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Effects of the hydrodynamics of Guamá river estuary on the dispersion of organic load in Tucunduba Igarapé, Belém, Pará (Brazil) State

Influência da hidrodinâmica do rio Guamá na dispersão da carga orgânica do Igarapé Tucunduba, Belém, Estado do Pará (Brasil)

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ABSTRACT

The objective of this study was to evaluate the contribution of the organic load to Tucunduba Igarapé. The data were collected over 12 h for continuous analysis of physical variables, and every 3 h for physicochemical analysis. The cross-sectional profile and flow rate were measured using an accustic doppler current profile, and the load of organic matter was estimates using equations. Three distinct flow periods were verified, two of which were governed by the hydrodynamics of the Guamá River estuary and the other by unidirectional flow from Tucunduba Igarapé to the Guamá River estuary. The organic loads of biochemical oxygen demand (0,03 kg d^{-1} – 0,07 kg d^{-1}) produced in Igarapé is greater than the contributions from the Guamá River estuary. The Guamá River estuary exerts a positive effect on the Igarapé by dispersing the produced organic loads and aiding its capacity for self-purification.

Keywords: Urbanization; Flow; Dissolved solids; Water quality.

RESUMO

O objetivo deste trabalho foi avaliar a contribuição da carga orgânica o Igarapé Tucunduba. Os dados foram coletados durante 12 h, com análises contínuas para variáveis físicas e a cada 3 h para físico-químicas. O perfil da seção transversal e a vazão foram medidos usando *Accustic Doppler Current Profile* e a carga de matéria orgânica estimada usando equações. Foram verificados três períodos distintos de vazões, sendo dois regidos pela hidrodinâmica do estuário do rio Guamá e outro pelo fluxo unidirecional do Igarapé Tucunduba para o estuário do rio Guamá. A carga orgânica de demanda bioquímica de oxigênio (0,03 kg d^{-1} – 0,07 kg d^{-1}) produzida na bacia é maior do que a contribuição do estuário do rio Guamá. O estuário do rio Guamá exerce um efeito positivo nesta bacia por dispersar as cargas orgânicas produzidas e por auxiliar sua capacidade de autodepuração.

Palavras-chave: Urbanização; Fluxo; Sólidos dissolvidos; Qualidade da água.

INTRODUCTION

Freshwater-receiving and non point sources of pollution carry a variety of toxic chemicals (Bisimwa et al., 2022; Yang et al., 2021; Zhao et al., 2019). Water pollution is a critical global problem, with over 80% of wastewater released into natural water systems worldwide. This situation is more pronounced in developing countries, where it is estimated that more than 95% of wastewater is discharged into water bodies without treatment, and limits the proper reuse of water resources, urgent actions are needed in managing wastewater, improv water quality, and restore water-related ecosystems (Ghimire et al., 2022).

Large cities worldwide are already facing water pollution problems due to urbanization, rapid population growth and economic development. Water is an essential resource for human activities and socioeconomic development, and the water quality in urban environments has important implications for human and environmental health (Luo et al., 2019).

In developing countries, disorderly urban occupations contribute to interventions in aquatic ecosystems such as streams, rivers, and lakes, which border large urban centers and are affected by several simultaneous environmental stressors, such as insufficient sanitary infrastructure systems (Alves et al., 2022; Pinto & Kondolf, 2020; Wantzen et al., 2019).

In Brazil, domestic sewage is one of the main problems for water resources, because of the lack of a collection network and or inefficient treatment of collected effluents (Santos et al., 2018). Studies have described the impacts of this problem on urban water bodies in different parts of the country (Campos & Barcarolli, 2023; Cidreira-Neto et al., 2022; Araujo et al., 2022; Simoni et al., 2022) in urban water bodies.

In the Amazon region Santos et al. (2020) evaluated land use and water quality in the Crato River, south of the state of Amazonas, and found that the advancement of urban areas over the water body has impaired its quality, and observed high concentrations of phosphorus, nitrogen and thermotolerant coliforms. According to the authors, water resources have degraded exponentially, mainly in places close to urban areas, where the deposited pollutants exceed the support capacity of the springs.

In the State of Pará, the growth and consolidation of the urbanization of the urban streams of Belém (State of Pará) were described by Azevedo et al. (2020) as an alarming environmental panorama, as densification caused changes in the processes of the hydrological cycle through soil impermeability, reduction of vegetation cover, and grounding of lower areas.

Among these Igarapés, Tucunduba Igarapé has a historical occupation without planning that did not consider its natural characteristics (Azevedo et al., 2020); it is a tidal channel that flows into the Guamá River estuary and is influenced by the meso-tide. A large proportion of the organic and inorganic waste produced in urban areas and open sanitary sewage, have been established as environmental and public health issues. Tucunduba Igarapé is a good example of the different types of solid and liquid waste generated by anthropogenic activities, such as industrial, vehicular, construction, and domestic activities, water quality has deteriorated in urban areas, which can cause health hazards for urban dwellers. Different types of pollutants such as heavy metals, organic/inorganic compounds, and biological and plastic materials may be mixed in water (Singh et al., 2022).

The contribution of allochthonous organic matter to a water body may cause a series of alterations in physicochemical parameters, with direct implications for the water quality and ecological dynamics of aquatic communities (Ifon et al., 2023). This evidence the importance of knowing the water quality of Tucunduba, even if it is a water body dynamized by the hydrodynamics of the Guamá River estuary, which could cause damage to the health of the population owing, to the large number of loads with polluting potential.

Studies have rarely mentioned the importance of hydrodynamics in easing wastewater degradation. In addition, few studies have measured the contribution of organic loads in urban Igarapés, and their capacity for self-purification has been assessed in the northern region of Brazil. Thus, the objective of this study was to evaluate the contribution of the organic load in Tucunduba Igarapé and the hydrodynamic effects of the Guamá River Estuary on water quality.

MATERIAL AND METHODS

Area characterization

Tucunduba Igarapé is located in the metropolitan area of Belém, Brazil. The climate of the State of Pará is typically equatorial, with annual average temperatures between 24º and 26º C, in addition to high rainfall, with an annual average of 2,889 in the vicinity of the Amazon River (Brito et al., 2020). According to the classification proposed by Köppen-Geiger, the climate of the State of Pará is included in the category Equatorial Hot Humid, which has a tropical rainy climate and is framed as climate zone Af (Porto et al., 2021).

The Tucunduba is a tidal channel, with a depth of less than 2m, which cuts through several neighborhoods of Belém and flows into the Guamá river estuary, characterized by being a mesotidal (semi-day) estuary, with a maximum height of 3.6m and minimum of 0.1m (Diretoria de Hidrografia e Navegação, 2023). This area is located in the upper section (fresh water, with vertical/horizontal movement of the dynamic tide) of the Guamá River estuary. Its depth can reach up to 7m. Recent simulations of the Guamá River Estuary show, hydrodynamic scenarios along a complete tidal cycle during syzygy and quadrature at the mouth of Tucunduba. The moment of half ebb tide stood out the most, both during the syzygy (1.03m/s) and quadrature (0.80m/s). However, during half flood the currents are lower by 0.74m/s (Syzygy) and 0.36m/s (Quadrature). Given this, it appears that these moments of the tide (syzygy) were responsible for the evacuation of tailings from Igarapé Tucunduba. During high tide and low tide, the currents are lower, respectively: 0.17m/s - Spring; 0.12m/s - Quadrature and 0.26m/s - Syzygy and 0.22m/s - Quadrature (Cunha, 2017).

Tucunduba Igarapé, located south of the city of Belém is located in a house on Travessa Angustura - in the Marco district. The Igarapé drains the neighborhoods of Canudos which has a population of 13,804 inhabitants; Terra Firme with 61,439 inhabitants; part of the neighborhoods of Guamá with 94,610 inhabitants; São Brás with 19,936 inhabitants; Marco with 65,844 inhabitants; Curió-Utinga with 16,642 inhabitants; and Universitário with 2,557 inhabitants, constituting a total of 7 neighborhoods.

The polygon of the Igarapé is located at coordinates 1°25'46.98" and 1°28'43.06" South Latitude and 48°25'34.03" and 48°28'44.15" West Longitude, with an area of 12.38 km^2 and its perimeter is 14,174.99 meters (Rodrigues & Luz, 2022).

Collection and analysis of data

The study was conducted on the campus of the Federal University of Pará, at a site in the Tucunduba Igarapé (coordinates 48° 27'15.10"W and 1° 28' 33.12" S) (Figure 1). The area corresponds to an estuarine várzea ecosystem, characterized as a high estuary, which is affected by the tidal waters of the Guamá river estuary.

Data were collected on April 9, 2013, for 12 h, with continuous analysis of physical variables (starting at 7 h in the morning), and every three hours for physico-chemical analysis (a total of five samples collected at the following times: 7:40 am, 10:40 am, 1:40 pm, 4:40 pm and 7:40 pm). Water samples were also collected in 1.000 L polyethylene bottles to determine the chemical parameters. All procedures were performed in accordance with the American Public Health Association guidelines (American Public Health Association, 2017).

Water samples were collected from the hydrological bottles. Data from turbidity, pH, total dissolved oxygen (TDO), temperature (TºC), salinity and electrical conductivity (EC) were quantified in situ using the HANNA probe HI 9829 model.

For the analyses of biochemical oxygen demand (BOD), dissolved oxygen (DO), total phosphorus and total nitrogen, water samples were preserved in appropriately acclimated thermal boxes, until they were processed at the Laboratory of Environmental Chemistry, Federal Rural University of the Amazon, according to American Public Health Association (2017).

The following methods were used in the laboratory: i) biochemical oxygen demand (BOD) – 5 day BOD test and dissolved oxygen (DO) – iodometric, according to American Public Health Association (2017); ii) total phosphorus (10127- molybdonadate with acid persulfate digestion, adapted from Standard Methods) and total nitrogen (10071 – TNT persulfate digestion method) - according to HACH manual.

The cross-sectional profile, velocity of the surface currents, and flow of the Tucunduba Igarapé were measured using the Accustic Doppler Current Profile (ADCP), vessel type, frequency of 3000 kHz, installed on the water surface with the help of a floating platform and transmitted via Bluetooth to a computer using the River Surveyor Live 3.0.

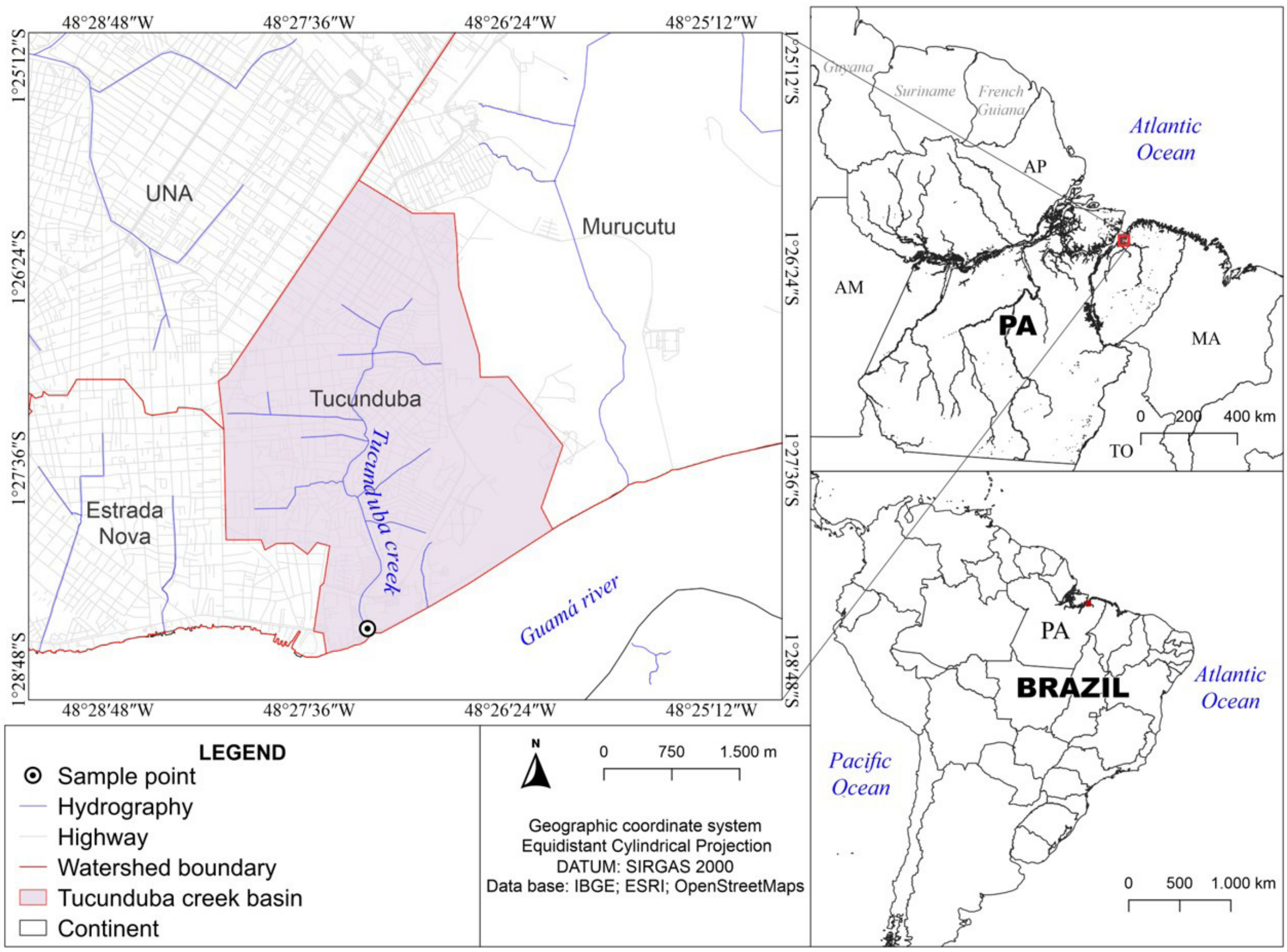

Figure 1. Study area localization in Tucunduba Igarapé, Belém (State of Pará).

Pollution loads were evaluated based on the Von Sperlling method (2014) according to Equation 1.

$$Load\left(\text{kg/d}\right)=\frac{\text{C}\left(\frac{\text{g}}{\text{m}^3}\right)\times V\left(m^3/d\right)}{1000\left(\frac{\text{g}}{\text{kg}}\right)} \quad (1)$$

where: C is the concentration of the analyzed product, Flow is the flow of the evaluated stretch, and V: Flow.

Statistical analysis

The PAST program was used for statistical analysis. Using normal data, descriptive statistical analyses of the physico-chemical variables and organic loads produced. Principal component analysis (PCA) analysis were performed to identify the set of variables that contributed the most to data variation.

RESULTS AND DISCUSSIONS

Three different flow periods were used in this study. Of these, two are governed by the hydrodynamics of the Guamá River estuary (flood and ebb) and the other by unidirectional flow, with a shorter effluent input time of the Tucunduba Igarapé.

A displacement of water mass from Guamá river estuary to the Tucunduba Igarapé occurred in the first period with a duration of 04:18 h, flow of 7.9 m^3/s and a volume of 122,434 m^3. The second one started after the summit of the high tide stand apex, with the flow of the water mass from the Tucunduba Igarapé to the Guamá river estuary, with a duration of 6 h, flow rate of 7.75 m^3/s and volume of 167,005 m^3. In the third period, flow and volume of water were reduced, remaining approximately constant for 01:03 h, with a flow rate of 1.97 m^3/s and a volume of 7.528 m^3. The total volume of water mass displaced in the 12-h period was 174,533 m^3 from Tucunduba Igarapé to the Guamá River estuary, while the entry volume in Igarapé was 122,434 m^3 (Figure 2).

A predominance of positive asymmetry was found, with less time and volume of water entering than leaving the Igarapé. This asymmetric process was also described by Mendes et al. (2022) for Baía de Guajará (Pará), where the flood tide currents collide with the ebb residues, so that this energy break favors the deposition of sediments.

According to Yu et al. (2020) understanding the evolutions of tidal duration asymmetry under hydrological and morphological conditions has important implications for ecosystem management and navigation.

Ji et al. (2022) reinforced that the time-spatial distribution of tidal current asymmetries is important for the transport of substances, not only sediment, but also contaminants and plastics. In a study conducted in Lingding Bay (southern China), the authors described that the results of tidal variations enrich the understanding of the response to human activities, which can be of practical significance for the management of estuaries in the maintenance of navigation channels and in the conservation of the ecological environment.

The hydrodynamic effects of ebb and the additional contribution of domestic effluents generated by residences in the surroundings were the major contributors to the predominance of greater flow and volume from Tucunduba Igarapé to the Guamá River estuary.

Physicochemical parameters showed marked variations, except for pH and temperature, with small oscillations (Table 1 and Figures 3a and 3b). The pH remained acidic, with values slightly higher during the discharge period of Tucunduba Igarapé and lower during the period near the high tide stand. However, the temperature was stimulated by the collection conditions, with higher values during the daytime and lower values at night.

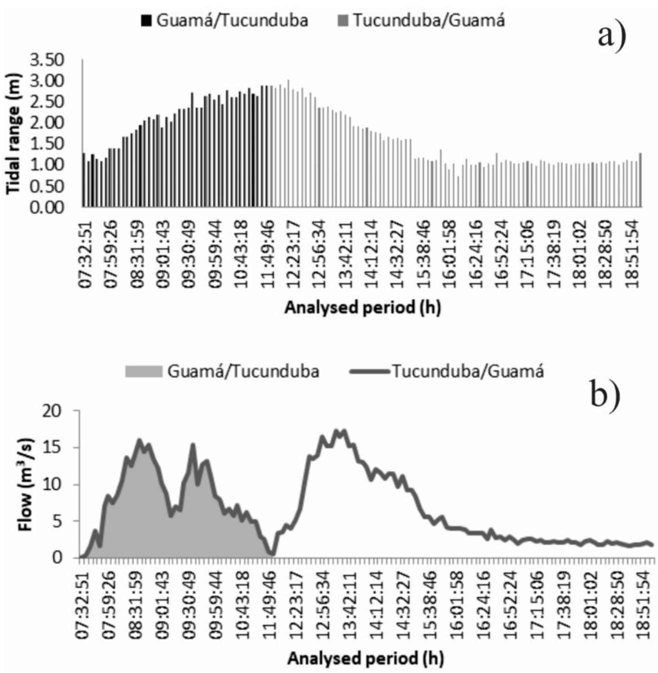

Figure 2. Dynamics of tide (a) and waste flow (b) of Tucunduba igarapé, data collected April 9, 2013.

Table 1. Statistical description of data on temperature (T), turbidity, biological oxygen demand (BOD), total dissolved solids (TDS), dissolved oxygen (DO), pH, temperature (T), electrical conductivity (EC) and salinity in the water in Tucunduba Igarapé, data collected April 9, 2013.

	Tidal (m)	pH	T °C	Turbidity NTU	BOD mg L^{-1}	TDS mg L^{-1}	DO mg L^{-1}	EC µS cm^{-1}	Salinity
[1]Mín.	0.7	5.5	27	0.5	2.4	19	1.7	38	0.0
[2]Máx.	3	6.9	30	410	8.6	243	5.2	486	0.2
[3]Aver.	1.7	6.1	28.1	144	4.5	128	3.6	255	0.1
[4]SD	0.6	0.4	1	130	2.8	100	1.4	200	0.1
[5]CV(%)	2.8	15.2	28.1	1.1	1.6	1.2	2.5	12	1.2

[1]Minimum. [2]Maximum. [3]Average. [4]Standard deviation. [5]Coefficient of variation.

Water temperature is one of the main abiotic factors affecting the structure and function of aquatic ecosystems and its alteration can have important effects on biological communities (Bonacina et al., 2022).

Water temperature plays an important role in maintaining the growth, reproduction, survival and distribution of organisms in physical environments. In addition, it influences the solubility of gases in water. In tropical estuarine ecosystems, rainfall plays an important role in the seasonal variability of the water temperature, salinity, OD, and TDS (Hasan et al., 2022).

Temperature variation in the waters of the Guamá River was described by Varela et al. (2020) because of the seasonality of the region. In the present work, the influence observed in the distribution of temperature values was related to the collection time, as shown in Figure 3b, at 4:40 pm the highest temperature value was observed (Table 1).

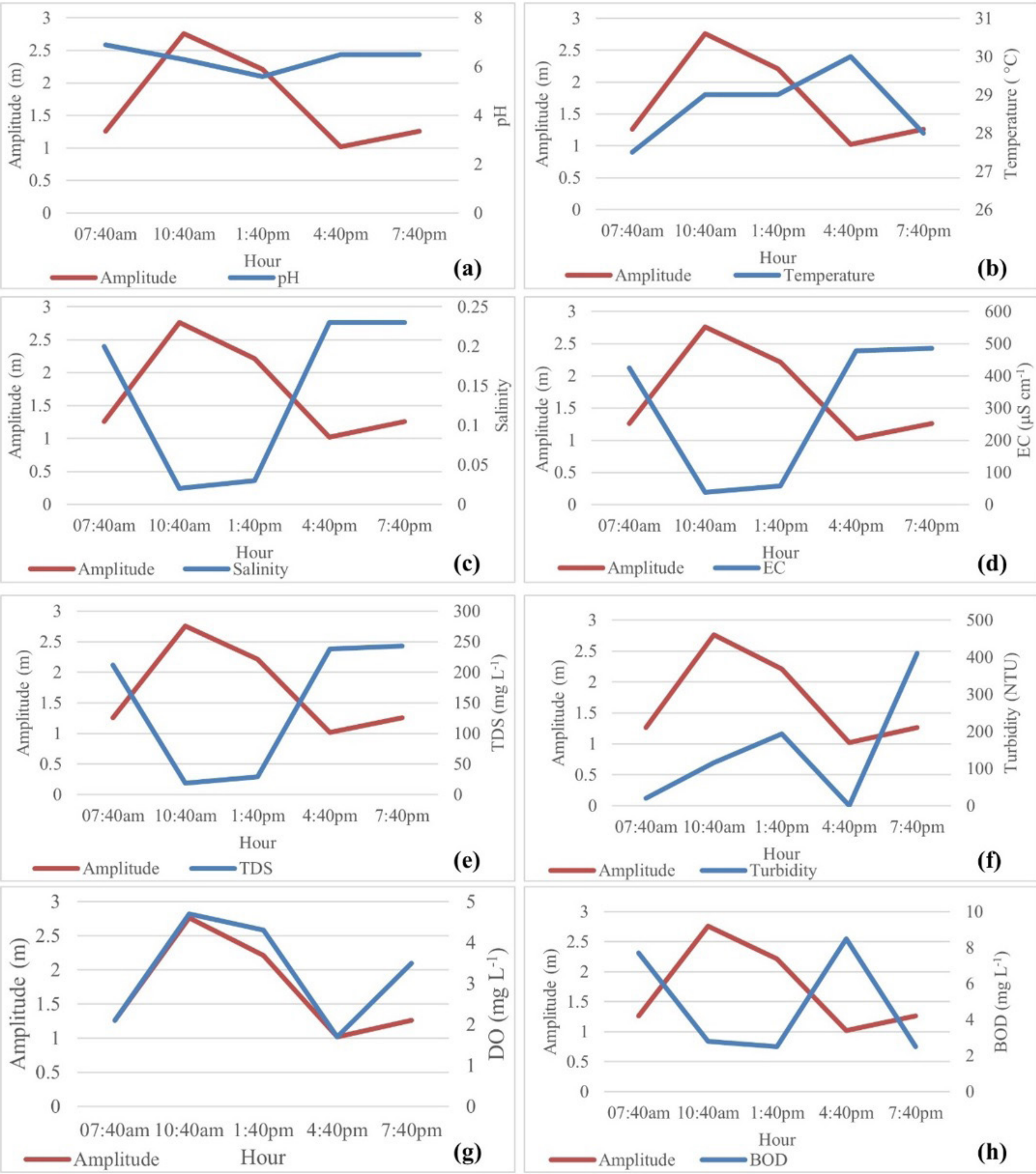

Figure 3. Variation of pH (a), temperature (b), salinity (c), EC (d), TDS (e), turbidity (f), DO (g), and BOD (h) during the tidal cycle in the Tucunduba Igarapé, data collected April 9, 2013.

Santos et al. (2020) observed small variations in temperature and pH between tides in an estuarine area in the State of Pará (Guajará-Mirim Estuary). The small variation in pH (Figure 3a) is related to the existing buffering effect in aquatic ecosystems, which is verified by the slightly acidic values found in the present study.

Despite the acidic values, it was observed that the pH was within the acceptable value for aquatic environments described by Hasan et al. (2022): pH less than 7 but greater than 8.5 is not ideal for productivity, and less than 4 is considered harmful to aquatic life. Waters from the estuaries of the State of Pará has acidic pH values and is related to the local geology (Oliveira et al., 2022; Santos et al., 2020; Varela et al., 2020).

Turbidity (Figure 3f), BOD (Figure 3h), and TDS (Figure 3e) values were higher during the ebb period from Tucunduba Igarapé to the Guamá River estuary, especially in the absence of tidal dynamics. In relation to DO (Figure 3g), the highest concentrations occurred in periods close to the high-tide stand, and the lowest concentrations occurred in the ebb of Tucunduba Igarapé, where critical values were achieved. The EC (Figure 3d) and salinity (Figure 3c) presented the same pattern of variation, in which the lowest values were achieved during the period of influence of the Guamá River estuary, and larger values were found during the discharge of Tucunduba Igarapé (Table 1).

The organic loads of BOD were higher over water flow from the Tucunduba Igarapé to the Guamá river estuary (Table 2). However, as water from the Guamá River estuary was introduced in the Tucunduba Igarapé (flood), the inputs of the BOD were reduced.

The organic loads that leave Tucunduba Igarapé are larger than the contribution that returns to the Igarapé through the hydrodynamics of the Guamá River estuary (Figure 4).

According to Lages et al. (2021) most of the urban water bodies in Brazil are at a high level of degradation, the BOD analysis can explain a lot about the degree of anthropic influence in these environments, since it can assess the level of degradation of organic matter in that environment.

Pereira et al. (2019) studied the hydrographic basin of the Capibaribe River (PE), which presents serious pollution problems, due to the lack of sanitary infrastructure in the municipalities that border the river, linked to low flow rates, and that domestic sewage from municipalities close to the basin contribute to the pollution of the Capibaribe River.

In the present study, the Igarapé Tucunduba is marked by several sources of diffuse pollution along its route that favor the increase of BOD in its waters.

The regression analysis allowed us to observe the following relationships: DO and tidal, EC and tidal, TDS and tidal (Figures 5a, 5c, 5e), indicating the influence of the tide on these variables. Salinity was related to EC, TDS and DO (Figures 5b, 5d, 5f). While DO was also related to TDS (Figure 5h), and BOD to flow (Figure 5g), the latter related to the sources of pollution that exist in Igarapé Tucunduba.

The main component analysis accounted for 69% of the total data variance. The first axis (PC1) explained 50% and the second axis, 19% (PC2). In the first axis, a negative relationship between DO and pH, BOD, TDS, EC, and salinity was observed, indicating that DO decreased with increasing BOD. The second axis turbidity was negatively related to BOD and temperature (Table 3).

The high TDS values are due to river discharge and the action of tides and currents, which cause turbulence in the sediments that resuspend particles into the water. Alencar et al. (2019) reported that in the less rainy period in the Bay of Guajará - Belém, dissolved solids are present in greater concentration, as they are influenced by the dissolution of materials present in the riverbed. This dissolution occurs because of less rainfall, with a greater drag on the riverbed and consequently, greater turbidity in these waters. During the rainy season, these solids tended to have lower concentrations because of the greater dilution caused by rainwater.

The lower concentrations during the flood were due to the lower concentration of organic matter and the capacity for self-depuration and renewal of the water owing to the hydrodynamic action of the Guamá River estuary. During the discharge period, in addition the prevalence of aerobic processes for the degradation of organic matter, the concentration is increased by effluents from domestic sewage and solid waste. Costa et al. (2021) also verified for the waters of the Tucunduba and Sapucajuba creeks that domestic effluents and the presence of decomposing organic matter affect the values of total solids, electrical conductivity, dissolved oxygen and redox potential.

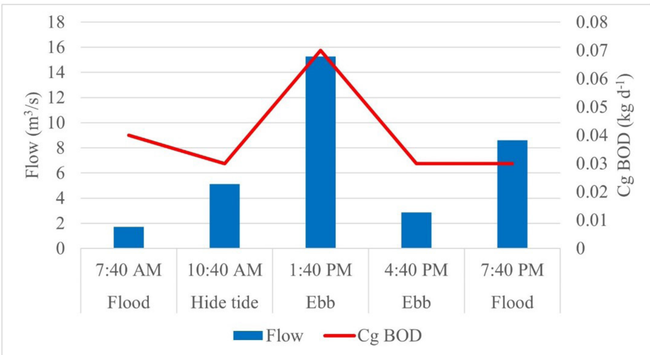

Figure 4. Distribution of the BOD load, with the maximum value recorded at the moment of greatest entry of the waters of the Igarapé Tucunduba, data collected April 9, 2013.

Table 2. Organic loads and flow in the Tucunduba Igarapé, data collected April 9, 2013.

Hydrodynamic	Hours	Flow (m^3/s)	Cg* BOD ($kg\ d^{-1}$)
Flood	07:40 am	1.72	0.04
High tide	10:40 am	5.11	0.03
Ebb	1:40 pm	15.27	0.07
Ebb	4:40 pm	2.86	0.03
Flood	7:40 pm	8.61	0.03

Cg*: organic load.

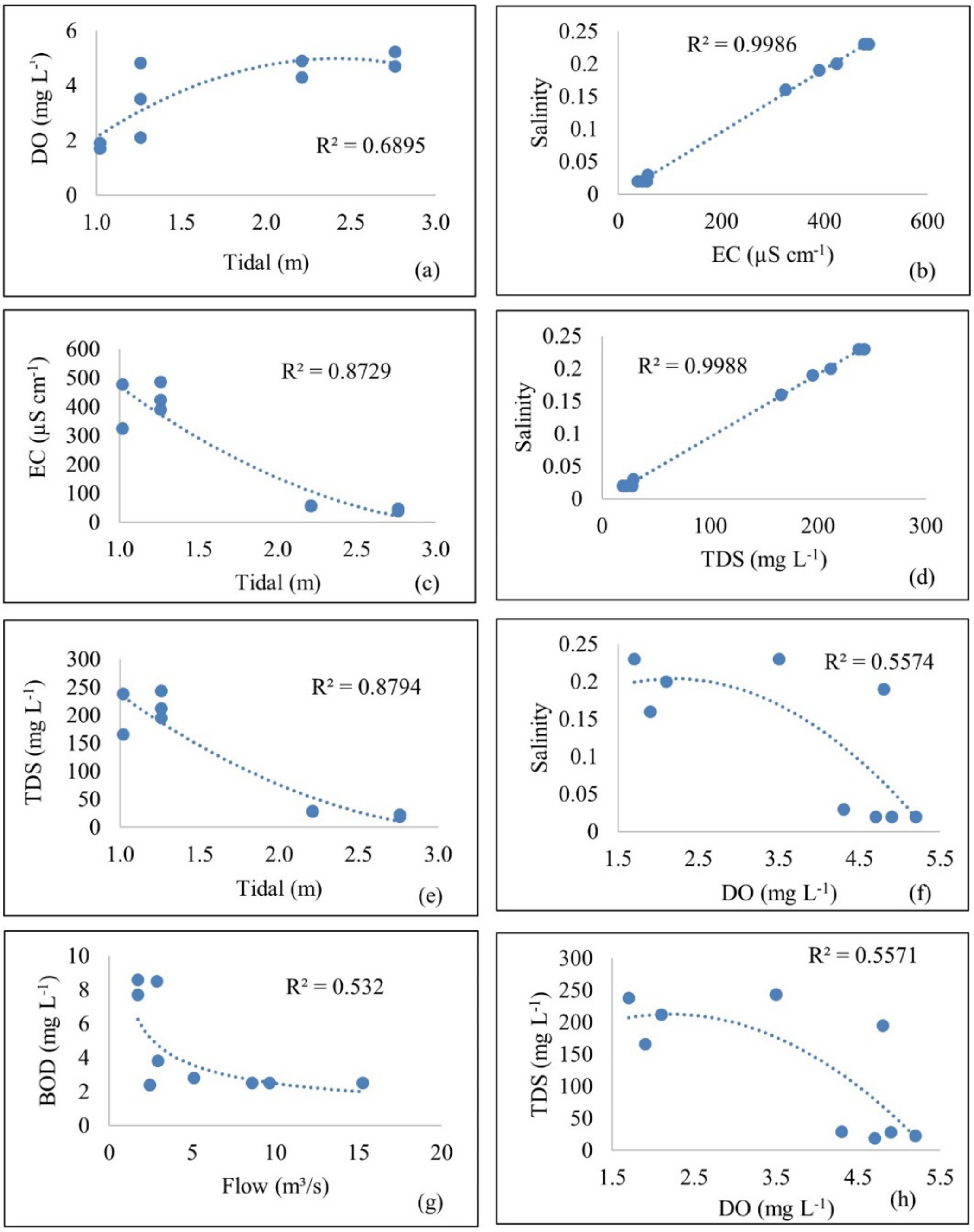

Figure 5. Regression analysis with data from Igarapé Tucunduba, data collected April 9, 2013: a) DO and tidal, b) salinity and EC, c) EC and tidal, d) salinity and TDS, e) TDS and tidal, f) salinity and DO, g) BOD and flow, h) TDS and DO.

Table 3. Analysis of the principal components of variables pH, BOD, DO, turbidity, TDS, EC, salinity, temperature in the Tucunduba Igarapé, data collected April 9, 2013 (marked loadings are > 0.40).

Variable	Factor 1	Factor 2
pH	**-0.83**	0.12
BOD	**-0.82**	**-0.55**
DO	**0.94**	0.27
Turbidity	0.30	**0.90**
TDS	**-0.94**	0.27
EC	**-0.94**	0.27
Salinity	**-0.94**	0.25
Temperature	0.19	**-0.70**
Explained variance (%)	**50**	**19**

The increase in turbidity and TDS during the discharge of Tucunduba Igarapé favored oxidative conditions, causing DO consumption and resulting in an increase in BOD, which explains the extremely low values. However, close to the high tide stand, the reverse process occurred, with a decrease in BOD, TDS, and turbidity, and an increase in DO concentrations.

Dissolved oxygen (DO) is the amount of gaseous oxygen dissolved in water, and is influenced by atmospheric pressure, temperature, salinity, water turbulence, photosynthesis, respiration, and waste. The amount of DO in a river or lake represents the quality of water (Ni'am et al., 2022). The DO content in aquatic ecosystems is related to photosynthesis and decomposition of organic matter in the tidal regime.

The mean values for EC (255.67 $\mu S\ cm^{-1}$) in the period during the flow from Tucunduba Igarapé to Guamá river estuary indicate total ion concentration in the high water, negatively affecting water quality. Values above 100 $\mu S\ cm^{-1}$ were considered by CETESB (Companhia de Tecnologia de Saneamento Ambiental, 2021) as indicators of possibly impacted environments. Thus, the values verified in the ebb flow indicated the contribution of ions in the water to domestic and industrial effluents. On the other hand, the hydrodynamics of the Guamá River estuary showed a positive effect, diluting, at the same time as it became the receptor of organic and inorganic substances, constantly increasing due to the increase in the generation of residues by the population, putting the Igarapé River at risk of contamination.

The salinity presented a similar oscillation to the EC, indicating that the presence of ions in the Tucunduba Igarapé greatly influenced the period of the greatest discharge of total dissolved solids, possibly associated with the residual release of the occupation around the Igarapé. This indicates that the residual input of Tucunduba Igarapé has a greater contribution to the input of dissolved ions in the water and that the Guamá River estuary does not affect the salinity of Tucunduba Igarapé.

The urbanization process around Tucunduba Igarapé has transformed into the main receiving body of pollution caused by the inadequate disposal of solid waste and untreated sewage. The presence of organic matter from sewage or solid waste results in an increase in BOD to the detriment of BOD. Furthermore, resuspension of these residues together with the sediments increased the turbidity and TDSs.

On the other hand, the reduction in these organic loads always occurred during the flood period of the Tucunduba Igarapé. The reduction in flood and high tide occurs due to the greater water supply available for its dilution (Martinelli et al., 2002), thus favoring self-depuration and minimizing deterioration in water quality.

CONCLUSIONS

The hydrodynamics of the Guamá River estuary and the residual discharges originating in Tucunduba Igarapé are the main parameters contributing to data variation; the Guamá River estuary acts positively on the concentrations of DO and BOD w,hile the Tucunduba Igarapé acts negatively on BOD, TDS, and turbidity. Such dynamics show the prevalence of a highly energetic scenario of a positive asymmetric wave in Tucunduba Igarapé, with mixing and circulation conditioned to the hydrodynamics of the Guamá River estuary, with water volume and ebbing period higher than the flood due to the additional residual contribution of urban effluents.

The organic loads of BOD, turbidity, and TDS produced by Tucunduba Igarapé were always higher than those produced by the Guamá River estuary. Thus, the river exerts a positive effect on the Igarapé, dispersing the organic loads produced and favoring its self-purification, capacity, in addition to attenuating the degradation of its water quality. On the other hand, such results should lead to public policies that reduce or eliminate waste input in the Tucunduba Igarapé, to reduce the risk of contamination of the Guamá River estuary, which is part of the hydrographic supply complex of Belém and metropolitan cities.

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