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Circulation and transport in short, low-inflow estuaries under anthropogenic stresses

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ABSTRACT

Data from field experiments were used to assess, for the first time, hydrodynamic and transport processes in three shallow low-inflow estuaries of Northeast Brazil (Ceará State). The estuaries of the Cocó, Pacoti and Pirangi rivers exhibit anthropogenic stresses related to freshwater withdrawals and sewage discharges and morphological changes. Sampling was carried out during complete spring tidal cycles at each estuary during consecutive days on November 6, 7 and 8, 2010. November is the end of the dry period, and the results represented expected extreme low inflow conditions. All estuaries showed well mixed water columns because of frictional influences. Cocó and Pacoti displayed ebb dominance while the Pirangi exhibited flood dominance, a result from morphological changes in the intertidal storage areas. Each estuary showed distinct longitudinal salinity distributions related to different water budgets, which were actually altered by human activities. The Cocó estuary was hyposaline because of waste water discharge from the city of Fortaleza. This estuary represented a source of materials to the coastal sea as it showed net export of Suspended Particulate Matter (SPM) and chlorophyll. The Pacoti estuary was slightly hypersaline but nearly neutrally buoyant as temperature compensated for salinity variations. The Pacoti also exhibited net seaward transport of SPM and chlorophyll. The Pirangi estuary showed strong hypersalinity and inverse estuarine circulation as a result of multiple river dams. The negative water budget combined with mangrove depletion led to magnifying trapping processes, thus resulting in net import of salt, SPM and chlorophyll. The three cases exemplified how estuaries on the order 10 km long can be sensitive to human-induced changes. These human changes affect their circulation structure and their function as source or trap for materials at the land–ocean interface.

1. Introduction

Estuaries are the main pathway of material fluxes between continents and oceans. Their function is affected by rapid changes from global climate change and anthropogenic alterations (Crossland et al., 2005; Jarvie et al., 2012; Statham, 2012). Estuarine geomorphologic diversity, coupled with drainage basin water budget (river discharge) and tidal regime results in distinct circulation and stratification patterns, e.g., highly stratified, partially mixed and well mixed (Dyer, 1997; Miranda et al., 2002). The circulation, in turn, is a main factor controlling the material budget of any estuary and will determine whether a given system is a source or a trap of material to or from the adjacent ocean (Dyer, 1995; Ralston et al., 2012; Schettini et al., 2013).

Circulation characteristics in estuaries can be modified by anthropogenic activities. Modifications include direct changes to the estuarine basin, such as land reclamation for urban or industrial use, channel deepening and widening by dredging, estuarine mouth stabilization and elongation by jetties, among others. Geometry alterations can change the tidal prism and the exchange rates (Meyers et al., 2013; Paiva et al., 2016). Deepening decreases the dissipation of tidal energy, leading to changes in vertical mixing and sediment transport (Nijs et al., 2010; Van Maren et al., 2015). Alterations outside the estuary itself, in the drainage basin, can also affect estuarine processes. Destruction of pristine forests for agriculture and mining increases the sediment supply, and dam construction decreases the sediment supply (Syvitski and Kettner, 2011). These changes in freshwater supply, especially in arid or semi-arid regions, can therefore affect estuarine dynamics.

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Freshwater supplies will influence buoyancy fluxes and ultimately salt intrusion in an estuary (Dyer, 1997; Geyer and MacCready, 2014). Water management of drainage basins can affect the estuarine water budget in different ways, such as (a) suppressing discharge peaks during the rainy period, (b) sustaining a higher minimum river discharge during drought periods (Frota et al., 2013), (c) interrupting the freshwater supply entirely, or (d) increasing/decreasing the water inflow by transference from/to other drainage basins (Schettini et al., 2016). Although these management strategies are contemporary and increasingly being implemented, very little is known regarding their consequences on estuarine transport and their effects on the system's ecology (González-Ortegón et al., 2015).

The Northeastern Brazilian region is particularly susceptible to management alterations of an estuary because of its semi-arid climate. The precipitation rate is $<$ 700 mm year^{-1}, with rains concentrated over 4–5 months and surrounded by prolonged drought periods. The amount of rain in this region is influenced by several factors at local, meso and global scales (Ferreira and Mello, 2005). The presence of the Borborema Mountains is the main local cause of the semi-arid conditions. The mountains extend along the North–South axis bordering the coast, inducing orographic rains and blocking the passage of humidity to the hinterland. The Atlantic dipole is another factor that likely affects precipitation values at regional scales (Alves et al., 2009), although the El Niño Southern Oscillation (ENSO) is a major factor governing regional precipitation (Santos and Brito, 2007). Positive ENSO years are associated with negative anomalies of precipitation. In particular, ENSO pulses of 1993 and 1998, reduced the rain during the wet period in the Brazilian Northeast Region, extending the dry period from one year to the next.

The rain irregularity and the climate changing toward dry conditions (Silva, 2004; Guerreiro et al., 2013), has motivated the construction of thousands of water reservoirs in order to ensure regular freshwater supply (Van Oel et al., 2009; Montenegro and Ragab, 2010). Most of these reservoirs are small (e.g. $\sim 10^6$ m^3), although there are few large reservoirs such as the Oroz and Castanhão in the Jaguaribe River drainage basin. These reservoirs were built in the 1960s and 1990s, respectively, and have storage volumes of 2.1 and 6.7 $\times$ 10^9 m^3, respectively. The main function of these reservoirs is to maintain a minimum discharge of the Jaguaribe River, which is the largest drainage system in the semi-arid region with 75, 000 km^2 (Frota et al., 2013). The building of these reservoirs was part of a major state water management program entitled "Eixão das Águas" (Big Water Axis). The overall goal was to ensure water supply to the Fortaleza City metropolitan area, which encompasses five municipalities and 3.6 $\times$ 10^6 inhabitants. In order to supply water to the city, more than 100 km of aqueducts were built in the 1990's, with flow capacities of 6 m^3/s, to transfer freshwater between watersheds.

Tens of small estuaries appear along the semi-arid Northeast Brazilian coast. Excluding the major drainage of São Francisco and Parnaíba rivers, most of the estuaries are influenced by the regional semi-arid climate, in the sense that during the dry period they have no freshwater inflow, and can be typified as low-inflow estuaries (e.g., Largier, 2010). Basically, all these estuaries are affected in some way by the construction of water reservoirs. The present study compared basic hydrographic structures of three of these estuaries, which can be epitomized as representative of the estuaries in the region. They are the Cocó, Pacoti and Pirangi estuaries, which have drainage areas of 530, 1200 and 4250 km^2, respectively. A sizeable portion of the Cocó drainage is in the Fortaleza Metropolitan Zone, which means that its water budget accounts for an additional contribution from the Fortaleza water supply system. The Pacoti system is moderately affected by reservoirs, while the Pirangi system is severely influenced by flow regulation. Ancillary data of turbidity and chlorophyll are also discussed, as indicative of sediment transport processes and biological primary productivity.

2. Physical setting

The estuaries of the rivers Cocó, Pacoti and Pirangi are located along the coast of Ceará State, on the shore of the Brazilian's Northeast Region (Fig. 1). Their mouths are located at 03° 46′14″S & 038° 26′08″W for Cocó; 03° 49′27″S & 038° 24′06″W for Pacoti; and 04° 23′07″ & 037° 50′29″W for Pirangi. These mangrove-fringed estuaries are short ($<$ 20 km long), shallow ($<$ 5 m deep), and indented along a coastal plain. The plain consists of sedimentary deposits of Tertiary and Quaternary sandstones, mudstones and conglomerates, presenting active dune fields (Hesp et al., 2009). The inlets of Cocó and Pacoti estuaries cut through sandstone outcrops, and the Pirangi inlet is influenced by a dynamic sand-bar.

The Cocó estuary crosses the Fortaleza Metropolitan Area, with a population of 2.5 $\times$ 10^6 people in its drainage area (Lacerda et al., 2008). The Pacoti estuary crosses a moderately populated area still with relatively large mangrove areas, although displaying environmental disturbances (Maia and Coutinho, 2012). The Pirangi estuary crosses a sparsely populated area, although most of the mangroves areas were replaced by former salt ponds that are now shrimp farms. Thus, the water quality in these estuaries is affected either by domestic or industrial sources, as in Cocó (Silva et al., 2004; Gonçalves et al., 2007), or by shrimp farming, as in Pirangi (Lacerda, 2006; Suárez-Abelenda et al., 2014).

The regional coastal climate is semi-arid warm, with the mean annual temperature of 26.6 °C, and monthly means ranging from 25.7 to 27.3 °C in July and January, respectively (Campos and Studart, 2003). The precipitation rate decreases from $<$1200 mm/yr at the coast to $<$700 mm/yr inland (Uvo and Berndtsson, 1996). The rains concentrate between January and June ($>$150 mm/month), with a peak in March–April ($>$300 mm/month). The dry period lasts from July to December, with very low or no precipitation at all in the period from September to November ($<$25 mm/month). The evaporation rate shows an inverse pattern relative to the rain, with the lowest rates (100–200 mm/month) between February and June, and the highest between August and October (Campos and Studart, 2003). The annual mean rate of evaporation is about 1900 mm/year. Fig. 2 shows the monthly precipitation and evaporation rates of the coastal zone of Ceará, with data from the Fortaleza and Aracati meteorological stations.

Data for river discharge are unavailable. However, as many fluvial systems in the Brazilian semi-arid region, it is likely that they have intermittent regimes, flowing during the wet period and few weeks afterward (Maltchik and Florin, 2002). Estimates based on drainage basin water budget by Molisani et al. (2006) on a monthly basis indicate that the river discharge for the Cocó, Pacoti and Pirangi estuaries is $\sim$6, 19 and 15 m^3/s, respectively, during the wet period. During the dry period the discharge is $<$ 1 m^3/s in the three estuaries, accounting for the effect of the main water reservoirs to their drainage. Therefore, this budget does not consider the role of water transfer between watersheds, especially for the Cocó estuary. Taking into account the water transfer rate of 6 m^3/s by the "Eixão das Águas", and considering losses of about 50%, there will still be a discharge of about 3 m^3/s all year long.

Regional tides are semi-diurnal, ranging between 1.0 and 2.5 m during the periods of neap and spring tides, respectively (Schettini et al., 2011; Frota et al., 2016). The continental shelf circulation is influenced by the North Brazil Current offshore (e.g. Johns et al., 1990) and by a nearly steady westward wind-induced current near shore (e.g. Soares and Castro Filho, 1996). Shelf waters are dominated by Tropical Water, with salinity values $>$ 36 g/kg and temperature around 28 °C (Dias et al., 2013). Early physical descriptions of the Cocó and Pacoti estuaries were made by Vasconcelos and Freire (1985) and Freire and Maia (1991), respectively. These preliminary studies pointed out that the tides are the main forcing of the currents in the estuaries. Freitas et al.