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Physical characteristics and discharges of suspended particulate matter at the continent-ocean interface in an estuary located in a semiarid region in northeastern Brazil

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A B S T R A C T

This study reports the hydrodynamics of the transport of suspended particulate matter (SPM) in the Jaguaribe River estuary, which receives the runoff from the largest drainage basin in the state of Ceará, Brazil. The estuary is located in the semiarid region of Brazil, where rainfall occurs primarily between January and May and results in water flow rates exceeding 3000 m^3s^{-1}. The drainage basin contains more than 4000 dams, which, during the dry season, block most of the flow of freshwater and sediment. The net balance and transport of sediments were calculated for the wet and dry seasons considering a tidal cycle of 13 h at the interfaces between the upper and middle estuary and between the middle and lower estuary. The Jaguaribe River estuary is classified as partially mixed with weak vertical stratification and a tendency toward being well mixed. The SPM transported during the rainy season originates in the drainage basin due to high river inflow, whereas during the dry season, resuspension and hydraulic fills generated by tides causes the accumulation of SPM in the middle estuary, forming a zone of maximum turbidity. The transport of salt in the estuary was predominantly caused by gravity flow and tidal propagation.

1. Introduction

The understanding of physical processes that regulate transport from the continent to estuaries and from there to the inner continental shelf (ICS) are based on direct measurements performed in these environments. Certain classic studies (Officer, 1976; Dyer, 1986, 1987; Miranda et al., 2002) highlight the complexity of studying the hydraulics of suspended fine sediments (cohesive and non-cohesive) and those transported by saltation due to the intrinsic hydrodynamic characteristics of estuarine systems. The deficit or accumulation of sediments in coastal zones can significantly alter the development of the coastline and result in losses and gains in coastal areas and damage to civilian structures (French et al., 2008; Valle-Levinson, 2010; Syvitski and Kettner, 2011). Increased loads of suspended particulate matter due to watershed development (Syvitski et al., 2005; Milliman and Farnsworth, 2011) cause considerable impacts on estuarine and marine ecosystems. These impacts include sedimentation (Weber et al., 2012; Flores et al., 2012), elevated turbidity reducing photic depth (Fabricius et al., 2013, 2014), and stressors associated with pollutants attached to sediment such as nutrients and trace metals (Dias et al., 2013a,b; Weber et al., 2006).

Delandmeter et al. (2015) showed that sediments are deposited and retained in a bay near a river mouth, while suspended sediments that travel longer distances are transported within freshwater plumes during flood events. Thus, at the continent-ocean interface, the transport of suspended particulate matter becomes complex and hardly predictable in estuaries where the influence of the tide leads to an increased residence time of freshwater, and therefore of fine sediments (clays, silts), in a turbidity maximum zone (TMZ) (Dyer, 1986). As a result, the fluxes of riverine suspended particulate matter (SPM) exported to the ocean in such

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estuaries are currently poorly documented, due to a lack of appropriate measurements that take into account the seasonal cycles of river discharges (Fettweis et al., 1998). When available, field measurements are expensive and are either specific to a time period or a geographical location (i.e. not representative of the riverine or estuarine section); they are recorded several (sometimes hundreds of) kilometers upstream from the river mouth and do not take into account the trapping of sediments in estuaries (Ludwig et al., 1996; Schlunz and Schneider, 2000).

The Jaguaribe River is the most important river in the state of Ceará (Northeastern, Brazil); its watershed measures approximately 76,000 km^2, which is almost 50% of the state's area. Campos et al. (2000) observed that until the 1950s, the flows in the Jaguaribe River were very irregular and ranged from 0 m^3s^{-1} in the dry season to 7000 m^3s^{-1} in the rainy season. This variability led to the construction of dams as a strategy to mitigate the effects of a lack of rain during 9 months of the year and to increase water availability to meet growing urban and agricultural demands (Marins et al., 2011; IBGE, 2014).

Dams change the downstream hydrologic regime and control the flow variability, making these flows independent of rain and making the physical and chemical quality of the estuarine water dependent on a balance between low stream flows and tidal forces, which can cause erosions of ancient sedimentary deposits (Marins et al., 2003; Godoy and Lacerda, 2013), due to decreasing of freshwater discharges. High salinity has been observed as far as 30 km inland from the river mouth (30 g kg^{-1}), whereas salinity in the middle estuary may be higher than in the adjacent coastal water (34.5–36 g kg^{-1}) (Dias et al., 2013a,b). Studies conducted between 2004 and 2006 indicated that during flood tides, water velocities reached 0.58 ms^{-1} with flow rates of 350 m^3s^{-1}, whereas during ebb tides, velocities did not exceed 0.4 ms^{-1} with flow rates of less than 200 m^3s^{-1}, highlighting the effect of the decrease in stream flow on the estuary system (Dias et al., 2009). In contrast with reservoirs built for energy generation with their steady outflows and smaller downstream impacts, reservoirs for water storage such as those in the Jaguaribe River basin affect freshwater flows in estuaries only in exceptionally rainy years (Dias et al., 2011). Lacerda et al. (2012) compared the effect of dams on the Jaguaribe River estuary during the dry season after a strong rainy year with water freezing in the mouths of rivers draining into the Arctic, when river flows are blocked and the residence time (RT) in marginal lakes are longer. Whereas during the period of higher river discharge, river flows are greater and reach the adjacent coastal zone, and RTs are shorter in estuaries. The trend of increasingly short intermittent rainy seasons has resulted in a greater influence of tidal waves in the Jaguaribe River estuary and in increased colonization by mangroves (Maia et al., 2006; Godoy and Lacerda, 2015), increased water salinity (Marins et al., 2003; Dias et al., 2013a,b), enlargement of beaches, development of islands in the middle estuary, and extensive erosion at the river mouth (Godoy and Lacerda, 2013). Due to changes in estuarine dynamics, the authors have observed an impacted sedimentary system comprising the full range of particle size (from mud to sand). Therefore, a better understanding of the suspended particulate matter on the estuary and on the variations in flows and currents associated with the dry and rainy seasons is essential to understanding the mixing process and to identifying the factors that cause mixing and advective transport of salt and other chemicals. The aim of this study was to physical characterization of an estuary located in the northeast of Brazil, in the semi-arid climate, showing how the material transport, net balance and the residence time may show a high variability between the rainy season and dry, linked to hydrodynamics imposed by successive dams along the river Jaguaribe.

2. Study area

The local climate is characterized by strong seasonality and two well-defined periods: a rainy season spanning from December to May, which can last until mid-July, with the highest rainfall (positive water balance) in April, and a dry season (drought, negative water balance) spanning from June to November, with the lowest rainfall in September. The seasonality of the rainfall is controlled by the Intertropical Convergence Zone (ITCZ), which, during the austral summer, causes northeasterly trade winds to bring air masses to and produce rain in northeastern Brazil between January and May. During the second half of the year, the ITCZ is weak and associated with southeasterly trade winds, which generate the dry season (Funceme, 2010).

The highest water levels in the drainage network of the Jaguaribe River basin (Fig. 1A) historically occurred from February to April, which coincides with the period of high rainfall in the region (Godoy and Lacerda, 2013). An analysis of historic water flows in the Jaguaribe basin (ANA, 2006) indicates that the flow rates decreased from 1978 to 1989. Maximum flow rates of 2250 m^3s^{-1} occurred in 1985. The flow rates were significantly lower between 1990 and 2006 with an average of 24.5 m^3s^{-1} and peaks as high as 251.3 m^3s^{-1} in 1996, with a decrease of up to 10-fold in the flows rates from the Jaguaribe River basin to the estuary system. The changes in flows in the Jaguaribe River during the 20-year period of 1987–2007 reflect the increase in the number of dams in the basin and the changes in rainfall due to global climate change (Moncunil, 2006). The construction of the dams began in the mid-twentieth century and ceased in the early nineties.

The dams located along the Jaguaribe River are for increasing water availability once there is a growing demand for water. In addition to increasing the stored liquid volume, the suspended sediments are retained by dams, affecting the morphodynamic balance in the estuarine region. During the rainy season, when the rainfall is within the historic averages, the effect of the dams is despised, and the volume of freshwater and suspended sediments arrive in the estuarine region, whereas during the dry season the estuarine system behaves as a sea arm (Dias et al., 2011).

Several studies conducted in the region, Dias et al. (2009, 2011, 2013a) have shown that there is a small spatial fluctuation between the interfaces higher/middle estuary and the middle/lower estuary, and that these interfaces are located in the cities of Aracati and Fortim. The interface Higher/Middle estuary (HE/ME) shows the fluvial and materials contributions of the drainage basin to the estuarine system, whereas the interface Middle/Lower estuary (ME/LE) shows the estuarine system contribution to the inner continental shelf, according to the classification of Dias et al. (2013a,b).

Dias (2007) reported that the total water flows in the estuary between 2005 and 2006 were dominated by flood flows in September 2005 and February 2006, when a dissipative effect of the tidal wave occurred in the flood plains of the river. In June 2006, this author observed a predominance of ebb flows. At that time, the total water volume varied depending on the type of tide, and the volume of fresh water in the system reached 95% of the total volume in February 2006. During the dry season, the total water volume was 44% more than that observed in February 2006, and this phenomenon is related to the spring tide observed in September. However, the fresh water fraction varied between 11.7% and 14.7% in September 2005 and June 2006, respectively. The flushing time spanned 2 h during the dry season and 12 h during the rainy season.

Dias et al. (2013) observed the formation of an estuarine plume during a period of intense rain in 2009. This plume extended 6 km along the shoreline and occupied the upper 2 m of the water column. Based on thermohaline indices, the authors characterized