In: III Simpósio Brasileiro de Oceanografia, 2008, São Paulo. Oceanografia e Mudanças Globais. São Paulo : Instituto Oceanográfico da USP, 2006, 545-558.

Numerical simulation of the hydrodynamic in the Curimataú estuary, RN Brazil

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Abstract

The Curimataú River estuary is a shallow partially mixed (type 2) tropical estuary, located in the Rio Grande do Norte (RN) state, northeast Brazilian coast (lat. 06°18'S); the main system is composed by three rivers: Curimataú, Cunhaú and Guaratuba. The numerical model Delft3D-Flow was used to study hydrodynamic features of the estuary. The model predictions were evaluated using the *Skill* parameter based in the comparison of the theoretical solutions with observations of hourly values of tidal heights, currents and salinity at an anchor station located at the cell (M=279; N=323). The applied computational grid is curvilinear with around 6,000 horizontal wet points, including the inner shelf. Open boundary conditions was obtained from the analysis of 2.7 years of hourly tidal heights, recorded at Natal harbor, and the inner boundaries conditions were controlled by freshwater input into the three main rivers. Initial conditions of hydrographic properties were uniform in the previous simulations and, only the temperature was set to a constant value in whole simulation. The steady-state of the fields of velocity and thermohaline properties was reached after almost four weeks of simulation of the baroclinic mode. The best fit between the model and the observations was for the semidiurnal spring tide oscillation with a *Skill*=0.98; for the velocities and salinities simulations during this tidal condition the best mean S*kills* values were 0.82 and 0.94, respectively.

Key words: Curimataú estuary, circulation, numerical model, validation.

1. INTRODUCTION

The Curimataú river estuary (lat. 06°18'S) in the Rio Grande do Norte state (RN), in the northeastern tropical region, is a coastal plain tropical estuary oriented in a SW-NE direction (Fig. 1). The Curimataú river estuary is driven by semidiurnal mesotidal with ranges at the river mouth over 2 m during spring tides and the main river source is located in the Paraiba state (PA) with a drainage basin with an area of 3,589 km^2, but only 830 km^2 of them within RN state. It is shallow (<10 m), being 500 m wide and deeper near the mouth (≈10 m) at high water, were alongshore barrier reefs are located (Fig. 1). Inshore the reefs, sedimentation and erosion due to the action of tidal currents are very intense and sand banks are exposed during low water. Almost 2 km up, the estuary widens out to 1,800 m at high water and is characterized by a central channel with a depth of 7 m. On the left and right margins wide shallow sand banks may be observed during the low tides and, near the confluence with the Cunhaú river, the main channel narrows to almost 300 m. Due to the erosion, transport and deposition processes linked to the evolution of coastal regions and adjacent beaches, a comprehensive study on the morphology of the estuarine environment, under the influence of the Curimataú river, was presented by Souza (2004) based on bathymetry, echo-sounding, sediment sampling, orbital and acoustic remote sensing imagery.

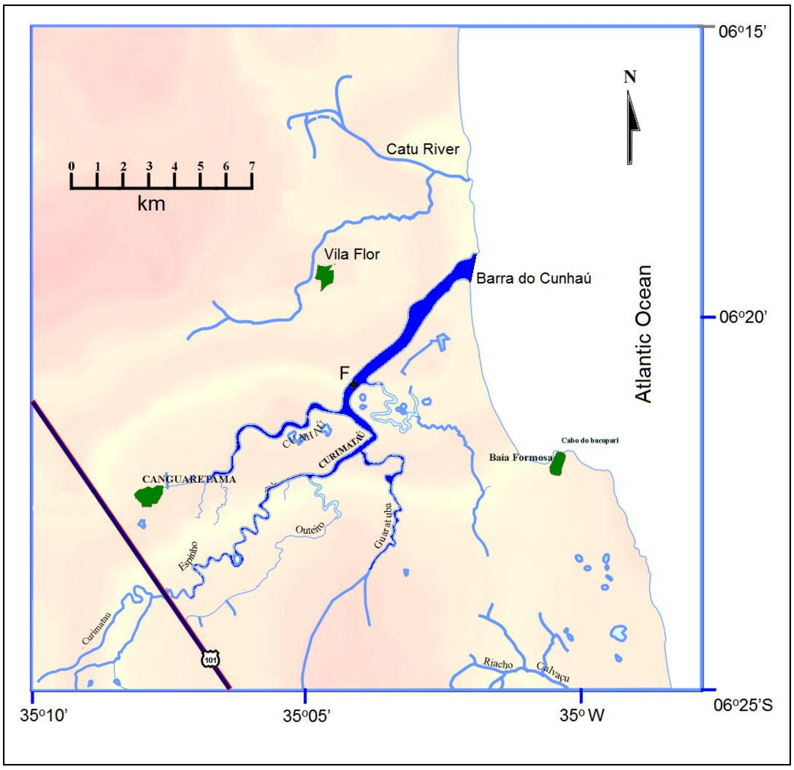

Figure 1. The Curimataú river estuary and the location of the anchor station (F).

In the past, the left and right margins of the estuary were densely covered with mangrove forests. The salt exploitation ended in 1970 making way for the growing shrimp farming. Since this time the mangrove forest on the left margin of the estuary has been further removed to give place to ponds to be used in this new productive enterprise. The coverage of the mangrove forest area has been estimated at 5.7 km^2 (Herz,1991); however, due to the growing occupation of the estuarine system, the mangrove forest area at the time of our experiment was much smaller.

The published estuarine literature on the physical oceanography of tropical estuaries along the northeastern Brazil has been concentrated in regional research. The closest estuary studied in the Rio Grande do Norte state was the Potengi river (lat. $05^o45'$S). A preliminary research on the environmental conditions and physical-chemical properties of this estuary was presented by Cunha (1982) and recently by Miranda *et al.* (2006); taking into account the salinity stratification it was classified as partially mixed estuary, the overall salinity variation was from 29.5 $^o/_{oo}$ to 34.5 $^o/_{oo}$ for both rainy and dry seasons, and the maximum speed in spring tide conditions was close to 1.0 m s^{-1}. The hydrology of the U-shaped Itamaracá estuarine system ($07^o34'$S) was studied by Medeiros & Kjerfve (1993) based on field experiments carried out during peak rainy and dry seasons. The fresh-water input during these experiments varied from 57.7 m^3s^-1 to 0.2 m^3s^{-1}, respectively, which ruled the system behavior; during the rainy season the system was partially mixed, prevailing the gravitational circulation, and it was well mixed in the dry season.

An analysis on the processes and time scales controlling the dynamics of the of the lower Joboatão river estuary located further south (lat. 08°14'S), was made by Araujo *et al.* (1999). A quantitative and comparative study on the forces maintaining stratification (solar heating, rainfall, longitudinal density gradient) and those responsible for the vertical mixing (mechanical stirring of tidal bottom stress, wind stress and evaporation) were studied. The estuary was well mixed both, in dry and rainy seasons, being the major source of energy for vertical mixing the bottom shear turbulence caused by tidal currents.

The hourly observations (May 06-07, 2001) of tidal heights, currents and salinity sampled during two semidiurnal neap-spring tidal cycles values at an anchor station located in the Curimataú main channel, used to validate the numerical model, were studied by Miranda *et al.* (2005) and Miranda *et al.* (2006); as a result of the combination of the semidiurnal tides, baroclinic forcing and river discharge, the lower reach of the estuary alternates between being partially mixed (type 2b, ν=0.64) during the neap tide, and being partially mixed but weakly stratified (type 2a, ν=0.99) during the spring tide showing a high tidal diffusion contribution for the up-estuary salt transport, according to the stratification-circulation diagram criteria of classification (Hansen & Rattray, 1966). During the neap tide condition the estuary dynamics was dominated by the buoyancy input from the river discharge (R_{iE}=5.6) and by the baroclinic gradient pressure force. However, in the following spring tide, the main forcing mechanism was the barotropic semidiurnal tides (R_{iE}=0.1). During this experiment the stratification–mixing process was strongly regulated by the spring-neap tidal cycles and the fresh water input (Miranda *et al*., 2005).

Due to the period of heavy rains an imbalance was observed in the net advective salt transport, indicating a decrease in the salt content within the estuary, due to the relatively strong component driven by the river discharge (7.30±1.10 kg m^{-1} s^{-1}). In the spring tidal-cycle the advective salt transport component driven by the river discharge decreased to 3.30±0.10 kg m^{-1} s^{-1}. This condition, associated with the Tropical Water mass intrusion, resulted in an increase in the salt content in the mixing zone. Since the covariance of the tidal height and the barotropic velocity deviations (Stokes'drift component) in the neap and spring-tide cycles was up-estuary, changing from –0.70±0.09 kg m^{-1} s^{-1} to –4.80±0.40 kg m^{-1} s^{-1}, respectively, it appears that this was due to the increased strength of the standing wave component of the partially progressive tidal wave regime (Miranda *et al*., 2005).

The description of the steady dynamic response and salt stratification of the Curimataú river estuary, due to the combination of the river discharge, density-driven forcing and wind was approximated by the two-dimensional Hansen and Rattray's (1965) analytical solution (Miranda *et al*., *op. cit*.). The model considers the steady-state balance separated into barotropic and baroclinic modes, with wind stress and no slip at the bottom as upper and lower boundary conditions, respectively. Although some adjustments had to be made in the free parameters the comparison between analytical and experimental results of the u-velocity profiles was evaluated with the relative mean absolute error (0.7), which indicated reasonably fair results. The experimental parameters used in the analytical model confirm the influence of the river discharge and the associated changes in the horizontal pressure gradient force in the neap-spring tide cycle behavior of the estuary dynamics. There were a number of questions raised by the analytical solution which were further investigated with a numerical modelling by Andutta (2006).

The aim of this paper is to provide additional theoretical results on the tridimensional velocity and salinity fields of the Curimataú estuary using the Delft3D-Flow numerical model quantitatively validated with the *Skill* parameter (Wilmott, 1981). For this purpose the model result for a particular grid point closed to the anchor station F (observations by Miranda *et al*., 2004) was computed and compared providing convenient evaluation of the model, up to the best fit (Skill→1) indicated by the skill parameter was obtained.

2. THE NUMERICAL MODEL AND VALIDATION

The three-dimensional model applied in the study of the Curimataú estuary is the Delft3D-Flow developed by Delft Hydraulics in Holland; it is a hydrostatic model that solves by the method of finite differences a set of balance equations: volume (continuity equation), momentum (Navier Stokes equations of motion, including the earth rotation effects), salt, heat and the equation of state of the sea water (Tumlirz equation, empirically developed by Eckart (1958)). The model is developed on a tridimensional reference system composed by a horizontal curvilinear plane, with u and v denoting the longitudinal and secondary velocity components ($u>0$ down-estuary, $v>0$ toward the left margin) and the σ- vertical coordinate ($w>0$ upward). The 3D discrete shallow water equations are numerically solved according to the Arakawa C-grid pattern with the pressure points defined at the centre of the cell and the velocity components perpendicular to the grid faces. The turbulent closure model assumed was the k-ε and the hydrodynamic module was used to simulate the three-dimensional velocity field of the estuarine non-uniform temperature and salinity water mass due to tidal forcing and the baroclinic gradient pressure force. The vertical velocity (w) in the σ-co-ordinate system is computed from the continuity equation (Delft Hydraulics, 2001).

The surface area of the estuary and its volume are approximately $4.8\text{x}10^6$ m^2 and $4.8\text{x}10^6$ m^3, respectively. The model domain of the Curimataú estuary is curvilinear with 279 x 323 x 5 cells in a total of 450,585 cells. The bathymetry raw data used to develop the numerical grid were collected by Souza (2004) for the estuarine channels. For the offshore regions and close to the estuary mouth, where there are coastal reefs, data from (SUDENE, 1970) and the bathymetric chart (DHN n°.B-800, 1978) were used. Although the only available bathymetric data were taken from different sources and sampling times, we are aware on the possibility of inconsistencies in the topographic field, mainly near the mouth which is undergoing rapid erosion and deposition. The final compilation of the bathymetric data shows the banks close to the mouth and the three shallow estuarine channels with depth variation from zero to around 7 m (Fig. 2); two kilometers from the mouth, the main channel is wider and a exposed sand bank may be seen on the ebbing tide.

The tidal height and phase of the 4 main semidiurnal (M_2, S_2, N_2 and K_2) and 2 diurnal (K_1 and O_1) components were used as barotropic forcing obtained from tidal analysis of a time series of 16,056 hourly data from the Natal harbor, located approximately 60 km northward of the estuary, using the methodology of Franco (2000). Because height and phase differences lower than 0.01 m and 0.5º, respectively, were observed in the external open coastal boundary the grid was forced by tides having the same characteristics.

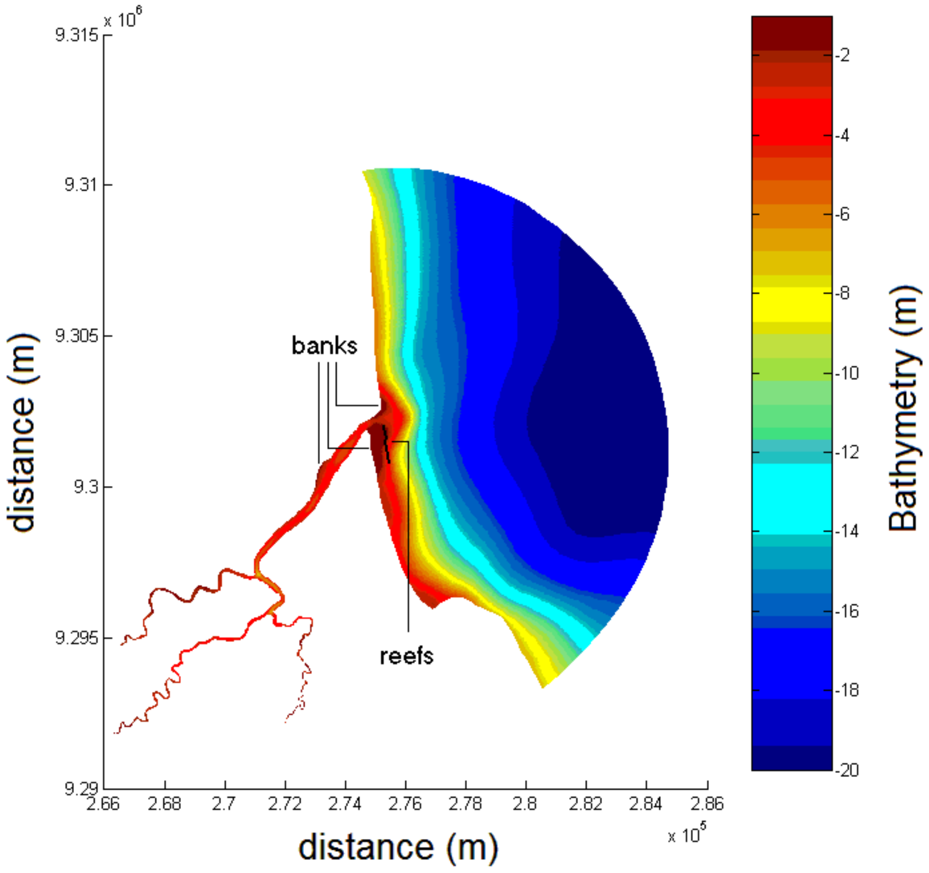

Figure 2 - Bathymetry of the model domain of the Curimataú estuary and the location of the anchor station F (cell M=279; N=323). Depths (m) are indicate by the bar scale.

A free radiation open coastal boundary condition is imposed to the velocity structure:

$$u(t) = U \pm \varsigma\sqrt{g.d^{-1}} \qquad (1)$$

where u (t) and U denotes the u-velocity component and its depth-mean velocity in the water column, ς is the free surface and d is the local depth.

The bottom friction boundary condition is given by:

$$\vec{\tau}_b = \frac{\rho_0 g \vec{u}_b \left|\vec{u}_b\right|}{C_{3D}^{\;2}} \qquad (2)$$

where $\left|\vec{u}_b\right|$ is the magnitude of the u-velocity component on the bottom layer and C_{3D} is the Chézy 3D coefficient. For the surface boundary condition the wind stress was assumed as zero, because the application of the Hansen & Rattray (1965) classical steady-state analytical model by (Miranda et. al., 2005) showed that local wind has a minimal effect on the estuarine circulation.

For the internal horizontal boundary condition due to the Curimataú, Cunhaú and Guaratuba rivers a closed boundary with a continuous fresh water discharge in each cell (Tab. 1) was used. Those values were obtained by adjusting discharge until the best approximation was achieved.

Table 1- Continuous fresh water discharge applied in each surface cell in the head of the rivers and its salinities for the Cunhaú, Curimataú and Guaratuba rivers.

River	Cells	Leak ($m^3.s^{-1}$)	Velocity ($m.s^{-1}$)	Salt
Cunhaú	5	5	0.10	10
Curimataú	6	14	0.15	0
Guaratuba	5	3	0.05	8

The quantitative agreement between the model output and the measurements at the anchor station F is measured according to the Skill method presented by (Wilmott, 1981):

$$\text{Skill} = 1 - \frac{\Sigma\left|X_{model} - X_{obs}\right|^2}{\Sigma\left(\left|X_{model} - < X_{obs} >\right| + \left|X_{obs} - < X_{obs} >\right|\right)^2} \qquad (3)$$

In this equation the quantities X_{obs} and X_{model} are the properties observed (u-velocity component, water level and salinity) and calculated by the model, respectively, compared with the time mean observed value ($<X_{obs}>$); the X_{obs} properties were measured close to the cell (M=279; N=323) during two neap-spring tidal cycles (25-hours). The parameter Skill varies from 1 to zero, indicating the best fit and a complete disagreement between observation and the theoretical result, respectively.

a- Water level

The comparison of the observed tidal oscillations at the anchor station F and the astronomical tides predicted with the six main components (four semidiurnal and two diurnal) showed high agreement between the measurements and the model results of the water level (Skill = 0.98) during the spring tide (Fig. 3). However, during the neap-tide measurements there was a huge rainfall, which interfered significantly in the dynamics of the estuarine system leading to a high estuarine Richardson number (Ri_E=5.6), as discussed in Miranda *et al.* (2005), which resulted in a poor Skill (0.51) in the comparison of the observed and predicted tidal oscillations. However, these results clearly indicated that in the spring tide the system was mainly forced by the barotropic semidiurnal tides, confirmed by the low estuarine Richardson number (Ri_E=0.1).

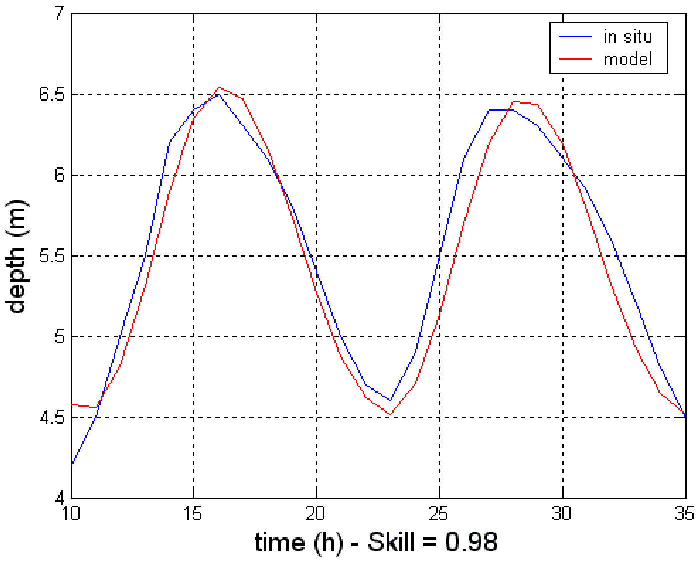

Figure 3-Comparison of the water depths oscillations measured in the anchor station F and the astronomical tide during two semidiurnal tidal cycles (25-hours) in the spring tide.

b- Velocity

The comparison of the model velocities at the grid point (M=279; N=323) and the measurements at the anchor station F during spring tide, presented good results as indicated by the mean skill parameter value of 0.82 (Fig 4). In addition, were also calculated the following positive and negative limit for the horizontal velocities at the grid cell, obtained by the baroclinic mode application: -0.40 m.s^{-1}<u<0.40 m.s^{-1}. Although this range of the maximum computed values are smaller, when compared to the observations at the anchor station (-0.80 m.s^{-1}<u<1.10 m.s^{-1}), the skill mean value during the two cycle semidiurnal tide (0.82) indicates a good fit between those values, and its variation during the two semidiurnal tidal cycles presented poor values (≤0.50) during short time intervals (lower panel on Figure 4).

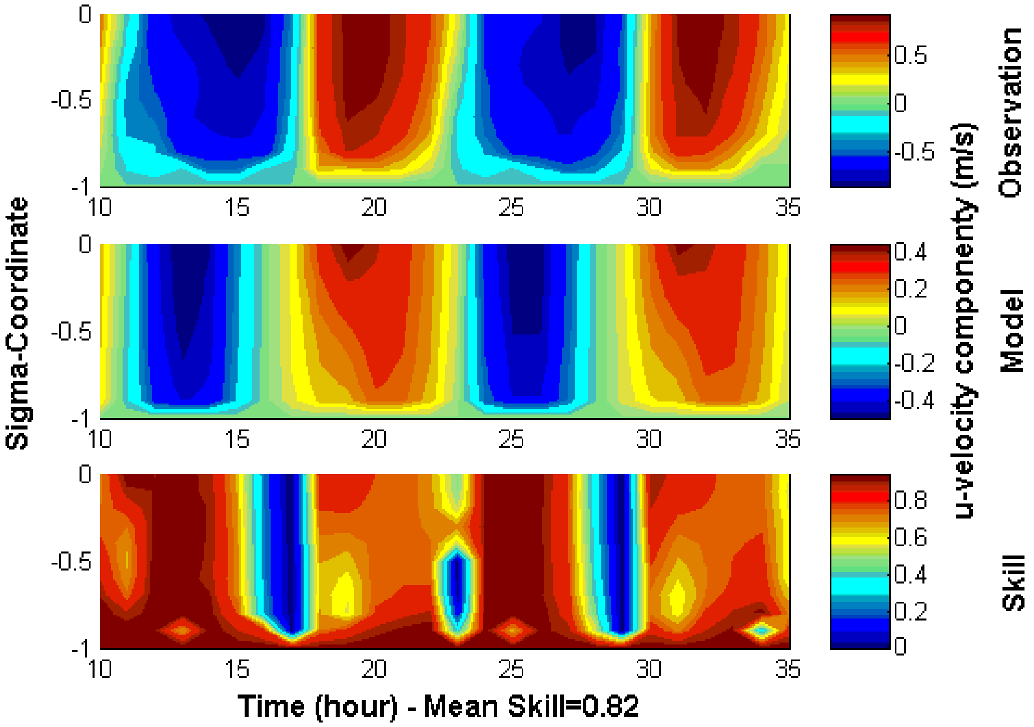

Figure 4-Comparison of the u-velocity component at the anchor station F (upper) versus the model (middle), during the 25-hours spring tide condition. The lower panel shows the *Skill* parameter. Bar scale in m/s, and u>0 and u<0 indicate ebb and flood currents, respectively.

c- Salinity

The comparison of the model salinities at the grid point (M=279; N=323) with the ones observed at the anchor station F for two spring semidiurnal tidal cycles presented better results, as indicated by the skill parameter of 0.94 (Fig 5); the theoretical salinities values ranged from ~31.0 to ~36.0 and were closed to the range of the measurements (29.0 to 36.7).

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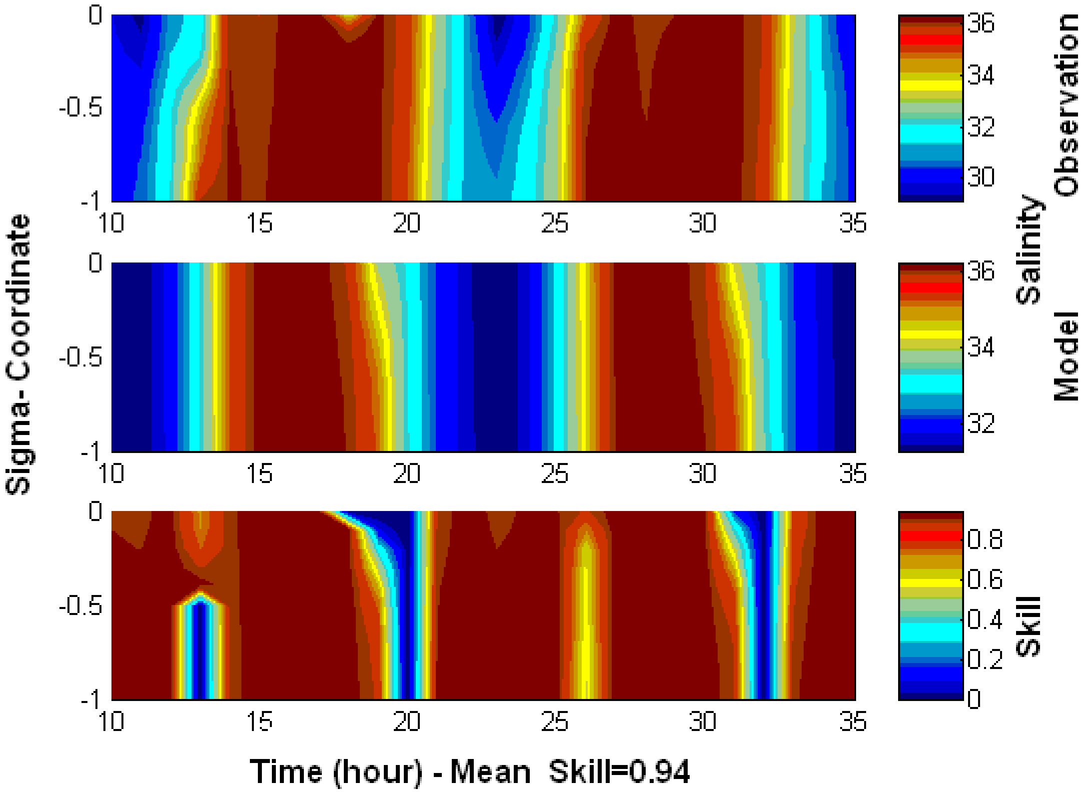

Figure 5-Comparison of the salinity at the anchor station F (upper) versus the model (middle), during the 25-hours spring tide condition. The lower panel shows the *Skill* parameter. Salinity and Skill values are shown in the bar scale.

4. RESULTS AND DISCUSSION

Taking into account the results on the model validation for the grid point (M=279; N=323) we were able to simulate the salinity and velocity fields along the main channel of the Curimataú estuary. To illustrate those fields two time steps simulations were chosen, corresponding to the spring-high (May 06, 16:00 h) and spring-low water (May 06, 22:00 h), presented in figures 6-7 and 8-9, respectively.

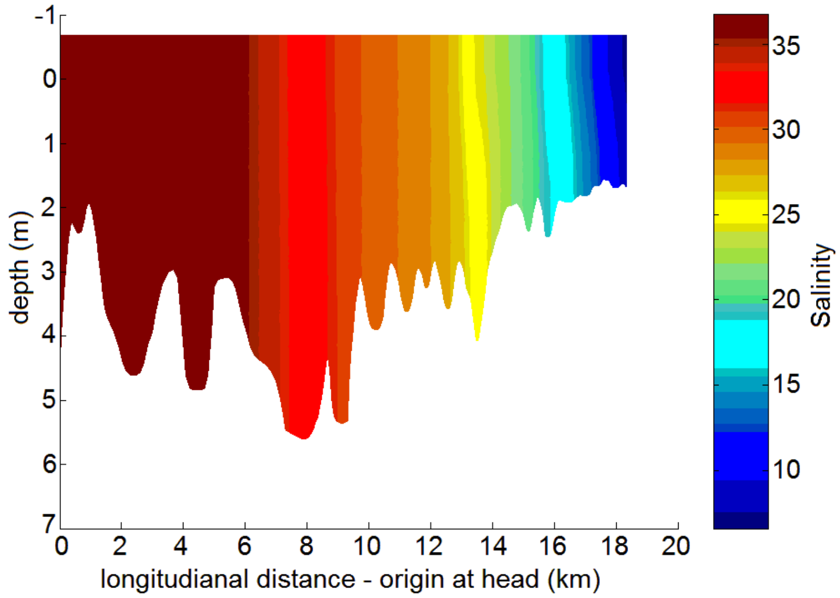

Figure 6. Longitudinal salinity field along the Curimataú estuarine channel at spring-high water (May 06, 2001, at 16:00 h). The anchor station F is located at a distance 0.4 km from the estuary mouth (salinity values in the bar scale).

The model results along the Curimataú estuarine channel indicates a well mixed estuary at the spring-high water (May 06, 16:00 h) with the salinity varying between ~8 to ~36 (Fig. 6). This figure also indicates clearly the high salinity Tropical Water (TW) mass intrusion characterized by S>36.0, which intrudes to 6 km up-estuary and has a strong influence on the salinity distribution along the estuary. The corresponding velocity field is shown in Figure 7. Its intensity varies from ≈-0.15 m s^{-1} to ≈0.15 m s^{-1} and is characterized by a complex pattern of bidirectional flow up and down-estuary which intensifies close to the estuary head; this field presents a well define level of no-motion with a convergent and divergent flows in its upper and lower layer, respectively, generating a downward vertical motion close to the head (≈16.0 km from the estuary mouth).

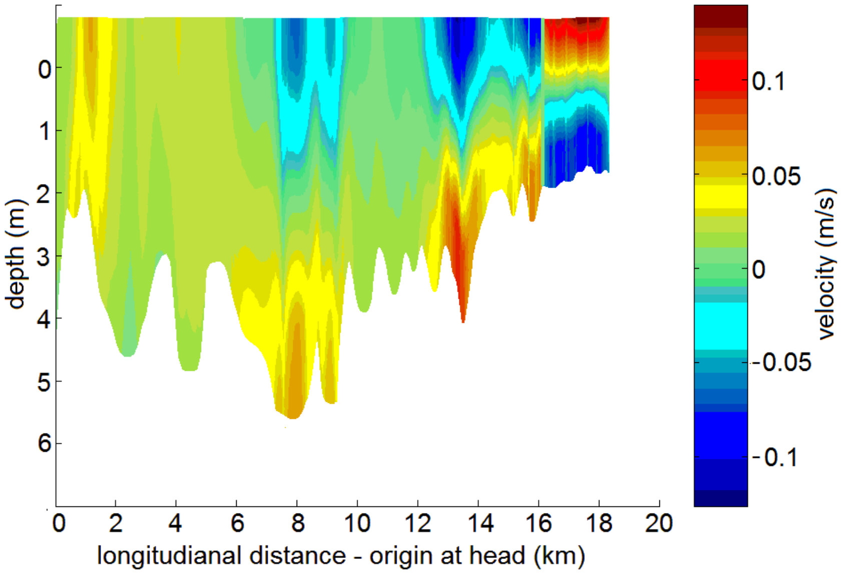

Figure 7.Longitudinal velocity field along the Curimataú estuarine channel at spring-high water (May 06, 2001, at 16:00 h).). The anchor station F is located at a distance 0.4 km from the estuary mouth (velocity values in the bar scale with positive values towards the mouth).

At the spring-low water (May 06, 22:00 h) the estuary is almost well-mixed and the salinity varies between ~8 and ~35, and indicates that due to the influence of the ebb flow the TW water was advected out of the estuary mouth. In the middle channel region, between 6 and 8 km from the mouth, the isohaline field revealed a subsurface halocline with a small vertical salinity gradient (Fig. 8). At this tidal stage the intensity of the velocity field varies from ≈-0.06 m s^{-1} to ≈0.15 m s^{-1} (Fig. 9) and exhibits the classical gravitational circulation of partially mixed estuaries with the circulation reversing at depth in a well defined level of no-motion; in this type estuary the diffusion is the main process contributing to the up-estuary salt transport in agreement with Miranda *et al*. (2005).

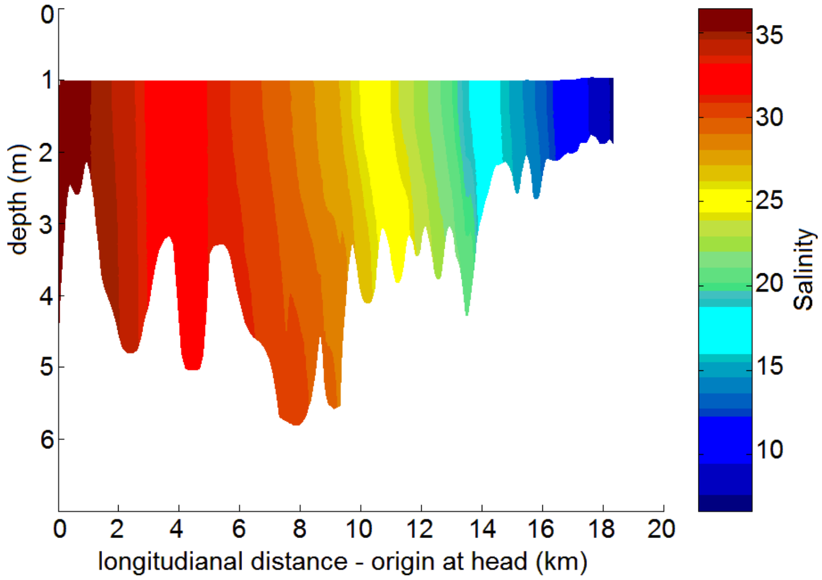

Figure 8. Longitudinal salinity variation along the Curimataú estuarine channel at spring-low water (May 06, 2001 at 22:00 h). The anchor station F is located at a distance 0.4 km from the estuary mouth (salinity values in the bar scale).

Although the results discussed above are for synoptic distributions of salinity and current fields along the estuarine channel, and were simulated at two tidal stages (low and high water), these results are closely related with the steady-state dynamic response and salt stratification of the Curimataú river estuary of the central regime, due to the combination of the river discharge and density-driven forcing approximated by the two-dimensional Hansen and Rattray's (1965) analytical solution and the Stratification-circulation diagram of Hansen & Rattray (1965,1966) which enabled the quantitative estuary classification as type 2a, being the diffusion process the main contribution to the up-estuary salt transport , ν=0.99 (Miranda *et al*., 2005).

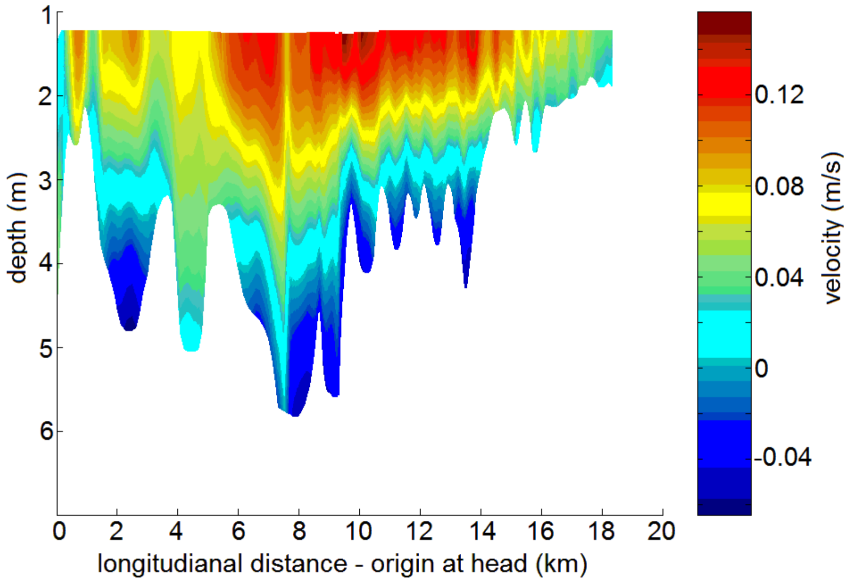

Figure 9. Longitudinal velocity field along the Curimataú estuarine channel at low water (May 06, 2001, at 22:00 h). The anchor station F is located at a distance 0.4 km from the estuary mouth (velocity values in the bar scale with positive values towards the mouth).

5. CONCLUSIONS

The Delft3D-Flow numerical model was used in the simulations of salinity and the u-velocity component fields along the main estuarine channel of the Curimataú river. The theoretical results were validated with the predictive parameter Skill using hourly values of a two-semidiurnal spring tidal cycle observed at an anchor station; the 25 hours time mean values of predictive skill were very high (0.98 and 0.94) for water level and vertical salinity profiles, respectively, and 0.82 for the vertical profiles of the u-velocity component.

The theoretical results were closely related with the steady-state dynamic response and salt stratification of the Curimataú river estuary of the central regime, due to the combination of the river discharge and density-driven forcing approximated by a two-dimensional analytical solution and the Stratification-circulation diagram of Hansen & Rattray (1965, 1966).

The reasonable theoretical results obtained from the model indicate that the momentum balance and salt conservation equation adequately represents the basic dynamics of the estuarine channel.

ACKNOWLEDGMENTS

We are grateful to the Coordenação do Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the M.Sc. fellowship concession for the first author and the Research Productivity fellowships concessions for the second and third authors. The collaboration of the graduate students from the Department of Limnology and Oceanography of the University of Rio Grande do Norte (DOL-UFRN) by the assistance in the field work also is very much appreciated. The Agência Nacional de Água (ANA) kindly provided the daily measurements of the Curimataú river discharge at the Pedro Velho gauging station.

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