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Small river basin and estuarine sediment fluxes: The magnitude necessary for coastal dispersion and siltation effects on a coral reef

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ABSTRACT

Increasing continental suspended sediment influx to coral reefs is an example of land-sea coupling that requires the identification of sources, magnitude of transport, and controlling processes. In Brazil, a small coastal basin (Macaé River) was identified as a source of suspended sediment to a coral reef on the coast of Cape Armação dos Búzios. Biannual suspended sediment loads were measured at the basin as were fluxes within the estuary and towards the coast during eight tidal cycles. Particle load and yield from this basin were typical of small coastal basins, showing high to moderate slopes and transitional land management. However, the magnitude of the river loads was lower than the sediment transport within the estuary, indicating that the estuary amplifies river fluxes and sustains the transference of suspended sediment alongshore to the coral reef. Nonetheless, the estuary displays both suspended particle retention and export capacity and, therefore, fluxes to the coast and the coral reef occur as episodic events.

1. Introduction

Increased continental runoff of sediment particles, mainly from river basins impacted by human activities such as deforestation and river channelization, which, in estuaries, are modulated by hydrodynamic processes, may affect distant coral reefs (Fabricius, 2005; Mclaughlin, Smith, Buddenmeier, Bartley, & Maxwell, 2003). Suspended sediment comprising organic and mineral particles delivered from drainage basins to oceans have been estimated worldwide. However, inventories should always be revisited to provide further information in this regard, including fluxes from small basins that, when grouped, can significantly contribute to global inventories (Milliman & Meade, 1983; Milliman & Syvitski, 1992). In addition, on a local scale, small rivers can also affect coastal ecosystems but little information is available on the magnitude of basin particle yield, estuarine control on fluvial transport to coastal waters, and possible coastal effects, including coastal reefs (Callaway, Grenfell, & Lønborg, 2014; Godiva, Evagelista, Kampel, Licino, & Munita, 2010; Milliman & Syvitski, 1992).

Godiva et al. (2010) identified particle sources to *Siderastrea stellata* Verril 1868 coral colonies at Cape Armação de Búzios, located on the southeastern Brazilian coast. Geochemical and aerogammaspectrometry surveys indicated that sedimentary material collected from the Macaé River basin was similar to the material obtained from the surface of the coral colonies, suggesting efficient coastal particle transport across 44 km from the river mouth and subsequent reef deposition. However, the transport from river basins to estuaries and subsequent transference from the coast to coral reef environments in several ecologically relevant regions in the southwest Atlantic are still poorly described, especially concerning small coastal basins (Godiva et al., 2010).

The aforementioned coastal river basin (Macaé River basin) is included in the Southeast Atlantic Basin group, Brazil (22°S - 29°S), comprising many small to medium basins (10^{-1} to 10^4 km^2) draining towards the Atlantic Ocean. Sediment transport from the Macaé River and its estuary illustrate the magnitude and other aspects of sediment transport in Southeast Atlantic Basins. An effective particle transport is expected, considering the high to moderate drainage basin slope. In addition, possible intensification of such fluxes is expected in view of the artificial elimination of river meanders and land use changes across the river basin (Marçal, Brierley, & Lima, 2017; Molisani et al., 2015). Thus, considering that more information on sediment fluxes from small rivers and related estuaries is required for

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international inventories, and that few studies identify the origin of particles deposited onto coral reefs, the current study investigated the magnitude and dynamics of particle fluxes from a small river basin and its estuarine modulation necessary to sustain coastal dispersion and proven siltation effects onto the coral reef.

2. Material and methods

2.1. Study area

The study site is located on the central-north coast of the state of Rio de Janeiro, Brazil. The coastal line comprises, four small river basins from north to south, draining into the sea and the Cape Armação dos Búzios, where coral colonies are located (Fig. 1). The rivers Macaé, Rio das Ostras, São João, and Una comprise drainage areas of 1765, 157, 2160, and 626 km^2, respectively.

The cape is composed of embayed beaches distributed along the coastline, influencing waves and, consequently, alongshore sediment transport. Essentially, the northern portion of the cape is affected by weak to medium north-northeast-east (N-NE-E) waves and currents generated by high pressure cells along the South Atlantic west coast, that, in turn, bring fine sediment from the drainage basins, mainly the Macaé River. Waves resulting from fair weather or storm conditions induce low to moderate hydrodynamic energy and, thus, a particle deposition environment in embayment beaches, such as Tartaruga Beach (Fig. 1), where coral colonies receive sediment mainly from the aforementioned Macaé River (Godiva et al., 2010). Cold fronts and moderate south (S) and southeast (SE) swells, in turn, influence the southern portion of the cape, experiencing no significant fluvial input (Bulhões & Fernandez, 2011).

The Macaé River is the main sediment particle contributor to coral reefs in Búzios (Godiva et al., 2010). This is a small drainage basin comprising an area of 1765 km^2 with a length of 136 km. Most of the Macaé River basin is located in the Macaé municipality (82%). The slope ranges from 288 to 1.0 m/km across the 74-km channel length from upstream to the middle river, and the relief gradient varies from 1570 to 100 m. In the last 62 km the slope ranges from 0.38 to 0.04 m/km. After river straightening for the last 26 km in the year 2000, the sinuosity index was reduced from 1.58 in 1968 (sinuous channel) to 1.01 (almost a straight channel), which may have resulted in increased material transport (Marçal et al., 2017). The geological setting of the study area comprises, mainly, the Região dos Lagos Complex and the São Fidélis Units, which differ in age (1.9 Ga vs. 900 Ma), rocks (gneiss vs. granite), and mineralogy (quartz, biotite, amphibolite, orthoclase, plagioclase vs. biotite, quartz, feldspar, granate, sillimanite, plagioclase) (Almeida & Silva, 2012). Over the last few decades, the drainage basin population has increased 7.5 times, as a result of support to the offshore petroleum and gas exploration throughout the Campos Basin alongside tourism, cattle, agriculture, increasing urbanization, and overall land use changes. The Macaé River estuary is a small estuary displaying tidal co-oscillation classified as semi-diurnal and under microtidal influence (0.1–1.3 m). The channel mouth width is about 130 m with a maximum depth of 3.8 m. Tidal flats, mangroves, and urban occupation prevail in this estuarine landscape.

2.2. Sampling procedures and data analyses

Instantaneous water discharge, suspended particle concentrations, and fluxes were measured monthly from February 2012 to February 2014 at the mouth of the Macaé River, characterized herein as the most downstream section of the catchment without any estuarine influence (salinity or tidal volume) (Fig. 1).

Instantaneous water discharge was calculated (Q_t, m^3/s) as:

$$Q_t = \bar{u} \cdot A_t \tag{1}$$

where ū (m/s) is the mean velocity of the cross-sectional area (A_t) at time *t*. Current velocities were measured using a mechanical flow meter (General Oceanics, model 2030) just below the surface (20 cm) and at 50 cm above the bottom of the water column, while river cross-sectional areas were calculated based on bathymetric measurements.

The suspended sediment transport, F_t (kg/s), was estimated as

$$F_t = Q_t \cdot C_t \tag{2}$$

where C_t (mg/L) is the suspended sediment concentration at time *t*. Suspended sediment particle concentrations were determined by filtration using Whatman 0.45 μm pore size membranes and gravimetry. During the most of the sampling period, the shallow river depth limited measurements, and only one water sample was taken from the cross section. When the river experienced increased water volume,

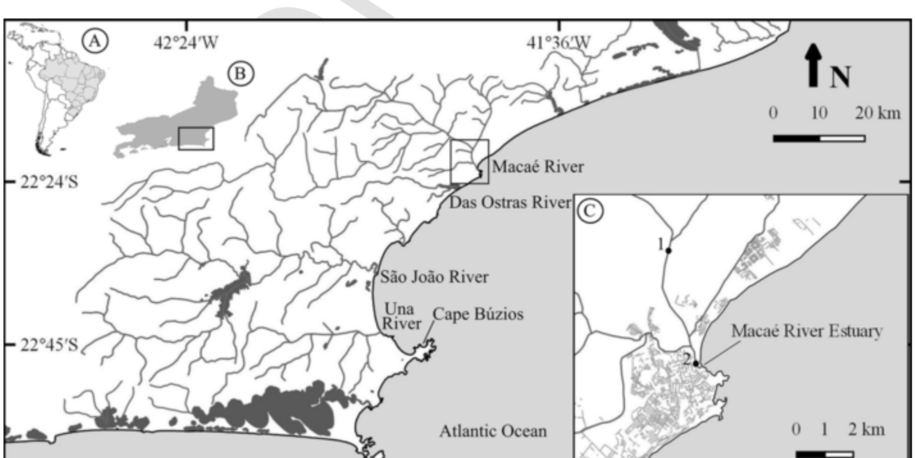

Fig. 1. Map of the study coastal zone, indicating the Macaé river estuary, drainage basins, Cape Búzios and Tartaruga beach. Sampling sites: #1 - biannual river basin flux and #2 - estuarine cross-section where the tidal cycles were measured.

two samples in the water column, as described above, were taken and averaged values represented the water column conditions for load calculation. Annual sediment particle loads were calculated averaging monthly loads, while sediment yield (t/km^2/yr) was estimated by dividing the annual load by the most downstream basin area without tidal influence measured at 1665 km^2. The basin area was manually vectorized based on the watershed hydrographic network, identified by previously digitalized and georeferenced topographic maps (scale 1:50,000). These procedures and the area calculation were done using the QGIS software (QGIS Development Team, 2015).

Semi-diurnal tidal cycle measurements in the estuarine channel were made during eight events, with samplings done at consecutive hour intervals covering the 13-h tidal cycle (Table 1). One transect extending perpendicularly across a cross-section in the estuary outlet (Fig. 1) was measured hourly by velocity profiles over both depth/width and area using an Acoustic Döppler Profiler (ADP - Sontek River Surveyor, 1.5 MHz), with bottom tracking capability, programed acquisition of velocity profiles at 5-s intervals and a vertical cell size of 0.25 m. Total cross-sectional discharge (m^3/s) was obtained by integrating the U-component velocity normal to the cross-sectional area applying the Sontek proprietary software using triangular closure of the margins and default approximations of near-surface and near-bottom non-measured layers.

Estuarine sediment particle inflow and outflow in the cross section (Q_s), expressed as kg/s, were estimated as:

$$\mathrm{T_{MPS}} = \iint_A C_t \vec{v} \cdot \vec{n} dA = \iint_A C_t \cdot u dA = C_t u A \quad (3)$$

where $\mathrm{T_{MPS}}$ is the suspended sediment discharge (kg), u is the integrated average velocity in the water column (m/s), C_t is the average concentration of the suspended sediment from two samples (middle and marginal, in order to integrate both the bank erosion process and bottom particle resuspension) across the cross section (mg/L), and A is the average area perpendicular to the longitudinal direction of the flux (m^2), $\vec{v} = \vec{v}$ (x, Z, t) is the velocity vector and $\vec{n}$ is the vector normal to the flow area A (Dias, Castro, Lacerda, Miranda, & Marins, 2016). By convention, positive (+) discharges were applied relative to the estuarine ebb-directed tide, representing export, and negative (−) values were applied for flood tide or retention. The sampling events listed in Table 1 were measured simultaneously in the river and the estuary. The river and estuarine sediment mass-balance budget considered only suspended sediment particles, and not gravel and sand bed loads, as mostly terrestrial fine-grained sediments (<63 μm) affect siltation rates in coral reefs, while heavier particles are usually immobilized within the bottom layers (Bartley et al., 2014; Risk, 2014).

The D'Agostino and Pearson omnibus normality test was applied to verify the normality of suspended sediment, salinity and water flow data (D'Agostino & Pearson, 1973). A one-way analysis of variance (ANOVA) followed by the Dunnett's test (parametric) (Dunnett, 1955) or Kruskal-Wallis test followed by Dunn's test (non-parametric) (Kruskal, 1952) were used to compare suspended sediment at different water depths, tides, and seasons. A significance level (p-value) of 0.05 was applied for all analyses ($p < 0.05$). The software GraphPad Prism 5.0 was used for all analyses (GraphPad Software Inc., San Diego, CA, EUA).

Table 1
Sampling events and tidal conditions.

Sampling date	Tide	Tidal range (m)
12 March 2011	Neap	0.8
13 April 2012	Neap	0.5
20 April 2012	Spring	1.2
13 August 2012	Neap	0.8
20 August 2012	Spring	1.4
13 March 2013	Spring	1.2
26 September 2013	Neap	0.5
02 October 2013	Spring	1.1

3. Results

Discharges from 9.0 to 213 m^3/s and concentrations from 10 to 175 mg/L were obtained during the two-year measurement of monthly water discharges and suspended sediment from the Macaé River basin to the estuary, with higher discharges and concentrations occurring in the rainy season (Fig. 2 and Table 2). Biannually, particulate loads ranged from 0.092 kg/s (July 2012) to the highest peak of 15.4 kg/s (March 2013). On average, higher values occurred in the rainy season (2.43 kg/s) compared to the dry months (0.35 kg/s). Peaks of transported suspended sediment followed the water discharge peaks, as exemplified by the highest particulate load determined in March 2013 (15.4 kg/s), associated with the highest water discharge (213 m^3/s) (Fig. 2) and a strong significant correlation between these variables ($r = 0.77$, $p < 0.001$) (Fig. 3). However, sediment fluxes and yield were not significantly correlated to rainfall during the sampling period (Fig. 3). On an annual basis, the measurements at the river basin outlet without any tidal influence indicate a catchment load of 39,244 t/yr. On the other hand, the mass of sediments annually leaving the drainage basin per unit of catchment areas comprised, on average (standard deviation), 38 ± 58 t/km^2/yr. Seasonally, particulate yield was higher during the rainy season (45 ± 84 t/km^2/yr) compared to the dry season (6.5 ± 3.0 t/km^2/yr) and, thus, was significantly correlated to the water discharge ($r = 0.78$, $p < 0.001$) (Fig. 3). Interannual yield variability also was reported between 2012 and 2013 (16 ± 25 t/km^2/yr) and 2013–2014 (31 ± 77 t/km^2/yr).

Within the estuary, water discharge and sediment particle concentrations displayed pronounced seasonal and spring-neap tidal variations, modulating transport to the coast. The water discharge throughout the estuary measured at different 13-h tidal cycles resulted in values ranging from 1.0 to 127 m^3/s (Fig. 4). Average water flows within the estuary compared to the river inputs indicate a net gain for most of the measured tidal cycles. The only exception was observed in April 2012 during the neap tide, when the fluvial input (27 m^3/s) and

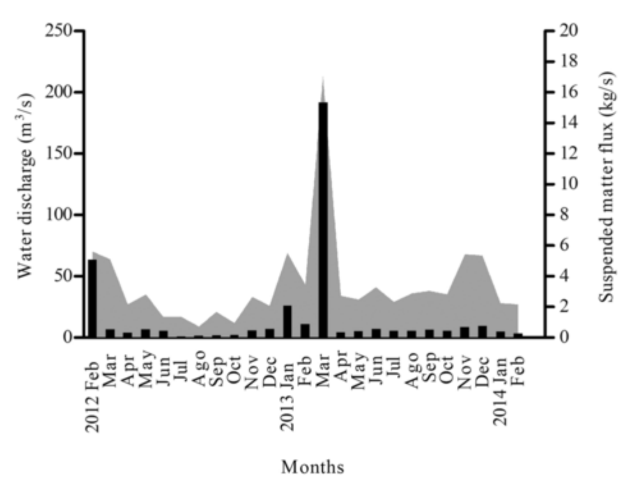

Fig. 2. Biannual suspended sediment flux (bars in kg/s) and water discharge (grey in m^3/s) from the Macaé River basin to the estuary.

Table 2
Summary of river and estuarine conditions sampled simultaneously during different tides and seasons (SMC: suspended matter concentration, Min: minimum, Max.: maximum).

	Neap (n = 4)	Spring (n = 4)	Rain (n = 4)	Dry (n = 4)
Min. river flow (m^3/s)	9.0	21	27	9.0
Max. river flow (m^3/s)	70	68	213	68
Min. river SMC (mg/L)	17	10	17	10
Max. river SMC (mg/L)	45	50	175	40
Max. tidal range (m)	0.80	1.2	1.2	1.1
Max. ebb velocity (m/s)	0.47	0.64	0.63	0.58
Max. flood velocity (m/s)	0.38	0.48	0.48	0.44
Max. ebb flow (m^3/s)	110	127	110	127
Max. flood flow (m^3/s)	66	104	104	90
Min. salinity	0.03	0.3	0.1	0.3
Max. salinity	35	36	33	36
Min. SMC (mg/L)	5.5	5.0	5.0	8.0
Max. SMC (mg/L)	90	109	72	103

net export from the estuary (45 m^3/s) indicated net loss of water to the coast. This condition was related to the highest precipitation (7-day rainfall accumulation of 102 mm) measured throughout the basin. This contributed to the river flow increase resulting in the collapse of the tidal barrier (neap tide) and the efficient of water seaward transport. Although a net water gain was observed within the estuary for most of the sampling period, lower water retention occurred during the rainy season (April 2011, April 2012, August 2012). During the dry season, precipitation decreased, probably contributing to the higher net gains of water within the estuary. During this period, the river discharge could not break down the tidal barrier, and the upriver baroclinic pressure contributed to the depositional rates of fluvial material within the estuary.

Suspended matter concentrations in the estuary ranged from 5.0 to 109 mg/L, above the range reported for the river sediment particle concentrations (Table 2). Similarly, higher water discharge magnitudes were measured during the ebb and flood tides within the estuary compared to those from the river flow (Table 2). Within the estuary, depth, suspended matter, and temporal and tidal variations were detected by comparing the surface and bottom, rainy and dry seasons, or neap/spring and flood/ebb tides. Averaging and computing the standard deviation of all sampling events, the statistical analysis ($p < 0.05$) indicated higher concentration of sediment particles at the bottom of the water column (38.6 ± 17 mg/L) compared to the surface (20.5 ± 7.3 mg/L). Statistically higher values were also observed during the neap tide (34 ± 25 mg/L) compared to the spring tide (27 ± 17 mg/L). As demonstrated by Whitehouse and Mitchener (1998), increased suspended matter by a factor of 3 was reported during neap tides, but only 10% during spring tides were related to wave stirring. Particle concentrations were unexpectedly higher during the dry season (34 ± 24 mg/L) compared to the rainy season (25 ± 14 mg/L), reflecting the influence of an episodic rain event during the dry season sampling.

Inflow and outflow loads within the estuary were calculated using the suspended matter concentrations and the flood/ebb water discharges during the sampling period (Fig. 5). On average, higher particulate fluxes were reported in spring (1.93 kg/s) compared to neap tides (1.24 kg/s), as well as higher in rainy (1.61 kg/s) compared to dry seasons (1.56 kg/s) (Fig. 5). Flood tides transported more particles (2.15 and 1.45 kg/s) than ebb tides (1.80 and 1.20 kg/s) during spring and neap periods, respectively. Although particulate sediment delivery to the coral colonies suggests efficient transportation from the drainage basin, the estuary processes mislead regarding this condition. As described for the water budget, the estuary retained more sediment particles than it exported to the coast during the sampling period. In two measurements coincident with high rainfall (April 2012 Neap and August 2012 Spring tides), the estuary exported sediment particles seaward, both from the drainage basin and those accu-

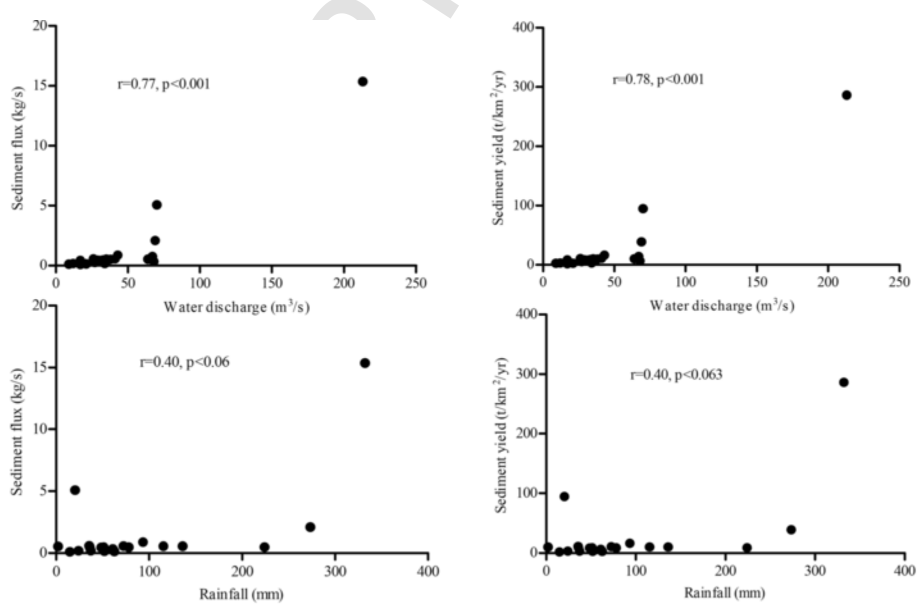

Fig. 3. Correlations between sediment flux or sediment yield, and rainfall or water discharge for the Macaé River basin during the sampling period.

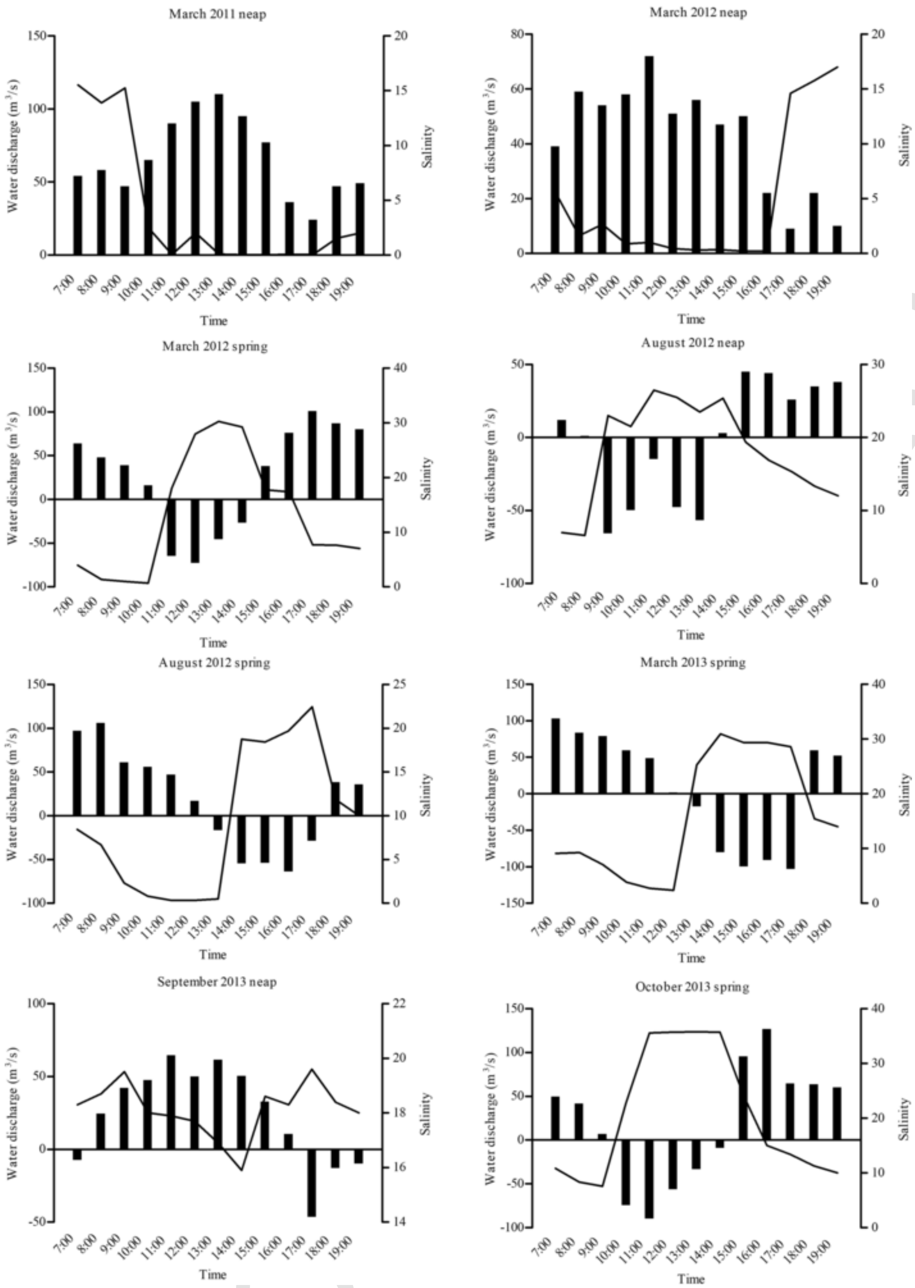

Fig. 4. Water discharge (bars) and salinity (lines) during measured tidal cycles (h) at the Macaé River estuary.

mulated within the estuary, with net losses of 1.47 kg/s and 0.56 kg/s to the coast. For other tidal cycles, budgets resulted in sediment particle net gain within the estuary (Fig. 6). It is important to mention that higher suspended matter concentrations, mainly in bottom waters, were observed during a sampling event under the influence of stormy coastal conditions (September 2013), when an estuarine net particle gain (0.28 kg/s) was found.

When comparing the water discharge and sediment particulate transport magnitudes between the drainage basin and the estuary, in general, the results indicate that more water and particles were transported within the estuary during flood and ebb tides compared to river discharges (Fig. 6). Water flow and suspended matter concentration magnitudes during flood and ebb tides were always higher in the estuary compared to the basin discharge (Table 2). Sediment particle export occurred not only during high episodic river discharges, but also during intermediate discharges (April 2012 and August 2012), during rainfall periods or single rain events (August 2013), in both neap and spring tides, but, in general, associated to the highest water velocities (0.37 and 0.34 m/s, respectively).

4. Discussion

According to Milliman and Syvitski (1992), small mountainous rivers are more likely to discharge larger percentages of their sediment loads directly into the coast compared to larger rivers, mainly episodically. Like many Southeast Atlantic Basins, the small Macaé River basin, with a high to moderate slope until the coastal plain, suggests efficient sediment transport to the ocean, mainly due to de-

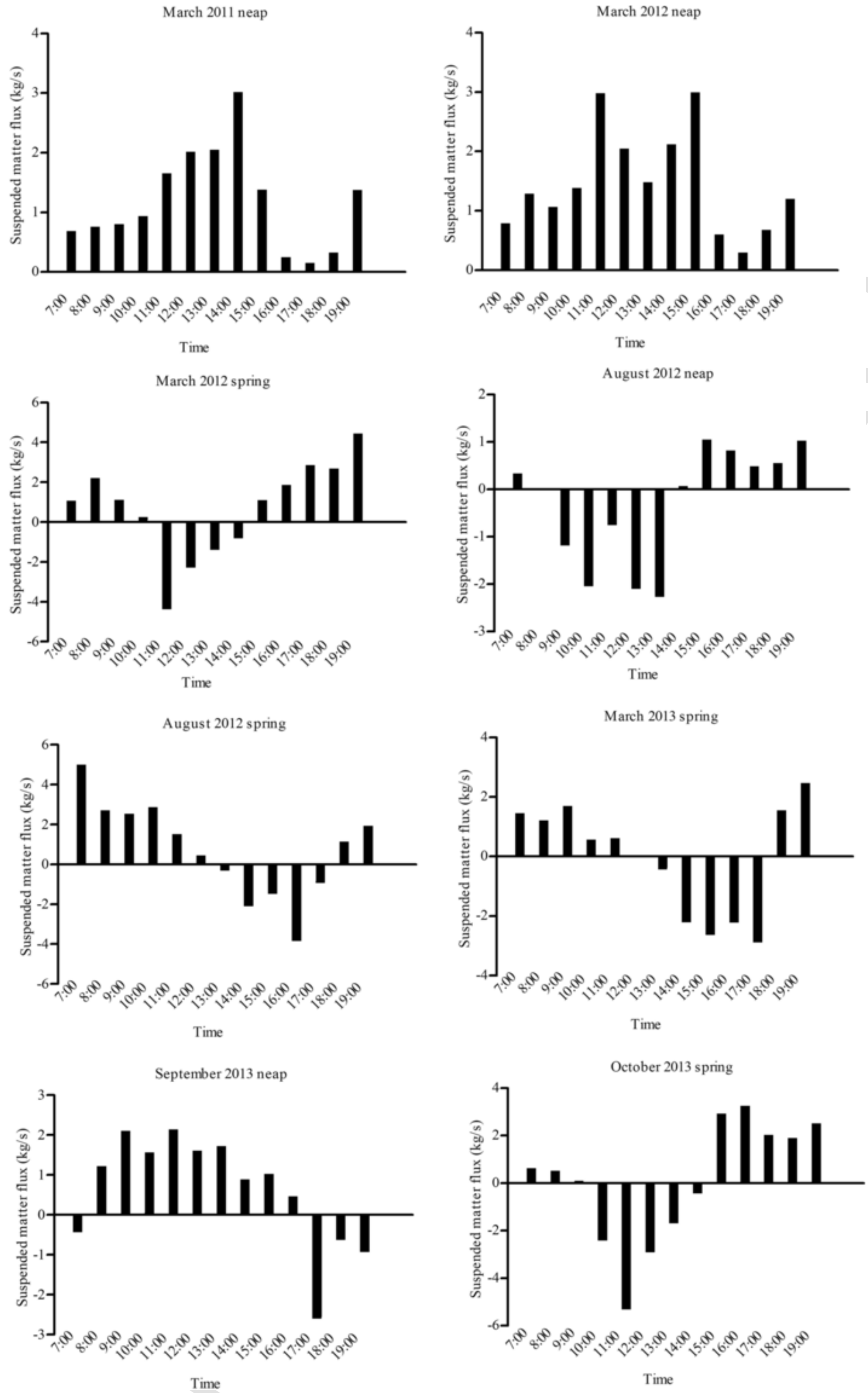

Fig. 5. Suspended matter fluxes (kg/s) during measured tidal cycles at the Macaé River estuary.

forestation and the straightening of the lower river. However, when comparing the Macaé River basin to other small coastal basins (areas on the order of 0.001×10^6 km^2), with low or no degree of human impact, the particulate load (0.04×10^6 t/yr) and average yield (38 t/km^2/yr) remained in the same range as reported in the literature (load: $0.01–10 \times 10^6$ t/yr; yield: 10–1000 t/km^2/yr), suggesting the current results are typical of small coastal basins loads (Milliman & Syvitski, 1992; Vanmaercke, Poesen, Broeckx, & Nyssen, 2014; Warrick, Madej, Goñi, & Wheatcroft, 2013). Seasonally, the sediment fluxes and yields determined in the current study were similar to values from other studies that support suspended-sediment transport generally related to river discharges and event-based rainfall, although these relations are not consistent across all watersheds (Warrick, Melack, & Goodridge, 2015). For small coastal basins in California

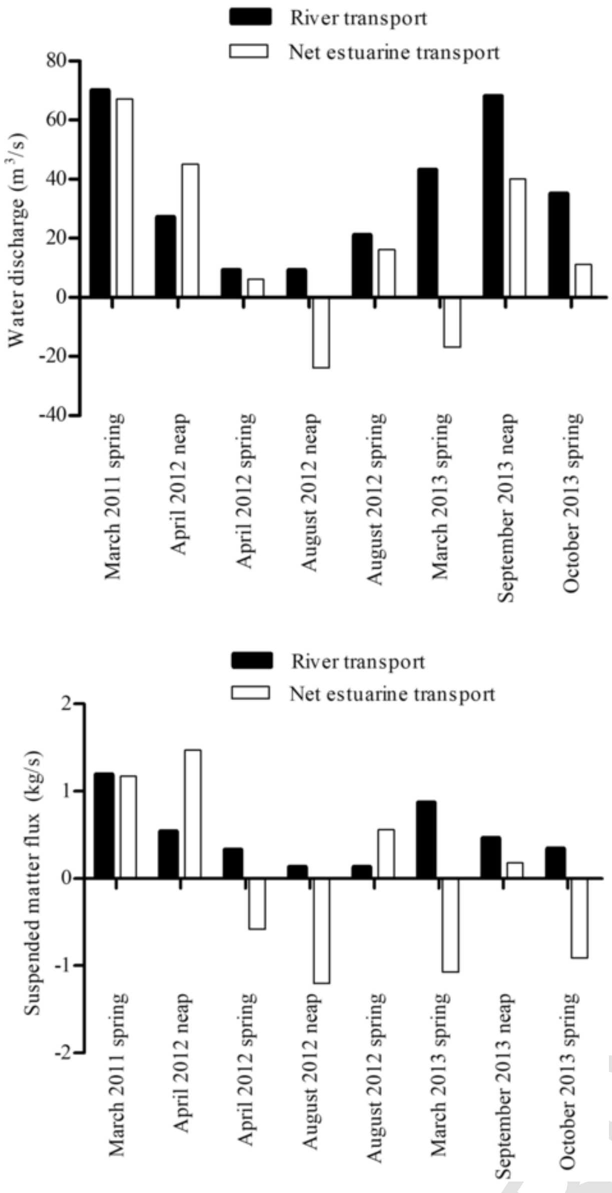

Fig. 6. Mass-balance budget of water discharge and fluxes of suspended matter through the river basin and estuary during different sampling events.

(U.S.), the annual sediment yield varied 400-fold, while, in the current study, the annual yield varied 167-fold during the sampling period, demonstrating seasonal variability in sediment transport in small mountainous coastal basins.

The interannual changes in sediment flux and yield reported herein for the Macaé River basin also confirm findings from other small coastal basins that indicate marked changes in sediment yields and discharges between years (Milliman & Farnsworth, 2011; Warrick et al., 2013). This interannual variability is related to runoff, vegetation cover, land use, and climate changes. While large uncertainties concerning yield and flux measurements are not usually considered, reinforcing the need for data acquisition, mainly in less studied small coastal basins critical for sediment delivery and coastal effects (Milliman & Farnsworth, 2011; Milliman & Syvitski, 1992; Vanmaercke et al., 2014). Thus, the Macaé River basin transitional landscape from a mountainous to coastal plain landscape suggests that both basin size/topography, as well as other aspects, such as land cover, may control sediment delivery. The Macaé River land cover comprises 41% forest (both pristine and logged fragments), 34% livestock production, 19% agriculture, 3% urban, and 3% other (Marçal et al., 2017).

Suspended matter delivery from the drainage basin is typical of small coastal catchments supplying the coast. However, sediment particle concentrations, transport, and water discharges within the estuary modulate sediment transference to the coast. For example, the net water discharge calculated from each 13-h cross section measurements suggests that the estuary is asymmetric, with an ebb-tide dominance, typical of many Brazilian estuaries (Dias et al., 2016; Miranda, Castro, & Kjerfve, 2002; Siegle, Schettini, Klein, & Toledo, 2009). Higher amounts of water and sediment particles were transported by tides in the estuary than by the river discharge, as described by Siegle et al. (2009) for the small Caravelas River (Brazil). Generally, ebb-tide dominated estuaries can act as sediment particle exporters to the coast (Dyer, 1995; French, 1997), although the Caravelas River estuary acts as a sediment particle importer during most of the time, similar to conditions also reported for the Macaé River estuary, which has ebb-tide dominance over tidal cycles, but resulting in sediment particle net accumulation. Accounting for all measurements, the net sediment fluxes seem to be neutral, but with episodic exports to the coast, noted during two sampling events. Another example of estuarine river flux modulation was the net particle retention within the estuary during a sea storm event. According to Talke and Stacey (2003), ocean swell adds near-bed energy to estuarine environments, and swell propagation into the estuary should be considered. The oceanographic conditions in the adjacent coastal ocean measured during the winter season in the study area (September 2013) indicated the predominance of southern waves, ranging between 2 and 3 m in height and with 10–12 s periods, in contrast to the summer season, with the prevalence of east waves 1–2 m high and 6–8 s periods (Pianca, Mazzin, & Siegle, 2010). Thus, sediment retention within the estuary is expected during higher height wave propagation.

In addition to the sediment influx due to river and estuary discharges, occurring episodically in both summer and winter periods, upwelling events during spring/summer and resuspension more intensely induced by cold fronts during fall/winter control the sediment transport alongshore until reaching the coral reef. Once transported from the estuary to the coast, satellite imagines suggest that resuspension plays an important role in plume formation, while predominantly NE winds induce transport to Cape Búzios (Godiva et al., 2010). Turbid waters during fall/winter indicate the influence of cold fronts on sediment particle resuspension and transport alongshore until Cape Búzios (Coelho-Souza, Pereira, Lopez, Guimaraes, & Coutinho, 2017). Atmospheric frontal systems, specifically cold fronts, occur almost weekly on the southeastern coast of Brazil, modifying wind velocity and direction and increasing wave intensity and height from southwest-south-southeast (SW-S-SE) (Pianca et al., 2010). The modified wind direction over the southeastern coast also causes inner and middle continental shelf surface waters to advect towards the coastline, due to Eckman transport and, thus, onshore currents may transport particles towards the coast, potentially reaching the inner-shelf and facilitating settlement (Carbonel, 2003). However, at the same time that sea storms induce sediment particle resuspension alongshore, they also prevent sediment transfer from the Macaé River estuary to the coast, as shown for measurements done in the dry season (September 2013), when the estuary displayed a net gain of particles of 0.28 kg/s. Furthermore, the shoreline of the study area is inserted in the Campos Basin (20–24° S and 39–42° W), which displays as major oceanographic features low river input and both a coastal and shelf upwelling of cold South Atlantic Central Waters. Upwelling is enhanced during spring and summer as a result of interactions between prevailing NE winds, the instability of the Brazil Current flow, and abrupt changes in the orientation of the continental margin (Campos, Velhote, & Silveira, 2000; Castelão & Barth, 2006; Valentin, Andre, & Jacob, 1987). This leads to the entrance of cold bottom water, contributing to sediment resuspension and transport alongshore (Godiva et al., 2010). Furthermore, the presence of meanders and cyclonic and anticyclonic eddies in the middle portion continental shelf can create upward and downward movements, as well as lateral transport of water masses, which also control the amount of fine particle deposition/resuspension (Mahiques et al., 2005).

Such water-mass transport processes act on the inner continental shelf (10–15 m isobath), that extends across the area, from the Macaé River basin until Cape Búzios, where mud banks are predominant, with particle size ranging from 4.5 to 7.5 phi (Muehe, Fernandez, Bulhões, & Azevedo, 2011; Saavedra & Muehe, 1993, p. 29). The impact of muddy fluvial particles from small catchments on coral reefs has been studied (Golbuu, Fabricius, Victor, & Richmond, 2008). In addition, the semi-beach arc formed alongshore from north until Cape Búzios indicated distinct grain sizes ranging from coarse sand (2 mm), in the north section, to fine sand and silt particles (<0.12 mm) comprising around 60% of the sediment in some Cape Búzios beaches (Andrade, Veloso, & Ribeiro, 2010). Thus, the peninsular morphology of Cape Búzios acts as a barrier for northeastern long-shore material drift induced by upwelling and resuspension processes, leading to the deposition of fine sand and silt particles at Tartaruga Beach and on the coral reefs. Furthermore, the cape also acts as a shadow zone, protecting this beach from southeast swells, as described by the reduction of wave propagation from 2.7 to 3.4 m alongshore to 0.1 m at Tartaruga Beach, preventing extensive resuspension of deposited fine particles onto the coral reefs (Bulhões & Fernandez, 2011; Muehe et al., 2011). The literature indicates that fine terrestrial particles can be transported from river mouths for large distances by flood plumes (tens of kilometers), and may be deposited in relatively shallow water (<20 m depth) and become easily resuspended by waves (Margvelashvili et al., 2018; Orpin, Ridd, & Stewart, 1999), which corroborates the particle transport observed across 43 km from the Macaé River mouth to the coral reef at Cape Búzios.

However, it is important to understand specific estuarine processes in order to explain why other basins across the studied coastal zone do not influence particle delivery to the coral reef at Cape Búzios (see Fig. 1). Throughout this coastline stretch, it is expected that suspended sediment sources originated from four small river basins and fine particles will be transported by the Brazil Current's southward flow (Peterson & Stramma, 1991). However, the approach applied by Godiva et al. (2010) allows for the distinction of three hydrographic basins (the Macaé River basin, São João River basin, and Una River basin) as potential sediment sources. The set of trace parameters identified the Macaé River as the most probable contributor to the coral reef site (Godiva et al., 2010), from which an average water discharge of 44 m^3/s and sediment flux from the estuary (0.56–1.47 kg/s) displayed the magnitude necessary to sustain coastal dispersion alongshore and siltation onto the coral reef. The particulate flux from the Una River is expected to be lower, based on its drainage area of 480 km^2 and water discharge of <4.0 m^3/s. On the other hand, the São João River basin, with an area of 2160 km^2 and nearer to the coral reef than the Macaé River, is expected to show a higher suspended matter load contribution. However, the basin was dammed to flood a 43 km^2-reservoir (as shown in Fig. 1), reducing particulate delivery from more than 50% of the basin area, which is now partially retained behind the dam, which reduces the water discharge to the coast to an estimated 17 m^3/s (Godiva et al., 2010).

Milliman and Syvitski (1992) questioned regarding how much sediment is carried by small mountainous coastal rivers and how much escapes to the coast, but had no answer to both questions, although loads are more likely to escape during high rainfall-driven river flow events. As pointed out by the results reported herein, the ebb-dominated estuary modulated the river flow, and retained sediment particles within the estuary most of the time. However, episodically, the estuary amplified the river flow and exported sediment to the coast during rainfall-driven events, including during the dry season. However, a gap is noted regarding studies concerning the documentation of the effects of small catchment-derived sediment particles on coral reefs, which are typically disconnected from studies that identify particle source, measured loads, and sediment transport and fate (Bainbridge et al., 2018; Mclaughlin et al., 2003), and, in fact, very few studies characterize suspended particle loads and seasonal fluxes from small rivers, suppling alongshore transport with verified coral reef siltation effects (Margvelashvili et al., 2018; van Maren, Liew, & Jahid Hasan, 2014). Thus, the current study indicated the magnitude of suspended sediment particle load from a small river basin (0.54 and 0.13 kg/s), which was amplified by the estuary and exported to the coast (1.47 and 0.56 kg/s), sustaining alongshore transport with observable coral reef siltation effects (Godiva et al., 2010).

However, the influence of river/estuarine fluxes on coral reefs can be difficult to assess. In northeast Brazil, the Abrolhos Bank's coral reef, the largest and most important coral area in the South Atlantic, undergoes siltation by increased sediment particle loads induced by land-based agriculture and industry sources (Dutra, Kikuchi, & Leão, 2006). Although it is expected that suspended sediment originates from adjacent coastal lands and their draining rivers, 70 km-seaward from the reef, studies have identified small interactions between these coastal rivers and corals, with the possible influence of more distant rivers with larger basins (Jequitinhonha and Doce river basins 215 km-north and 220 km-south and comprising basin areas of 70,000 and 83,000 km^2, respectively) (Marone & Camargo, 1996).

5. Conclusion

This study indicates that the small Macaé River basin displays marked seasonal and episodic water fluxes, as well as sediment particle fluxes and yield ranging from 9.0 to 213 m^3/s; 0.09–15 kg/s; and 1.7–286 $ton/km^2/yr$, respectively, with a marked sediment load control by water discharge. However, suspended sediment particle loads were mostly retained within the ebb-tide dominated estuary, including sediment loads induced by sea storm events. Nonetheless, during episodic rainfall-driven events and specific tides, the estuary amplified river loads from 0.54 to 1.47 kg/s and 0.13–0.56 kg/s and exported sediment seaward. Such a load magnitude from a small coastal river basin maintains alongshore transportation controlled by upwelling, resuspension by cold fronts, and predominant NE winds, leading to siltation effects onto coral reefs.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijsrc.2019.04.002.

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