

INFLUENCE OF A DROUGHT EVENT ON HYDROLOGICAL CHARACTERISTICS OF A SMALL ESTUARY ON THE AMAZON MANGROVE COAST

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ABSTRACT

The effects of atypical climatic conditions, such as those of a drought event, are remarkably accentuated in minor estuaries filled with sediments and with reduced or sporadic freshwater input, where the salinity intrusion is pronounced. To understand these effects, hydrological and hydrodynamic parameters were evaluated during a drought period in a small estuary located on the eastern Amazon coast in northern Brazil. Five campaigns were conducted between June 2012 and June 2013. Samples were collected from the surface and bottom layer every three hours over a 25-hour period at three stations of the Taperaçu Estuary. To compare drought and post-drought periods, in terms of salinity and chlorophyll-a, data was recorded until June 2015. Taperaçu is a relatively shallow estuary of the Amazon coastal zone, which is characterized by the absence of any direct fluvial discharge, although it does receive freshwater input from adjacent wetlands, as well as less saline waters from the Caeté Estuary through the Taici Creek. Hydrological variables were controlled by rainfall levels and the tidal range, and the water became more saline and more oxygenated, with reduced dissolved nutrient and chlorophyll-a concentrations when precipitation decreased. Significant variation was found between the months of June 2012 (most intense drought) and 2013 (less intense drought). The connection to the neighboring Caeté Estuary, and adjacent mangroves and wetlands contributed to the influx of nutrient-enriched waters. Overall, then, it is hoped that the results of this study can contribute to the understanding of the effects of drought events in other minor estuaries on the highly indented Amazon coast, as well as in other areas of the equatorial zone with similar environmental characteristics.

Keywords: estuarine dynamics, drought, mangroves, small estuary, Amazon coast.

1. Introduction

Mangroves are highly productive ecosystems found in the intertidal zones of equatorial, tropical and subtropical estuaries. These environments are normally considered to be a potential source and/or effective sink of nutrients and organic matter (Dittmar and Lara 2001). Associated typically with estuarine environments, these ecosystems play an important role in coastal areas, due to their significant input of terrigenous sediments, organic matter, and nutrients into coastal waters (Burford et al. 2008; Shilla et al. 2011). Mangroves function as nutrient filters, modifying the biological productivity and biogeochemical cycles in estuarine systems (Dittmar and Lara 2001; Nagelkerken et al. 2005). In mangrove-estuarine systems, the characteristics of hydrodynamic factors such as tides, currents, and river discharge are critical for the exchange of water, nutrients, sediments, and organisms between intertidal and coastal areas (Arumugan et al. 2016; Claudino et al. 2015; Ray et al. 2014).

The Brazilian Amazon coast encompasses one of the largest continuous tracts of mangrove forest found anywhere in the world (Kjerfve and Lacerda 1993) with dozens of estuaries, including that of the Amazon River itself. This coastal zone straddles the equator (5°N–4°S), and forms one of the world’s most extensive and well-preserved areas of tropical coastline. Coastal processes in this low latitude zone result from a combination of local macrotides (tidal range of 4–12 m during spring tides), moderate energy waves (H_s up to 2.0 m), strong tidal currents (normally above 1.0 m s^{-1}) and high levels of rainfall (~ 2000–3000 mm). In addition, the enormous discharge of freshwater from the Amazon River (located 150 km from the study area) and 23 other estuaries, containing suspended particles and dissolved nutrients from local river basins, affect the whole of the Amazon coastal waters (Geyer et al. 1996; Nittrouer and DeMaster 1996).

The availability of these dissolved nutrients, associated with the region's high-energy hydrodynamics, sustains high levels of biological productivity (DeMaster and Pope 1996; Goes et al. 2014). While these processes have been analyzed in detail in the region's principal estuaries (those of the Amazon and Pará rivers), as well as in the Amazon plume that encroaches the Atlantic Ocean, few data are available for coastal waters, mainly for its minor estuaries, despite their relative abundance. In fact, minor estuaries have received comparatively little attention worldwide, although a number of recent studies have focused on different aspects of the role of the size of an estuary on its hydrological characteristics (Jickells et al. 2014; Pye and Blott 2014). Studies of this type have contributed to the understanding of the effects of natural phenomena such as atypical climatic conditions and anthropogenic interference on the hydrological characteristics of minor estuaries, and their consequences for local biological communities. In particular, minor effects on small estuaries may have far-ranging impacts due to their spatial limitations, with secondary effects for the entire system (Callaway et al. 2014).

In recent years, the Amazon coastal zone has been increasingly impacted by atypical climatic conditions (Pereira et al. 2013; Andrade et al. 2016), although what happens during years of drought events is not well-understood. While an increase in rainfall levels and fluvial discharge affect the waters of whole Amazon coast, no information is available on how drought events may affect the oceanographic processes in these ecosystems. During the present study, the drought event was not related to an El Niño Southern Oscillation, but was the result of a complex relationship between Atlantic sea temperatures and rainfall in the Amazon, when an increase in the sea surface temperature (SST) provoked a decline in rainfall rates in the eastern Amazon and Northeast Brazil (Marengo et al., 2013a). Two recent short-term events – known locally as the "droughts of the century", which occurred in 2005 and 2010 – have received a great deal of attention (Gloor et al. 2013; Marengo et al. 2011a) due not only to their serious environmental and social consequences for the whole Amazon region, but also for their potential impacts on global climate (Gratiot et al. 2008; Marengo et al. 2008, 2011b).

Small estuaries filled with sediments and with reduced or sporadic freshwater input – such as the Taperaçu Estuary – can be found in a number of parts of the world. The Taperaçu is a minor Amazon estuary with less than 30 km in length. It is also relatively shallow (mean depth 4 m) and currently has no fluvial input, but receives freshwater input from adjacent wetlands during the rainy season. Local mangrove forest plays an important role in the input and distribution of nutrient in adjacent coastal waters during high tides. The connections between local tidal creeks and areas of mangrove also provide an important pathway for the exchange of materials (Cohen et al. 1999; Dittmar and Lara 2001). During high tides, the Taperaçu is connected to the upper sector of the Caeté Estuary (Asp et al. 2012); and, together with the adjacent mangroves, this connectivity contributes to the rich biological productivity of the estuary (Magalhães et al. 2011, 2013).

Local anthropogenic interference is also minimal. In this coastal zone, phytoplankon and microphytobenthos – dominated by diatoms such as *Asterionelopsis glacialis*, *Skeletonema* sp., *Campylosira cymbelliformis*, *Coscinodiscus concinus*, *C. perforates* Ehrenberg, *Dimmeregrama minor* and *Cyclotella meneghiniana* (Costa et al. 2011; Matos et al. 2011), and phytoflagellates (non-identified nanoplankton) – contribute to the high local phytoplankton biomass and primary productivity. These organisms, together with the local mangrove forests appear to be the primary determinants of the high chlorophyll-a concentration in the study area, as proposed by Wollf et al. (2000) for the neighboring Caeté Estuary. Few data are available on the nutrient concentrations of the Taperaçu Estuary, although it is known to support a high density of phytoplankton biomass, which sustains high levels of secondary biological productivity (Costa et al. 2008; Magalhães et al. 2009; Palma et al., 2013).

The local natural features of the Taperaçu make of it an excellent study site for the understanding of the effects of atypical climatic conditions, such as a drought event. To test whether lower rainfall levels affect hydrological variables, the present study evaluated an anomalous dry season in the study area. In this context, the study includes three main questions: a) How do anomalous climatic events (such as droughts) affect oceanographic processes? b) What are the effects of these atypical events on small Amazon estuaries? c) What is the role of the tides in sustaining the connectivity of different Amazon coastal environments? The main aim of this study was thus to evaluate the effects of drought on these conditions in a small, equatorial estuary on the Amazon coast, which is connected to adjacent nutrient-rich environments. For this, the spatial and temporal dynamics of physical, chemical, and biological variables (chlorophyll-a) were studied during a period of abnormally dry climatic conditions. As the rainfall pattern is similar to that of other Amazon coastal areas (INMET, 2013), it is hoped that the results of the present study can contribute to the understanding of the specific effects of similar conditions (i.e., drought events) on that highly indented coast, as well as in other areas of the equatorial zone that have similar environmental characteristics.

2. Study area

The present study focuses on the Taperaçu Estuary, which is located on the Amazon Macrotidal Mangrove Coast of the northern Brazilian state of Pará. This estuary is in the municipality of Bragança, about 150 km southeast of the mouth of the Amazon River (Fig. 1), and has a surface area of 21 km^2 and a catchment of approximately 40 km^2 (Araújo Jr. and Asp 2013). This funnel-shaped body of water is relatively shallow with extensive sandbanks running down its midline, half of which are exposed during low tide, forming deep channels (up to 12 m), mainly at the margins of the estuary (Asp et al. 2012).

Local hydrodynamics are driven primarily by the tidal regime, but also by local winds and wind-waves. The local tides are semidiurnal and may range up to 5–6 m near the mouth of the estuary during spring tides and between 3 and 4 m during neap tides. Wind-waves are of secondary importance in the local hydrodynamics, and their propagation is reduced primarily by the sandy shoals. Tidal currents are typical of shallow estuaries, reaching values above 1.5 m s^{-1} (Asp et al. 2012).

Insert Figure 1.

The local climate is humid equatorial with a period of relatively high precipitation (rainy season), typically between January and June, when total rainfall often exceeds 2000 mm, winds blow with a mean intensity of up to 3.0 m s^{-1} and mean temperatures are around 26–27°C. During the second half of the year (dry season), monthly rainfall is normally no more than 100 mm and mean temperatures are around 28°C (INMET, 2013). The driest months are marked by negligible precipitation and by the strongest winds (mean speeds over 4.0 m s^{-1}), leading to a surplus of evaporation over precipitation (INMET, 2013). Figure 2 shows the annual precipitation recorded in the study area over the past 16 years, highlighting the driest years (2012 and 2013).

Precipitation levels have a direct influence on the temporal oscillations in the salinity of the waters of the whole Amazon coast (Pereira et al. 2012, 2013), but in the Taperaçu, in particular, spatial fluctuations in salinity are controlled by the influx of marine waters into the lower sector of the estuary, and the input of freshwater from local wetlands and less saline waters from Caeté Estuary into the upper sector of the Taperaçu (Magalhães et al. 2015).

Insert Figure 2.

3. Data and Methods

To understand the functioning of this minor estuary during an anomalous period of climate (low rainfall), spatial and temporal oscillations in physical, chemical and biological variables were monitored over a 13-month period, between June 2012 and June 2013. During this period, five field campaigns were undertaken during: (i) the rainy season: 13–14th June 2012, 19–20th March 2013, and 3rd–4th June 2013, and (ii) the dry season: 22–23th September 2012 and 5–6th December 2012.

Each campaign was conducted during the neap tide over a 25-h sample period at three stations representing the upper, middle, and lower estuarine sectors (Fig. 1). Neap tide conditions were chosen because the tidal range is lower, inundating a smaller area of the mangrove. It is thus reasonable to assume that hypotheses related to tides under neap tide conditions may also be applicable to spring tide conditions, although the opposite is unlikely to be true.

The post-drought campaigns were made to better support the influence of atypical rainfall levels, using salinity and chlorophyll-a as parameters. Nine campaigns were undertaken every three months, between September 2013 and June 2015. In addition, monthly rainfall levels were obtained between 2012 and 2015 from the Tracuateua station of the Brazilian Institute of Meteorology (INMET), located about 20 km from the study area.

3.1 Field Survey

To understand how circulation patterns contribute to the supply chain of dissolved nutrients and the input of waters of reduced salinity, oscillations in water levels were measured simultaneously at the three stations using a bottom-mounted mooring, to which tide gauges were attached. A mini-current meter (Sensordata) was also attached to the mooring in the middle sector to record current speeds and directions. Current data for June 2013 are missing due to equipment malfunction. Water level oscillations, and the speed and direction of the currents were recorded every 10 min.

To determine how rainfall levels affect the oscillations in the hydrological variables in a minor Amazon estuary, data on temperature, salinity, turbidity, dissolved oxygen (DO) and oxygen saturation (DO%) were collected simultaneously in a vertical profile (1 m below the surface and 1 m above the bottom) at each station. A bottom-mounted mooring to which the CTDs were attached was also used and every three hours, the equipment was brought to the surface for 1 h. One hundred and fifty measurements were taken by each CTD over the 25 h sample period (i.e., readings were taken every 10 min). The CTDs were equipped with dissolved oxygen and turbidity sensors (RBR). Every 3 hours, 5 L Niskin oceanographic bottles (General Oceanics) were used to obtain the water samples (surface and bottom). These samples were used to determine the pH, and dissolved nutrient and chlorophyll-a concentrations. A total of 270 water samples were collected during the study period.

To compare drought and post-drought periods, in terms of salinity and chlorophyll-a, data was recorded until June 2015 using the same campaign methods than that applied during drought period.

3.2 Laboratory Analyses

Water samples were vacuum-filtered through glass-fiber filters (Whatman GF/F 0.7 µm, 47 mm), and both the samples and the filters were freeze-dried for further analyses of nutrients and chlorophyll-a, respectively. In the laboratory, pH was determined by a pHmeter (Hanna). Dissolved inorganic nutrient concentrations (nitrite: NO_2^-, nitrate: NO_3^-, ammonium: NH_4^+, orthophosphate: PO_4^{3-} and dissolved silicon compounds: DSi) were determined by spectrophotometry, following the procedures described by Strickland and Parsons (1977) and Grasshoff et al. (1983). Chlorophyll-a was extracted with 90% acetone *v.v*. and determined spectrophotometrically, following the protocol of Parsons and Strickland (1963) and UNESCO (1966). The specific equations were applied to obtain the chlorophyll-a concentrations of each sample. Dissolved inorganic nitrogen (DIN) levels were calculated by NO_2^- + NO_3^- + NH_4^+. Filtered water samples were also frozen for subsequent analyses of total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP). The TDN and TDP values were determined by applying an adaptation of the simultaneous oxidation of the nitrogen and phosphorus compounds using an alkaline persulfate-oxidizing solution (Grasshoff et al. 1999).

3.3 Statistical Analysis

Hydrological data were analyzed spatio-temporally, according to depth (surface and bottom), sector (upper, middle and lower), season (dry and rainy), month and tidal phase (ebb and flood). The assumptions of data normality and homogeneity of variances were tested using Lilliefors' (Conover 1971) and Bartlett's Chi-square tests (Sokal and Rohlf 1969), respectively.

When the data were not normal or homogeneous, they were *log* (x + 1) transformed to produce a near-normal or near-homogeneous distribution. Analyses of Variance (ANOVA-*F* test) were used. A one-way ANOVA was then run to assess whether the hydrological variables vary by sampling depth, sector, season, month and tide. In addition, a two-way ANOVA was used to examine the hydrological interactions, sector *vs* season and sector *vs* month. Whenever the data were non-normal or heterogeneous, even after transformation, the non-parametric Mann-Whitney *U* and Kruskal-Wallis *H* tests were used. When a significant difference was found among sectors and months, *a posteriori* pairwise comparisons were based on the Fisher LSD test and the Student-Newman-Keuls analysis. A Spearman correlation matrix was used to evaluate the relationships among the hydrological variables, rainfall and wind speed. All these analyses were run in STATISTICA 8, with $\alpha = 0.05$.

4. Results

Our results show as inter-annual oscillations in rainfall level can affect hydrological variables in a small estuary in Amazon coast. Firstly, the influence of rainfall level was shown on salinity and chl-a data, comparing drought and non-drought period. After, rainfall level, hydrodynamics and hydrological patterns were detailed during a drought period.

4.1 Influence of rainfall levels on salinity and chlorophyll-a parameters: drought and non-drought period

To show how rainfall levels can affect temporal oscillations in hydrological variables, figure 3A presents cumulative rainfall levels and averages of spatial salinity data every three months between 2012 and 2015, detaching drought and non-drought periods. This drought period was marked by the annual rainfall levels of 1552 mm in 2012 and 1612 mm in 2013, representing only 60% of the annual mean recorded between 2000 and 2015 (Fig. 2). Comparing rainfall level and water salinity between 2012 and 2015, it is possible to show that a reduction in 400-500 mm during drought period (2012-2013) results in higher salinity waters (around 50%), when compared with the non-drought period of 2014 and 2015. The effects of drought and non-drought periods on the salinity of the water can also be observed in figure 3B, when lower rainfall levels (June 2012) are reflected in higher salinity levels, as well as lower chl-a concentrations (Fig. 3C).

Insert Figure 3.

4.2 Hydrodynamic forces

Hydrodynamic forces appear to be essential to the understanding of the spatial and temporal fluctuations observed in hydrological variables, as well as the connectivity of the tides with adjacent environments. Tides are responsible for connecting the Taperaçu with lower salinity waters, as well as with rich-nutrient environments, where oscillations in water levels (range 2–4 m) were typical of mesotidal conditions (Fig. 4A). By comparing measurements from the outer and inner sectors, it was possible to observe substantial tidal attenuation when tidal waves propagate through the estuary, being of the order of 10% in the dry season (December 2012, when strong winds blew) and 50% in the rainy season (June 2013, when wind intensities were the lowest). This means that the influence of marine waters in the upper estuary is greatly reduced during rainy season. During this period, the source of freshwater provided by the wetlands located in the upper sector is at its maximum level because this area is completely flooded due to the increased rainfall.

The highest tidal ranges observed during the study period were recorded in September 2012 (Fig. 4B). During the high tide, the water level reaches nutrient-rich environments such as the mangrove and other wetland areas, as well as receiving the input of less saline waters from the upper sector of the Caeté Estuary. The asymmetric pattern of the semi-diurnal tides, with a longer ebb and shorter flood tide, also contributes to the persistence of nutrient-rich waters within the estuary for longer periods. In the upper sector, for example, ebb tide periods varied from 8 h 10 min to 10 h (Fig. 4B). This asymmetry was less pronounced in the lower sector, where minimal differences were observed between the flood (5 h 30 min–6 h 10 min) and ebb (6 h 20 min–7 h 20 min) phases.

An asymmetric pattern was also recorded in current intensity in the middle sector (Fig. 4C). Normally, a single peak of current intensity is observed during the ebb tide, while two or more peaks can be observed during the flood phase, with a final peak just before high tide, as a consequence of the inundation of the mangrove. A longer inundation period results in a sudden increase in ebb current intensities, as observed in September and December (0.72-0.75 m s^{-1}). Thus, during periods of higher hydrodynamic energy, the duration of the re-suspension process varied considerably.

Insert Figure 4.

4.3 Spatial variation

Spatial variations reflect the influence of the connectivity of the Taperaçu Estuary with adjacent environments, and the significant longitudinal variation in the majority of the study variables is shown in Table 1. In addition, this is a well-mixed estuary, with no significant variation ($p > 0.05$) being recorded between the bottom and surface layers in any of the hydrological variables. The means and standard deviations of the hydrological variables recorded at the three stations (upper, middle and lower sectors) are shown in figure 5.

The highest turbidity values were found in the zone of maximum turbidity (middle sector), with mean values of above 400 NTU (Nephelometric Turbidity Unit) being recorded (Fig. 5B), and significant differences (Table 1) being found among the sectors.

Salinity and pH increased downstream between the upper and lower estuary sectors (Fig. 5C). The input of freshwater from neighboring wetland areas, as well as the less saline water from the Caeté Estuary contributed to the variation in salinity ($F = 53.7$; $p < 0.001$), with values ranging from 24.1±9.6 in the upper sector to 33.5±3.5 in the lower sector, and pH ($F = 12.0$; $p < 0.001$) from 7.5±0.3 (upper sector) to 7.7±0.4 (lower sector). A greater influence of winds and waves in the lower sector also contributed to the significant differences in DO and DO% (Table 1), which presented maximum means of 4.9±0.5 mg L^{-1} (Fig. 5D) and 107.7±10.7% in the lower sector, respectively.

The connectivity of the Taperaçu Estuary with nutrient rich environments (mangroves, wetlands and the Caeté Estuary) contributes to the eutrophic characteristics of the upper sector of the Taperaçu. Thus, PO_4^{3-} (F = 40.1; $p < 0.001$), TDP (H = 911.1; $p < 0.001$), DSi (U = 2023.5; $p < 0.001$) and chlorophyll-a (U = 2102.0; $p < 0.001$) presented a gradient increasing upstream from the lower to the upper sectors with maximum mean values reaching, respectively, 1.3±1.0 µmol L^{-1}, 1.8±1.2 µmol L^{-1}, 124.1±77.5 µmol L^{-1} and 26.3±28.0 mg m^{-3} (Fig. 5I-L). The highest mean concentrations of NO_2^-, NH_4^+ and TDN were also observed at the upper sector (Fig. 5E and G-H), but no significant longitudinal variation ($p > 0.05$) was recorded (Table 1).

Insert Figure 5.

Insert Table 1.

4.4 Temporal variation

The temporal variation in hydrological variables was influenced by physical forces, such as rainfall and hydrodynamic processes, and also biological processes, such as photosynthesis. Temporal fluctuations were found between the months of the dry and rainy seasons, and a comparison was made between the months of June in the two years. As rainfall was higher in the first semester of 2013 (Fig. 2), June of that year was significantly richer in chlorophyll-a and dissolved nutrients (Fig. 6E and Table 1). These findings indicate that lower rainfall levels, such as those recorded in the first semester of 2012 (most intense drought period), result in more saline and less oxygenated waters, with lower nutrient and chlorophyll-a concentrations. Each hydrological variable is described below, and their monthly means and standard deviations are shown in figure 6.

Water temperatures remained relatively high and stable (varying by only 2°C) throughout the study period, and significant differences were only recorded on a monthly level (Table 1). Turbidity (Fig. 6A) also showed significant monthly variation, with the highest mean values recorded in June (mainly in 2012) and in December when strong winds and currents were recorded (means > 500 NTU). A significant positive correlation (Table 2) was found between wind and turbidity ($r_s = 0.13$; $p < 0.05$).

On the other hand, salinity (Fig. 6B) varied considerably between seasons, resulting in significant differences between the rainy and dry seasons ($p < 0.001$), with more saline waters being observed during the dry season. Significant differences (Table 1) were also found among months, and the most saline waters (above 30) were recorded during the driest months. A clear difference was also found between the June of 2012 and 2013, with the more intense drought event of 2012 being reflected in more saline waters (31.9±2.1), due to both lower rainfall levels and more intense winds which result in higher evaporation. These findings are supported by a highly significant negative correlation (Table 2) between rainfall and salinity ($r_s = -0.68$; $p < 0.001$), and by a highly significant and positive correlation between wind speeds and salinity ($r_s = 0.51$; $p < 0.001$).

As for salinity, higher values were recorded in the dry season for DO, DO%, chlorophyll-a, DSi, PO_4^{3-} and TDP. During the dry season, DO and DO% values (Fig. 6D) were at their highest (above 5.0 mg L^{-1} and 100%, respectively), coinciding with the most intense winds (highly significant positive correlations with DO, $r_s = 0.47$, $p < 0.001$ and DO%, $r_s = 0.53$, $p < 0.001$) and chlorophyll-a concentrations ($r_s = 0.23$; $p < 0.001$, probably due to photosynthetic activity).

Significant monthly variation was also recorded in the chlorophyll-a concentrations (Table 1), with the highest concentrations (Fig. 6L) being recorded in September (25.6±31.5 mg m^{-3}), coinciding with the least turbid water (Fig. 6A). Significant differences in chlorophyll-a concentrations ($p < 0.01$) were also found between day and night, with higher concentrations being observed during the daylight period (14.4±9.1 mg m^{-3}), as well as in different tidal phases, with higher concentrations being recorded during the ebb tide (16.2±12.0 mg m^{-3}), when turbidity is reduced. However, a positive correlation was found between chlorophyll-a and turbidity ($r_s = 0.25$; $p < 0.001$). In addition, PO_4^{3-} ($r_s = 0.58$; $p < 0.001$), TDP ($r_s = 0.60$; $p < 0.001$) and DSi ($r_s = 0.48$; $p < 0.001$) were also significantly and positively correlated with chlorophyll-a concentrations (Table 2).

An opposite trend was recorded during periods when rainfall was higher (mainly in the rainiest months of 2013) and salinity decreased. The highly significant and negative correlation found between rainfall and wind speeds ($r_s = -0.70$; $p < 0.001$) was consistent with the less oxygenated waters observed during the rainy season, but in June 2012 (most severe drought) the water was more oxygenated than in June 2013. Comparing June 2012 and

June 2013, it was possible to record peaks in the concentrations of nitrogenous compounds (Fig. 6E-G), such as NO_2^- and NH_4^+, when the drought event was weaker, indicating an increase in the washout from local mangroves by the rainfall. These results are supported by the highly significant and positive correlation recorded between NO_2^-, NH_4^+ and DIN and rainfall (NO_2^-, r_s= 0.36; p < 0.001; NH_4^+, r_s= 0.61; p < 0.001; DIN, r_s= 0.35; p < 0.001) and by the highly significant negative correlation found between these nitrogenous compounds and salinity (NO_2^-, r_s= -0.33; p < 0.001; NH_4^+, r_s= -0.44; p < 0.001; DIN, r_s= -0.29; p < 0.001, Table 2).

Insert Figure 6.

Table 2.

The spatial and temporal interactions shown in Table 1 reinforce the influence of both these factors, the most intense drought period (2012), and the connectivity of the Taperaçu with adjacent nutrient-rich environments, mainly near the upper and middle sectors. The interactions between sectors and months were associated with significant differences in all variables, except silicate, although no significant variation (p > 0.05) was recorded between the sectors and tidal phase in any of the hydrological variables.

5. Discussion

The past ten years have seen increasingly severe droughts and floods in the Amazon region, with some of these events being characterized as "once-in-a-century" occurrences (Lewis et al. 2011; Marengo et al., 2013b). Despite this, few studies have focused on the consequences of anomalous rainfall patterns on the characteristics of these coastal waters. In addition, nutrient and chlorophyll-a concentrations are strongly influenced by anomalous climatic events in different latitudes. Wilkerson et al. (2002), for example, investigated hydrographic, nutrient and chlorophyll-a data under typical and atypical rainfall conditions in Gulf of the Farallones. During the La Niña event, those coastal waters were richer in dissolved nutrients and chlorophyll-a concentrations when compared with the El Niño period. Similar results have been found in other parts of the world, such as the Pacific coast of Panamá (Valiela et al. 2012). More eutrophic conditions were also found in the water of the Caeté Estuary when compared periods of higher (Monteiro et al. 2016) and lower (Sousa et al. 2016) rainfall levels. But, how does the reduction in rainfall levels affect oscillations in hydrological variables in a small Amazon estuary?

During the rainy season, the increased fluvial discharge dominates most Amazon estuaries (Costa et al. 2013b; Pamplona et al. 2013; Pereira et al. 2010), reducing the salinity of the region's coastal waters, including those of the Taperaçu Estuary (Costa et al. 2013a; Magalhães et al. 2015; Souza-Junior et al. 2013). Thus, the effect of the drought event seems to be greater during the rainy season, possibly because 80-90% of the total annual precipitation occurs during this period. In this study, abnormally low precipitation levels in April, May and June 2012 resulted in more saline waters in the latter month, whereas higher precipitation rates in 2013 resulted in less saline and more eutrophic waters in June. In fact, the water was less saline, more alkaline, more oxygenated, and nutrient and chlorophyll-a concentrations were much higher (over 50%) in June 2013 in comparison with the same month of the previous year, reflecting the much higher rainfall (more than 30%) during the period between March and June, in comparison with the same period in 2012. Overall, then, during the rainy season under typical conditions, these waters are less saline (over 40%, figure 3A) than those recorded during this drought period and much less saline (over 60%, i.e., around 10) under a La Niña event (Andrade et al. 2016), showing that this small estuary was adversely affected by the drought event.

In addition, TDN reached higher concentrations, mainly in June 2013 (higher precipitation rates), while negative correlations were recorded between NH_4^+ and NO_2^- and salinity (Table 2). ~~The highest concentrations of nitrate was also recorded in June 2013, when in comparison with the same month of the previous year.~~ Pereira et al. (2013) showed that, during the rainy season of a La Niña event near the study area, hydrological conditions are accentuated by the increased rainfall levels and fluvial discharge, with the coastal waters becoming less saline, and richer in dissolved nutrients.

In an adjacent area, Wolf et al. (2000) showed that 10% of all biological productivity (g m^{-2} yr^{-1}) may be derived from phytoplankton and microphytobenthos (mainly diatoms). In this study, chlorophyll-a concentrations (indirect metric of biomass) were also highest in the upper sector of the estuary, mainly during non-drought period (Fig. 3C) reinforcing the influence of the anomalous climatic event on hydrological variables. The increasing penetration of sunlight into the water column in September appears to have created ideal conditions for the growth of phytoplankton and microphytobenthos, as indicated by the higher chl-a concentrations. The lower nitrogenous concentrations recorded during this month were probably a consequence of intense autotrophic consumption, as indicated by the high chl-a concentrations. On the other hand, the positive correlation between chl-a and turbidity (Table 2) indicates that the re-suspension of the mangrove detritus and the microphytobenthos may have also contributed to the increase in chl-a concentrations, as reported for other tropical estuaries (Wollf et al. 2000, Murolo et al. 2006, Pamplona et al. 2013).

Comparing our results with those of other studies of mangrove regions, it is possible to confirm that this minor estuary sustains similar chlorophyll-a concentrations to those found in much larger Amazonian estuaries (even during a period of intense drought), such as the Paracauari (up to 26 mg m^{-3}; Costa et al. 2013a) and Quatipuru (up to 30 mg m^{-3}; Pamplona et al. 2013), and even higher concentrations than those found in other tropical estuaries under similar rainfall levels (up to 5 mg m^{-3}; Pan et al. 2016) and sub-tropical estuaries under different rainfall levels (up to 15 mg m^{-3}; Hart et al. 2015)."

However, what is the origin of the nutrients in an estuary with absence of any direct fluvial discharge? On the Amazon coast, tidal range plays an important role in the determination of the dissolved nutrient profile due to the flooding of the extensive areas of mangrove during each tidal cycle. The high tide may connect certain nutrient-rich environments, as in the present study area, where the flooding of the Taici Creek creates a connection with the Caeté River, and the flooding of adjacent mangroves and wetland areas leads to an additional input of less saline water and richer in dissolved nutrients and chlorophyll-a, mainly in the upper sector. Studies have shown that the water in the upper and middle sectors of the Caeté Estuary (where the Taici Creek is located) are less saline during the rainy season (i.e., around zero) and slightly richer in nitrogenous compounds, for example, with average total dissolved nitrogen around 30% (approximately 30 µmol L^{-1}) higher than the levels recorded in the Taperaçu estuary (Monteiro et al. 2016; Sousa et al. 2016). It thus seems reasonable to assume that the Caeté Estuary can be an important source of nutrients for the Taperaçu Estuary.

Another factor contributing to the nutrient concentrations in the upper sector is the storage of water in the mangrove sediment. In a tidal creek in the adjacent Caeté Estuary (“Furo do Meio”), Dittmar and Lara (2001) showed that water may be stored in the mangrove sediment following inundation or rainfall, and is then released during the ebb tide. In the present study, the comparison of the salinity levels over the tide cycle in June (2012 and 2013) indicated that the water was most saline during 2012, when the drought was most intense. In both years, however, salinity decreased during the ebb-low tide, indicating that pluvial water was stored in the mangrove and then released during the ebb tide, in particular in 2013, coinciding with the highest PO_4^{3-}, TDP and DSi concentrations.

Overall, the upper and middle sectors presented similar hydrological conditions when compared with the lower sector. However, an opposite pattern was recorded in the majority of the study variables recorded in June 2012 and 2013 (one-way ANOVA, Table 1). Significant differences were also found among the spatial and temporal interactions (two-factor ANOVA, Table 1) reinforcing the influence of the lower rainfall level in 2012, and the connectivity between the upper and middle sectors with adjacent nutrient-rich environments.

6. Final Considerations

Our results showed how physical forces can influence the oscillations in hydrological variables in a small Amazon estuary during a drought event. As would be expected for an estuary with no major freshwater input and high levels of hydrodynamic energy, there is little vertical variation in the water column, although marked longitudinal gradients were found among the three sectors of the estuary. Rainfall is the principal physical variable controlling local hydrological oscillations, and when precipitation decreases, as observed during a drought event, the water becomes more saline, and has reduced dissolved inorganic nutrient and chlorophyll-a concentrations. The considerable local tidal range also plays an important role in the control of local phytoplankton biomass and the profile of dissolved nutrients through the inundation of adjacent mangroves and wetland areas. The connection to the neighboring Caeté Estuary through the Taici Creek further contributes to the influx of less saline and nutrient-enriched waters. Given the combination of these processes, the Taperaçu, despite being a relatively small estuary, plays an important role in the input of dissolved nutrients and chlorophyll-a to the adjacent coastal waters, even during a period of intense drought. It seems likely that these observations can contribute to the understanding of the effects of equivalent conditions (i.e., drought events) in other minor estuaries on the highly indented Amazon coast, as well as in other areas of the equatorial zone with similar environmental characteristics.

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Figure Captions

Fig 1. Study Area: (A) South America; (B) Location of the Taperaçu estuary on the Brazilian Amazon Coast; (C) Positions of the sampling stations in the upper (1), middle (2), and lower (3) sectors of the Taperaçu estuary, with the arrow indicating the position of Taici Creek, which connects the Taperaçu and Caeté estuaries.

Fig 2. Total precipitation levels (mm) between 2000 and 2015. The arrows are highlighting the driest years (2012 and 2013) and the dashed line represents the median precipitation level recorded between 2000 and 2015.

Fig 3. (A) Cumulative rainfall levels every three months and mean salinity water in Taperaçu Estuary, during drought and no-drought period. The gray hatching represents the drought period. (B) 25 h time series of salinity in June (*) of the four study years (2012-2105) in the upper sector. (C) Mean salinity and chlorophyll-a data during drought (2012-2013) and post-drought periods (2014-2015).

Fig 4. (A) Water level oscillations (m) obtained from Hydrographic and Navigational Department of the Brazilian Navy (DHN). The red lines indicate the days on which data were collected; (B) Water level oscillations (m) recorded in the upper and lower sectors (◇ = the sample period at 3 hour intervals); and (C) the current intensity (black line) and direction (●), and tidal elevation (gray shape) recorded in the middle sector.

Fig 5. Means and standard deviations (positive direction) recorded in the three sectors for water temperature (A), turbidity (B), pH (C), DO (D), nitrite (E), nitrate (F), ammonium (G), total dissolved nitrogen (H), orthophosphate (I), total dissolved phosphorus (J), silicate (K), and chlorophyll-a (L). Salinity (mean and standard deviation) values were plotted in the panels in which the variables increased downstream (C) or upstream (I, J, K and L).

Fig 6. Monthly means and standard deviations (positive direction) recorded for water turbidity (A), salinity (B), pH (C), DO (D), nitrite (E), nitrate (F), ammonium (G), total dissolved nitrogen (H), orthophosphate (I), total dissolved phosphorus (J), silicate (K), and chlorophyll-a (L). The gray hatching represents the rainy season.

Figure 1

Click here to download Figure Figura1EC.tif

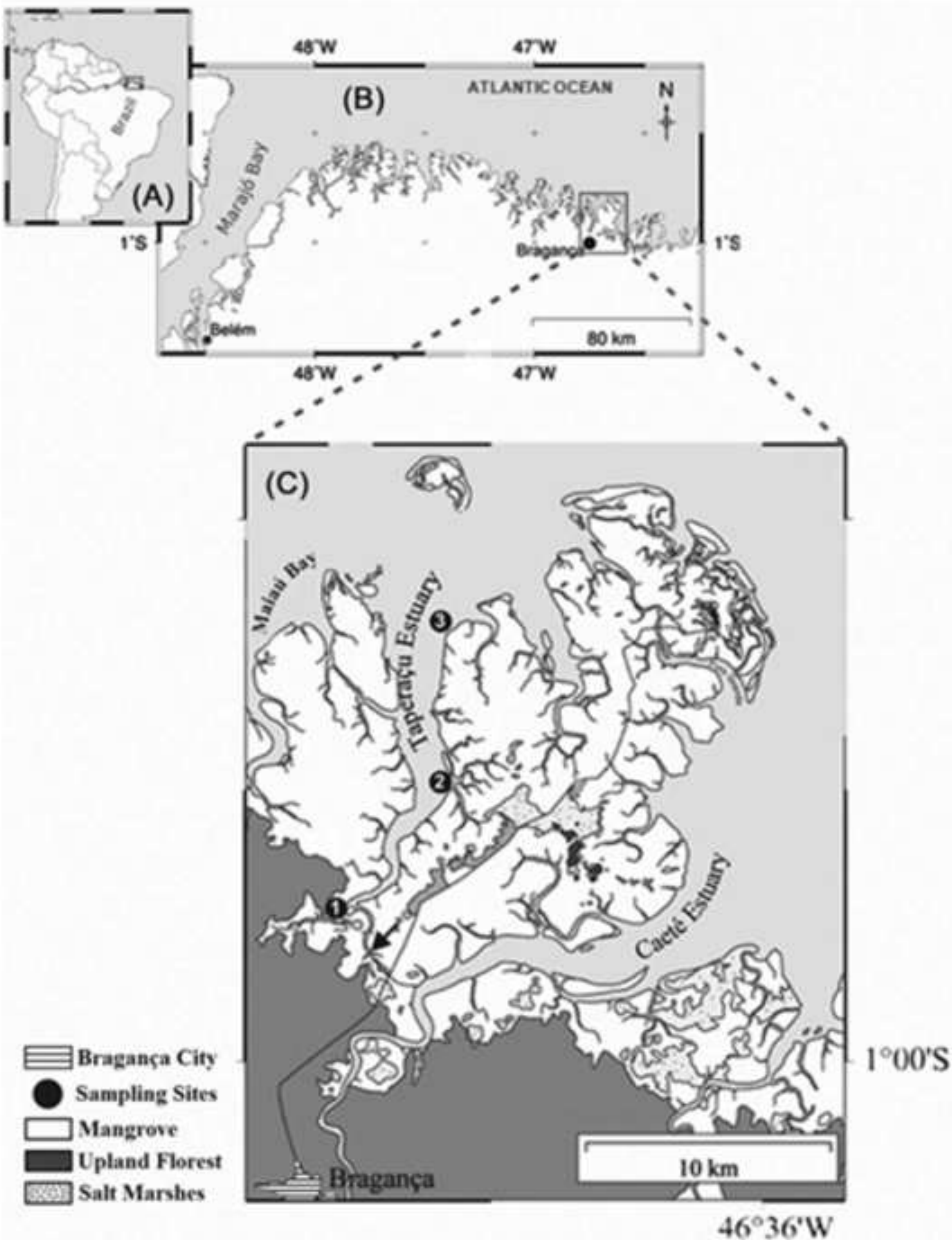
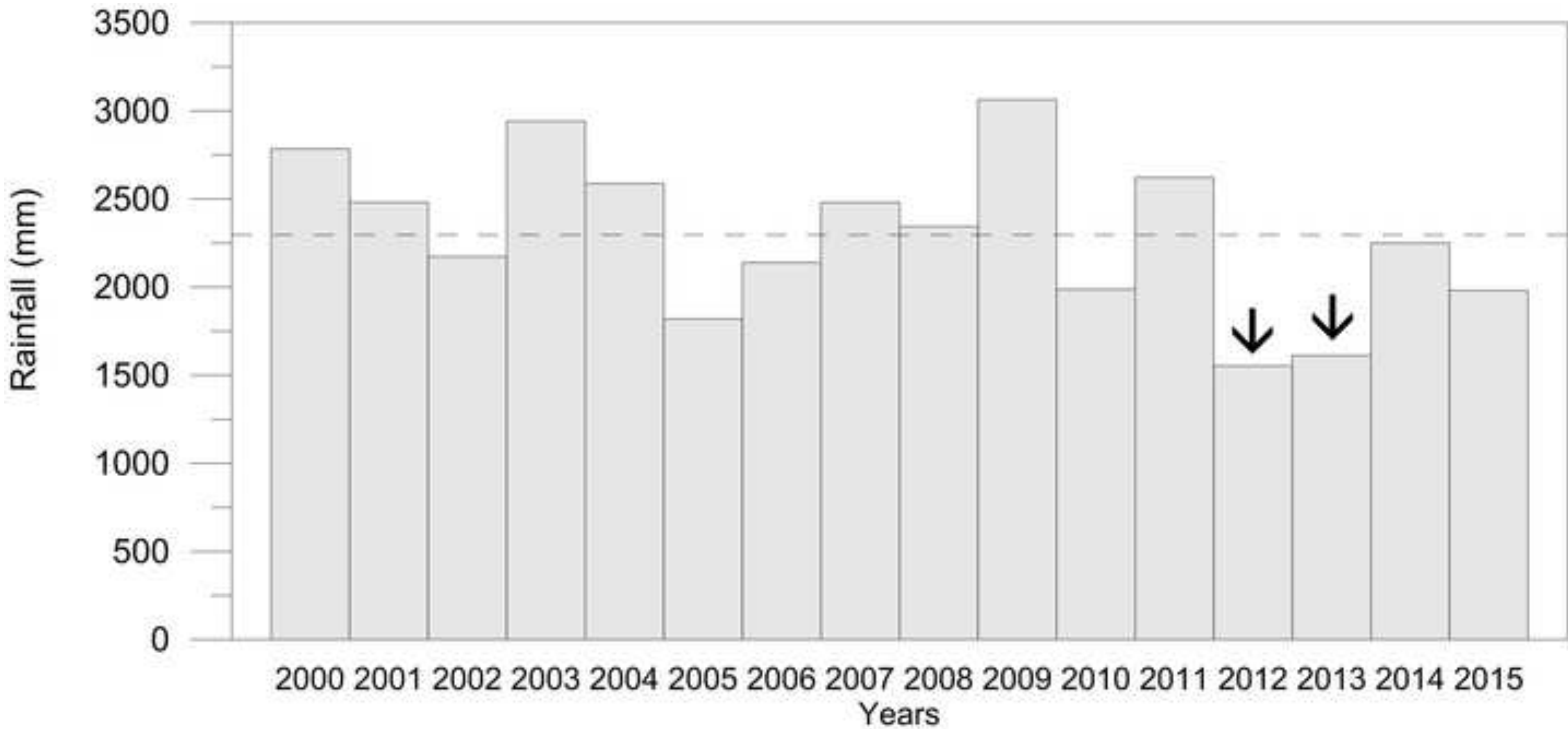


Figure 2



3500
3000
2500
2000
1500
1000
500
0
Rainfall (mm)
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
Years

Figure 3 Click here to download Figure Figure3ESCOR2.tif

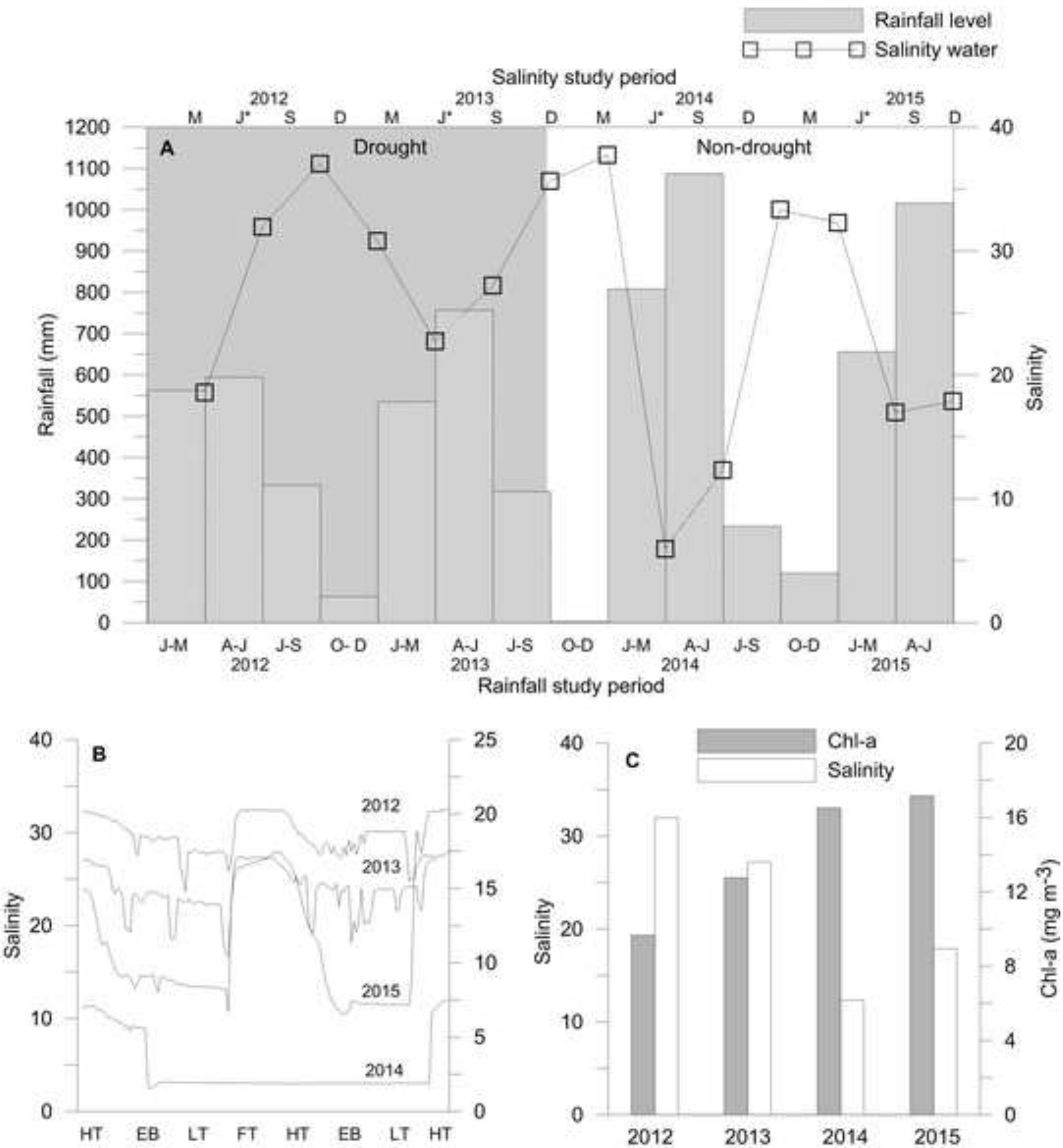
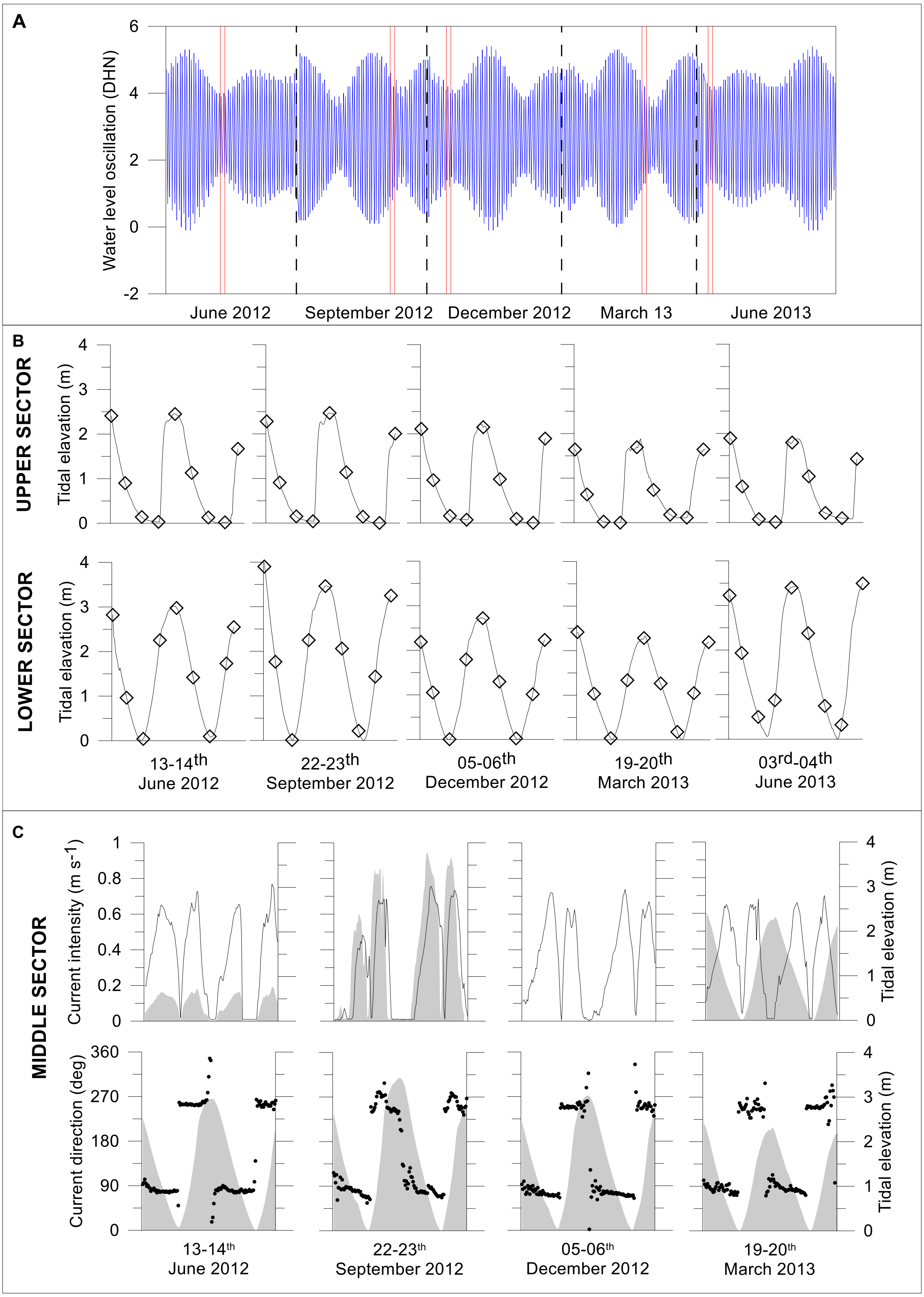


Figure 4



A
Water level oscillation (DHN)
6
4
2
0
-2
June 2012
September 2012
December 2012
March 13
June 2013
B
UPPER SECTOR
LOWER SECTOR
Tidal elevation (m)
Tidal elavation (m)
4
3
2
1
0
13-14th
June 2012
22-23th
September 2012
05-06th
December 2012
19-20th
March 2013
03rd-04th
June 2013
C
MIDDLE SECTOR
Current intensity (m s-1)
1
0.8
0.6
0.4
0.2
0
Tidal elevation (m)
Current direction (deg)
360
270
180
90
0
13-14th
June 2012
22-23th
September 2012
05-06th
December 2012
19-20th
March 2013

Figure 5 Click here to download Figure Figure5ESCOR1.tif

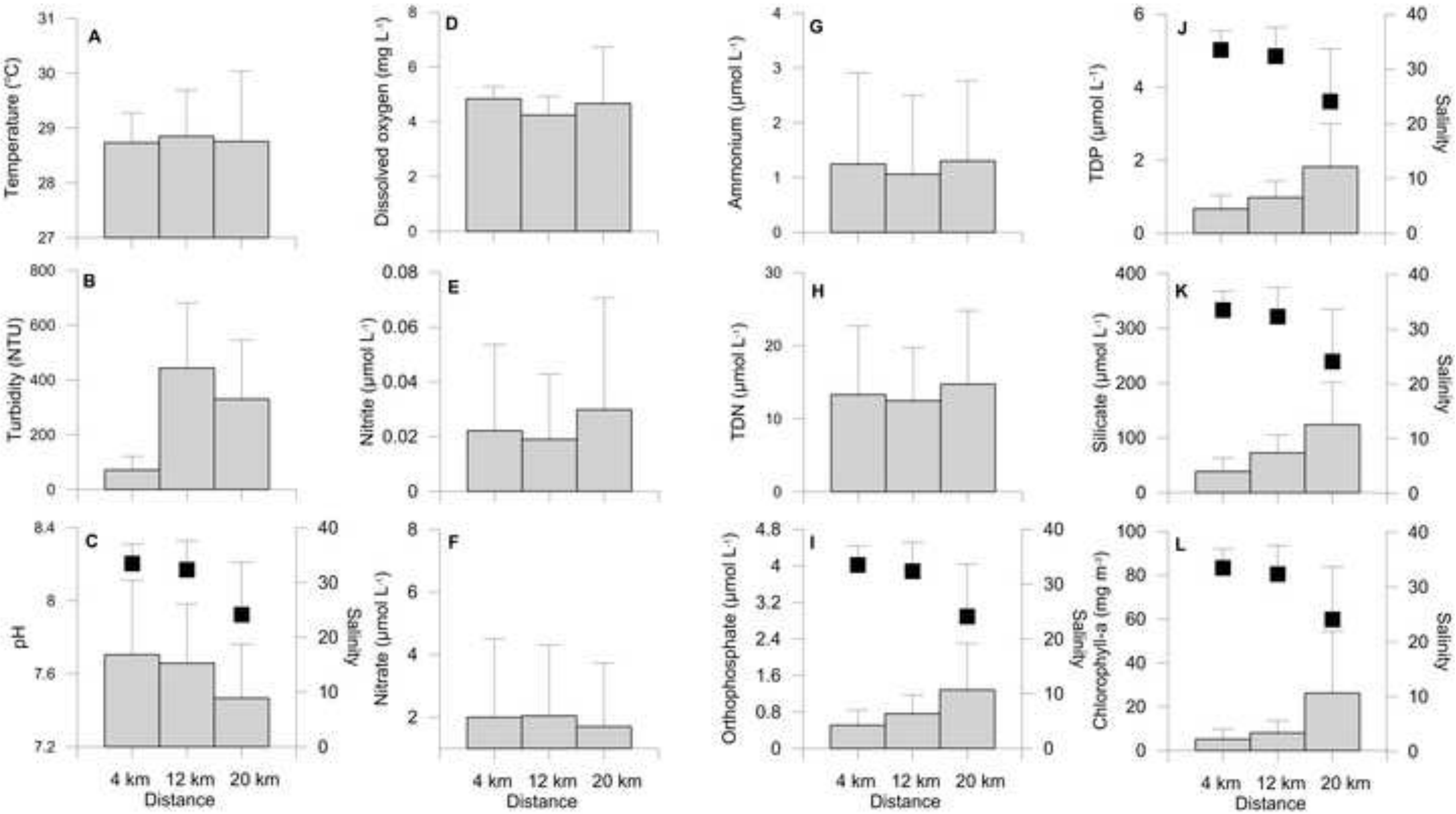


Figure 6

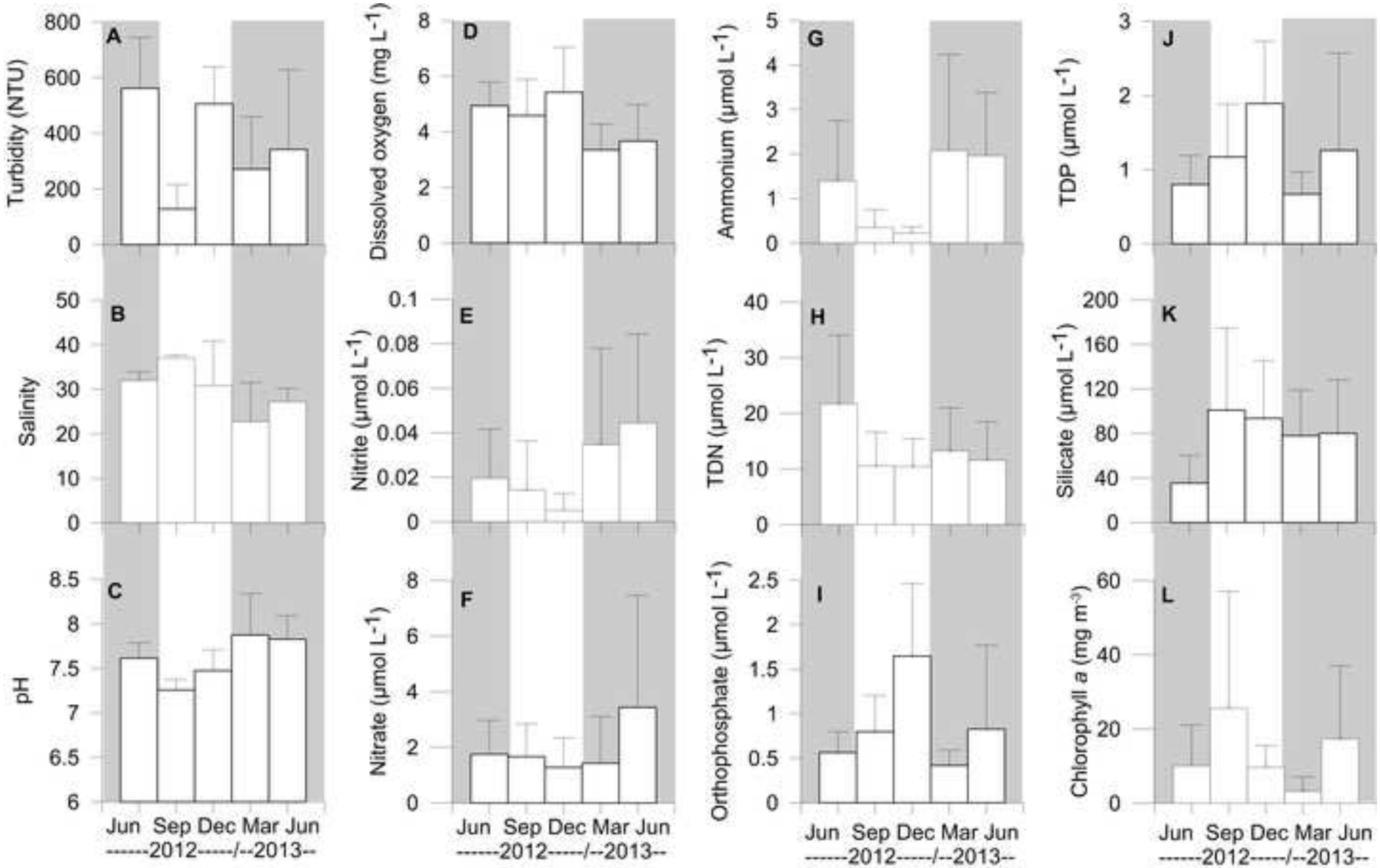

A
B
C
D
E
F
G
H
I
J
K
L
Turbidity (NTU)
Salinity
pH
Dissolved oxygen (mg L-1)
Nitrite (µmol L-1)
Nitrate (µmol L-1)
Ammonium (µmol L-1)
TDN (µmol L-1)
Orthophosphate (µmol L-1)
TDP (µmol L-1)
Silicate (µmol L-1)
Chlorophyll a (mg m-3)
Jun Sep Dec Mar Jun
------2012-----/--2013--

Table 1

Table 1. Summary of the univariate statistical analyses of the hydrological variables and chlorophyll-a in the Taperaçu estuary, northern Brazil. The spatial (sectors) and temporal scales (season, month and tide phase) were evaluated by ANOVA, and the Mann-Whitney and Kruskal-Wallis tests. If the ANOVA or Kruskal-Wallis test indicated significant variation among stations or months, *a posteriori* pair-wise Fisher's LSD and Student-Newman-Keuls analyses were run. The interactions between sectors *vs.* seasons and sectors *vs.* months were assessed by a two-factor ANOVA.

Variables	SPATIAL	TEMPORAL			Interactions	
	Sectors (1)	Seasonally (2)	Monthly (3)	Tidal phase (4)	1 x 2	1 x 3
Temp	n.s.	n.s.	JUN/12 DEC SEP MAR JUN/13***	n.s.	n.s.	***
Salin	S1 S2 S3***	DRY RAI***	SEP JUN/12 DEC MAR JUN/13***	n.s.	n.s.	***
DO	S1 S2 S3**	DRY RAI***	JUN/12 DEC SEP MAR JUN/13***	n.s.	***	***
DO%	S1 S2 S3***	DRY RAI***	JUN/12 SEP DEC JUN/13 MAR***	n.s.	***	***
Turb	S1 S2 S3***	n.s.	JUN/12 DEC SEP MAR JUN/13***	FLO EBB*	***	***
pH	S1 S2 S3***	DRY RAI***	JUN/12 DEC SEP MAR JUN/13***	n.s.	**	***
chl-a	S1 S2 S3***	DRY RAI***	JUN/13 SEP JUN/12 DEC MAR***	FLO EBB ***	n.s.	***
NH_4^+	n.s.	DRY RAI***	SEP DEC JUN/12 MAR JUN/13***	n.s.	n.s.	***
NO_2^-	n.s.	DRY RAI***	DEC SEP JUN/12 MAR JUN/13***	n.s.	n.s.	**
NO_3^-	n.s.	DRY RAI***	JUN/12 SEP DEC MAR JUN/13***	n.s.	n.s.	*
$PO^3{}_4^-$	S2 S1 S3***	DRY RAI***	DEC MAR JUN/12 SEP JUN/13***	FLO EBB ***	n.s.	***
DSi	S2 S1 S3***	DRY RAI***	JUN/12 DEC MAR SEP JUN/13***	FLO EBB ***	n.s.	n.s
TDN	n.s.	DRY RAI***	JUN/12 SEP DEC MAR JUN/13***	FLO EBB **	n.s.	*
TDP	S1 S2 S3***	DRY RAI***	DEC JUN/12 MAR SEP JUN/13***	FLO EBB **	n.s.	***

Environmental variables: Temp = temperature, Salin = salinity, DO = dissolved oxygen, DO% = oxygen saturation, Turb = turbidity, pH = Hydrogenionic potential, chl-a = chlorophyll-a, NH_4^+ = ammonium, NO_2^- = nitrite, NO_3^- = nitrate, PO $^3{}_4^-$ = orthophosphate, DSI = dissolved silicon compounds, TDN = total dissolved nitrogen, TDP = total dissolved phosphorus. n.s. Sectors of the estuary: S1 (upper sector), S2 (middle sector), S3 (lower sector). Seasons: DRY = dry, RAI = rainy. Study months: JUN/13 = June 2013; SEP = September; DEC = December, MAR = March, JUN/13 = June 2013. Tidal phase: FLO = flood; EBB = ebb. n.s = non-significant. * Significant at <0.05, ** Significant at <0.01, *** Significant at <0.001.

Table 2

Table 2. Spearman correlation matrix between environmental variables in the Taperaçu estuary, northern Brazil during the field campaigns. WS = wind speed, Chl-a = chlorophyll-a, Turb = turbidity, Salin = salinity, pH = Hydrogenionic potential, Temp = temperature, DO = dissolved oxygen, DO% = oxygen saturation, DSI = dissolved silicon compounds, PO_4^{3-} = orthophosphate, NH_4^+ = ammonium, NO_3^- = nitrate, NO_2^- = nitrite, DIN = dissolved inorganic nitrogen, TDN = total dissolved nitrogen, TDP = total dissolved phosphorus.

	Rainfall	WS	Chl-a	Turb	Salin	pH	Temp	DO	DO%	DSI	PO_4^{3-}	NH_4^+	NO_3^-	NO_2^-
WS	-0.70***													
Chl-a	-0.36***	0.23***												
Turb	-0.03	0.13*	0.25***											
Salin	-0.68***	0.51***	0.04	-0.23***										
pH	0.63***	-0.40***	-0.28***	-0.10	-0.32***									
Temp	-0.05	0.07	0.38***	0.16*	0.00	0.18**								
DO	-0.35***	0.47***	0.05	-0.04	0.14*	-0.04	0.38***							
DO%	-0.36***	0.53***	-0.01	-0.17*	0.38***	-0.02	0.41***	0.90***						
DSI	-0.11	-0.25***	0.48***	0.37***	-0.23***	-0.28***	0.04	-0.30***	-0.45***					
PO_4^{3-}	-0.48***	0.19**	0.58***	0.39***	0.17**	-0.37***	0.32***	0.03	-0.11	0.57***				
NH_4^+	0.61***	-0.31***	-0.10	0.02	-0.44***	0.44***	0.06	-0.17**	-0.15*	-0.02	-0.33***			
NO_3^-	-0.11	0.20**	0.02	0.02	0.03	-0.08	0.02	0.10	0.15*	-0.11	-0.10	-0.01		
NO_2^-	0.36***	-0.20**	-0.12*	-0.09	-0.33***	0.13*	0.03	-0.16*	-0.11	-0.04	-0.28***	0.32***	0.06	
DIN	0.35***	-0.11	-0.09	-0.03	-0.29***	0.23***	0.05	-0.06	-0.00	-0.11	-0.34***	0.63***	0.68***	0.28***
TDN	0.12	0.20**	-0.01	0.02	-0.06	0.05	-0.03	0.12*	0.13*	-0.14*	-0.09	0.16**	0.25***	0.14*
TDP	-0.38***	0.11	0.60***	0.41***	0.09	-0.35***	0.30***	-0.01	-0.15*	0.59***	0.91***	-0.25***	-0.09	-0.23***

* Significant at <0.05;
** Significant at <0.01;
*** Significant at <0.001.