Evolution of erosive and hydrodynamic impacts on water quality in tidal channels at the mouths of the Araguari and Amazon rivers

Paula Lopes[1], Admilson Torres[2], Helenilza Cunha[1], and Alan Cunha[1]

[1]Universidade Federal do Amapa
[2]Instituto de Pesquisas Científicas e Tecnológicas do Estado do Amapá

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Abstract

An intense erosive process has recently caused progressive hydrogeomorphological changes in the mouths of two large rivers belonging to the Amazon River Delta, on the estuarine coast of Amapá State, namely: Araguari and Amazonas. Consequently, Araguari River was captured by the Amazon River and it influenced the sediment and water quality dynamics when two tidal channels expanded in opposite directions; this process affected both hydrographic basins and blocked Araguari River mouth. The aim of the current study is to analyze the space-seasonal variations of hydrodynamic and water quality parameters influenced by the following factors: location (channels connected to Araguari and Amazonas rivers), seasonality (dry/rainy) and spring tidal phase (flood/ebb). The herein adopted methodological stages comprised a) flow measurement with Doppler current profiler; b) water sampling (physicochemical and suspended sediments); c) suspended solids transport estimates; and d) multivariate statistical analysis of parameters. Results have indicated significant space-seasonal variation in these parameters ($p<0.05$). Water balance in the dry period has shown that Urucurituba Channel absorbs 100% of Araguari River flow, distributes 29% of it in the floodplain and discharges 71% of Araguari River flow into the Amazon River. This channel received 86% of Araguari River flow and absorbed 14% of the flow deriving from the floodplain in the rainy season, which totaled 100% of its flow at Amazon River mouth- solid discharge was proportional to 107,982 t of tidal cycle-1. Multivariate analyses have shown significant variations in 90% of the investigated parameters, which were influenced by such as location, seasonality and tidal phase ($p<0.05$). It was possible concluding that the recent channels have significantly affected the hydrodynamics, sediment transport processes and water quality of both basins. This phenomenon is currently in intense and irreversible hydrogeomorphological evolution, and it mainly affects the Araguari River estuary

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KEYWORDS

Hydrological Processes, Sediment Transport, Tidal Channels, Connectivity, Water Quality, Amazonian Estuaries.

1 INTRODUCTION

The Amazon River is the largest river in the world in terms of extension, area and discharge – its mean net discharge reaches 172,000 m^3s^{-1} (Gallo and Vinzon, 2015) and represents approximately 16-20% of all continental freshwater received by oceans worldwide (Latrubesse et al., 2017; Ward et al., 2013; 2015). Its solid discharge represents approximately 600 to 800 x 10^6t.year^{-1} (Filizola and Guyot, 2009, 2011); maximum discharge reaches up to 1,200 x 10^6t.year^{-1} (Meade et al., 1985) and presents proportional amount of nutrients, dissolved and particulate organic carbon dispersed in the Amazon River plume (Valério et al., 2018).

Araguari River, which is contiguous to Amazon River mouth, is the largest and most important river in Amapá State / Brazil; its area comprises approximately 42,700 km^2, 600 km in length, its mean annual flow is of approximately 1,000 m^{3-1}, and its original course flew into the Atlantic Ocean until 2012 (Santos et al., 2018). However, nowadays, Araguari River flows into Amazon River mouth, rather than into the Atlantic Ocean, due to the phenomenon known as "capture" by the Amazon River, which involves tidal channels, intense erosion processes and hydrodynamic changes originating on the left bank of Amazon River and on the right bank of Araguari River. (Santos et al., 2018). In addition, approximately 55% of the coastline in the North Channel of the Amazon River is undergoing erosion due to dynamic balance disturbances resulting from changes in basin-drainage processes taking place in these ecosystems (Torres et al., 2018).

On the one hand, the effects of these erosive imbalances stand out (Li et al., 2017; Torres et al., 2018), since they favor the emergence of deltas (Santos et al., 2018), as well as increased susceptibility to saline intrusions (Rosário et al., 2016) and geomorphological changes in river mouths (Kolker et al., 2012; Petts and Gurnell, 2005; Silva et al., 2020). Consequently, they affect flood period amplitudes (Junk, et al., 2014, 1996) and biogeochemistry (Allison et al., 2014). Such impacts are intensified by the combination among physical features of the hydrographic basin, loss of connectivity between waterbodies and increased frequency of extreme events associated with climate change (Cunha and Sternberg. 2018).

On the other hand, associated anthropic factors, such as land use and occupation, also lead to sediment retention and transport. The implementation of hydroelectric power plants, extensive non-controlled livestock and navigation systems (Syvitski et al., 2005; Latrubesse et al., 2017; Santos et al., 2018; Silva et al., 2020) stand out among these factors. It is so true that hydrosedimentary imbalances have been causing silting-up of riverbed and banks, as well as impairing the navigability (Bernini et al. 2016) and maintenance of ecosystem services in large river systems presenting significant sedimentary input, such as the Amazon River (Ward et al., 2013).

Despite the ecological-environmental importance of the Amazon River for Brazilian coastal management processes, studies focused on investigating water-sediment interactions and sediment transport processes taking place in it remain scarce in the literature (Torres et al., 2018). Therefore, there are considerable gaps in the literature about the way local, seasonal and tidal factors affect tidal channels and connections between both hydrographic basins. Although Araguari River has collapsed due to the connection and significant expansion of Urucurituba Channel (Santos et al. 2018), it is possible seeing its previous secondary contribution to an upstream channel network, namely: the Gurijuba-Igarapé Novo Channel. These channels appear to compromise the hydrodynamics of Araguari River mouth, in addition to affect the quality of the water, cause temporary salinization, change the hydrological pulse pattern and increase the connectivity between rivers and lakes. Such factors have led to the extinction of pororoca (Cunha and Sternberg 2018) (Figure 1).

The aim of the current study was to elaborate water and seasonal solid load balances to test and correlate hydrogeormorphological changes in the quality of the water in Araguari River, whose mouth collapsed due to "capture" of its flow by the Amazon River, through tidal channels such as Urucurituba and Gurijuba-Igarapé Novo. The study hypothesis is that these two channels got developed through fast erosive processes that started in the Amazon River and propagated towards Araguari River (Santos et al., 2018) (Figure 1).

FIGURE 1

The following sub-hypotheses were statistically tested: 1) Urucurituba Channel presents higher sediment transport rate than Gurijuba-Igarapé Novo Channel (> 50%), which causes the hydrological collapse of Araguari River mouth; 2) the rainy seasonal period, in combination to the tidal phase, significantly intensifies the solid discharge contribution coming from the Amazon River, which is later transported into Araguari River estuary. Therefore, this dynamics favors erosive events, as well as changes suspended sediment concentrations and water quality parameters; 3) the new configuration and complexity of the formed drainage system affects water balance and leads to variations in water quality parameters; and 4) factors such as location, distance from the Amazon River, seasonality and tidal phase can explain variations in suspended solid concentrations and in the quality of the water at Araguari River mouth.

2 MATERIALS AND METHODS

2.1 Study site

The study site lies between the right bank of lower Araguari River and the left bank of lower Amazon River, in the coastal-estuarine zone of Amapá State / Brazil. It is featured as a flat and low coast influenced by fluvial (North Channel of the Amazon River) and coastal (semidiurnal tides) processes (Torres et al., 2018) (Figure 1). It has hydromorphic soil associated with recent geological formations that originated quaternary plain areas that, in their turn, are naturally vulnerable to erosion processes (Rabelo, 2006).

The climate in the region is ruled by the Intertropical Convergence Zone (Schneider et al., 2014). The rainy season goes from December to July, whereas the dry season goes from August to November. Mean annual air temperature ranges from 27ºC to 27.5ºC, whereas mean annual rainfall rate ranges from 2,400 to 2,600 mm.year^{-1} (Oliveira et al., 2010).

Araguari River basin covers 1/3 of the total territory of Amapá State. It shelters important protected areas, from its source in Tumucumaque Mountains National Park to its low course near Piratuba Lake Biological Reserve (Dias et al., 2016).

Maximum flow of 3,415.8 m^3s^{-1} (May 2014) and minimum flow of 155.5 m^3s^{-1} (December 2013) were recorded between 2013 and 2015 in middle Araguari River, at Porto Platon station, which is located 270 km away from the original mouth (Cunha et al., 2014). However, the coastline of lower Araguari River, close to Amazonas, is influenced by tides whose amplitude is of approximately 3.4 m, in the North Channel of Amazon River (Figure 1).

Hydroelectric power generation (Coaracy Nunes series of plants - UHECN, Ferreira Gomes - UHEFG and Cachoeira Caldeirão - UHECC) is the main economic activity in the middle section of Araguari River basin (Cunha et al., 2011; Silva et al., 2017). Mining activity (gold, manganese, iron and pebble extraction) is carried out in its high section (Matta et al., 2008), whereas extensive buffalo breeding is performed in its low section, mainly in floodplain areas in the region (Silva et al., 2020).

2.2 Net discharge

Net discharge and current velocity were measured in acoustic Doppler profiler (Acoustic Doppler Current

Profiler - ADCP, RD Instruments, Rio Grande model, 600 kHz), based on recommendations by Mueller and Wagner (2009).

Positive flow values ($Q > 0$) indicate flow downstream the Amazon River estuary (ebb), whereas negative flow values ($Q < 0$) indicate opposite flow direction – i.e., upstream the hydrographic basin (flood). $Q = 0$ indicates lack of net flow in the measured section (low or high tide). Monitoring stations are shown in Figure 1. Measurements were only taken during spring tide (12.5h cycle), in the dry (October 2017) and rainy (May 2018) seasons.

2.3 Suspended Sediments

One liter (1 L) of water-sediment mixture was collected on the surface of the channel (0.30 m deep) at 1-hour intervals, until the end of a tidal cycle, for suspended sediment (S_{SC}) analysis purposes - 127 samples were collected in both seasonal campaigns.

S_{SC} was obtained by filtering 250 mL of water samples in glass fiber membranes (0.45 µm porosity). It was used as dependent parameter and suspended solids discharge (Q_{ss}) estimator. Q_{ss} was used as dependent variable in order to test the sediment transport hypothesis based on environmental factors, hydrodynamic variables and water quality.

2.4 Suspended solids discharge

Q_{ss} was estimated by only taking into consideration the S_{SC} load, which represented approximately 80-90% of the effective total solid discharge (Carvalho et al., 2014). The calculation was based on the simplified method described by the aforementioned authors and represented by the following equation:

$Q_{SS} = 0.0864.\ Q.\mathrm{SSC}$ (1)

wherein: Q_{ss} represents the suspended solids discharge (t tidal cycle^{-1}), Q is net discharge (m^3s^{-1}) and S_{SC} is the suspended sediment concentration (mgL^{-1}). Factor 0.0864 is the constant used for conversion into ton per day.

2.5 Water Quality Parameters

Water samples were collected in 2-L sampling bottle, in the middle of the channel section (surface), at 1-h intervals and throughout the semidiurnal tide cycle and in the dry (December) and rainy (May) periods.

Air temperature was measured in digital thermometer. Parameters such as water temperature, electrical conductivity, total dissolved solids and pH were measured in multiparameter probe (HANNA, model HI 9828). Turbidity was analyzed in AP 2000 IP turbidimeter (Policontrol Analytical Instruments) based on the nephelometric method. Secchi disk was used to measure water transparency. Instrutherm oximeter (model MO-900) was used to determine dissolved oxygen (DO) and DO saturation. Oakton Pcstestr 35 probe was used to measure salinity level.

2.6 Statistical Analysis

Hydrodynamic and water quality data were subjected to descriptive analysis and, subsequently, to uni- and multivariate analyses (R Development Core Team, 2020). After data non-normality were tested (Shapiro-Wilk test), Spearman correlation analyses were applied to test correlations between S_{SC} and Q_{ss} *versus* water quality parameters, based on factors such as distance between collection points and the Amazon River, seasonality and tidal phase (flow and current velocity, Q and V, respectively).

Non-parametric Kruskal-Wallis test was used to investigate the spatial-seasonal effects of hydrodynamics and water quality on S_{sc} and Q_{ss}, based on the aforementioned factors (Crawley, 2007).

In addition, discriminating principal component analysis (DPCA) was applied to jointly test hydrodynamic and water quality variables (MacKinnon et al., 2016). After suitable transformation, DPCA was used to create normality and to equalize variances (Jombart and Collins, 2015). The goal was to enable the efficient discrimination of water quality and hydrodynamic groups based on few synthetic variables built as linear combinations of the original variables, which have the widest variation between and within groups (α [?] 0.05) (Supplement).

3 RESULTS

3.1 Net Discharge (Q_{net}) and Current Velocity (V)

Q_{net} was monitored in five stations during the dry season and in four stations during the rainy season (Figure 2). Q_{net} was higher in Urucurituba Channel during the dry season, it recorded the highest value at URU1 station (768 m^3s^{-1}). The second highest Q_{net} was observed at URU2 station (548 m^3s^{-1}). Gurijuba River mouth presented the third highest Q_{net} (409 m^3s^{-1}). Araguari River (ARA1) and Igarapé Novo (IGN) recorded the lowest Q_{net} values - 158 m^3s^{-1} and -47 m^3s^{-1}, respectively. Negative discharge represents the resulting current in reverse, downstream to upstream IGN station. In other words, water flow into the section was higher than its outflow during the dry season.

FIGURE 2

The IGN station recorded considerable Q_{net} increase (891 m^3s^{-1}) during the rainy season. In this case, it is essential emphasizing that positive Q_{net} has indicated water outflow inversely proportional to what happened during the dry season. ARA1 station recorded Q_{net} = 3,137 m^3s^{-1} and maintained positive discharge values during the tidal cycle, even during the flood phase. On the other hand, URU2 station recorded maximum Q_{net} value = 3,688 m^3s^{-1}, whereas URU1 station reached maximum Q_{net} value of the same order (3,165 m^3s^{-1}). Q_{net} recorded for URU2 and URU1 in the rainy season were 6.7 and 4.1 times higher than the ones recorded in the dry period, respectively. This outcome suggests progressively increased loss of flow from Araguari River to Amazon River.

The dry season at URU1 section has significantly varied in comparison to the rainy season (Figure 2). However, this variation was even greater in comparison to results observed by Santos et al. (2018), who recorded Q_{net} = 897 m^3s^{-1} during the rainy season (March 2015) (Figure 3). Thus, Q_{net} recorded in the present study, in May 2018, was approximately 353% higher than that of 3 years before. There was also considerable Q_{net}increase of approximately 162% in IGN between two dry seasons (September 2014 and October 2017), although on a smaller scale (Figure 3). This outcome suggests dynamic and progressive hydrological and hydrosedimentary processes.

FIGURE 3

With respect to water balance during the dry season, most of the flow into Araguari River is blocked by the silting up of its former mouth, follows through Urucurituba Channel and flows into Bailique archipelago, in the Amazon River mouth. A second fraction of the flow - accumulated in Igarapé Tabaco region - returns to URU1 during ebb (Figure 4A), whereas during flood, it flows towards the old mouth and tends to spread to the lake regions through an affluent (Igarapé Tabaco). This flow leads to significant changes in water quality, such as salinization processes (Cunha and Sternberg, 2018). A third fraction of it (220 m^3s^{-1}), which represents the difference in flow between URU1 and URU2 stations, is diverted into the floodplain (complex network of channels and branches in the floodplain). Thus, the right bank of Urucurituba Channel is connected to Gurijuba-Igarapé Novo Channel and, again, to Araguari River (Figures 1 and 4A) – it receives water inflow during the high tide.

Most water flowing into Urucurituba Channel (URU1) during the rainy season comes from Araguari River. A second fraction of the flow heads towards Igarapé Tabaco region and returns to URU1 during ebb, and it indicates prevalence of fluvial discharge (ebb tide) in water balance. Finally, a third fraction of the water flow, which was estimated at 523 m^3s^{-1} (Figure 4B), comes from the floodplain into Urucurituba Channel.

Thus, Urucurituba Channel, in URU1, assumingly captures 100% of Araguari River flow during the dry season, loses 29% of this total because it gets retained in the floodplain and dumps 71% of Araguari discharge into the Amazon River (URU2 = 548 m^3s^{-1}) (Figure 4A). On the other hand, URU1 receives 86% of direct flow coming from Araguari River anad absorbs additional 14% coming from the floodplain during the rainy season. It totals 100% of the discharge coming from Araguari River flowing into the Amazon River (URU2 = 3,688 m^3s^{-1}) (Figure 4B).

FIGURE 4

Mean current velocity ranged from 0.49 to 0.89 cm^{-1} in the dry season and from 0.41 to 0.85 cm^{-1} in the rainy season. Maximum current velocity reached 0.88 ms^{-1}(URU1) in the flood tide and 1.01 ms^{-1} (URU1) in the ebb tide.

3.2 Suspended Sediments (S_{SC}) and Suspended Solids Discharge (Q_{ss})

S_{SC} recorded significantly low value (50-100 mgL^{-1}) in ARA1, low value (100-150 mgL^{-1}) in IGN and extremely high value (> 300 mgL^{-1}) in URU1 and URU2 sections, during the dry season (Figure 5). S_{SC} recorded extremely low value (< 50 mgL^{-1}) in ARA1 and IGN, low value (100-150 mgL^{-1}) in ARA2 and URU1, and extremely high value (> 300 mg L-1) in URU2, during the rainy season. Turbidity presented behavior similar to that of S_{SC}, with extremely high values (> 300 NTU) corresponding to Secchi depth < 10 cm.

Difference in S_{SC} between the most upstream (ARA1) and the most downstream (URU2) station was 3.1 times greater in URU2, during the dry season, as well as 20 times greater in URU2, during the rainy season.

FIGURE 5

Q_{ss} ranged from -494 t tidal $cycle^{-1}$(IGN) to 21,354 t tidal $cycle^{-1}$ (URU1) during the dry season; it significantly ranged from 1,243 t tidal $cycle^{-1}$ (IGN) to 107,982 t tidal $cycle^{-1}$ (URU2) during the rainy season (Figure 6). Therefore, sediment flows were significantly higher during the rainy season than in the dry season. Q_{ss} has increased from ARA1 to URU1 and decreased from URU1 to URU2. Negative value observed in IGN likely indicates sediment load brought by flood tide currents, during the dry season. However, the suspended sediment load transported from ARA1 to URU2 has increased during the rainy season.

FIGURE 6

IGN has imported suspended sediments brought by the flood tide to Araguari River during the dry season. Thus, the input and output mass balance between URU1 and URU2 has shown sediment accumulation in the floodplain (approximately 6,679 t tidal $cycle^{-1}$) (Figure 7A). Part of these sediments was likely transported to Gurijuba-Igarapé Novo Channel and, again, to Araguari River (Figure 7A). Q_{ss} balance between Araguari River and Urucurituba Channel has shown insignificant S_{SC} contribution upstream river (ARA1) in comparison to the load carried downstream, since the river has clear water and solids get retained by three series of dams (Santos and Cunha, 2015). Therefore, the main sources of solids in lower Araguari River come from URU1 and from Igarapé Tabaco region (Figure 7A). Thus, most sediment load is transported from these two areas via ARA2 during ebb tides.

FIGURE 7

Q_{ss} in URU1 was 1.7 times higher during the rainy season than during the dry season; it reached 35,673 t tidal $cycle^{-1}$ (Figure 7B). On the other hand, mass balance between the URU1 and URU2 stations has shown increased suspended solids transport in the rainy season (approximately 72,309 t tidal $cycle^{-1}$) (Figure 7B). It may have happened because erosion processes have greater capacity to remobilize sediments and carry solids stored in flooded fields.

According to estimates, URU1 has captured 100% of solid discharge coming from lower Araguari River during the dry season, lost 31% of what was retained in the flooded fields and dumped 69% of Q_{ss} coming from Araguari River into the Amazon River (URU2 = 14,675 t tidal $cycle^{-1}$) (Figure 7A). On the other hand, URU1 received only 33% of Q_{ss} coming from lower Araguari River, as well as other 67% of it coming from flooded fields, and it totaled 100% of Q_{ss} coming from Araguari River discharged into the Amazon River (URU2 = 107,982 t tidal $cycle^{-1}$) (Figures 7B).

3.3 Physical-chemical water parameters

Kruskal-Wallis test has shown significant differences in water quality for all 4 environmental factors (distance, location, seasonality and tide), based on 11 physical-chemical parameters and on 17 hydrodynamic parameters ($p < 0.05$). Multiple regression tests have shown significant correlations of S_{SC} and Q_{ss}(dependent) to other water quality and hydrodynamic variables (Tables 1 and 2). Results have indicated significant spatial-seasonal variation in the investigated parameters and significant correlations between different hydrodynamic and water quality parameters associated with erosive processes.

TABLE 1

TABLE 2

Physical-chemical variables in Araguari River - Maré Channels - Amazonas River recorded significant differences, mainly during the dry season (reduced dilution capacity) (Abreu et al., 2020), with emphasis on variables associated with increased solids contents in lotic aquatic ecosystems, namely: EC, TDS, Turbidity, S_{SC} and Transparency (Tables 2 and 3).

However, based on the spatial factor, EC and TDS recorded significant variation between both seasons in all sites – it was relatively smaller in ARA1. Turbidity has followed the same variation trend. Such a variation was smaller at URU2, which recorded high turbidity levels in both seasons - 328 (NTU) during the dry period and 313 (NTU) during the rainy season. Similar behavior was recorded for associated parameters (S_{SC} and Transparency) at URU2 station (Table 3).

TABLE 3

Salinity was higher at URU1 and URU2 – it presented greater seasonal than spatial variation (Tables 2 and 3). Maximum salt concentration found in URU2 was 0.05 ppt and 0.04 ppt in URU1, during the dry season. This behavior was also observed by Cunha and Sternberg (2018) in Northern Igarapé Tabaco during the dry season in 2015, when maximum salt concentration reached approximately 0.08 ppt. High TDS and EC values were correlated to salinity during the dry season.

DO recorded low concentrations during the rainy season (Tables 1, 2 and 3). However, mean DO has remained higher than 5 mgL^{-1}, based on the limit established by CONAMA Resolution n. 357/2005 (Brazil 2005). Nevertheless, critical points have shown means lower than, or remarkably close to, this limit (5.0 mgL^{-1}) during the rainy season. Urucurituba Channel has shown minimum values of approximately 3.71 mgL^{-1} at the mouth (URU 2) and 4.66 mgL^{-1} close to the confluence with Araguari River (URU1) during the rainy season. Mean DO concentration at Gurijuba River mouth (GUR) reached 5.0 mgL^{-1} during the dry season, whereas Araguari River, just upstream Urucurituba Channel (ARA2), presented mean DO of 5.1 mgL^{-1} during the rainy season (Table 3).

Water pH was slightly acid during the rainy season, if one takes into consideration that the acceptable range for this parameter is 6.0 [?] pH [?] 9.0 for class II rivers (Brasil 2005). However, all stations recorded pH lower than 6.0 during this period - Araguari River (ARA1) and Igarape Novo recorded the lowest values – mean pH was 4.9. On the other hand, water pH during the dry season was approximately 6.0 and temperature was higher than 29degC (Table 3).

Spatial variation in water quality was also significant (Tables 1 and 3), except for water and air temperature (T_w and T_{air}), which tended to show homogeneity in the investigated geographical area. Similar results were observed by Cunha and Sternberg (2018) along lakes distributed on the estuarine coast of Amapa State. Temperature homogeneity was observed in all stations and in the two seasons. However, it presented significant variations during the tidal phases ($p < 0.05$) (Table 1).

Distances between monitoring sites and the Amazon River recorded significant differences, which suggested influence of water connectivity and water quality variables, except for water and air temperatures ($p > 0.05$) (Table 1).

4 DISCUSSION

4.1 Net discharge and erosive potential

Net discharge (Q_{net}) from Araguari River towards Amazon River during the dry season reached 548 m^3s^{-1}; it increased to 3,688 m^3s^{-1} during the rainy season. Therefore, river discharge was the main forcing agent between Araguari River and Amazon River mouth during the rainy season, which recorded magnitude 6.7 times greater than that of the dry season.

Urucurituba Channel is the one with the greatest erosive potential, both in lower Araguari River and in Amazon River mouth (Bailique). Maximum seasonal Q_{net} values were recorded in the two points of the channel (URU1 and URU2), which, consequently, recorded maximum current velocity values: V_{URU} [?]1.01 ms^{-1} in the ebb tide and 0.67 ms^{-1}in the flood tide – it is worth emphasizing velocity and depth are directly proportional to susceptibility to erosion (Novo, 2008). For example, expressive depths of approximately 28 m in almost the entire URU1 length, and of approximately 24 m in URU2 were notable (Santos et al., 2018). There was greater influence of tides spreading from Urucurituba and Gurijuba-Igarape Novo channels and from branches in the floodplain to ARA1, during the dry season. Torres et al. (2018) have suggested that the recent clogging at Araguari River mouth, due to drainage of its water by Urucurituba Channel, has contributed to increase Q_{ss} and Q_{net} at Amazon River mouth, which has significantly accelerated erosion and accretion processes in Bailique archipelago region.

Despite the scarcity of information about the region, records show that mean discharge in June 2011 reached 2,540 $m3s^{-1}$ (rainy season) and 316 $m3s^{-1}$ in December 2011 (dry season) 60 km away from the old river mouth, just downstream the confluence with Igarape Tabaco (Santos, 2012). However, Araguari River discharge has significantly decreased. In June 2013 (rainy season), it decreased to 34 $m3s^{-1}$ and, subsequently, recorded negative discharge of –212 m3 s^{-1} (drought in September 2013), which indicated permanent flow direction inversion due to greater influence of the upstream tide, which has fully changed the hydrodynamic pattern of its mouth (Santos et al. 2018).

Water and sediment transport balances (Figures 4 and 7) have suggested high hydrological and hydrosedimentometric complexity in the region, as well as identified accelerated Urucurituba Channel evolution, which not only resulted in the expansion of a main drainage channel, but induced severe erosion processes, as well as uncontrolled branching of several waterbodies and of their connections. For example, Gurijuba-Igarape Novo Channel stands out for its connection to Urucurituba Channel, given the presence of interconnected branches that increase the flow direction complexity, since these flows interact with each other, are chaotically distributed across the floodplain and get intensified by the tidal regime (Gallo and Vinzon 2015; Abreu et al., 2020). However, they remain intense even during the dry period, when the connection between floodable fields and the main system still influences the ecological dynamics in the region (Cunha and Sternberg, 2018).

Several environmental consequences arise from this new hydrological dynamics since it influences and worsens erosive processes and enables the development of new channels. This process intensifies the natural geological fragility of coastal estuarine areas and makes them apparently more attractive to agriculture and, consequently, to soil trampling by buffaloes due to riparian vegetation removal (Trimble 1994, Santos 2006).

4.2 Sediment transport: scenarios and implications

The hydrographic basins of Araguari and Amazonas rivers present different geological features, which result in white water in Amazon River and in clear water in Araguari and Igarape Novo rivers. Thus, the main physical difference between both water types lies on the amount of suspended load carried by both drainages, which is even more prominent during the rainy season (Sioli, 1984), when the clear water in ARA1 and IGN stations presents $S_{SC} < 20$ mgL^{-1} and the white water in other stations present values > 100 mgL^{-1} (Figure 5).

Urucurituba Channel recorded concentrations in the range of 130 mgL^{-1} (URU1) [?] S_{SC} [?]339 mgL^{-1} (URU2) in May 2018. Mesotidal intrusion through URU2 is one of the main forces transporting, and regulating the dynamics of, suspended solids. Similar situations, although under macrotidal regime, were observed by Carneiro et al. (2020) in Para River estuary. According to Asp et al. (2018), Caete River estuary presents wide tidal plains in an extensive range of macrotidal incursions, whose discharge and elevation lead to seasonal S_{SS} variations. Gensac et al. (2016) reported impact on S_{ss} dynamics at Amazon River mouth, mainly during the rainy season, when S_{SS}tends to decrease down the estuary, despite the flow peaks observed in Amazon River during this period (Valerio et al, 2018).

In the present case, Q_{ss} variations may have happened due to dilution, sedimentation and resuspension processes (Meade et al. 1985), and it suggests that Araguari River flow in the period of greatest fluvial discharge (rainy season) overlaps the hydrodynamics of the tides and substantially decreases the input of suspended sediments (unconsolidated and subconsolidated). On the other hand, the main factor controlling this difference in magnitude during the dry period lies on the dynamics of tides capable of overlapping Araguari River flow, since they transport white water with high S_{ss} contents from the Amazon River into the basin, mainly via Urucurituba Channel.

The middle portion of Araguari River does not present high suspended sediment load because it was formed on Precambrian lands of Guiana Shield (Allison et al. 1996; Brito 2008; Barbara et al. 2010; Santos & Cunha, 2015). However, ARA1 has shown expressive suspended solid discharge (1,354 t tidal cycle^{-1}) during the rainy season, which was 3.4 times higher (4,586 t tidal cycle^{-1}) than that during the dry period (Figure 6). Thus, in comparison to estimates (Q_{ss} = 575 t tidal cycle^{-1}) by Santos and Cunha (2015), these solid discharge data suggest greater influence of flood tide currents through the channels interconnecting both basins.

Therefore, the highest S_{ss} and Q_{ss}values observed for Urucurituba Channel did not only result from sediments transported by Amazon River, whose main source derives from erosive processes in the Andes (Gibbs 1967, Sioli 1984, Meade et al. 1985, Filizola and Guyot 2009), but it is also controlled by the action of local tidal currents that lead to significant erosion in the floodplain itself and in its sub-consolidated substrate. Santos et al. (2018) have observed mean erosion rate of 5 m month^{-1}(60 m year-1) at URU1 site; they also reported that this section of the channel was only 55 m wide in 2011, but it had significantly increased to 321 m in 2016. In addition, maximum depth in this section of the channel was [?]35 m, similar to that of the Northern Channel of Amazon River (Abreu et al., 2020). If one takes into consideration that erosive potential increases as depth and flow speed increases (Novo, 2008), it is possible assuming that Urucurituba Channel tends to maintain and increase the rates of these processes due to its geomorphological features. Besides presenting the highest mean depth (28 m) in the measured cross section (URU1) and 34 m elsewhere (Santos et al. 2018), this channel also presents the highest mean current velocity among all channels ([?] 0.89 ms^{-1} during the dry season and [?]0.85 ms^{-1} during the rainy season).

The continuous and growing increase in suspended solids transport confirms the hypothesis about sedimentation evolution and worsening in the old Araguari River mouth, downstream ARA2 station and Urucurituba Channel, a process that has strong impact on the region because of the silting-up process taking place at the old river mouth. Impacts resulting from this process are significant; among them, one finds loss of environmental and ecosystem services, such as hydrological regime regulation, water quality, biodiversity maintenance (Junk et al. 2014), hydrological connectivity intensification/loss and, mainly, pororoca extinction (Cunha and Sternberg, 2018). Consequently, new deposition zones were identified, such as the one at the confluence of Urucurituba Channel with Araguari River, besides the formation of banks, islands on the left river bank and the clogging of Araguari channel, just upstream and downstream the confluence with the great tidal channel. Banks, which already have vegetation, are part of the new morphodynamics and depositional system along the river; they may be expanding in response to sediment transport adjustments observed in this stretch (Wang and Xu 2018). Currents upstream Araguari River present reduced velocity due to these processes. For example, Urucurituba Channel acts as suspended sediments' exporter to floodplains during the dry season. On the other hand, during spring tides, it imports suspended sediments from floodplains, from Araguari River fluvial discharge and, finally, from the reflux discharge coming from Igarape Tabaco region, during the rainy season (Figure 7).

Therefore, the hypothesis of significant hydrodynamic and sedimentary changes was confirmed by intensified erosive events in Bailique Archipelago, Southern Urucurituba Channel (Figures 4 and 7), which receives expressive liquid and suspended solids contribution that did not exist until a few years ago (Torres et al. 2018). This outcome suggests that Urucurituba Channel indicates negative sedimentary mass balance (erosion) ranging from 14,675 t tidal cycle^{-1}(12%), during the dry period, to 107,982 t tidal cycle^{-1} (88%), during the rainy season (Figures 6 and 7). However, the deposition zone (dry season) lies at Gurijuba River mouth, which presents intense accretion processes capable of forming islands, as well as muddy banks that progressively evolve to islands due to fast vegetation adaptation in this zone (Santana and Silveira 2005, Torres et al. 2018).

4.3 Water quality variability and tidal propagation influence

According to one of the research hypotheses, seasonal hydrological effect is one of the main factors influencing water quality dynamics in this estuarine region (Tables 1 and 3). Increased concentration of parameters associated with sediments (S_{SS}, Turb, TDS and Secchi) and with saline intrusion (EC and salt) was also observed by Santos et al. (2014) in the region in 2011. Such an increase has been attributed to reduced dilution capacity observed in rivers during the lowest flow period, as well as to erosion processes taking place in rivers and channels.

According to Geyer (1995), fresh water coming from Amazon River mouth is partly maintained by the magnitude of its discharge, which is enough to produce strong current towards the ocean, even during low flow periods (Abreu et al., 2020). However, increased salinity level during the dry season, although incipient, can be attributed to lower river dilution in this period (hydrological effect of lower water volume and meteorological effect due to salt "precipitation" through the atmosphere) – this outcome suggests different oceanic influences on the Amazonian coast. Salinity level during the rainy season (0.01 ppt) (Tables 1, 2 and 3) was equal to salt levels observed before the influence of Urucurituba Channel (Santos et al. 2018). Salinity was a severe environmental issue in the region between 2013 and 2014, so much so that Araguari River flow has significantly decreased and enabled significant saline intrusion in the estuary through the original mouth (Figure 1) - [?]174 times greater than that of 2011 (ranging from 0.01 to 1.74) (Santos et al. 2018). However, salinity level has significantly decreased after 2013, due to simultaneous silting and blockage of flow at the river mouth - salinity value of 0.26 ppt was recorded in March 2015. Later, there was salinity peak reduction, such as the one observed in lakes connected to Araguari River (Piratuba Lake) - remaining salinity levels ranged from approximately 0.04 to 0.08 ppt (Cunha and Sternberg 2018).

The herein observed seasonal DO pattern has suggested opposite effect to that observed by Barbara et al. (2010) in Cutias do Araguari, 60 km upstream Gurijuba Channel, which recorded lower DO concentrations during the dry season (minimum of 6 mgL^{-1}) and higher concentrations of it during the rainy season ([?]8 mgL-1) (Tables 2 and 3). However, DO levels remained higher than 6 mgL^{-1}. Santos et al. (2014) have found low OD values in lower Araguari River, downstream the study site (<3.0mgL^{-1}), during the rainy season. Many of these values also remained low in subsequent campaigns, after the greatest influence of Urucurituba Channel (Santos et al. 2018). However, greater oxygen saturation, upstream Araguari River, may take place due to hydraulic accidents (dams) (> 7.0mgL^{-1}), where differentiated turbulence favors atmospheric reaeration processes (Silva et al., 2020).

Araguari River, as well as Gurijuba-Igarape Novo and Urucurituba channels, develop in a floodplain, without hydraulic accidents, in downstream direction, which may lead to reduced reaeration rates (Santos et al. 2014). On the other hand, Amazon River naturally presents low DO values very often (lower than 5 mgL^{-1}), mainly due to high respiration rates, as well as to high particulate and dissolved organic matter concentrations in water (Ward et al. 2013, 2015, Sawakuchi et al. 2017). Thus, DO concentration decrease can be easily attributed to the influence of Amazon River on Araguari River, due to oxygen demand and nutrient supply such as N, S and P (Ward et al., 2015). The influence on overall water quality starts at Urucurituba Channel, which enables higher DO concentrations in IGN and ARA1 stations (> 6 mgL^{-1} in the two seasons) and lower DO concentrations in the remaining monitoring stations (Tables 2 and 3). However, low oxygen concentration can also be associated with high turbidity, which reduces light penetration (essential to photosynthesis), mainly in the region of lakes (Brito 2008; Cunha and Sternberg, 2018). On the other hand, Damasceno et al.

(2015) have found high DO concentration values (7.18 mgL^{-1} during the dry season and 6.52 mgL^{-1} during the rainy season) in a section upstream Amazon River mouth (Macapa) - these values were higher than the ones often observed for these channels.

The observed pH corresponds to acidic water, due to high organic matter concentration and decomposition by microorganisms (Ward et al., 2013), which increases during the rainy season. However, Barbara et al. (2010) observed trend of seasonal pH variation in the middle course of Araguari River, which recorded very low pH value = 4.7 (confluence of the main Amapari River tributary) and pH = 5.2 at IGN, which is 54 km away from the study site. This seasonal pattern was observed in large Amazonian rivers (Jari River) and in lakes connected to these rivers (Ajuruxi Lake); besides, it is seen as typical feature of Amazonian waters (Da Silva et al. 2013, Damasceno et al. 2015, Abreu and Cunha 2017). It happens because semidiurnal tides (Gallo and Vinzon 2015) take place on a daily basis in the Amazon River Delta and used to influence almost all water quality parameters in lower Araguari River until 60-80 km away from its original mouth, at the time it flowed into the Atlantic Ocean (Santos et al. 2014). However, nowadays the tidal wave spreads up to 75 km from the new river mouth, as indicated by the negative flow at IGN station (Figure 4A).

The lower influence of flood and ebb tides on parameters such as DO, DO_{sat} and S_{SC} differ from that observed in other studies focused on investigating water quality under tidal influence in Amazonian estuaries. Moura and Nunes (2016) recorded significant tidal effects for Turbidity, pH and DO – Turbidity was mostly evident at low tide, whereas pH and DO were mostly evident at high tide. Alves et al. (2009) have also found positive correlation between DO and tidal currents. Araujo (2018) has found positive relationship between flood tide and parameters such as EC, TDS, salinity and turbidity in Guajara Bay (Para), as well as negative correlation to water temperature and lack of significant effects on pH and DO.

The differentiation caused by tides suggests the interaction between two water types coming from Araguari and Amazonas rivers. For example, pH values ranging from 5 to 8 are typical of Amazon rivers with clear water (Junk et al. 2011). Thus, the smallest spatial variations indicate stretches presenting intense mix of white water coming from Amazon River with clear water coming from Araguari River. Both rivers present slightly higher acidic pH at low tide and values closer to neutral pH at high tide. On the other hand, increased turbidity, TDS, EC and decreased water transparency during high tide are highly significant due to increased transport of suspended load from the Amazon River - these parameters are highly correlated to Q_{SS}.

Differences in tidal amplitudes also affect water quality response and vary depending on spatial drainage configuration. Tidal amplitude under syzygy condition is greater downstream the estuary. URU2 and GUR recorded tidal amplitude in the order of 3 m, whereas URU1 recorded 1.9 m; however, this amplitude decreased to just 1.2 m towards the core of the hydrographic basin (ARA1) (Figure 1). Thus, the spatial factor (distance from the Amazon River) reflects on several water quality parameters and is more intense in Urucurituba Channel than in Gurijuba-Igarape Novo Channel. In addition, the morphological drainage pattern of Gurijuba River tends to hinder water flow from Amazon River to Araguari River, due to greater distance between the two basins through this channel. On the other hand, Urucurituba Channel presents significantly straight drainage channel, hydrodynamic magnitudes increased by tides and greater influence of water velocity and discharge, which favor different water quality responses.

A detailed, although summarized, analysis of all water quality and hydrodynamic variables is available in the supplementary file of this manuscript (Supplementary Figures 1 and 2).

5 CONCLUSIONS

Based on results, analyses and discussions, it was possible getting to the following conclusions:

1. Urucurituba Channel has captured 100% (768 m^3s^{-1}) of Araguari River flow during the dry season, retained 29% of this total in the floodplain and exported 71% (URU2 = 548 m^3s^{-1}) of Araguari River discharge into the Amazon River. URU1 station received 86% of Araguari River flow during the rainy season, as well as other 14% coming from the floodplain, which totaled 100% (URU2 = 3688 m^3s^{-1}) of

Araguari discharge dumped into the Amazon River. This process has favored erosive events, as well as changes in S_{ss} and water quality parameters.

2. The complexity of the new drainage system has significantly influenced water balance, sediments and water quality; it changed depending on location, distance, seasonality and tidal phase and explained up to 93% of the variation in S_{sc} concentration at Araguari River mouth. However, there was greater influence of the energy of tides propagating towards ARA1 during the dry season, whereas the fluvial discharge of Araguari River during the rainy season was the main forcing tide capable of overcoming the influence of tides in the estuarine zone of Araguari River.
3. The hypothesis that Urucurituba and Gurijuba-Igarape Novo channels are mainly responsible for variations observed in S_{SC} and water quality in Araguari River estuary, whose features change from clear to white water, was herein confirmed. It happened because Urucurituba Channel and the floodplain act as areas of intense erosion processes.
4. The tidal effect hypothesis was partly rejected with respect to variations in DO and S_{ss} parameters, but it influenced other physical-chemical water quality parameters that significantly varied among the six sampling stations (except for $T_w$and T_{air}). This outcome has refuted the hypothesis of physical-chemical similarity between waters due to intense hydrodynamic mixing processes in those specific stations.

Despite the intense effort to assess water and suspended solids balance in the region, the present study should be expanded in the future by further experimental campaigns in order to confirm whether this phenomenon is a trend or just temporary.

DATA AVAILABILITY STATEMENT" in the main document.

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