Hydrology of a well-mixed estuary at the semi-arid Northeastern Brazilian coast

Hidrologia de um estuário verticalmente bem misturado da costa nordeste semi-árida brasileira

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Abstract: Aim: This study focuses on the ebb and flood water inputs for dry and rainy seasons to the Jaguaribe River estuary (Brazil). The Jaguaribe Basin covers 72,043 km^2, representing almost half of the Ceará State's territory in Northeastern Brazil. It extends along 633 km contributing to the Western Equatorial Atlantic Ocean. The observed tidal regime is of the meso-tidal semi-diurnal type; **Methods:** In 2004, the average velocities of flood and ebb tides were calculated using a spherical buoy, a limnimetric ruler and a deterministic model. In 2005, a comparative study between the measures performed with the buoy and an Acoustic Doppler Current Profiler (ADCP) was also carried on; **Results:** The average velocities of flood and ebb tides, using the spherical buoy, the limnimetric ruler and the deterministic model, varied from 0.11 to 0.24 $m.s^{-1}$ (flood) and from 0.11 to 0.28 $m.s^{-1}$ (ebb). In 2005, the measures done with the buoy and the Acoustic Doppler Current Profiler (ADCP) presented differences between 50 and 80%. However, in 2005, the water fluxes calculated from average velocities measurements (101.1 $m^3.s^{-1}$ using the spherical buoy and the limnimetric ruler; and 115.3 $m^3.s^{-1}$using the ADCP) showed a smaller error; **Conclusions:** The comparability of the two techniques to calculating average water fluxes to 12 hours sampling campaigns pointed the similarity between these data. During these evaluated periods the tidal prism presents seasonal variation between 12.6 and –73.1 $m^3.s^{-1}$ showing a smaller tidal prism during the dry season and with an increasing tendency in the rainy period. The Jaguaribe estuary is an importer system of marine waters explaining the dominance of marine biogeochemical processes in the estuary.

Keywords: estuarine fluxes, Acoustic Doppler Current Profiler, tidal prism, seasonal variations, Jaguaribe River.

Resumo: Objetivo: O objetivo deste estudo foi calcular os fluxos de entrada e saída, em diferentes períodos climáticos regionais, do estuário do Rio Jaguaribe (CE-Brasil) em campanhas realizadas durante três anos (2004 a 2006). O Rio Jaguaribe localiza-se no semi-árido brasileiro, sendo o principal curso d'água do Estado do Ceará, possui uma bacia de drenagem de 72.000 km^2 e percorre 633 km, contribuindo para as descargas da costa nordeste oriental brasileira. O regime de maré é do tipo semi-diurno marcado por meso-marés; **Métodos:** Em 2004, as velocidades médias para maré enchente e vazante foram calculadas usando-se uma bóia esférica, régua limnimétrica e um modelo determinístico, enquanto que em 2005, foram feitas medidas comparativas de velocidade da água usando esta técnica e simultaneamente um perfilador de corrente Doppler acústico (ADCP); **Resultados:** As velocidades médias para maré enchente e vazante calculadas, usando-se uma bóia esférica, régua limnimétrica e um modelo determinístico, foram de 0,11 a 0,24 $m.s^{-1}$ (enchente) e 0,11 a 0,28 $m.s^{-1}$ (vazante) para o ano de 2004. Em 2005, as medidas comparativas de velocidade da água usando a bóia esférica/régua limnimétrica e simultaneamente um perfilador de corrente Doppler acústico (ADCP) mostraram em média variações de 50 a 80% entre estas medidas. Entretanto, os valores de vazão obtidos a partir das velocidades médias de 2005 (101,1 $m^3.s^{-1}$, usando a bóia esférica e régua limnimétrica; e 115,3 $m^3.s^{-1}$, usando ADCP) mostraram uma diminuição do erro. No período avaliado, o prisma de maré variou sazonalmente entre 12,6 a –73,1 $m^3.s^{-1}$ mostrando que no período de seca o prisma de maré é pequeno e no período de chuva, mesmo com o aumento do volume de água doce, o estuário se comporta como um estuário importador de águas marinhas; **Conclusões:** As medidas de vazões comparativas entre as técnicas usando bóia esférica/régua limnimétrica e um perfilador de corrente Doppler acústico (ADCP) referentes ao estuário médio do Rio Jaguaribe para um período de 12 horas de amostragem na costa nordeste oriental brasileira mostraram-se similares. O prisma de maré medido a partir destas técnicas foi pequeno ou de valor negativo e explica a predominância de processos biogeoquímicos marinhos no estuário.

Palavras-chave: fluxos estuarinos, perfilador de corrente Doppler acústico (ADCP), prisma de maré, variações sazonais, Rio Jaguaribe.

1. Introduction

Many tropical estuaries of the world have been recently the subject of hydrological studies due to the large benefits they provide to the coastal zone. However, the existing data are still insufficient to understand the physical and hydrological processes responsible for their sustainability (Mehta, 1994; Marone and Jamiyanaa, 1997; Khadam and Kaluarachchi, 2004; Wolanski and Spagnol, 2003; Khadam et al., 2006).This is particularly true for the semi-arid coast of Ceará, Northeastern Brazil, where more than 40% percent of the state's population, about 5 million people, inhabit (IBGE, 2004). Improving life quality since 1960 has resulted in growing agriculture, urbanization and industrialization, requiring increasing supply of good quality water. As a result damming of natural water courses also increased exponentially, completely changing natural watershed to a point when about 90% of the totality of the state's water resources are artificially controlled. Therefore, such hydrological information is crucial to support decision makers to plan for the sustainable development of the region. It is presently fundamental to understand who tropical estuaries under semi-arid climate respond to changes in land use and human occupation of their watersheds (Jonge and Van Beusekon, 1995; Kjerfve et al. 1996; Lessa et al., 1998).

At the Jaguaribe River estuary, Northeastern Brazil, environmental changes are presently taking place due to river damming, water withdraw for agriculture and aquaculture purposes and increasing human population demand. A major aspect of these changes is the reduction of freshwater flow to the ocean, in particular 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 these impacts (Lacerda, 2007).

The evaluation of anthropogenic pressures on coastal watersheds is generally performed by means of historical temporal series of water flux and geomorphological relationships with water flow developed during hydraulic studies (Souza, 2003). These relationships are fundamental to characterize environmental changes by giving estimates of actual river flux and their magnitudes and fluctuations (Miranda et al., 2002; Hay, 1998; Mulder and Syvitski, 1996).

The Jaguaribe River estuary, at the oriental sector of the Ceará State coastline (Figure 1) is the largest estuary of this portion of the Brazilian coast, but existing data on the hydrology of this well mixed estuary (Marins et al., 2003) is still limited, as knowledge of estuarine circulation patterns, determining pollution dispersal, nutrient fluxes, residence times, and many other estuarine processes (Kjerfve, 1975, 1978; Kjerfve and Proehl, 1979; Kjerfve et al., 1997; Sylaios and Boxal, 1998; Wolanski and Spagnol, 2003). To enlarge the information on the functioning of this estuary, a three years study on the hydrology of the estuarine region was developed, based on field campaigns carried on during dry and rainy seasons in September/04 and 05, and June/06. During the campaigns salinity, temperature, flow velocity and instantaneous and residual fluxes were measured using two different methodologies based on Kjerfve and Proehl (1979), modified by CETESB (1998) and by means of an ADCP profiler (Piedracoba et al., 2005).

2. Material and Methods

2.1. Study area

The Jaguaribe Basin covers 72,043 km^2, representing almost half of the Ceará State's territory in Northeastern Brazil. It extends along 633 km contributing to the Western Equatorial Atlantic Ocean (PNRH, 2005). Major tributaries on the right margin are the Carius, Salgado and Figueiredo rivers and on the left margin the Banabuiú and Palhano rivers. About 87% of the water flux is artificially controlled by dams (Veríssimo et al., 1996; Soares Filho, 1996). The Jaguaribe River mouth harbors a medium estuarine zone located between 4° 23' 26" S and 37° 43' 58" W and 4° 36' 58" S and 37° 43' 45" W.

Regional climate, including seasonal variation of rainfall, is regulated by the Intertropical Convergence Zone (ITCZ) where air masses from both hemispheres converge. During the southern hemisphere winter and spring the ITCZ weakens moving northward, resulting and very dry months with strong eastern winds. The magnitude of the ITCZ displacement is affected by El Nino teleconections (Funceme, 2004), and can off also modify the movement of sand dunes that dominate the coastal line of the Ceará State (Maia et al., 2005). Local climate is semi-arid, with average annual rainfall increasing from 737 to 983 mm with average speed of 6.3 to 7.9 m/s (Jimenez et al., 1999), between Itaiçaba, 30 km inland to Aracati, 17 km from the mouth. The behavior of the climate humid tropical to arid in the south of the state is the same along this equatorial Brazilian state. Historical rainfall shows higher precipitation (200 to 400 mm) between March and April. During the peak of the dry period between August and November, precipitation can frequently be zero (Funceme, 2004).

Maximum tidal amplitude reaches 2.8 m (DHN, 2001) and the generally small freshwater supply results in salinity intrusion for a few km inland. Saline intrusion during the dry season in Jaguaribe River reaches Itaiçaba City, about 34 km inland (Marins et al., 2003) and stopped by a threshold. The total estuarine area covers 1,350 km^2.

The brackish water tidal flood plains are covered by about 13,000 ha of mangroves (Herz, 1991), but the saline intrusion is coming into the river the mangroves areas (Lacerda and Marins, 2002; Lacerda, 2007). This

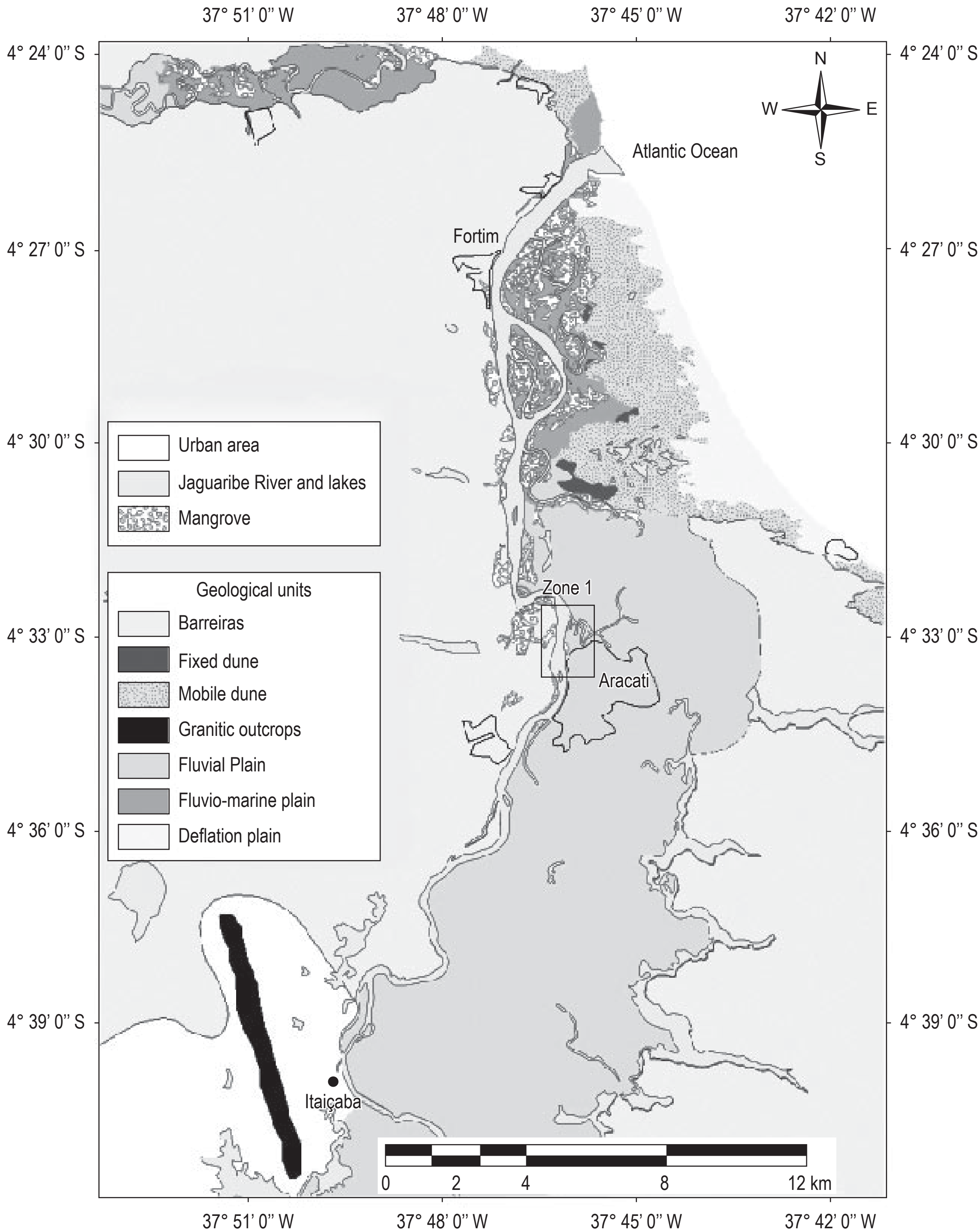

Figure 1. Location of thestudy area in the Jaguaribe River estuary, NE Brazil.

river is responsible for about 70% of the total freshwater input to the adjacent Atlantic Ocean from the occidental Northeastern Brazilian coast. Average freshwater discharge ranges from 60 to 130 $m^3.s^{-1}$ (ANEEL, 2000), but has been affected by the building of dams, water withdrawn for urbanization, agriculture and aquaculture. Prior to the building of the first large reservoir and the introduction of large-scale agriculture, discharges to the Atlantic Ocean reached varied widely from 0 to 7,000 $m^3.s^{-1}$. During the 1960's and 1980's, it decreased to 80 and to 60 $m^3.s^{-1}$ after 1996. With the building of the new Castanhão Reservoir (4.5×10^9 m^3 of storage capacity), the freshwater input to the ocean is regulated to vary from 22 to 57 $m^3.s^{-1}$ (Campos et al., 2000). Similarly, sediment fluxes were also affected.

Present estimated sediment load to the ocean from the Jaguaribe River is about 60.000 ton.yr^{-1} (Cavalcante, 2000), calculated from data inputs of Peixe Gordo, at 210 km from the mouth of the river. This low sediment supply results in a coastal morphology dominated by marine and aeolean processes and significant changes in geomorphology during the past century. Marine sand transport is estimated as 600,000 $m^3.yr^{-1}$, whereas aeolean transport reaches about 200,000 $m^3.yr^{-1}$ (Valentini, 1994). Although significant mangrove erosion is occurring at the river estuary, the large marine and aeolean sand transport also cause sedimentation of mangroves and coastal lagoons (Lacerda and Marins, 2002). Therefore, hydrological changes probably dominate the geochemistry of estuarine sediments.

2.2. Measurements of flow velocity and flux

Three sampling campaigns were performed in September/04 and 05 (Dry period), and June/06 (end of the rainy season). In situ measurements were done hourly for 12 hours between quadrature and sizigia tides.

A deterministic model based on tidal prism was used to calculate flow velocity and water flux, adapted from CETESB (1988) and Kjerfve and Proehl (1979), for non-meandric rivers. Cross section 10 m transects at the interface of the tidal zone (TZ) and at the mixing zone (MZ) (Dias et al., 2005), were established. A spherical buoy was deployed and left to stabilize for 5.0 m and the time period after passing an initial point (∂d_0) and reaching a final point (∂d_i) was measured using a chronometer. A limnimetric ruler was built to measure water level fluctuations during the sampling period. Calculated current speed, tidal elevation and depth of the river section were used to estimate river flux.

In September/05 the bathymetry of the entire estuarine region was performed using a ecobathimeter coupled with a GPS (GPSMAP 238 *Sounder* GARMIN) with transductor resolution of 0.01 m and temperature sensor. Based on this bathymetric profile, a transversal section of the river was delimited. The section area was calculated using the limnemetric ruler for each sampling instant. Based on this surface flow velocity was estimated (Equation 1).

$$\varphi = \frac{\partial d}{\partial t} \tag{1}$$

where: ϕ = surface flow velocity; ∂d = distance in meters covered by the floating buoy between time ∂d_0 and ∂d_i after stabilization; ∂t = time required to cover the established distance by the floating buoy.

After calculating ϕ, we estimated the average surface flow velocity (ζ_m), using Equation 2.

$$\zeta m = \varphi \times f \tag{2}$$

where: ζ_m = average surface flow velocity; ϕ = surface flow velocity($m.s^{-1}$); f = correction factor taking into consideration bottom rugosity, wind action and Coriolis force. The factor for tropical estuaries used by CETESB (1998) needs an average correction between 15 and 20% for utilization in well-mixed and with shallow estuaries, as the Jaguaribe River, being established the band between 0.98 and 1.02. With the calculated ζ_m values and section area (m^2) for each sampling instant during a semi-diurnal tidal cycle (every hour during 12 hours) it was possible to calculate {Qτ}, according to Equation 3.

$$Q\tau = A^{(m^2)} \times \zeta m^{(m/s)} \tag{3}$$

where: $Q\tau$ = total water flux for the section ($m^3.s^{-1}$); A = section area (m^2) taking into consideration the bathymetric profile and water level ζ_m= average flow velocity ($m.s^{-1}$).

Simultaneously the hydrodynamic circulation of the estuarine canal was characterized by using an Acoustic Doppler Current Profiler (ADCP, 1200 kHz, YSI), along a transverse section at the upper estuarine region (Zone 1, in Figure 1), which integrates the incoming continental materials from the watershed to the estuarine zone. At this site, hourly profiles were recorded through 12 hours. Vertical and horizontal velocities were recorded for three depths every 5 seconds within a range of 0.1 to 1,000 $cm.s^{-1}$ and a precision of ± 1% for horizontal velocity with a resolution of 0.1 $cm.s^{-1}$.

Simultaneously to the flow measurements, major hydrochemical parameters (temperature, salinity, dissolved oxygen and conductivity) were determined in situ using a multi-probe YSI 5906 probe.

2.3. Estimating the estuarine input and output water fluxes

Longitudinal water fluxes were calculated according to Sylaios and Boxall (1998), taking into considerations the total section flux {Qτ}, integrating input (V_{flood}) and output (V_{ebb}), fluxes according to Equations 4 and 5:

$$Vflood = \int_{t=0}^{t=r} Q(y,t)dt \tag{4}$$

$$Vebb = \int_{t=0}^{t=r} Q(y,t)dt \tag{5}$$

where: V_{flood} and V_{ebb} represent the tidal prism during one tidal cycle, flood and ebb tide respectively in ($m^3.s^{-1}$); t = tidal period in seconds; t = o, t = τ e t = T represent low tidal period i.e. the tidal prism at the chosen section defined according to De Jonge (1992) as in Equation 6:

$$Vprism = Vflood - Vebb \tag{6}$$

3. Results and discussion

3.1. Current velocity and estuarine salinity

The observed tidal regime for the Jaguaribe River estuary is a meso-tidal semi-diurnal type, showing a particular elevation during spring tide. Consequently instantaneous surface currents and salinity show a complex pattern where currents are directly affected by tidal forcing in a similar way to that showed by Sylaios and Boxall (1998) in the Test estuary (Hampshire, southern England).

In 2004, a large irregularity of the rainy period with a 4-times (in the first semester, the average precipitation was of 167 mm that characterizes a period of positive hydrological balance, while that in the semester second the average precipitation it was of 20 mm) increase in river volume occurred. Maximum volume reached 44 × 10^3 m^3, with 85% being fresh water. In September/04, during the first campaign, water volume reached 11 × 10^3 $m^{3,}$ about 50% being fresh water (Dias et al., 2007). This irregularity of rainy period is presented by this drainage between 25 to 30 years (Duursma, 2002).

Flow velocities for flood and ebb tides at zone 1, estimated from Equation 2 during the field campaigns are shown in Table 1.

In September/04, the current velocity during ebb period was observed at the surface of the water column (0.11 and 0.28 $m.s^{-1}$), with a delay of approximately $2^{1/2}$ from the tidal peak. Average current velocity reached 0.23 $m.s^{-1}$. Current velocity during the flood period (0.11 and 0.24 $m.s^{-1}$) occurred $1^{1/2}$ before the tidal peak with average velocity of 0.17 $m.s^{-1}$ (Figure 2).

Table 1. Flow velocity variation and average values during flood and ebb periods at the Jaguaribe River estuary.

Sampling period	Type of sampling	ζ m ($m.s^{-1}$) flood	ζ m ($m.s^{-1}$) Ebb
September/04*	Spherical buoy	0.11-0.24 (0.17)	0.11-0.28 (0.23)
September/05*	Spherical buoy	0.10-0.60 (0.35)	0.20-0.40 (0.30)
September/05	ADCP	0.14-0.26 (0.24)	0.14-0.19 (0.17)
June/06	ADCP	0.23-0.52 (0.42)	0.26-0.38 (0.31)

* Values obtained using Equation 2.

In September/05, a regular year with annual rainfall inside the historical record (in the first semester, the average precipitation was of 55 mm that characterizes a period of positive hydrological balance; however in the semester second, the average precipitation was of 0 mm, that characterizes a period of negative hydrological balance), maximum current velocity during ebb tide (0.4 $m.s^{-1}$) was observed 3 hours before the ebb tide peak and reached an average of 0.3 $m.s^{-1}$ (Figure 3). During the flood tide maximum velocity occurred 4 hours after the peak of the ebb tide (0.6 $m.s^{-1}$) and showing average current velocity of 0.35 $m.s^{-1}$, as it observed below in the Table 1. These current velocities occurring in September/05 are typical of well mixed tropical estuaries with depths smaller than 5.0 m (Sylaios and Boxall, 1998; Kitheka et al., 2004).

As observed in 2004, an extremely rainy year, the total flow was dominated by fluvial waters, with current velocities typical of fluvial forcing and with seawater input considered as zero. In 2005, a regular year, the total flow was dominated by marine waters, showing higher velocities due to the lack of fluvial waters caused by droughts and river damming along the Jaguaribe River watershed, resulting in a very small amount of freshwater reaching the estuary. These results are well presented by the salinity measures of the estuarine water at Zone 1 during the campaigns (Figure 4). This dry year scenario with low river fluxes can explains the erosion of coastal features verified at the Jaguaribe mouth, due to lack of fluvial input to the estuarine region, as pointed by Lacerda and Marins (2002).

At the interface between flood and ebb tides, zeroing of ebb and flood tide forcing was not observed in the water column, resulting in zero velocity as typical of mid-water and deep currents due to vertical mix of the water column during low tide (Sylaios and Boxall, 1998).

To improve the understanding of the hydrological data and consequent dynamics controlling the physical processes at the Jaguaribe River estuary, an ADCP was used to measure current velocity of the selected river sections in September/05 (dry period) and June/06 (rainy

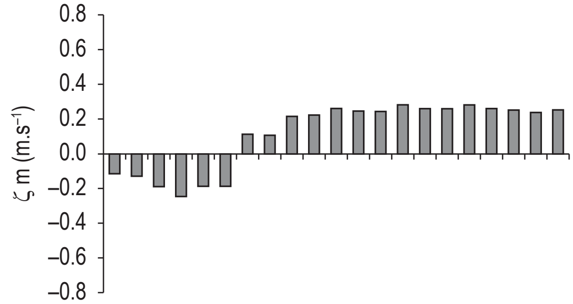

Figure 2. Flow velocity {ζ m ($m.s^{-1}$)} during flood and ebb tides at zone 1 (Figure 1) during a 12 hours period (7:30 AM to 5:30 PM, time intervals of 30 minutes) calculated according to Equation 2, for September/04.

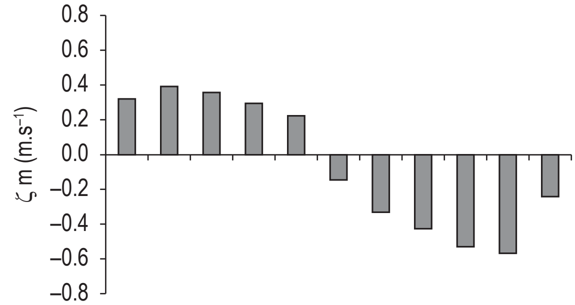

Figure 3. Flow velocity {ζ m ($m.s^{-1}$)} during flood and ebb tides at zone 1 (Figure 1) during a 12 hours period (6:00 AM to 6:00 PM, time intervals of one hour), calculated according to Equation 2, for September/05.

period). Current velocities for September/05 are presented in Figure 5, integrating average values at the bottom and surface layers at Zone 1. Maximum ebb period velocity occurred two hours before the peak of low tide reaching 0.20 m.s^{-1}. Highest current velocity during the flood period occurred 3 hours after the beginning of the low tide period reaching 0.27 m.s^{-1}.

When the delays of flood and ebb currents obtained with the ADCP are compared with the observed measurement with the limnimetric ruler, there is a displacement of 50 to 80%, probably because the ADCP integrates totally the water column.

In June/06 maximum ebb velocity occurred one hour before the ebb tide peak reaching 0.32 m.s^{-1}. Flood period maximum velocity occurred $2^{1/2}$ hours after the low tide reaching 0.52 m.s^{-1} (Figure 6).

Water salinity during the observed period varied between 5 and 12‰ (September/04); and from 0.1 to 0.2‰ (June/06). In September/05 (dry season), the observed salinity varied from 24.7 to 30.9‰ (Figure 4).

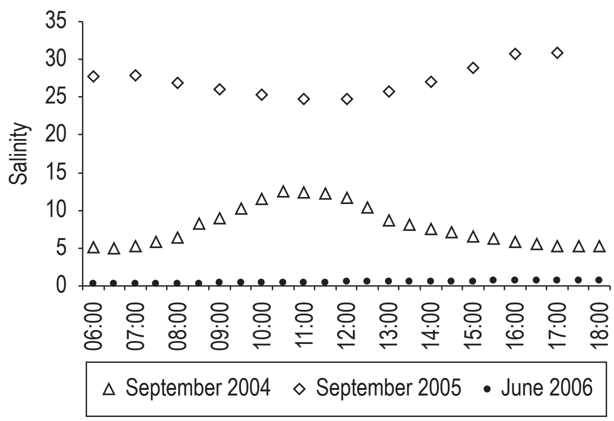

Figure 4. Salinity ($^{o}/_{oo}$) variations at the Jaguaribe River estuary, Ceará State in September/04 and 05, in June/06.

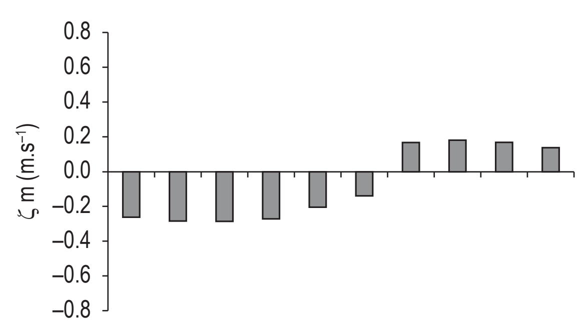

Figure 5. Flow velocity {ζ m (m.s^{-1})} during flood and ebb tides at zone 1(Figure 1) duringa 12 hours period (6:00 AM to 6:00 PM, time intervals of one hour), calculated using the ADCP, for September/05.

3.2. *Seasonal variation of the estuarine fluxes*

Total water fluxes to the Jaguaribe estuary varied from 20.4 to 350 m^{3}.s^{-1} during the studied period (Figure 7) showing a typical seasonal pattern.

During dry periods, stronger saline intrusion increases total water flux in the estuarine channel, mostly due to flood period fluxes. Fresh water flux is negligible. In 2004, when maximum fresh water volume was observed in the estuarine channel, total water fluxes varied from 20.4 to 69 m^{3}.s^{-1} (Figure 8). However, in 2005 a significant increase in total water fluxes was observed 26 to 226.7 m^{3}.s^{-1} (Figure 9). This was due to the low freshwater input to the estuary, increasing the tidal forcing during that period. The same sampling period (dry season) was used ADCP, where average values flow water of Flood and Ebb tidal at the dry season, observed the total fluxes varied from 78 to 172.2 m^{3}.s^{-1} (Figure 10).

In June/06, rainfall reached 70 mm, much higher than the historical average for this month, the highest values

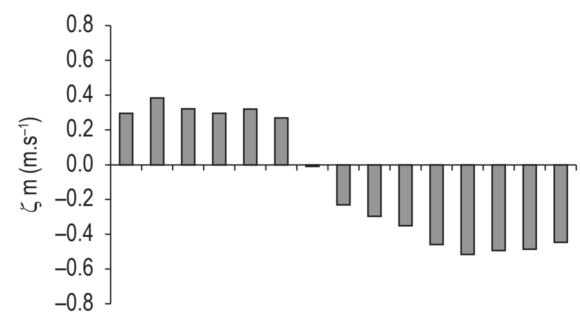

Figure 6. Flow velocity {ζ m (m.s^{-1})} during flood and ebb tides at zone 1 (Figure 1) during a 13 hours period (5:00 AM to 6:00 PM, time intervals of one hour), calculated according to ADCP, for June/06.

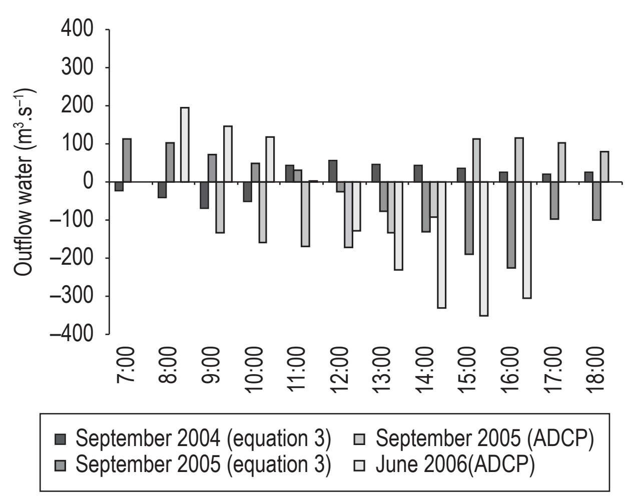

Figure 7. Calculated fluxes based on Equation 3 and measured with the ADCP for a 12 hours period (7:00 AM to 6:00 PM, time intervals of one hour) at Zone 1 (Figure 1).

measured during the past 100 years, resulting in salinity of 0.2. Instant fluxes ranged from 2 and 351 $m^3.s^{-1}$ (Figure 11), confirming the extremely high variability of river flow in short periods of time in the Jaguaribe River estuary (Campos et al., 2000).

Comparing historical river fluxes with our measurements, it is clear that river fluxes are larger in rain periods (February to March), but at the estuary fluxes are higher during dry periods when tidal forcing is maximum.

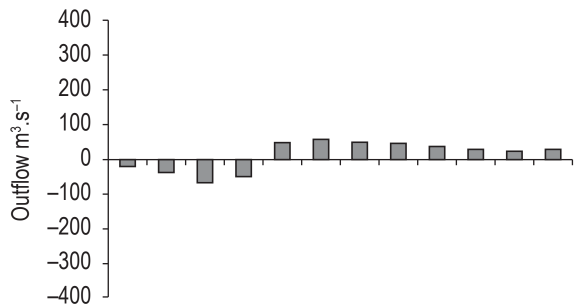

Figure 8. Water fluxes Q ($m^3.S^{-1}$) during flood and ebb tides at zone 1 (Figure 1) during a 12 hours period (7:00 AM to 6:00 PM, time intervals of one hour), based on Equation 3, for September/04.

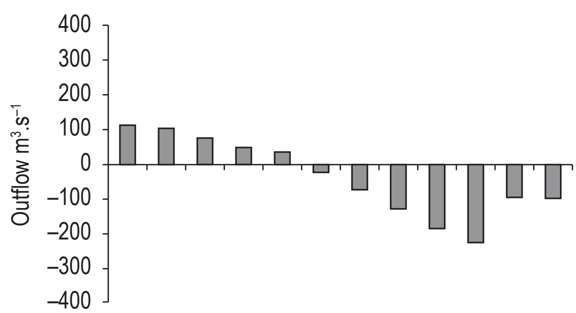

Figure 9. Water fluxes Q (m^3. S^{-1}) during flood and ebb tides at zone 1 (Figure 1) during a 12 hours period (7:00 AM to 6:00 PM, time intervals of one hour), based on Equation 3, for September/05.

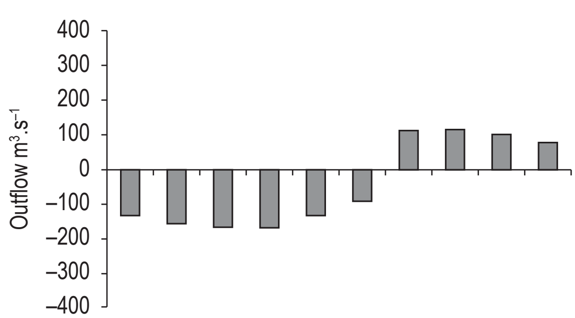

Figure 10. Water fluxes (m^3. S^{-1}) during flood and ebb tides at zone 1 (Figure 1) during a 10 hours period (8:00 AM to 5:00 PM, time intervals of one hour), calculated according to ADCP, for the dry season.

3.3 Residual tide

The tide prism was calculated from formulate applied by Sylaios and Boxall (1998) in the estuary of Southampton (England) (Equation 6). As it can observe in Table 2, a significant difference between the evaluated periods exists. Total fluxes of Flood and Ebb, observed in September/05, had an increase of more than 50% in relation to the observed ones in 2004. This fact can be inferred, since the difference between the two studied water masses, when in 2004, a great one was observed in large input freshwater in estuarine canal, not allowing flooding fluxes marine waters in continent.

If to collate the gotten average values fluxes water (Q) through the Equation 3 it dates to ADCP in the sampling, this difference does not exceed 13%, showing the effectiveness of the methodologies used in this study to average outflows, standing out that the results gotten with the Equation 3, they take in consideration only the superficial portion of the water mass. However the tidal prism calculated according ADCP, the sampling period was of 12.6 at 73.1 $m^3.s^{-1}$, where the high values observed the rainy season.

Residual fluxes or Tidal Prism in well mixed estuaries, such as the Jaguaribe River, depend on the position of the site where the measurement is taken, the tidal amplitude, the fluvial discharge and meteorological variability.

Tidal prism values were representative for each studied period showing no negative values suggesting high freshwa-

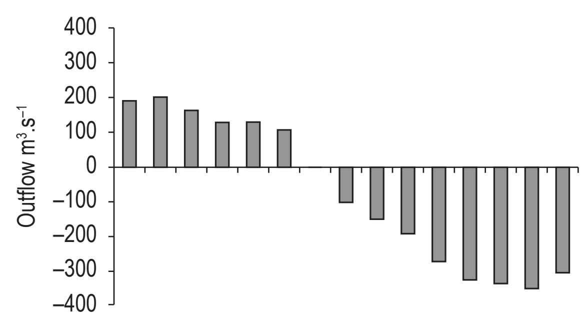

Figure 11. Water fluxes (m^3. S^{-1}) during flood and ebb tides atzone 1 (Figure 1) during a 15 hours period (5:00 AM to 7:00 PM, time intervals of one hour), calculated according to ADCP, for the rainy season.

Table 2. Water fluxes during ebb and flood periods and prism flux at the Jaguaribe River estuary. Average values.

Sampling period	V_{Flood} ($m^3.s^{-1}$)	V_{Ebb} ($m^3.s^{-1}$)	V_{Prism} ($m^3.s^{-1}$)	Q ($m^3.s^{-1}$)	Salinity
September/04*	51.5	38.9	12.6	40.2*	7.8
September/05*	124.4	73.3	51.1	101.1*	27.2
September/05 ADCP	132.3	94.8	37.5	115.3	29.0
June/06 ADCP	153.5	226.6	–73.1	197.3	0.2

* Values obtained using Equation 3.

ter input from the fluvial end member, and the importance of river damming in controlling water availability to the estuary and the sea. Tidal amplitude increases or decreases water level at the estuary suggesting the strong tidal influence upon the estuary that influences the biogeochemical processes as observed by earlier studies (Marins et al., 2003; Marins et al., 2007; Eschrique et al., 2008).

4. Conclusions

This article shows the importance of preliminary studies on the physical and hydrodynamic characteristics of circulation of well-mixed estuaries, situated in the semi-arid (Northeastern Brazil), relating the tidal effect of with the standards water of circulation, showing clearly the function of deterministic models in the study of these regions.

The tidal effect seems to be dominant in the estuarine canal in periods of dry season, making with that the Flood fluxes are higher to the Ebb Fluxes, denoting a classification of importer estuary in the period of dry season, for the estuary of the Jaguaribe River.

When compared the gotten fluxes according to Equation 3 and ADCP for zone 1 (Figure 1) of the estuarine canal of the Jaguaribe River for the year of 2005, these values do not exceed 13% of the total value, thus allowing one raised trustworthiness of the adopted methodologies in this study.

The values of the tide prism had been representative for each sampling period, not being observed negative values, that indicate high values of freshwater fluxes candy of the fluvial system, clearly showing that the successive dams to the long one of the draining of basin of the Jaguaribe River are affecting drastically the hydrological availability for the estuarine system and adjacent ocean.

The tidal amplitude of raise and diminish the water level in the estuary, showing a strong domain of the Flood fluxes, explicit the existing of tides domain in the estuary.

The tidal amplitude can arrive the 2.8 m, the observed tidal regime is a meso-tidal semi-diurnal type. A comparison of this amplitude to the curve of average ideal tide from data of the board of tide for the Port of Areia-Branca Termisa (Rio Grande do Norte), for being the next coastal zone estuary, is observed that a fluctuation of 2.1 m in national graphic standard of tide inside means a fluctuation of the estuary of 1.4 m. However, valley to stand out that the tide curve ideal, for the given ones of standard national graphic of tide, is symmetrical and the curve measure is not symmetrical, due to waste of the tide wave on flooding plains.

The system of currents in Jaguaribe River shows a very complex pattern during the tidal cycle, with variability outside the river main channel. This differentiation of the system of currents influences the transport of materials to the sea.

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