoon, this influence is smaller, probably because the discharges of the Paraíba do Meio River (annual mean of 17.6 m^3/s) are lower than those of the Mundaú River (annual mean of 33.5 m^3/s) and the volume of Mundaú Lagoon (annual mean of 41,650 hm^3) is smaller than that the volume of Manguaba Lagoon volume (annual mean of 101,100 hm^3) (Cunha et al., 2021).

The stations located in the channels (D and I) present a low correlation between the water quality parameters and the fluvial flow, showing that the water quality in the channels is little influenced by the river discharges variations. Therefore, it is possible to assume that in the channels, the tide is the most important forcing of circulation and, consequently, the transport of dissolved substances.

CONCLUSIONS

The results show that water quality in the northeastern and central regions of the lagoons is heavily influenced by river discharges, while in the southeastern part and access channels, the changes are due to tidal oscillations. Only in the recesses, located in the southeastern portion of the Mundaú Lagoon, were the effects of wastewater discharge more apparent, due to the significant nutrient load, and the smaller effects of tidal oscillations and river discharges.

Significant changes in the TRIX index were observed during the rainy season, because of the larger river discharges oscillations of the Mundaú and Paraíba do Meio Rivers. The

TRIX index of the lagoons behaves as follows: in the Mundaú and Manguaba Lagoons, the index declines and rises, respectively, with an increase in river discharges. Thus, it can be inferred that in the Mundaú Lagoon, the river discharges favor nutrient dilution (DIN and PID), reducing its concentrations and, as a consequence, decreasing TRIX values. In the Manguaba Lagoon, the tributary river contributes to the increase in nutrient concentration, resulting in high TRIX values.

No significant effects of tidal inlet changes were observed for the water quality of the lagoons. This occurs because the access channels act as filters, reducing the tidal amplitude in the inner portion of the lagoons. Thus, the regions near the tidal inlet (Stations D and I) were the most impacted by the changes that occurred in this area. Finally, the main source of pollution in the Mundaú Lagoon are the wastewater discharge points located in the southeastern portion. Wastewater discharge did not contribute significantly to the concentrations of the Manguaba Lagoon quality parameters, indicating that the river discharges is the main cause of changes in water quality.

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Authors Contribution

Teresa Elane Bezerra Luz: contributed to the development of the methodology; obtaining data; reference search; configuration of data used in modeling; performed water quality modeling; analyzed the results obtained in the modeling; wrote the text of the article.

Mariana Kummer da Rocha Pinheiro: contributed to data collection and reference research; performed the modeling and hydrodynamic analysis of the system under study; assistance in configuring the data used in the modeling.

Ada Cristina Scudelari: assisted in the development of the methodology; collaborated with the search for references; assisted in the configuration of the modeling data; assistance in the analysis of results; review of the article text.

Cynara de Lourdes da Nóbrega Cunha: assisted in the development of the methodology; collaborated with the search for references; assisted in the configuration of the modeling data; assistance in the analysis of results; review of the article text.

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