HYDROLOGICAL PROCESSES
Hydrol. Process. **25**, 2188–2201 (2011)

(wileyonlinelibrary.com) DOI: 10.1002/hyp.7972

Comparative analysis of rating curve and ADP estimates of instantaneous water discharge through estuaries in two contrasting Brazilian rivers

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Abstract:

This work quantifies, using ADP and rating curve techniques, the instantaneous outflows at estuarine interfaces: higher to middle estuary and middle to lower estuary, in two medium-sized watersheds (72 000 and 66 000 km^2 of area, respectively), the Jaguaribe and Contas Rivers located in the northeastern (semi-arid) and eastern (tropical humid) Brazilian coasts, respectively. Results from ADP showed that the net water balances show the Contas River as a net water exporter, whereas the Jaguaribe River Estuary is a net water importer. At the Jaguaribe Estuary, water retention during flood tide contributes to 58% of the total volume transferred during the ebb tide from the middle to lower estuary. However, 42% of the total water volume (452 m^3 s^{-1}) that entered during flood tide is retained in the middle estuary. In the Contas River, 90% of the total water is retained during the flood tide contributing to the volume transported in the ebb tide from the middle to the lower estuary. Outflows obtained with the rating curve method for the Contas and Jaguaribe Rivers were uniform through time due to river flow normalization by dams in both basins. Estimated outflows with this method are about 65% (Contas) and 95% (Jaguaribe) lower compared to outflows obtained with ADP. This suggests that the outflows obtained with the rating curve method underestimate the net water balance in both systems, particularly in the Jaguaribe River under a semi-arid climate. This underestimation is somewhat decreased due to wetter conditions in the Contas River basin.

KEY WORDS tropical river; river discharge; ADP; rating curve; estuary

Received 30 April 2010; Accepted 2 December 2010

INTRODUCTION

Human interventions in watersheds for the purposes of improving navigation, increasing water withdrawal for agriculture, industrial and urban uses and flood control often result in modifications of the natural flow regimes and salinity distribution in estuaries. These changes in land use also result in conflicts between water users that increase the need of infrastructure (e.g. roads, housing) and create migration problems (Hansen and Rattray, 1965; Li *et al*., 1998; Crossland *et al*., 2005). Similarly, the natural dynamics of ecosystems and their biodiversity, as well as water quality are also greatly affected by human interventions in watersheds. To ensure a minimum amount of freshwater flowing into the nearby coastal area in order to maintain the health of estuarine ecosystems, it is necessary that water resource management protects the environmental flows and maintains an acceptable salinity gradient. In this context, environmental flows are defined as the amount of water that is left in a fluvial system or released into the estuary, which is able to keep optimum environmental conditions of the estuarine ecosystems (Li and O'Donnell, 1997, 2005; Lacerda and Marins, 2002; King *et al*., 2003). Therefore, model scenarios of watershed management and sustainable utilization will extensively depend on reliable and accurate measurements of water and sediment flows from rivers to the coastal zone (Crossland *et al*., 2005).

Discharge measurement is an issue of major importance for the evaluation of water balance at the catchment scale, for the design of water control and conveyance structures and for rainfall–runoff and flood routing model calibration and validation. Although several direct measurement approaches exist, only indirect approaches tend to be used operationally, at least in medium and large rivers, in most studies around the world. Usually, discharge estimates are based on a one-to-one stage–discharge relationship or steady-flow rating curve, which is derived on the basis of a number of simultaneous stage and discharge measurements. A measure of stage is then directly converted into discharge by means of the developed rating curve. Such an approach can be considered adequate for all rivers under steady-flow conditions, when flood waves show a marked kinematic behaviour. In all other cases the variable energy slope, associated with the dynamic inertia and pressure forces

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relevant to the unsteady flow discharge, leads to the formation of a hysteretic rating curve also known as the loop-rating curve (Mulder and Syvitski, 1996; Hay, 1998; Miranda *et al.*, 2002; Souza and Knoppers, 2003; Araújo and Piedra, 2009).

However, the relationship between the stage and discharge values of the rating curve for extreme events are usually extrapolated by using different mathematical methods and are not directly measured. Our practice shows that by using the acoustic Doppler profiler (ADP) we can record the actual relation between the water stage and the flow velocity at the occurrence of tidal waves very successfully. ADPs have been used for measuring water velocity for about 25 years, primarily deployed at fixed locations to study ocean and estuarine currents. In the late 1980s, ADPs began to be used to make velocity measurements from a moving vessel. The early instruments were narrowband ADPs that required relatively deep water (more than 3–4 m), which limited their use to deep rivers and estuaries. In 1992, a more advanced acoustic Doppler instrument, known as a broadband acoustic Doppler current profiler, was developed that could be used to measure velocities in shallow waters (as shallow as 1·0 m) with a high degree of vertical resolution (0·10 m) (Gordon, 1989; Morlock, 1996; York and Oberg, 2002).

The northeastern Brazilian rivers have a small network of water level monitoring. Also, most drainage basins have in their normal course numerous dams and reservoirs intended to store water to supply the human activities located in its surroundings. Climate conditions observed in northeastern Brazil, typically show long dry periods that significantly reduce the fluvial discharges in the adjacent coastal zone. These characteristics of further accuracy of outflow are estimated using the rating curve. This implies that the steady-flow rating curve is no longer sufficient and adequate to describe the real stage–discharge relationship.

Some authors showed that the use of data from the limnimetric ruler presuppose the absence of downstream data and cannot be applied to estuarine environments, due to tidal influences. However, many studies have used data from the estimates of outflows obtained from the rating curve to estimate the outflow and material discharges from the drainage basins to estuaries, assuming that the outflows measured in gauged stations are the same as observed in the estuary. These studies, however, neglect the uncertainties presented by the method and the tidal action, which strongly affects the estuarine discharges and the water residence time (Al-Kharabsheh, 1999; Chellappa and Costa, 2003; Güntner *et al.*, 2004; Medeiros *et al.*, 2007; Molisani *et al.*, 2007). Grison and Kobiyama (2005) showed that the limnimetric ruler method presents higher uncertainty, showing large deviations in the resulting outflows for medium and small volumes of water. However, for high water volumes the method presented very low uncertainty. The same was observed by Petersen-Overlier *et al.* (2009) for numerous rivers worldwide. Few studies, however, compared river basins with similar sizes under different climate and/or land use, using the two different discharge estimation techniques.

The aim of this work was to compare the results obtained by measurements of outflows using the conventional methods (rating curve) and the acoustic profile (ADP) to define the most appropriate to the characteristics at the different river interfaces: higher to middle estuary and middle to lower estuary, in two medium-sized watersheds, the Jaguaribe and Contas Rivers (72 000 and 66 000 km^2, respectively) located in the northeastern (semi-arid) and eastern (tropical humid) Brazilian coast, respectively. The comparison of outflows obtained with the use of ADP and rating curve in the systems may contribute to the understanding of the limitations of these techniques to obtain fluvial and estuarine discharges and consequently contribute to understanding the transport of materials from the drainage basins to the adjacent coastal zone.

Both river basins are presently witnessing strong and fast land-use changes, including river damming for energy generation and water withdrawal increasing irrigated agriculture and urbanization. Therefore, it is urgent to consistently determine their environmental flows in order to keep the integrity of their coastal ecosystems and provide support for their sustainable management.

DESCRIPTION OF THE STUDIED AREAS

The Jaguaribe basin covers about 72 000 km^2, representing almost half of the Ceará State's territory, in northeast Brazil. The Jaguaribe River Estuary is located between 4°23′S and 4°37′S and 37°44′W and 37°44′W (Figure 1) under semi-arid climate and with an average annual rainfall increasing from 400 mm inland to 1000 mm at the coast. Historical rainfall data show higher precipitation (200–400 mm) between March and April. During the peak of the dry period, between August and November, precipitation can be frequently zero (Funceme, 2004). Sandy coastal plains with large aeolian dune fields, driven by the nearly year-round constant winds with average wind speed of 6·3–7·9 m s^{-1} from the SE, characterize the coastline (Jimenez *et al.*, 1999).

Regional climate, including rainfall seasonal variations, is regulated by the inter-tropical convergence zone (ITCZ), where air masses from both hemispheres converge. During the austral winter and spring, the ITCZ weakens and moves northward, resulting in very dry months with strong eastern winds. The magnitude of the ITCZ displacement is affected by El Niño teleconnections (Funceme, 2004) and can modify the migration of sand dunes, which dominate the Ceará coastline (Maia *et al.*, 2005).

Tidal regime is predominantly semi-diurnal, with maximum amplitude reaching 3·0 m. The low freshwater supply results in the intrusion of saline waters to a few kilometres inland (Marins *et al.*, 2003) forming brackish tidal flood plains which are covered by about 11 640 ha

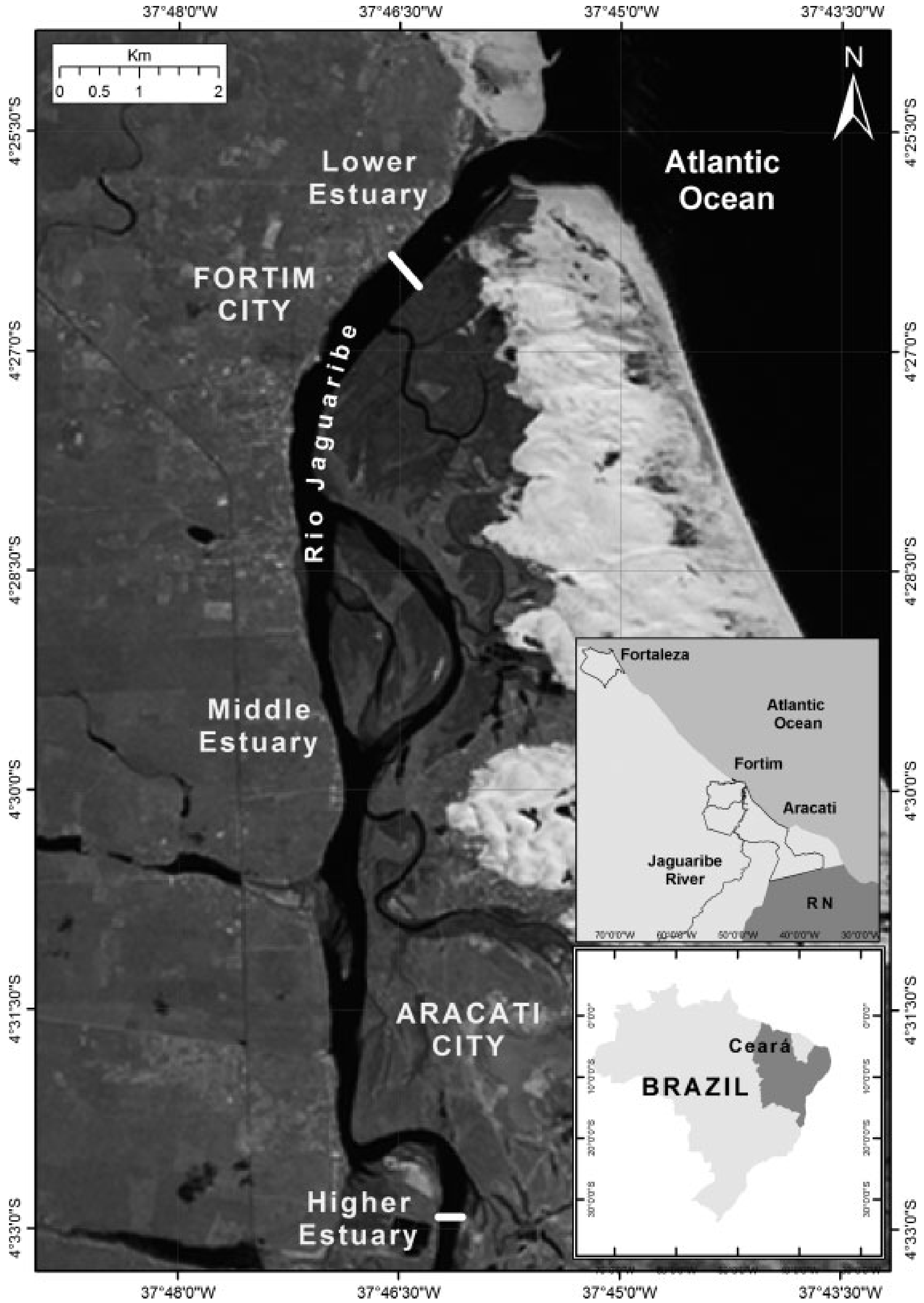

Figure 1. Location map of the Jaguaribe River Estuary, northeast Brazil. Cross-sections marked by a white line are the locations of the ADP profiles performed in June 2006 and February 2008

of mangroves (Maia *et al.*, 2006). This river is responsible for about 70% of the total freshwater input to the adjacent Atlantic Ocean at the occidental northeastern Brazilian coast. Historically, average freshwater discharge ranged from 60 to 130 m^3 s^{-1}. Environmental changes are currently taking place due to river damming, water withdrawal for agriculture and aquaculture purposes and increasing human population demand. A major aspect of these changes is the reduction of freshwater discharge to the ocean, particularly during the dry season, leading to changes in the hydrochemistry and in the erosion–sedimentation equilibrium along river banks, at the river mouth and along the shore just adjacent to the estuary (Lacerda and Marins, 2002; Marins *et al.*, 2003). Also, global climate changes may eventually maximize the impacts originated from regional land-use changes (Lacerda, 2007). Finally, with the building of the new Castanhão reservoir, which started operating in 2006 ($4{\cdot}5 \times 10^9$ m^3 of storage capacity), the freshwater discharges decreased to only 20 m^3 s^{-1}, downstream from that dam. Similarly, sediment fluxes were also affected by dam construction (Marins and Lacerda, 2007; Dias *et al.*, 2009). The actual discharge to the ocean is highly dependent on the hydrological regime of the drainage basin and the determination of river discharge and the comparison with the historical record are key steps for understanding the Jaguaribe River dynamics and allow the drawing of scenarios for its sustainable utilization and management.

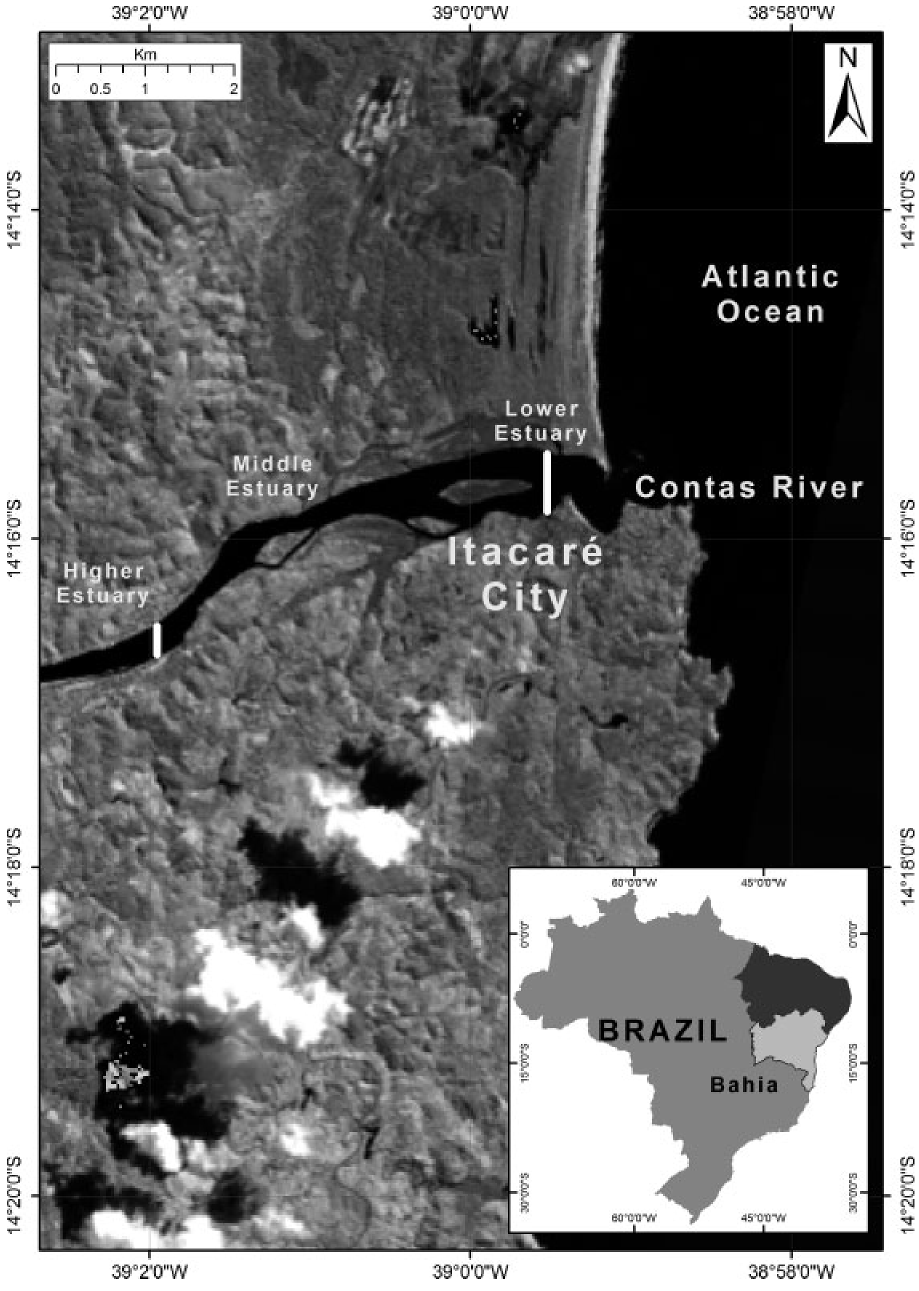

Figure 2. Location map of the Contas River Estuary, northeast Brazil. Cross-sections marked by a white line are the ADP transects performed in June 2006

The Contas River watershed covers about 66 000 km^2, being the largest in the Bahia State, northeastern Brazil (Figure 2). The climate is tropical, with an annual precipitation varying from 1200 mm inland to 2400 mm near the coast, the wettest portion of the Contas River watershed. This coastal portion in the basin presents an exuberant vegetation cover of tropical rain forests and a dense network of streams and rivers with low electric conductivity and suspended particulate matter (SPM) concentrations (110 μS cm^{-1} and 5·0 mg l^{-1}, respectively) measured during low discharge periods (De Paula, 2007).

The main channel extends for up to 700 km, from the headwaters, as high as 1700 m of altitude in the *cerrado* (a savanna-like biome). The river crosses the caatinga biome, a semi-arid environment in its middle course and finally reaches the coast under the Atlantic tropical rain forest. The estuary, located at 14·3 °S and 39 °W, is characterized by a well-defined channel at the Itacaré City. This channel is limited by terraces extending from the end of the fluvial stretch until the upper estuary and actually disappears only a few hundred meters before the river mouth. This topographic setting results in very narrow flooded margins restricting mangrove occurrence and the formation of a broad coastal plain.

Tidal regime in the estuarine portion of Contas River is semi-diurnal, with 1·0 m maximum amplitude. However, salt intrusion is observed during low discharge periods at the lower estuary (De Paula, 2007), when salt intrusion can reach between 5–6 km upriver (Campos, 2001). The annual average historical outflow to the sea, between 1970 and 2002, was 150 $\mathrm{m}^3\ \mathrm{s}^{-1}$ with peaks up to 1200 $\mathrm{m}^3\ \mathrm{s}^{-1}$ during periods of extreme rainfall.

Throughout the watershed are several human activities such as mining, agriculture, cattle and human water supply, which coupled with damming are the major drivers of environmental pressures onto the estuary and adjacent coastal areas (De Paula *et al.*, 2007). In spite of the size of the drainage basin, over 50% of the net discharge comes from the lower portion of the basin, which is located downstream of the Funil hydroelectric power plant dam. The lower basin representing about 15% of the total area of the basin, presents outflows of 3–4 times greater than the Contas River as a whole. The Gongogi River sub-basin (6600 km^2), much of which is located in the lower basin of Contas River, contributes between 30 and 40% of outflows observed throughout lower basin (De Paula *et al.*, 2007).

MATERIALS AND METHODS

ADP measurements of velocity field and outflows

The samplings were conducted in June 2006 (Contas and Jaguaribe Rivers) and February 2008 (Jaguaribe River). Data acquisition was performed in spring tides for the two estuaries on subsequent days in June 2006, starting at the interface of higher to middle estuary for the two systems and middle-to-lower estuary for the Contas River. The tidal variation during the samplings was 0·7–2·2 and 0·6–2·4 m of the Jaguaribe and Contas Estuaries.

An algorithm for computing discharge from ADP water velocity profile and bottom-track data was developed by KL Deines for tests on the Mississippi River in 1982 (Christensen and Herrick, 1982). An advantage of this measurement algorithm was that the vessel did not have to maintain a straight course while traversing a river. In fact, the vessel could traverse a river diagonally or along any arbitrary path (bank-to-bank) and still collect an accurate discharge measurement. The general equation for determining river discharge through an arbitrary surface s is (Equation 1)

$$Q_t = \int_s \overline{\boldsymbol{V}_f} \cdot \overline{\boldsymbol{n}}\,\mathrm{d}s \qquad (1)$$

where Q_t is the total river discharge, V_f the mean water velocity vector, n a unit vector normal to ds at a general point and ds the differential area. For moving-boat discharge applications, the area S is defined by the vertical surface beneath the path along which the vessel travels. The dot product of $\boldsymbol{V_f} \cdot \boldsymbol{n}$ will be equal to zero when the vessel is moving directly upstream or downstream and will equal $|\boldsymbol{V_f}|$ when the vessel is moving normal to $\boldsymbol{V_f}$ (both vectors are in the horizontal plane).

Because the ADP provides both vessel velocity and water velocity data in the vessel's coordinate system, it is convenient to recast Equation (1) in the following form (from Christensen and Herrick, 1982) (Equation (2)):

$$Q_t = \int_0^T \int_0^d (\overline{\boldsymbol{V}}_{\boldsymbol{f}} \times \overline{\boldsymbol{V}}_{\boldsymbol{b}}) \cdot \overline{\boldsymbol{k}}\ \mathrm{d}z\ \mathrm{d}t \qquad (2)$$

where T is the total cross-section transverse time, d the total depth, $\boldsymbol{V_b}$ the mean vessel velocity vector, k a unit vector in the vertical direction, dz the vertical differential depth and dt the differential time. The derivation of this equation by Christensen and Herrick (1982) is summarized in Simpson and Oltmann (1993). Converting $(\boldsymbol{V_f} \cdot \boldsymbol{V_b})\boldsymbol{k}$ into rectangular coordinates yields

$$\overline{\boldsymbol{V}}_{\boldsymbol{f}} = a_1\bar{\imath} + a_2\bar{\boldsymbol{j}}$$
$$\overline{\boldsymbol{V}}_{\boldsymbol{b}} = b_1\bar{\imath} + b_2\bar{\boldsymbol{j}}$$

and (Equation 3),

$$(\overline{\boldsymbol{V}}_{\boldsymbol{f}} \times \overline{\boldsymbol{V}}_b) \cdot \overline{\boldsymbol{k}} = a_1b_2 - a_2b_1 \qquad (3)$$

where a_1 is the cross component of the mean water velocity vector, a_2 the fore/aft component of the mean water velocity vector, b_1 the cross component of the mean vessel velocity vector, b_2 the fore/aft component of the mean vessel velocity vector, $\boldsymbol{i}$ the unit vector in the cross-component direction and $\boldsymbol{j}$ the unit vector in the fore/aft-component direction.

The ADP provides velocity data both in vessel-related coordinates and in earth-related coordinates. Either coordinate system can be used to compute discharge as long as both water and vessel velocities are described in the same system. In practice, the discharge integral is approximated by a summation of many sections of measured discharge. The equation takes the form (Equation (4))

$$Q_m = \sum_{i=1}^{N_s} \left[\int_0^{d_i} f_i\ \mathrm{d}z \right] t_i \qquad (4)$$

where for brevity, let $f = a_1b_2 + a_2b_1$, Q_m the measured channel discharge, N_s the number of measured discharge subsections, i the index for a subsection, d_i the depth of the subsection, f_i the integrated f value for subsection i, dz the differential vertical depth of subsection i and t_i the elapsed travel time between the ends of subsections i and $i-1$.

The estuarine channel outflows of the two rivers were characterized by using an acoustic current meter (ADP, 1500 kHz, SONTEK/YSI). Unlike conventional current meters, ADPs measure current profiles by using three sound beams to determine velocity in three dimensions. Thus, ADP measures not only horizontal velocity, like conventional current meters, but also the vertical component (Gordon, 1989). The size of the vertical cell was 25 cm. Measurements were performed along a cross-section in the Jaguaribe River and the Contas River at the interfaces between the higher and the middle estuary and between this and the lower portion, where the river discharges into the sea (Figures 1 and 2, respectively). These sections were chosen according to the variation of the estuarine mixing zone, representing the contribution of the drainage basin to the estuary and down towards the adjacent coastal zone (Miranda *et al.*, 2002). Hourly profiles were registered through 12 h in the four transects. Vertical and horizontal velocities were recorded at every 5 s within a range of 0·1–1·000 cm s^{-1}, a precision of ±1% for the horizontal velocity with a resolution of 0·1 cm s^{-1} (Cacchione and Drake, 1982; Zedel *et al.*, 1996; Polonichko *et al.*, 2000).

The geometric orientation of each sensor allows the velocity calculation of the fluid using an orthogonal Cartesian coordinate system (OXYZ), relative to the equipment position and orientation. The internal compass, with an accuracy of ±2° and slope sensor that measures the roll and pitch with an accuracy of ±1°, assists in obtaining the fluid velocity of the orthogonal Cartesian system, independent of system orientation. The current's direction and intensity are calculated by averaging the three values obtained along the three axes.

Estimating outflow with rating curves

Stage–discharge relations have been used for well over a century and many authors have reported the results of investigations of different issues related to the development and application of these relations (Birkhead and James, 1998; Franchini *et al.*, 1999; Fenton, 2001). The rating curves or stage–discharge relationships are usually developed from periodic measurements of stage and discharge taken around the mean stage in the river. Discharges are computed from velocity measurements and are plotted against the stages to obtain the rating curve. During floods or high stages, measurement conditions offer serious practical difficulties and therefore it is often necessary to extend the rating curve beyond measured highest discharges. However, low flow extrapolation is required for the management of domestic, industrial and agricultural water needs (Moramarco and Singh, 2001; Reitan and Petersen-Overleir, 2006; Petersen-Overlier *et al.*, 2009).

One of the traditional methods for rating curve extension is the logarithmic method. In this method an equation of the form (Equation 5)

$$Q = k(y - y_0)^b \tag{5}$$

is assumed to be an appropriate fit between the discharge Q and the stage in the river, y. The constants y_0, b and k are to be determined using the observed data on y and Q. The value of y_0 corresponds to zero discharge in the stream, which is a hypothetical parameter and cannot be measured in the field.

The stage is plotted against the discharge on a log–log for the relationship given by Equation (5). A best-fit linear relationship is obtained for the data points lying in the high-stage range and the line is extended to cover the range of extrapolation. Alternatively, coefficients of Equation (5) are obtained by least square error method by regressing X on Y and can be written as (Equation (6))

$$X = \alpha Y + C \tag{6}$$

where the dependent variable $X = \log(y - y_0)$ and $Y = \log\ Q$. If N is the number of data points lying in the high stage, then the coefficients α and C are obtained as (Equations (7) and (8)):

$$\alpha = \frac{N(\Sigma\, XY) - (\Sigma\, X)/(\Sigma\, Y)}{N(\Sigma\, Y^2) - (\Sigma\, Y)^2} \tag{7}$$

and

$$C = \frac{(\Sigma\, X) - \alpha(\Sigma\, Y)}{N} \tag{8}$$

The relationship governing the stage and discharge is now (Equation (9)):

$$(Y - Y_0) = C_1 Q^{\alpha} \tag{9}$$

where C_1 = antilog C. Equation (9) can be used to determine discharges corresponding to high stages.

In Brazil, as in most other countries, the segmentation limits are decided subjectively and each segment fitted separately. We will therefore proceed by only considering a single-rating curve segment (Petersein-Ovelier, 2005; Sivapragasam and Muttil, 2005). Such equations commonly give good estimates of the discharge, when used to interpolate at water levels lying between the maximum and minimum values used to derive them, but when extrapolation to values lying outside this range is required, large errors of estimation may arise (Hudson *et al.*, 1999; Cole *et al.*, 2003; Engeland *et al.*, 2006).

The outflows data used in this study, for the Jaguaribe River, were obtained from a limnimetric ruler that was built about 17 km the river mouth, located at the interface between the fluvial end of the estuary (higher estuary) and the middle estuary (Figure 1). At this region of the estuary, the tidal influences are observed according to the fluctuation of the semi-diurnal tide mostly during spring tides. Many authors (Knoppers and Kjerfve, 1999; Knoppers *et al.*, 2005; Molisani *et al.*, 2006; Rodrigues *et al.*, 2009) have been using data of the limnimetrics rulers located at greater distances from the sea (in the case of Jaguaribe River, located more than 35 km upstream from the estuary) to estimate discharge and material fluxes to the estuary and from there to the coastal zone, completely underestimating the actual continental fluxes to the sea (Figure 3): for example, where dams exist between the section of discharge estimation and the sea, such as in the case of the Jaguaribe River or when significant differences in climate regime and local geomorphology exist along the watershed basin, such as in the Contas River basin.

At the Contas River, the ruler is located downstream the Funil Hydroelectric power plant dam but upstream the estuary and therefore out of the saline influence but may be affected by the tidal dynamics as it is located in Ubaitaba City (Figure 3) (located more than 35 km upstream the estuary). In other words, the data obtained from the limnimetric rulers for the Jaguaribe and Contas Rivers are from the interface between the higher and the middle estuary, representing the outflows coming from the drainage basin to the estuary. The section's

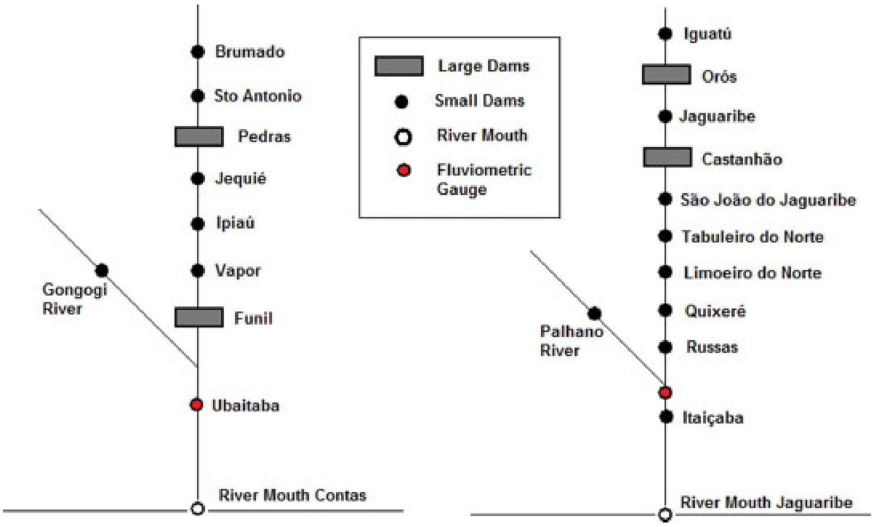

Figure 3. Distribution of large and small dams and location of fluviometric gauges (red circle) in the Contas and Jaguaribe Rivers

discharges between the middle and lower estuary were only estimated through ADP measurements.

During the sampling in the Contas and Jaguaribe Rivers Estuaries, the salinity was also measured *in situ*, using an YSI 85 probe, for each hour. Precision of such filed determinations was 0·1 units.

RESULTS AND DISCUSSION

The published estuarine literature on the physical oceanography of tropical estuaries along the northeastern Brazil has been concentrated in regional research. The tidal co-oscillation at the estuaries' mouths is classified as meso-tidal and semi-diurnal according to its height and periodicity, respectively, ranging between 1·1–1·4 and 1·8–2·0 m in neap and spring-tide periods, for the Contas and Jaguaribe Rivers, respectively (Dias, 2007; Dias *et al*., 2007). Many studies conducted in tropical estuaries (Cunha, 1982; Medeiros and Kjerfve, 1993; Araujo, *et al*., 1999; Miranda *et al*., 2005) observed a higher tidal influence during dry period, where the estuaries were controlled for a semi-diurnal barotropic tide. Nicolite *et al*. (2009) observed that during lower discharges water level variation in the estuarine channel is due to the co-oscillation of the astronomical tides and/or meteorological tides in the estuary of the Paraiba do Sul River.

The salinity curve (Figure 4) shows the variation in salinity over a complete tidal cycle to the Jaguaribe (Figure 4A) and Contas (Figure 4B) Estuaries. Figure 4A shows the salinity variability observed towards the end of the rainy season (June 2006) where the values observed varied from 1·2 and 1·8. During this period no tidal influence was observed. The low salinity values denote the great fluvial influence (unidirectional flow) in this period. However, for the beginning of the rainy season in 2008 (February) the salinity values varied from 18·9 to 32·5 showing a higher tidal influence in the evaluated period. According to Dias *et al*. (2009), the salinity of surface waters of the Jaguaribe River Estuary showed a pattern of daily variation, following the tidal influence and displaying a seasonal pattern, with the higher values observed in the dry period. For the Contas River the salinity curve (Figure 4B) shows the occurrence of stratification in the region of the mouth during flood tide and a more homogeneous mixing during the ebb tide confirming previous observations by De Paula *et al*. (2007). The estuaries studied are formed by relatively well-defined channels, favouring separation-driven processes by density differences of seawater intrusion in fluvial fluxes and also the mixing of these water masses after tide changes (Miranda *et al*., 2002).

This behaviour was observed by Miranda *et al*. (2005), in a study performed in the Curimataú River, where the author shows that the salinity ranges from 20 to 36 in the period of major fluvial discharges and from 30·2 to 30·7 in the dry season. This behaviour shows a major amplitude in the variation of salinity, showing an increased influence of coastal waters (CW) during periods of lower fluvial discharges (dry season).

ADP current velocity and outflows in the Contas and Jaguaribe Rivers Estuaries

Figure 5A shows the behaviour of the velocity field obtained at the interface between the higher to middle estuary, in the Jaguaribe and Contas Rivers. Current velocities for June 2006 (rainy period), integrating average values from the surface to the bottom, showed maximum ebb velocity occurring 5 h before the peak of low tide, reaching 0·38 m s^{-1}. Highest current velocity during flood occurred 5 h after the beginning of low tide, reaching −0·52 m s^{-1}. In the Contas River, measured current velocities for June 2006 showed maximum ebb velocity occurring 3 h before the peak of low tide, reaching 0·67 m s^{-1}. Highest current velocity during flood occurred 1 h after the beginning of low tide, reaching −0·65 m s^{-1}.

Figure 5B shows the behaviour of the velocity field obtained at the interface between the middle and lower

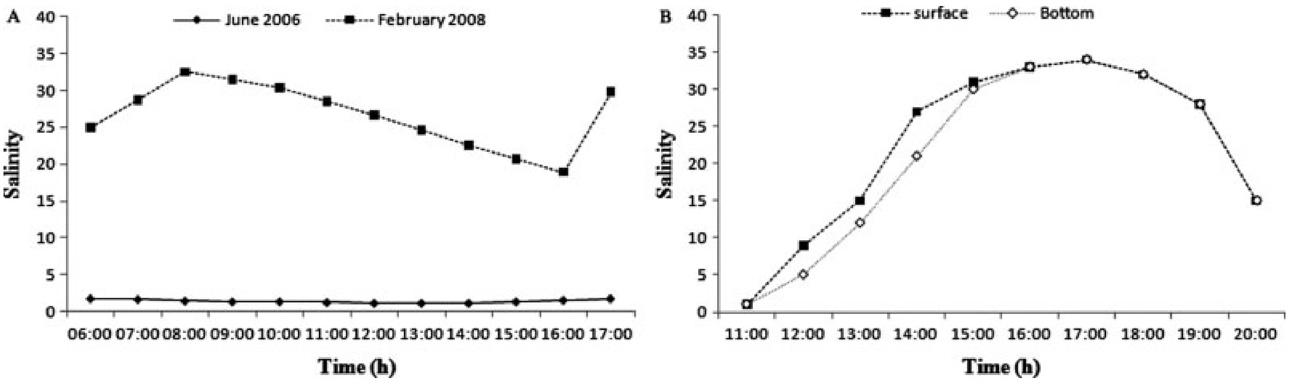

Figure 4. Variability of salinity over a complete tidal cycle to the estuaries of the Jaguaribe (A) and Contas (B) Rivers

Table I. Velocity field variation and average values during floods and ebb tides at the Contas and Jaguaribe River Estuaries, obtained with ADP for June 2006 for the Contas River and for June 2006 and February 2008 for the Jaguaribe River

	Velocity field (m s^{-1})			
	Higher to middle estuary		Middle to lower estuary	
	Ebb	Flood	Ebb	Flood
Jaguaribe River Estuary	0·26–0·38 (0·31)	−0·01to −0·52 (−0·32)	0·32–0·50 (0·40)	−0·28to −0·69 (−0·51)
Contas River Estuary	0·10–0·67 (0·50)	−0·18to −0·65 (−0·33)	0·27–1·00 (0·78)	−0·20to −0·55 (−0·42)

estuary, in the Jaguaribe and Contas Rivers. The velocity field in the case of the Jaguaribe and Contas Rivers was obtained in February 2008 and June 2006, respectively. Maximum ebb velocity occurred 4 hours before the peak of low tide, reaching 0·50 m s^{-1}. Highest current velocity during flood occurred 5 h after the beginning of low tide, reaching −0·69 m s^{-1}. The velocity field observed in the Contas River presented maximum ebb velocity occurring 3 h before the peak of low tide, reaching 1·00 m s^{-1}. Highest current velocity during flood occurred 1 h after the beginning of low tide, reaching −0·55 m s^{-1}.

Table I shows the range of variation and the average velocity field of flood and ebb tides, for both the Contas and Jaguaribe Rivers Estuaries.

The average ebb current velocities at the higher to middle estuary interface in the Jaguaribe River Estuary is 38% lower, when compared to the average velocities observed for the same region in the Contas River Estuary. However, average flood current is similar at this interface in the two rivers. The highest values observed during ebb tide in the Contas River compared to the Jaguaribe River show the larger importance of the fluvial component in the Contas River (Figure 5A). However, increased current velocities during flood tides show the importance of marine waters to the estuarine dynamics of the Jaguaribe River.

At the interface between the middle and lower estuary the average ebb current velocity in the Jaguaribe River is 49% lower than in the Contas River. Average flood current velocities observed in the Jaguaribe River is 17% lower than the average flood velocities measured in the Contas River (Table I).

The observed differences in the two estuarine systems are due to the difference in climate and water use between the two basins, associated with geomorphological differences, whereas in the Contas River damming is to provide hydroelectricity and therefore keep a controlled outflow from the dam. At the Jaguaribe River, damming is for water withdrawal, thus keeping water outflow at minimum values, during most of the time and even zero flow during extreme dry periods. Also, higher tidal amplitude at the Jaguaribe River results in high flow velocities, mainly during the flood tide.

The outflows at the Jaguaribe River Estuary (Figure 6), from the higher to the middle estuary, varied from 5 to 351 m^3 s^{-1} during ebb tide and from −110 to −201 m^3 s^{-1} during flood tide, whereas from the middle to lower estuary, during the ebb and flood tides, measured outflows varied from 345 to 1123 m^3 s^{-1} and −771 to −1395 m^3 s^{-1}, respectively.

The outflows to the Contas River Estuary (Figure 6), from the higher to the middle estuary, varied from 13 to 332 m^3 s^{-1} during the ebb tide and from 98 to −465 m^3 s^{-1} during the flood tide. From the middle to the lower estuary, during ebb and flood tide, the measured outflows varied from 175 to 608 m^3 s^{-1} and −84 to −105 m^3 s^{-1}, respectively.

The net balance is defined as the difference between the input and output water volumes to the systems (Sylaios and Boxall, 1998; Miranda *et al.*, 2002; Souza and Knoppers, 2003). Observing the average input and outputs for the Jaguaribe River (Figure 7), the net water balance is negative, with the middle estuary retaining 42% of the water volume entering the system; the

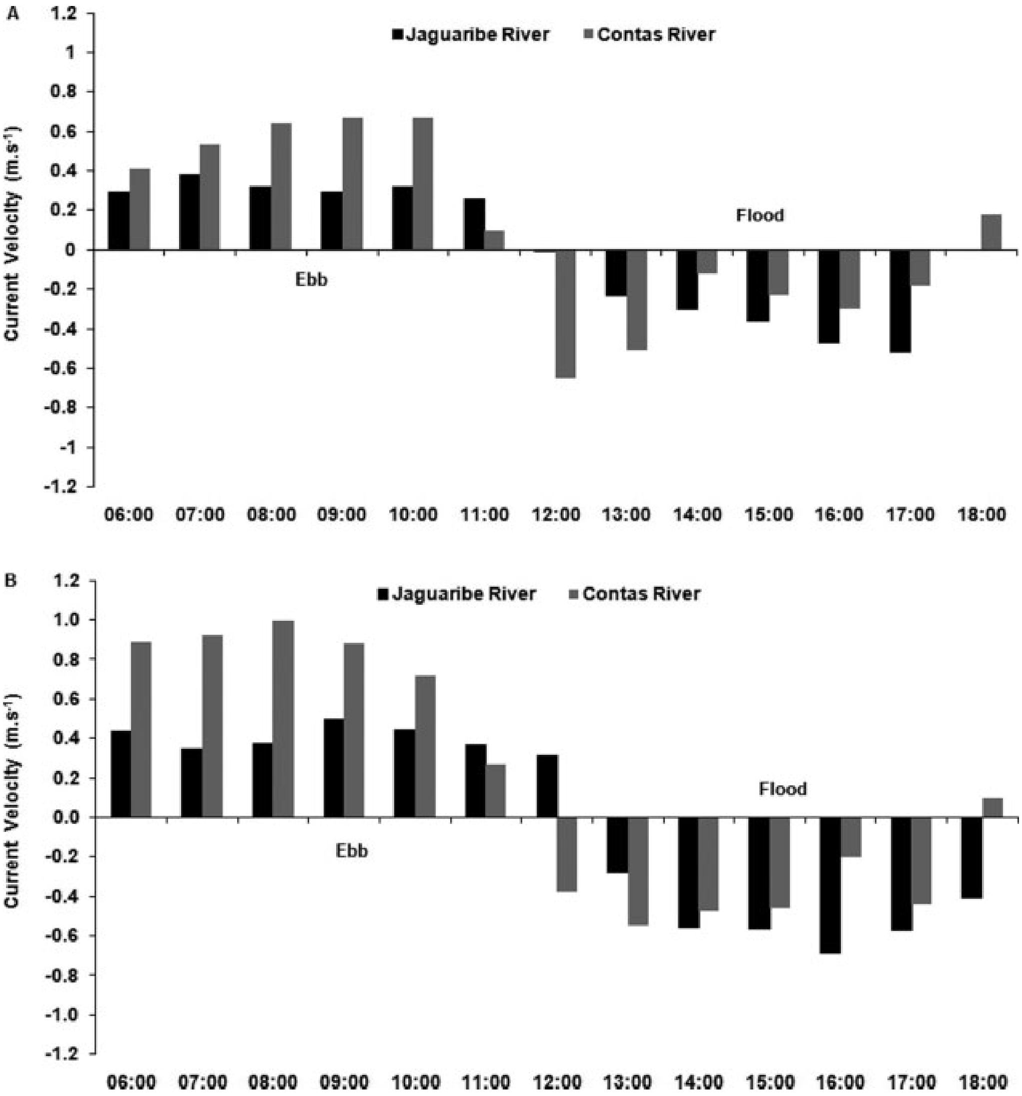

Figure 5. Current velocity (m s^{-1}) during flood and ebb tides at the interface between the higher to middle estuary (A) and middle to lower estuary (B) in the Jaguaribe (black bars) and Contas River (grey bars) Estuaries, for a 13-h period (06 : 00 to 18 : 00) with a time interval of 1 h in June 2006 (Jaguaribe and Contas Rivers) and February 2008 (Jaguaribe River), respectively

estuary behaves as an importer of water. The water retained in the Jaguaribe Estuary during ebb and flood tide events, likely results from the major influence of higher tidal volumes in the estuarine system and of a lower intake of freshwater from the higher estuary and the river proper. For example, Dias *et al.* (2009) observed that during the dry season, stronger saline intrusion increases the total water flux into the estuarine channel, mostly during the flood period. Marins and Lacerda (2007) observed that saplings of the mangrove *Laguncularia racemosa* R. Gaertn. (black mangrove) are colonizing riverbanks and beaches up to 30 km inland from the coast as a result of extensive saline intrusion.

Observing the average input and outputs for the Contas River (Figure 7), the net balance is positive, with the higher estuary contributing 90% the water volume to the middle estuary and then to the lower estuary, thus the estuary behaves as a water and materials exporter. The exporting nature of the Contas River, both in ebb and flood, is due to the dominant influence of the freshwater inputs from the river and its tributaries to the lower basin and the relative weaker influence of the meso-tidal regime, although De Paula *et al.* (2007) observed, during spring tides, stronger saline intrusions reaching up to 5–6 km inland.

In general, the net balance for the Contas and Jaguaribe Rivers is very distinct, whereas the Contas River behaves as a net water exporter; the Jaguaribe River Estuary behaves as a net water importer, at least under the conditions dominating the study period. At the Jaguaribe Estuary, water retention during flood tide contributes to 58% of the total volume transferred during the ebb tide from the middle to lower estuary. However, 42% of the total water volume (452 m^3 s^{-1}) that entered during flood tide is retained in the middle estuary. At the Contas River Estuary, 90% of the total water is retained during the flood tide contributing to the volume transported in the ebb tide from the middle to the lower estuary.

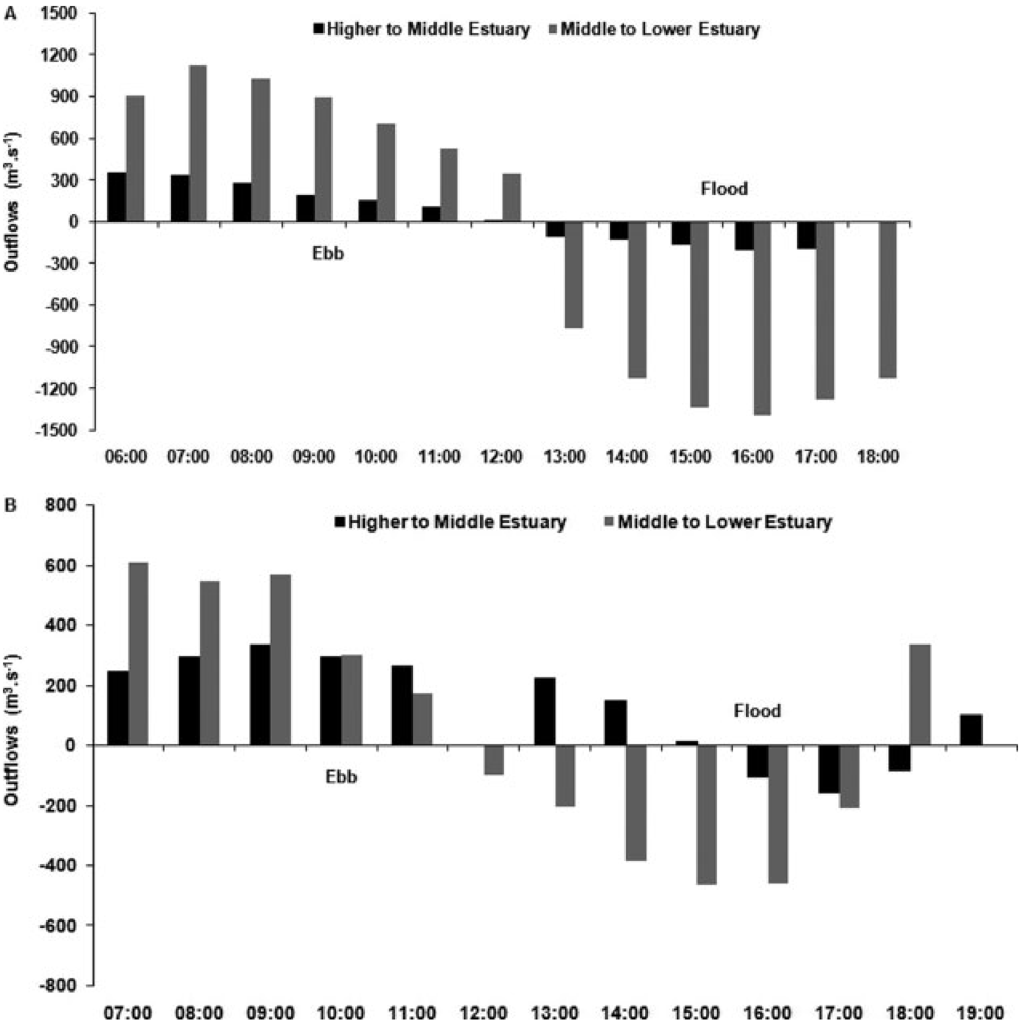

Figure 6. Outflows during flood and ebb tides at the higher to middle estuary interface (black bars) and from the middle to lower estuary (grey bars) in the Jaguaribe River (A) and Contas River (B), for a 13-h period in June 2006 (Jaguaribe and Contas Rivers) and February 2008 (Jaguaribe River), respectively

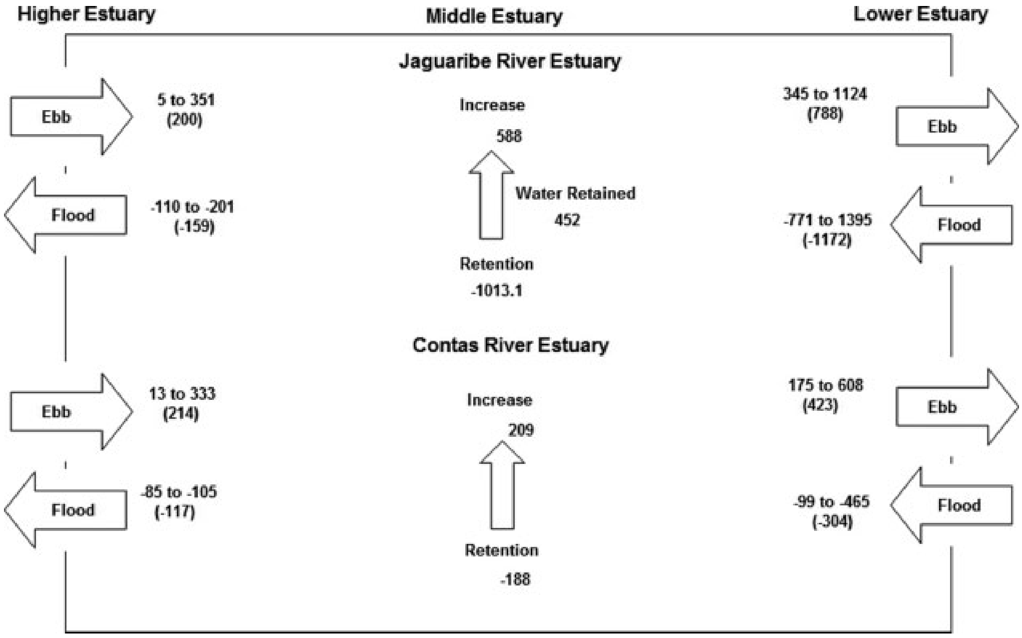

Figure 7. Net balance in the Jaguaribe and Contas Rivers, during ebb and flood tides in June 2006 (Jaguaribe and Contas Rivers) and February 2008 (Jaguaribe River), from ADP data. Outflows are represented in $m^3 \ s^{-1}$

Rating curve estimates

The rainfall quantity and distribution for the two rivers differed during the studied periods. Although both sites were under wet conditions, the largest rainfall in the Contas River occurred from June to September with the largest volumes occurring in July (1000 mm). In the Jaguaribe River, maximum rainfall (500 mm) occurred from March to June with the largest volumes occurring in April.

The outflow estimates obtained with the rating curve method for June is described below. The Brazilian National Water Agency (ANA, 2008) reported that outflows for the Contas River Estuary ranged from 66 to 136 $m^3 s^{-1}$ (average of 90 $m^3 s^{-1}$) for the year 2004 and from 32 to 190 $m^3 s^{-1}$ (average of 111 $m^3 s^{-1}$) for the year 2005. In June 2006, outflows reported for the Contas River varied from 21 to 190 $m^3 s^{-1}$ (average of 81 $m^3 s^{-1}$). During the same period the calculated outflows for the Jaguaribe River, according to ANA, showed variation from 3 to 9 $m^3 s^{-1}$ (average of 6·3 $m^3 s^{-1}$), 5 to 11 $m^3 s^{-1}$ (average of 7·5 $m^3 s^{-1}$) and 4 to 9 $m^3 s^{-1}$ (average 6 $m^3 s^{-1}$) for the years of 2004, 2005 and 2006, respectively, as shown in Table II.

Even considering that outflows obtained with the rating curve method for the Contas and Jaguaribe Rivers were relatively constant in time because of discharge normalization due to the presence of dams, outflows would be about 65 and 95% lower than discharges obtained with ADP, for the Contas and Jaguaribe Rivers, respectively. When compared, outflows of ANA based on a limnmetric ruler located 34 km from the coast with those obtained by Dias *et al.* (2009) at the interface between the higher and the middle estuary, but based on observations of the limnimetric ruler located at 17 km from the river mouth in the Jaguaribe River, they would still be 65% lower.

When comparing the results obtained by Dias *et al.* (2009) and considering the outflows regularity and using an average value of 70 $m^3 s^{-1}$ for rating curve-based outflows for the years 2004 and 2005, with the outflows obtained with the ADP method, we can observe that rating curve outflows are 65% lower, showing that rating curve estimates are not representative of the net water balance in both areas, underestimating it by more than 50%, and therefore are of little use to estimate water and material flows to the ocean. Also, rating curve-estimated outflows to the estuary failed to take into account the influence of sea water input and residence time when calculating instantaneous fluxes along consecutive tidal cycles.

The historical outflow data series calculated for the Jaguaribe River based on the ANA database (ANA, 2008; Figure 8) clearly shows a reduction in the drainage basin outflows to the estuarine channel due to the operation of dams in the river. From 1961 to 1989, maximum outflows of the order of 3200 and 2250 $m^3 s^{-1}$ were observed in 1975 and 1985, respectively. In the 1990s, a reduction of outflows was observed with an average of about 30 $m^3 s^{-1}$ and maximum outflows of only 370 $m^3 s^{-1}$. These results demonstrate that between 1990 and 2007 the maximum outflows from the Jaguaribe drainage basins to the estuarine channel are approximately 88% lower, when compared to the maximum outflows observed in the 1970s and 1980s, respectively.

The outflow measurements with limnimetric rulers in the Contas River Estuarine channel show maximum outflows from 1988 to 2006 (Figure 8). The evolution of maximum outflows through time is totally different from that of the Jaguaribe River. No significant attenuation of maximum values is observed. This is probably a result of a constant energy generation-derived water discharge from the Funil dam and of the 50% contribution to the total discharge to the estuary from its tributary, the Gongogi River.

The fluvial discharge estimation derived from limnimetric ruler and extrapolation stage–discharge curve in most rivers in the world is held once a day at the monitoring stations, where the relative height of the water level is converted into flows according to Equation 9. In rivers flowing into the sea, this monitoring is carried out upstream of the estuary mouth, where the flow is purely unidirectional (without tidal influence). Therefore, a limiting factor in using these flow estimates obtained with the use of stage–discharge curve is the distance from the estuary that these measures are acquired, because the fluvial discharges always come late at the mouth of estuaries in relation to the instant acquisition of the stage in the upstream limnimetric station and in turn are also lagging behind the rainfall in the drainage basin.

Besides the dominant seasonal variations the outflows may present variability of the order of days, in response to abnormal rainfalls in the drainage basin. Classic examples of the use of outflow estimates (obtained through the stage–discharge curve) for the calculation

Table II. Outflow variations and average values during ebb periods at the Contas and Jaguaribe River Estuaries, obtained with ADP for June 2006, with rating curve (ANA) for June 2004, 2005 and 2006 and with Dias *et al.*'s (2009) rating curve for June 2004 and 2005

	Higher to middle estuary (ebb)					
	ADP	ANA			Dias *et al.* (2009)	
	2006	2004	2005	2006	2004	2005
Jaguaribe River	5–351 (200)	3–9 (6·3)	5–11 (7·5)	4–9 (6)	21–69 (40)	26–227 (100)
Contas River	13–333 (214)	66–136 (90)	32–190 (111)	21–190 (81)	Not measured	Not measured

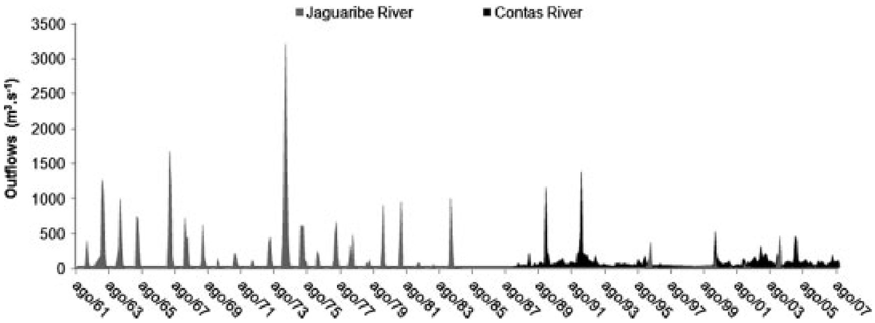

Figure 8. Historical outflows ($m^3\ s^{-1}$) obtained with the rating curve method, in the Jaguaribe and Contas Rivers (ANA, 2008)

of fluxes of suspended sediments and various materials that are transported through the drainage basin to the nearby coastal area may be observed in (Nicolitte *et al*., 2009; Medeiros and Kjerfve, 1993; Molisani *et al*., 2007; Petersen-Overleir, 2005; Santos *et al*., 2009). The authors use the outflow estimates that were obtained, on average, up to 30 km from the estuaries' mouth to calculate the import and/or export of materials to the adjacent coastal zone, neglecting important factors for the estuarine dynamics, such as lateral and bottom friction, wind stress, barotropic and baroclinic components of the gradient pressure force (per unit mass) and tide co-oscillation, which can generate large uncertainties in these estimates, underestimating and/or overestimating the transport of materials from the drainage basin to the adjacent ocean.

The random (wrong note by the observer of the water level) and systematic (poor preservation of the limnimetric rules) errors are other important sources of error for the estimation of outflows by this method. Extrapolation of a stage–discharge curve, always there is great uncertainty, especially at the top and bottom of the curve, due to the limited amount of data in small and large outflows. However, Miranda *et al*. (2002) show that by the accurate determination of the drainage basin area that is effectively monitored by a fluviometric gauge (A1) and the area located downstream (A2), one can create a correction factor $[C = (A1 + A2)/A1]$, which helps to minimize the estimated outflows errors.

There are several advantages in the use of ADPs in relation to the traditional flow measurement. The flow measurement with hydrometric reel requires, depending on the size of the river, at least 20 individual measurements along the section, which typically include several hours of work. Already measurements with ADPs are significantly faster, lasting minutes rather than hours, with results equally accurate. The use of ADPs permits to carry out measurements in harsh environmental conditions, such as during the period the major floods. Situations where there are abnormalities in the outflow (e.g. reflux) and sections are geometrically inadequate for measuring with a reel will not affect the performance of ADP, because changes in the direction of flow are measured and considered in calculating the flow.

CONCLUSIONS

The estimated outflows using the limnimetric ruler and rating curves in this study underestimated by more than 50% the ADP-measured outflows to the estuarine channel in the Contas and Jaguaribe Rivers, suggesting the inefficiency of the method to calculate instantaneous flows and net balances of water and materials to estuaries, and mostly to the ocean, at least for medium size rivers under several human interventions as the ones studied here. Many random errors and uncertainties observed in small and medium levels of water are associated with the use of limnimetric rulers and rating curves, in particular in estuarine environments where the bidirectional water flow (freshwater and seawater inputs) is the limiting factor for the use of fluviometric gauges because this type of measurement is more accurate in unidirectional flows.

The different results from the two methods regarding the freshwater discharges into the estuarine environments to the Jaguaribe River Estuary are more stickling, due to river damming and increasing freshwater withdraw for human consumption, agriculture and other uses in this basin. Although discrepancies were also observed between the two methods in the Contas River, the large tributary contribution and the damming for hydroelectricity generation reduces the differences between estimates obtained with the two methods. The results show the relevance of the *in situ* outflows data acquisition using techniques (e.g. ADP) which allow higher precision measurements, when compared to those obtained with the rating curve method, in particular when flows to the ocean are of utmost interest.

ACKNOWLEDGEMENTS

This study is part of the 'INCT—Continent–Ocean Materials Transfer' project supported by CNPq, Brazil, Process no. 573·601/2008-9. The authors also thank the Blue Amazon Program from CAPES for providing grants to FJSD.

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