Anais da Academia Brasileira de Ciências (2014) 86(2): 555-570
(Annals of the Brazilian Academy of Sciences)
Printed version ISSN 0001-3765 / Online version ISSN 1678-2690
http://dx.doi.org/10.1590/0001-37652014114012
www.scielo.br/aabc

Hydrodynamic Aspects at Vitória Bay Mouth, ES

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Manuscript received on September 27, 2012; accepted for publication on June 5, 2013

ABSTRACT

Understading the hydrodynamic behavior and suspended particulated matter (SPM) transport are of great importance in port regions such as Vitória Harbor, which is located at Vitória Bay, Vitória – ES, Brazil. Vitória Bay is an estuary that has not been systematically assessed through a temporal analysis in order to identify its hydrodynamics characteristics and SPM exchange. This study aims to investigate salt and suspended particulate matter flux at the estuarine mouth of Vitória Bay by understanding the temporal variation of salinity, temperature and tidal currents within the water column and at the channel cross-section. Results showed that the estuarine mouth tended to present partial stratification periods during neap tides and little stratification in spring tides. The circulation pattern was mainly influenced by the tide, with little influence from river discharge. With regard to the SPM, the mouth of the estuary tended to show low concentrations, with the highest values occurring during the dry season. A close relationship between momentary discharge, SPM and salt fluxes was observed. Despite all the data was collected at the mouth of the estuary, the system showed an importation trend of salt in all cycles and SPM importation for three of the four studied tidal cycles. Thus, Vitoria Bay is not exporting SPM to the adjacent inner shelf.

Key words: Estuary, hydrodynamics, suspended particulate matter, Vitória Bay.

INTRODUCTION

Estuarine dynamics are controlled by river discharge, tides, waves, wind, meteorological forcings and the geometry of the estuary (Nichols and Bigs 1985, Miranda et al. 2002). One of the most suitable methods for analyzing large amounts of hydrographic data associated with an estuary is to calculate the longitudinal flow of salt and suspended particulate matter (SPM), making it possible to visualize the resulting transport (Medeiros and Kjerfve 2005). By studying the behavior of SPM, therefore, we can establish its residence time in the estuary and the influence of tidal currents in sediment transport (Dyer 1997).

Estuaries do more than just export materials; these environments act as a filter, retaining most of the substances from the watershed and coastal zone. Thus, investigations on the hydrodynamic behavior and SPM transport are of great importance in port regions such as Vitória Harbor. Vitória Bay, despite being an estuary of social, economic and environmental importance for the development of the state of Espírito Santo, has not been systematically assessed through a temporal analysis to identify its characteristics and SPM hydrodynamic exchange. Previous studies regarding the management of Vitória Harbor have always been of a practical nature

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and have addressed dredging navigation or safety. Thus, this estuarine system has been the target of numerous anthropogenic disturbances with virtually no scientific knowledge of their behavior, except for some studies involving hydrodynamic modeling, with limited data acquired *in situ.*

This study aims to investigate the flow of salt and suspended particulate matter at the estuary mouth of Vitória Bay by understand salinity, temperature and the temporal variation in currents within the water column and at a channel cross-section.

STUDY AREA

From a geomorphological point of view, Vitória Bay (Fig. 1) is a drowned river valley. The Santa Maria da Vitória river is the main source of fresh water, with an average flow of 15.7 m^3/s (Rigo 2004), followed by the Format/Marinho and Bubu rivers, among others (Veronez et al. 2009). The presence of dams in the middle and downstream of Santa Maria da Vitória River controls the flows that reach Vitória Bay.

WithinVitória Harbor, there has been an increasing need for dredging; over the years, similar types of interventions have created a much deeper channel in the section between the mouth and the inflexion point to the north. Consequently, this portion is dynamically different from the rest of the system.

Vitória Bay is a microtidal estuary. Neves et al. (2012) observed that an asymmetrical current pattern occurs near Vitória Harbor, particularly during spring tides, with the ebb tide reaching more than 1 m/s and the flood tide approximately 0.3 m/s. This asymmetry is also found during neap tides, although it is not as prominent; the ebb and flood current speeds are approximately 0.3 and 0.1 m/s, respectively. According to these authors, the region of the estuary near Vitória Harbor has the characteristics of well-mixed estuaries during the spring tide and partially mixed during neap tides.

In terms of SPM dynamics, Neves et al. (2012) show that SPM transport and bedload are directly associated with the tidal current patterns, primarily the ebb tide, demonstrating a trend of sediment export in this portion of the system. Moura et al. (2011), estimating SPM concentration throughout the water column to the inner portions of the estuary, also observed higher concentrations during spring tides and near the bottom. Furthermore, those authors found a higher concentration at moments of higher current velocity during both ebb and flood tides.

Wind direction in this region is predominantly from the northeast, with winds from the southeast less frequent but with greater intensity and associated with cold fronts. The period of greatest rainfall occurs from November to March; lower levels of rainfall occur from June to September.

MATERIALS AND METHODS

The investigation of SPM and salt flows at the mouth of Vitória Bay was performed by taking measurements along a channel cross section (Fig. 1). This section was chosen because it, geomorphologically, represents the estuary mouth. Measurements were taken during both the rainy and dry periods and included neap and spring tides. The survey consisted of the acquisition of speed and current direction and physical parameters (salinity, temperature and SPM).

Data were collected during four periods: two during the dry season and two during the rainy season. For each station, data were obtained during one cycle of spring and neap tide cycle (approximately 12 hours per cycle). The neap cycle during the dry season was denoted as QS (09/15/2010), and the spring tide was labeled SS (09/22/2010). During the rainy season, neap tide cycles were labeled as QC (11/29/2010) and spring tides as SC (12/03/2010).

Velocity and current direction measurements were taken continuously along the transect, at 20-minute intervals, using an ADP (Acoustic

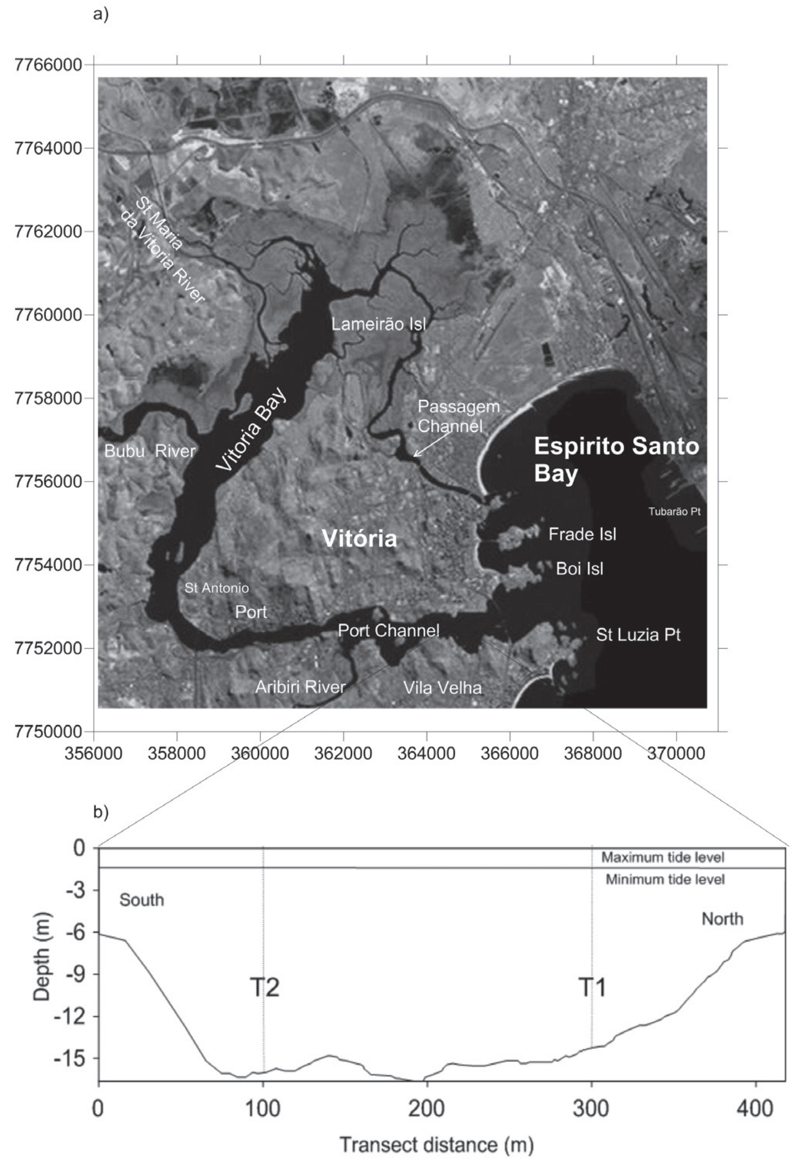

Figure 1 - a) Study area; **b)** channel morphology and sample stations (T1 e T2). The cross section shows three sub-sections described as south and north shores and main channel.

Doppler Profiler) SonTek River Surveyor M9/YSI 3 to 0.5 kHz with bottom track (SonTek/YSI, San Diego, CA, USA). To analyze the current patterns, the data were averaged over 5m in horizontal and split into a longshore (east-west) and a cross-shore component (north-south).

To obtain salinity, temperature, and depth data in the water column, we used a OBS3A-CTD (Campbell Scientific), acquiring data hourly during a tidal cycle on two points of the transect (T1 and T2) (Fig. 1b). Density values were calculated using the equation for the state of sea water at atmospheric pressure, $\rho = \rho\ (S,T)$, where S represents salinity and T is the temperature. Despite having a turbidity sensor in the OBS3A, the data could not be used due to a calibration inconsistency with the SPM collected in situ, most likely due to the low SPM concentration. Water samples (1000 ml) were collected hourly with a Van Dorn bottle at the two points (T1 and T2), and at three depths (surface, middle and bottom) totaling 39 samples per cycle. The water samples were stored in the dark until the next day, when filtering was performed.

The samples were filtered using GF/F filters with pores of 0.45 microns. The SPM concentration level was determined by calculating the ratio of dry mass retained on the filter to the filtered volume.

Fluxes were obtained using the method described by Miranda and Castro (1996) and Miranda et al. (2002). The average of salt flow (*Fs*) ($Kg.m^{-1.}$ S^{-1}) is the average of instantaneous flow (*Ms*) during one or more tide cycles:

$$F_S = \frac{1}{T}\int_0^T M_S\,dt = < \overline{\rho}\overline{uSh} > \qquad (1)$$

where $\overline{\rho}$ is the density, (Kg/m^3) $\overline{u}$ is the velocity (m/s) and $\overline{S}$ is the average salinity in the water column, and h is the depth (m).

For the SPM flow, the same relationship can be considered (Dyer 1995, 1997) Therefore, the flow of SPM ($Kg.m^{-1}$ S^{-1}) is described by:

$$F_{MPS} = \frac{1}{T}\int_0^T M_{MPS}\,dt = < \overline{uCh} > \qquad (2)$$

where $\overline{C}$ is the average concentration in the water column of SPM (Kg / m^3).

The stratification analysis was calculated using the Layer Richardson number (R_{iL}). Richardson's number (R_i) compares the influence of the vertical density gradient ($\partial\rho/\partial$z) and the influence of shear velocity ($\partial u/\partial$z) in the process of water column stabilization, indicating their stratification ability. However, due to difficulties in obtaining precise measurements for the gradient, the Layer Richardson number (R_{iL}) has been primarily used in a modified form to better reflect the characteristics of the entire flow, and is defined as:

$$Ri_L = \frac{gh\Delta\overline{\rho}_v}{\overline{\rho}\overline{u}^2} \qquad (3)$$

where h is the local depth; $\overline{u}$ and $\overline{\rho}$ are the average speed and density in the water column, respectively, and $\Delta\overline{\rho}_v$ is the density difference between the bottom and the surface.

Dyer (1982) proposed practical limits for the Layer Richardson Number according to the mixing process; thus, where $Ri_L > 20$, the turbulence generated by the bottom is unable to reduce stratification, leading to stratified estuaries; when $20 > Ri_L > 2$, the mixing process develops steadily, but there is still some stratification (i.e., partially mixed estuaries); and where $Ri_L < 2$, there is complete mixing of the water column or well-mixed estuaries.

To understand the residual flow knowledge about the tidal residual is required, which is obtained by calculating the tide asymmetry. In this study, asymmetry index was used (AI_{DV}) (Mantovanelli et al. 2004). This dimensionless index was based on parameters proposed by Lincoln and Fitzgerald (1998) and is represented by the sum of duration asymmetries (A_D) and velocity (A_V), where:

$$AI_{DV} = A_D + A_V \qquad (4)$$

The asymmetry of time is described by the difference between the time of ebb and flood tide (t_v) divided by the sum of the two (t_e).

$$A_D = (t_e - t_v) \,/\, (t_v + t_e) \qquad (5)$$

The velocity asymmetry is the difference between the average longshore velocity in the water column during the ebb and flood ($\overline{u_v}$) divided by the sum of two ($\overline{u_e}$).

$$A_v = (\overline{u_v} - |\overline{u_e}|) \,/\, (\overline{u_v} + |\overline{u_e}|) \qquad (6)$$

Thus, when:

$AI_{DV} = 0$, the tidal wave is symmetrical for time and velocity;

$AI_{DV} > 0$, the residual circulation and water transport are directed to ebb;

$AI_{DV} < 0$, the residual circulation and water transport are directed to flood.

RESULTS AND DISCUSSION

Temporal Variation of the Properties and Currents

Table I summarizes the main findings, considering measured and calculated data during each cycle. It was observed that along the channel, the residual flow was consistently seaward (positive values in Table I), except for the QC cycle, when the residual flow was toward the mainland (negative values). On the south shore of the channel, water residual transport was mainly toward the mainland, except for the SC cycle, which was toward the sea. On the north shore, the residual flow was toward the sea in the neap tide cycles and toward the mainland during the spring tide cycles.

TABLE I
Values for each cycle. $<\delta S>$ = salinity range between the surface and bottom; $<\bar{\rho}>$ = average density in the water column; $<Ri_L>$ = the average Layer Richardson number per cycle; QS = neap cycle during the dry season; = SS spring cycle in the dry season; QC = neap cycle during the rainy season; SC = spring cycle in the rainy period. Positive values are toward the ocean; negative values are toward the mainland.

		09/15/10 QS	09/22/10 SS	11/29/10 QC	12/03/10 SC
Area (m^2)	Mean	4973.7	4906.8	4933.0	5123.4
	Maximum	5276.0	5344.3	5304.4	5680.8
	Minimum	4391.6	**4235.5**	4701.8	4834.7
Mean width (m)		436.00	425.21	**418.88**	**440.8**
Residual Discharge ($m^3.s^{-1}$)	Channel	**18.39**	**235.31**	-106.1	88.46
	North shore	0.07	-0.07	0.03	-0.01
	South shore	-0.03	-0.013	-0.02	0.24
Tidal Range (m)		1.00	1.52	1.04	1.35
Longshore velocity ($m.s^{-1}$)	Residual	0.004	0.04	-0.02	0.01
	Mean flood	**-0.04**	-0.22	-0.14	-0.21
	Mean ebb	0.03	**0.38**	0.11	0.26
$<\delta S>$		3.1	0.4	4.9	1.9
$<\bar{\rho}>$		1023.46	1023.89	1022.99	1023.66
$<Ri_L>$		13.10	0.76	13.43	3.75

According to Valle-Levinson et al. (2009), flows governed by the tide have the highest exchange during spring tide, and the flow in the main channel is towards the sea with the characteristic of progressive tidal waves. In flows where the density has a predominant role and friction has greater effectiveness, the largest water exchange occurs in neap tides, with characteristics of standing waves, where the residual flow in the main channel is toward the mainland. As the flow discharges, residual longshore velocity, except in the QC, was towards the sea. It is noteworthy that residual velocities in ebb water were higher in spring tide cycles (0.38 and 0.26 m/s during the dry and rainy season, respectively). In the neap tide, the residual velocity during flood prevailed with -0.04 m/s in the dry season and - 0.14 m / s in the rainy season.

With respect to salinity, it was observed that during the neap tides, the difference between the surface and bottom was higher in relation to spring tide cycles, indicating greater stratification; where as during SS, this value was less than unity, indicating almost no stratification. The Layer Richardson number reaffirms this mixed pattern, and in the cycle (SS) showed a value of 0.76. Furthermore, this cycle had a higher average density (1023.89 kg m^{-3}), indicating a more saline water, followed by SC, QS and finally QC (Table I).

Figures 2 to 5 show the profiles of salinity, temperature, Layer Richardson number, and the tide range, where point T1 is near the north shore and T2 is located near the south shore. A direct relationship was found between the temporal variation in salinity and tide range; salinity followed the tide pattern (Figs. 2, 3, 4). Moreover, during QC (Fig. 3), stratification was noticeable immediately after low tide (between 16 and 18 hours), with ranging salinity from 28 at the surface and 35 at the bottom and the Layer Richardson number above 20. During the QS cycle (Fig. 2), a stratification tendency was observed with a salinity of 31 at the surface and 35 at the bottom and a higher Layer Richardson number (10 to 15); however, it did not reach the boundary value of 20 that Dyer (1982) defined as stratified. Moreover, the tidal range was higher during a rainy neap cycle (QC 1.04 m) than during a dry neap cycle

(QS 1.0 m) (Table I), which likely contributed to this slight stratification. According to Dyer (1997), for a mixed estuary, a substantial high tide is a requirement, but in a microtidal estuary, this intense homogenization can also be afforded by a low river inflow into the estuary. This fact was also verified by Pereira et al. (2010) and Schettini and Miranda (2010) in the Caravelas Estuary (BA, Brazil) and Schettini and Carvalho (1999) in the Babitonga Bay (SC, Brazil).

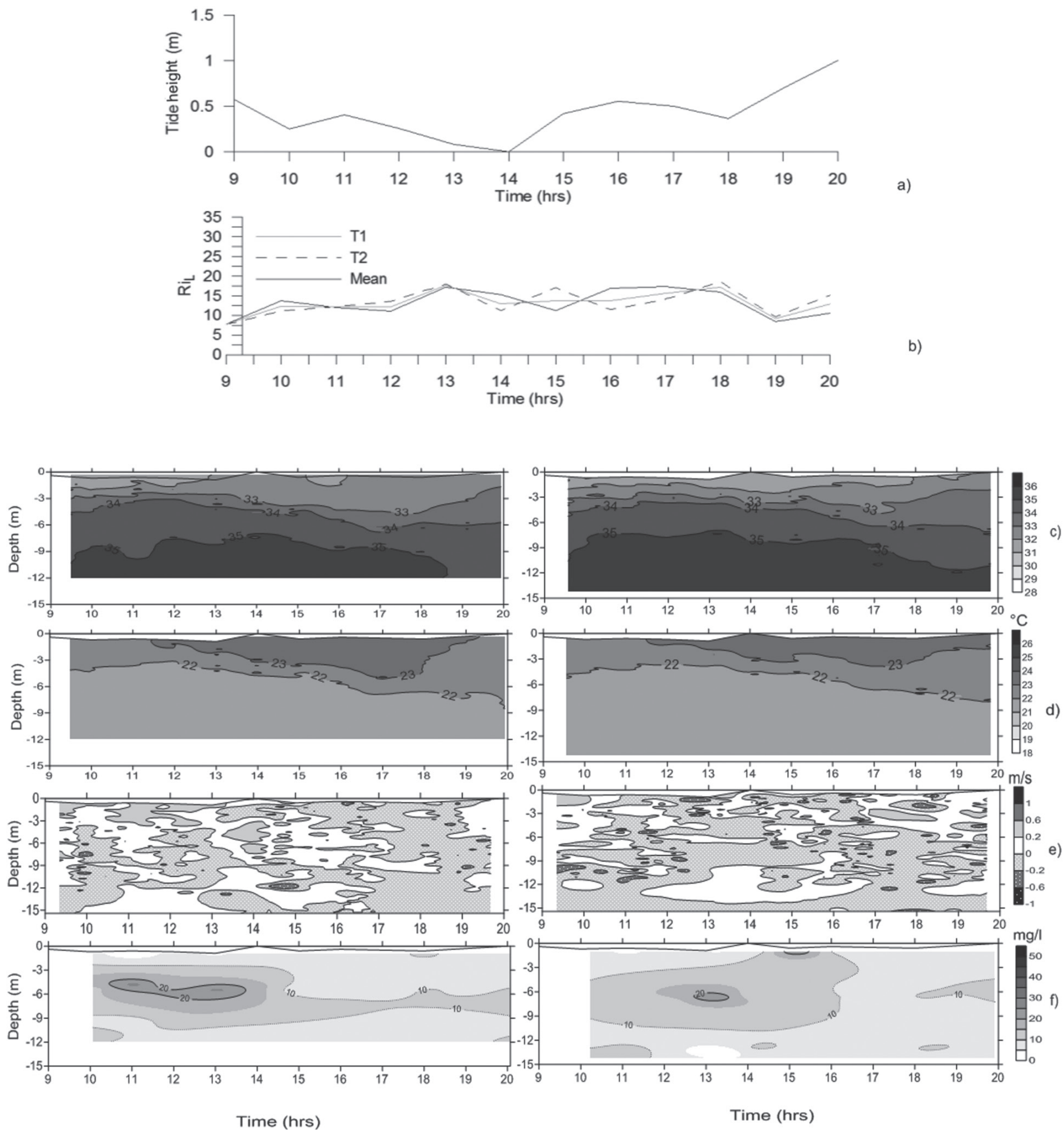

Figure 2 - Temporal profiles of QS (neap cycle during the dry season - 09/15/2010); **a)** tide elevation (m); **b)** Layer Richardson number; **c)** salinity (PSU) **d)** temperature (°C); **e)** longitudinal velocity (m/s); **f)** SPM (mg/L);. Left column is station T1 and right column station T2.

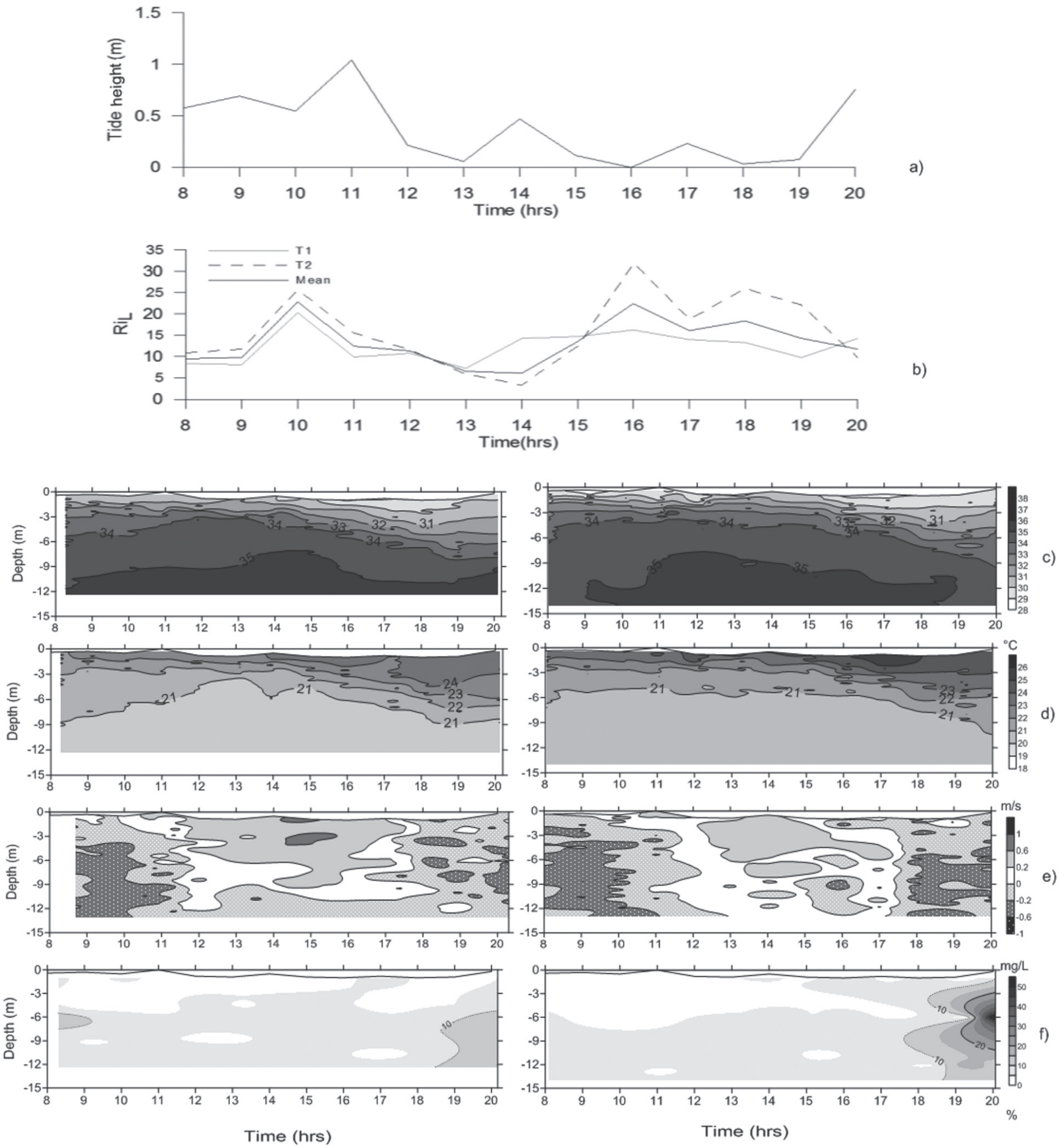

Figure 3 - Temporal profiles of QC (neap cycle during the rainy season - 11/29/2010); **a)** tide elevation (m); **b)** Layer Richardson number; **c)** salinity (PSU) **d)** temperature (°C); **e)** longitudinal velocity (m/s); **f)** SPM (mg/L); .Left column is station T1 and right column station T2.

Stratification was very low during SC (Figs. 5b, c). The values for Ri_L were almost always 2, except during periods of high or low tide, where the layer Richardson number increased, becoming close to 10 (Fig. 5b), confirming that if the river flow is low, the tide is the variable that most influences the salinity distribution at this portion of the estuary. During SS (Fig. 4b), Ri_L values were below 2, in this case a mixed condition, except for the period of low tide (approximately 9-10 hours) when

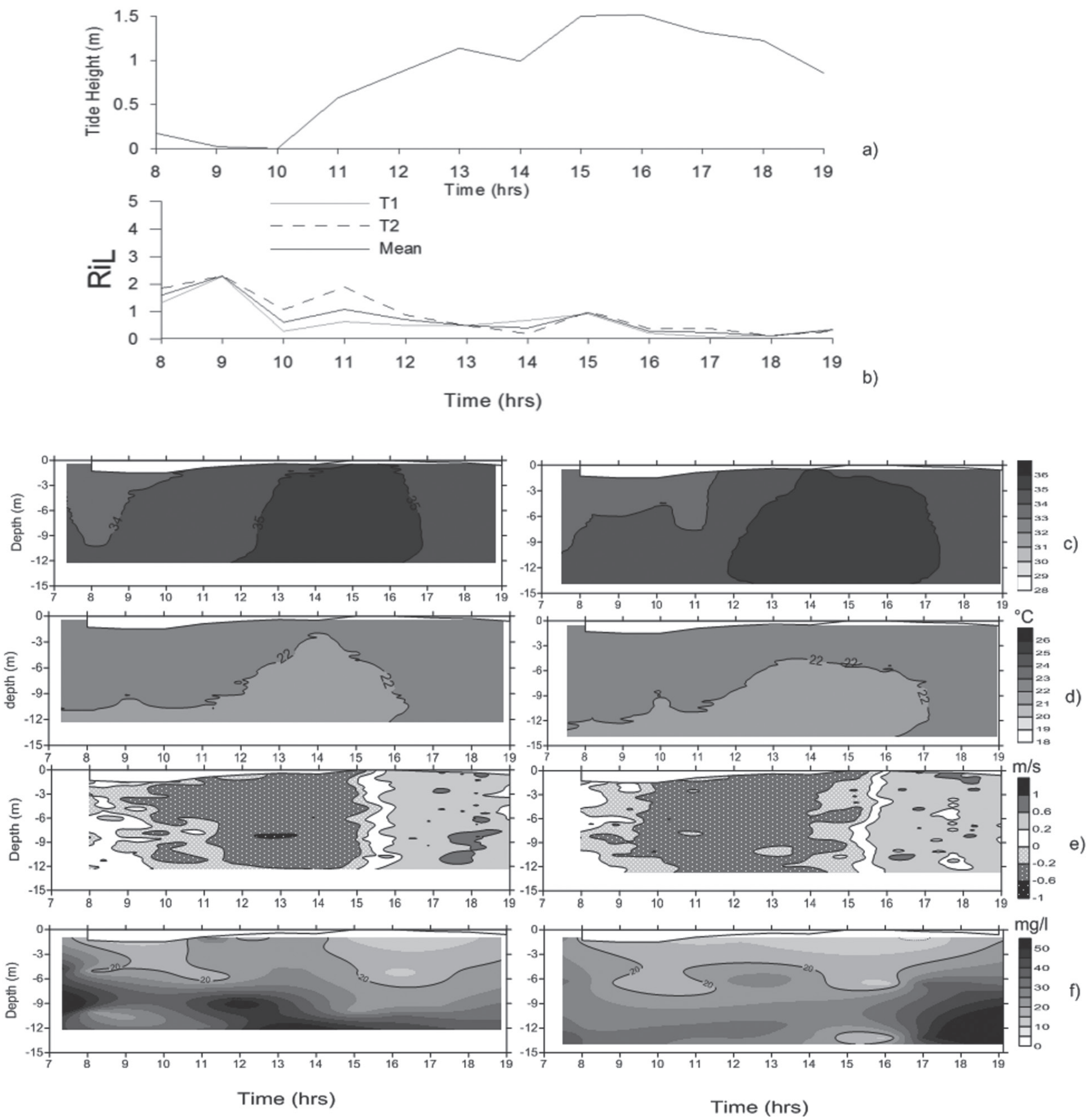

Figure 4 - Temporal profiles of SS (spring cycle during the dry season - 09/22/2010); **a)** tide elevation (m); **b)** Layer Richardson number; **c)** salinity (PSU) **d)** temperature (°C); **e)** longitudinal velocity (m/s); **f)** SPM (mg/L); Left column is station T1 and right column station T2. Different scale due to values.

the values were slightly higher (Figs. 3b, c). The same patterns in stratification variation, between spring and neap tides, and consequently the same correlation with the Layer Richardson number, were observed by Zem (2008), Mantovanelli et al. (2004) and Genz (2006).

As with the salinity, the temperature also appeared (even with small variation) to be affected by the tide; higher temperatures coincided with times of low tide and lower temperatures with high tide (Figs. 2d, 3d, 4d, 5d). The presence of mangrove and tidal flats means that during high

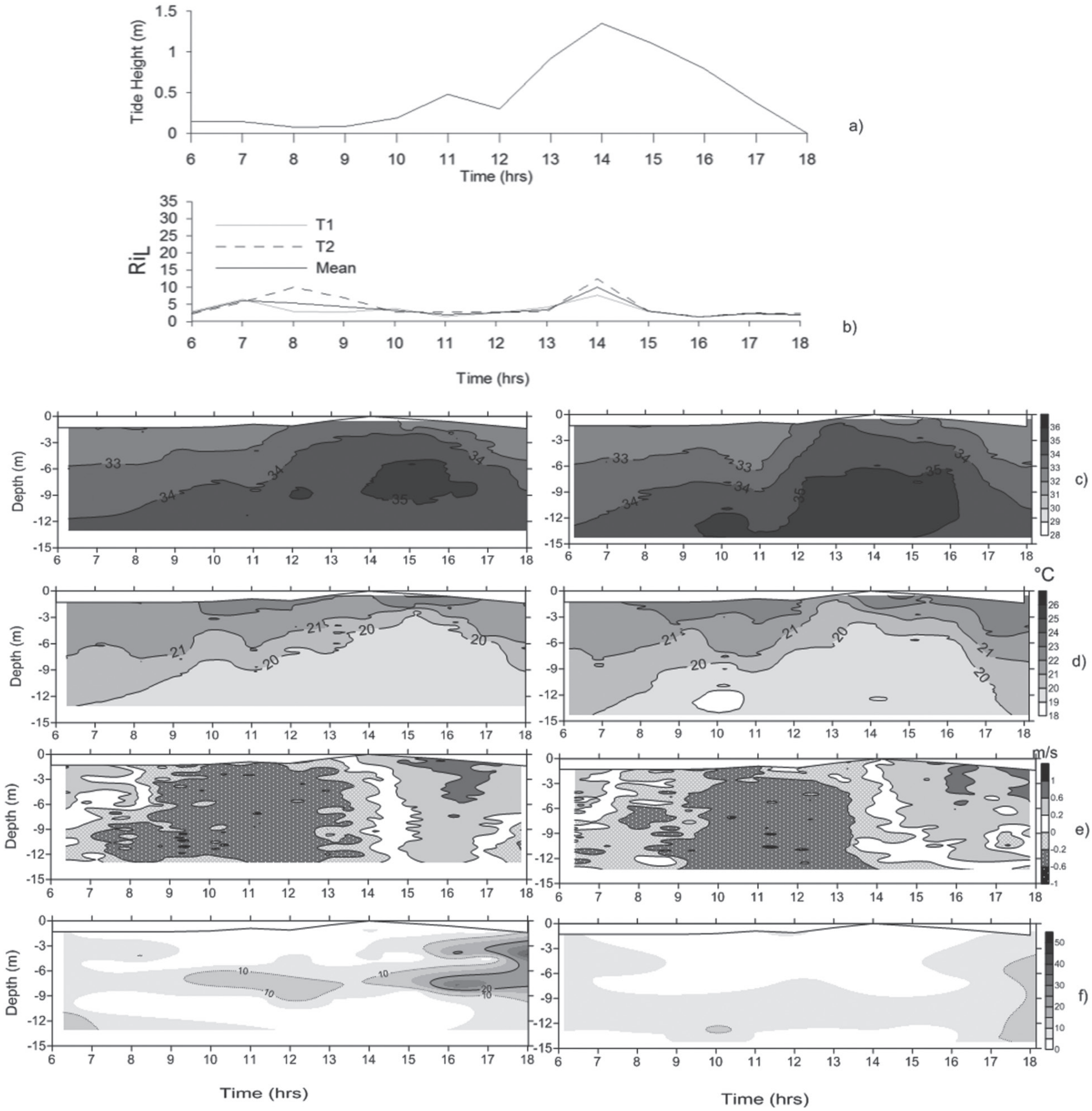

Figure 5 - Temporal profiles of SC (spring cycle during the rainy season - 12/03/2010); **a)** tide elevation (m); **b)** Layer Richardson number; **c)** salinity (PSU) **d)** temperature (°C); **e)** longitudinal velocity (m/s); **f)** SPM (mg/L); .Left column is station T1 and right column station T2.

tide, the water is stored, allowing it to heat. Thus, higher temperatures are related to water coming from the estuary upstream and cooler water transported from the ocean. The same relationship holds for the neap and spring tide; during the neap tide, the area reached by the water is smaller; therefore, the temperature did not increase significantly (Figs. 2d, 3d, 4d, 5d).

In general, it was observed that during the neap tides, the estuary was partially mixed. In the rainy season, during periods of high and low water, there was strong stratification. Such a situation is conditioned by the small tide amplitude and a small increase in freshwater discharge initiating the entrainment mechanism. This process is a unidirectional transfer, where the salt of the lower layer passes to the upper layer, which is less saline through the advection, originating a movement in the estuary through the bottom layer (Dyer 1997, Miranda et al. 1995, 2002).

In contrast, the spring tide cycles exhibited characteristics of well-mixed estuaries. Thus, during spring tides, the predominant process was turbulent diffusion, which, together with entrainment, tends to cause mixing. According to Dyer (1997), turbulent processes can be of three types: those generated by the stress with the bottom or channel margin; those generated by the influence of the salinity vertical gradient; and turbulence from the surface caused by wind and wave action. These processes occur due to higher tide amplitude (relative to the neap tide), where current velocity is higher; therefore, friction causes a destabilization of the water column and breakage of stratification, leading to mixing.

The essential difference between entrainment and turbulent diffusion is the degree of turbulence in the surface and bottom layers. If the turbulence is equal in both layers, entrainment is minimized, and the mixing process occurs by turbulent diffusion. Alternately, if the bottom layer is static, then there is no turbulent diffusion along the interface, and the mixing process is entirely entrainment. Thus, entrainment occurs at high values of Ri_L, and turbulent diffusion at low values. Consequently, highly stratified estuaries are dominated by entrainment, whereas in partly mixed estuaries, turbulent diffusion is dominant (Dyer 1997).

Flow Characterization

The tidal current is the primary forcing acting in the stratification and mixing process; the secondary forcing is freshwater discharge (Mantovanelli et al. 2004). In spring tide periods, there is an increase in the current velocities due to increasing amplitude of the tide, which contributes to expansion of the mixing process. Conversely, when there is a decrease in current velocity, the advective process generates a greater vertical stability, thus enabling the initiation of stratification. This explanation confirms what was described above for the study area as well as findings from previous studies by Kjerfve (1986), Kim and Voulgaris (2008), Siegle et al. (2009) and Mantovanelli et al. (2004). In contrast, the degree of salinity stratification governs the estuarine dynamic by acting as a feedback loop once it inhibits an increase in vertical mixing, decreasing the turbulent viscosity (Scully et al. 2005).

Mantovanelli et al. (2004) found that greater asymmetry is common during the spring tide, due to the intensification of the currents. It is important to note that tidal asymmetry influences the stratification pattern throughout the water column (Kim and Voulgaris 2008).

The results of the asymmetry analysis are shown in Table II, for the all tidal cycles studied.

TABLE II
Duration asymmetry (A_D), Velocity asymmetry (A_V) and residual (AI_{DV}).

	QS (09/15/10)	QC (11/29/10)	SS (09/22/10)	SC (12/03/10)
A_D	0.24	0.21	-0.30	-0.08
A_V	-0.12	-0.12	0.20	0.12
AI_{DV}	0.12	0.09	**-0.10**	0.04

In Table II, there is a duration asymmetry and residual positive (toward the sea) in most cycles except for the spring tide cycle during the dry season (SS), where the asymmetry was toward the mainland. However, this was the only cycle that the tide did not reach the same levels of low tide and high tide (Table II). Asymmetry toward the sea was also observed by Garel et al. (2009) in spring tide cycle at times of low river discharge; this finding was related to turbulent diffusion originating from a well-mixed estuary, as occurs in the study area for this cycle.

Moreover, it is clear that the neap cycles tended to have an asymmetry in duration toward the sea and velocity toward the mainland, while the opposite occurred for the spring tide cycles. Regarding the variation between the dry and rainy seasons, there was greater asymmetry in the first due to turbulente diffusion; the rainy season tended to be somewhat more symmetrical, mainly in the spring period, where the index approached zero.

This asymmetry was also influenced by the presence of mangroves in the region upstream of the estuary, which causes a delay in the tide around high tide, favoring an increase in the time of flooding and decreasing the time during the ebb. Consequently, the ebb velocity becomes more intense than the flooding (Rigo 2004). In neap tides, the influence of mangroves is low, leaving the estuary with characteristics of shallow estuaries, which generally have flood dominance (Dyer 1997, Rigo 2004). Corroborating the findings of this study, Rigo and Chacaltana (2006) determined that a 50% difference in current intensity occurred when mangrove areas were not considered in a modeling study. Thus, the estuary would be able to develop a flood asymmetry.

In addition, a small laterality was also observed between flood and ebb during spring tides. The flood tide has a higher velocity in the southern part of the mouth and the ebb in the north (Fig. 6). Another point that confirmed the behavior described above was that salinity and temperature had greater vertical variation in T2 during the flood and at T1 during the ebb (Figs. 2c, d, 3c, d, 4c, d, 5 c, d).

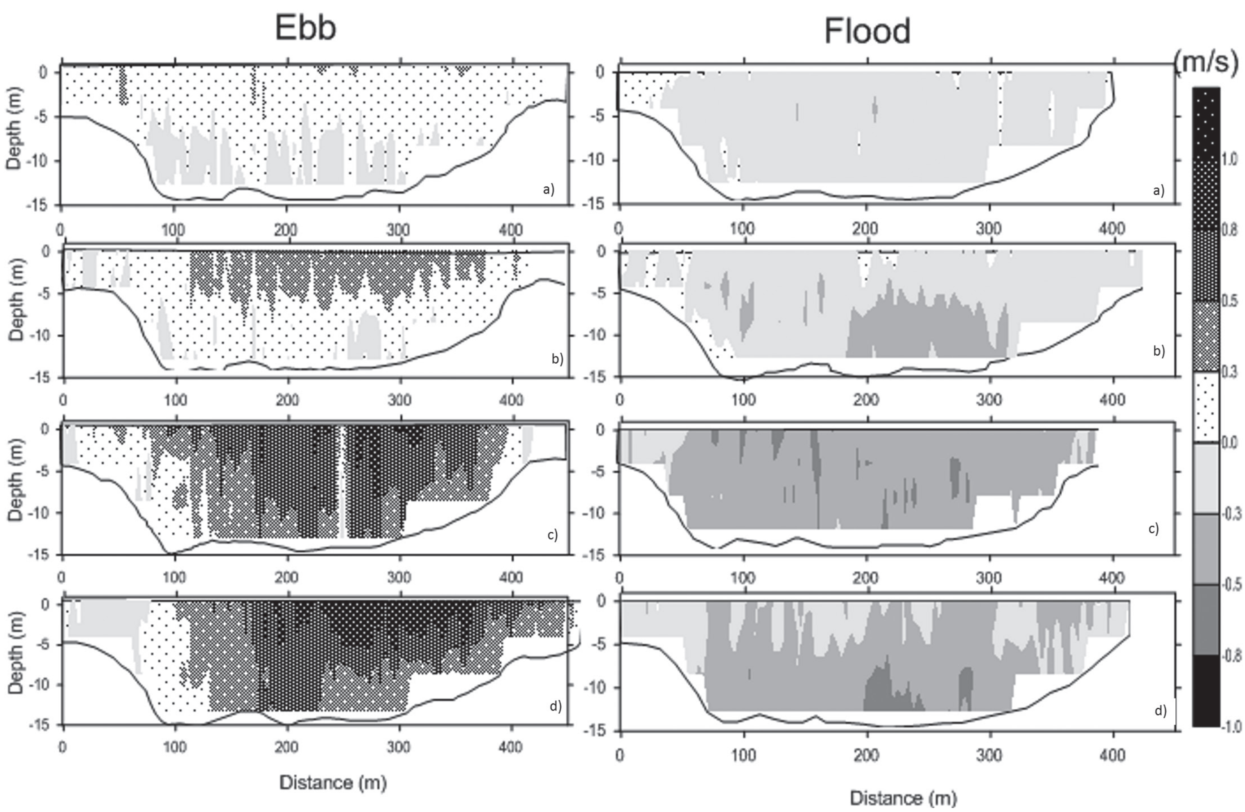

Figure 6 - Mean values for longitudinal velocity (m/s) along the channel cross section, during ebb and flood tides. **a)** QS – neap cycle during the dry season - 09/15/2010; **b)** SS- spring cycle during the dry season - 11/29/2010; **c)** QC – neap cycle during the rainy season - 09/22/2010 and **d)** SC – spring cycle during the rainy season - 12/03/2010.

The residual flow in estuaries is a result of competition between two processes: tidal pumping and gravitational circulation. The first (tidal pumping) causes a flow toward the continent in the upper layer and a seaward flow in the lower layer proportional to $< a.u / h >$, where a is the tide amplitude, u is the velocity at the surface and h is the channel depth during one or more tidal cycles. The tidal pumping is more effective in shallow estuaries where the a/h ratio is higher. Thus, the residual transport is toward the mainland in shallow areas and towards the sea in deep channels, as was seen for the dry season for both spring and neap tides (Table II). In the second case (gravitational circulation), the opposite occurs; the residual flow towards the sea is in the surface layer and toward the mainland in the bottom layer, induced by the density gradient. Thus, the flow is often toward the continent in deep channels and toward the mouth in shallow channels. In our case, the neap tide during the rainy period fits as well (Table II) (Pritchard 1952, Wong 1994, Li et al. 1998, Blanton and Andrade 2001).

SPM Temporal Variation and Quantitative Characterization

The concentrations of SPM were low, the maximum values were 55 mg/l (Figs. 2f, 3f, 4f, 5f). The higher mean values were for both neap and spring tides for dry season with values of 9.48 and 25.05 mg/l, respectively. The rainy season had a concentration of approximately 6 mg/l (Table III). Medeiros and Kjerfve (2005) and Goni at al. (2009) found similar results for Itamaracá and Winyah Bay in Brazil and Canada, respectively. This low SPM concentration during rainy seasons may indicate that the river sediment load is small as it is effectively filtered by the mangrove forest. Moreover, the highest concentration in the dry season may indicate increased biological activity and increased bottom sediment resuspension.

TABLE III
Mean values for the points T1, T2 and the channel cross section.
SPM - concentration of suspended particulate matter.

		QS (09/15/10)	QC (11/29/10)	SS (09/22/10)	SC (12/03/10)
SPM (mg/l)	T1	9.63	5.96	25.79	7.05
	T2	9.33	7.24	24.30	5.16
	Cross section	9.48	6.60	25.05	6.10

Higher concentrations of SPM, in general, occurred for the late onset of ebb and the beginning of flood (Figs. 2a-f, 3a-f, 4a-f and 5a-g). Kitheka et al. (2003) found the same pattern for Tana Estuary in Kenya, suggesting that the higher concentrations during the flood are related to an intake of turbid water, and during ebb tide due to bottom sediment resuspension. However, according to Figures 2f, g, 3f, g, 4f, g, 5f, g, for this portion of Vitória Bay, the peaks during the ebb were in the middle of the water column, indicating material from the upper parts of the estuary; and during the flood, the peaks were in the bottom layer, indicating a resuspension, which was contradictory to the findings by Kitheka et al. (2003).

The relationship between SPM concentrations has also been related to discharge variations. Generally, peak periods are associated with higher concentrations of SPM in the water column. However, this relationship can be modified due to human impacts on the watershed, such as hydrological changes resulting from the dams (Medeiros et al. 2011). As the Santa Maria da Vitória River, the main freshwater source to the estuary, has a controlled flow due to a catchment for urban water supplies downstream, no clear relationship should exist between the discharge and the concentration.

Spring tides are associated with higher concentrations of suspended particulate matter, and this fact is related to higher current velocity, enabling a greater capacity for the bottom sediment remobilization (Figs. 4, 5f and e, f). Conversely, during the neap tides, when lower velocity was observed, lower concentrations of suspended particulate matter were also found (Figs. 2e, f, 3e, f).This phenomenon was observed to some extent in the dry season, but during the rainy season, the concentrations were similar between spring and neap tides (Table III). This finding may be related to the tidal height variation between neap and spring tides. During the studied rainy period, this variation was small, of approximately 30 cm. This same correlation between the current velocities and SPM concentrations has been confirmed in other areas (Capo et al. 2009, Kitheka et al. 2005, Alvarez and Jones 2004).

A relationship between the velocities and SPM concentrations could not be linked to the erosion and deposition cycle that occurs in estuaries. According to Capo et al. (2009), when the duration of deposition and erosion mechanisms is significantly different from tidal duration, these processes require a long time to reach the water column. Thus, the peak of SPM concentration can occur at decreasing velocity some time after the shear stress threshold has been reached. In other words, the phenomenon of hysteresis, the tendency of a material or system to retain its properties in the absence of the stimulus that generated them, can occur.

According to Dyer (1995), the SPM is not considered conservative, answering to the flow with a time delay. If this delay did not occur, the SPM transport direction would be the same as the tide current residual. This delay between the current and the SPM concentration, therefore, can lead to a residual SPM transport even when there is no residual current (Dyer 1997). Several processes can generate such a delay as described by Dyer (1995): a delay through velocity threshold for movement (threshold lag); erosion delay (erosion lag); current action delay (scour lag) and settling lag. The scour lag would explain the SPM peak in the middle of the water column during the ebb in both spring rainy season (Fig. 5f) and neap dry season (Fig. 2f);

During the neap tides, the threshold lag was observed. As higher current velocities occur during flooding, it is likely that the velocity threshold necessary to remobilize the sediment was reached. However, the highest concentrations were seen at ebb tide because SPM was still being transported by the currents. (Figs. 2f, 3f)

There was no pattern detected for the spring tide cycles. The spring tide during the rainy season (SC) behaved like the neap tide, except for the velocity threshold; at one point, the highest velocity was observed during the ebb. During the spring tide of the dry season, it was not possible to detect the threshold lag because the velocities near the bottom were always high except during slack water. However, soon after the slack water, the sediment was resuspended. Many of these processes operate simultaneously and are difficult to discriminate. Thus, SPM dynamics control the magnitude and peak timing of maximum SPM.

SALT AND SPM FLUXES

Table IV illustrates the residual flux of each cycle and for each point of the cross section (T1 and T2). As seen, in the neap tides, salt and SPM were consistently imported. Moreover, during the spring tides, there was salt import in T2 and export in T1, but the residual was to the estuary (Table IV) because flood currents had higher velocities in T2 and the ebb in T1.

The SPM flow behavior of the spring tides did not follow the salt pattern. During dry season, there was SPM import in T1 and export in T2, but also with the residual water directed into the estuary. In the rainy season, there were only exports (Table IV). Medeiros and Kjerfve (2005) detected a trend in salt and SPM importation for Itamaracá, except for the spring tide in periods with higher river discharge. According to those authors, tidal pumping caused the import. This process occurs due to tide asymmetry, which causes the SPM flow to be higher at flood than during ebb tide. With increasing tide asymmetry, the upstream river influences become more important in amplifying the tide velocity during the ebb; thus, SPM is pumped from the mouth into the estuary.

TABLE IV
Salt residual lows (Kg/ms), SPM (g/ ms) for T1 and T2. Positive values indicate flow toward the ocean (values highlighted).

	SALT		SPM	
	T1	T2	T1	T2
QS (09/15/10)	-2.16	-5.45	-0.03	-1.81
QC (11/29/10)	-6.62	-10.97	-3.00	-5.29
SS (09/22/10	0.83	-15.10	-14.30	0.94
SC (12/03/10)	3.78	-10.29	6.50	0.35

In times of low river discharge, tidal pumping is more effective increasing movement up the estuary, even if the residual water is seaward (Capo et al. 2009). When flood events are significant, the SPM residual transport is toward the mouth. Several authors have shown that tidal pumping is the predominant process for the import of sediments (Capo et al. 2009, Medeiros and Kjerfve 2005, Garel et al. 2009, Goni et al. 2009). This process explains the salt residual flow in all cycles and the SPM residual flow with the exception of the rainy spring tide cycle, where the flow was toward the sea.

Another factor favoring material importation is the presence of mangrove forests upstream of the estuary. Studies of SPM fluxes conducted in other areas found that mangrove forests usually trap sediments during the flood, without a significant export during the ebb tide (Wolanski and Ridd 1986, Kitheka et al. 2003).

One possible explanation for the SPM export during spring tide in the rainy season is increased river advection (Dyer 1995), which provides a material residual movement toward the sea (Table IV). In the case of neap tides for the same period, longer flood duration causes more material to enter the estuary. According to Mantovanelli et al. (2004), the amount of material transported into the estuary is proportional to its asymmetry. In this case, the tide being almost symmetrical (AIDV = 0.04), the river discharge may have a greater role in transporting SPM estuary downstream.

In some ways, establishing a clear relationship between flow and SPM balance was an extremely difficult task due to the errors in the flux measurements. However, most studies show SPM import in a mixed and partially mixed estuary (Dyer 1997).

CONCLUSIONS

The mouth of Vitória Bay tended to present partial stratification periods in neap tides and little stratification in spring tides, when the turbulence was sufficient to generate mixing. However, with increasing freshwater input into the system during the rainy season, there is a tendency toward stratification. This trend is caused by the development of a halocline, impeding the effectiveness of bottom stress to generate mixing, even during spring tides. Thus, the circulation pattern in this estuary portion was mainly influenced by the tide, with little influence from river discharge.

With regard to the SPM, the mouth of the estuary tended to show low concentrations, with the highest values occurring during the dry season.

A positive current asymmetry was observed (toward the sea) for the studied cycles, except during the spring tide in the dry season. This asymmetry was not reflected in the SPM flux patterns however indicating a delay in SPM in relation to the flow. In addition to this aspect, there was a close relationship between momentary discharge, SPM and salt fluxes. Thus, there was an importation of salt in all cycles and SPM import for three cycles, indicating that tidal pumping was the dominant process in the fluxes of the study area.

Thus, despite being at the mouth of the system, it demonstrates that occur a material importation pattern. These conclusions show how critical it is to have an understanding of the hydrodynamic characteristics of an area before proposing significant alterations to the system. Unfortunately, Vitória Bay has long had extensive anthropogenic alterations such as sewage discharges, embankment and dredging, among others, without the benefit of such studies. It should be noted that this was a preliminary investigation. It is appropriate and recommended that studies of longer duration and greater spatial extent within Vitória Bay be performed for comprehensive understanding of the salt, SPM characteristics and balance, among other essential aspects. This investigation is the only way to create a scientific and technical basis for utilizing an estuarine ecosystem in a manner compatible with protecting both environmental quality and the quality of life for the local population.

ACKNOWLEDGMENTS

The first author was supported, during the study, by a scholarship awarded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). The study was supported by Fundação de Amparo a Pesquisa do Estado do Espírito Santo (FAPES Grant number 45440123/09).

RESUMO

Entender o comportamento hidrodinâmico e o transporte de MPS é de grande importância em regiões portuárias como o Porto de Vitória, localizado na Baía de Vitória, Vitória-ES, Brasil. A Baía de Vitória, é um estuário que nunca foi alvo de pesquisas sistemáticas de análise temporal com objetivo de identificar suas características hidrodinâmicas e de troca de MPS. Assim, esse estudo visa investigar os fluxos de sal e MPS na desembocadura do estuário da baía de Vitória, através da compreensão da variação temporal da salinidade, temperatura e correntes ao longo da coluna d'água e na seção transversal do canal. Os resultados mostraram que a desembocadura estuarina tendeu a apresentar uma estratificação parcial nos períodos de quadratura e pouca estratificação no período de sizígia. O padrão de circulação neste trecho do estuário é influenciado principalmente pela maré, com pequena influência da descarga fluvial. Em relação ao MPS, a desembocadura do estuário mostrou uma tendência de baixa concentração, com os maiores valores ocorrendo durante a estação seca. Uma forte relação momentânea foi observada entre os fluxos de MPS e sal. Apesar de todos os dados terem sido coletados na desembocadura do estuário, o sistema mostrou uma importação de sal em todos os ciclos e importação de MPS em três dos quatro ciclos de maré estudados. Assim a Baía de Vitória não está exportando MPS para a plataforma adjacente.

Palavras-chave: Estuário, hidrodinâmica, material particulado em suspensão, Baía de Vitória.

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