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Environmental Hydrodynamics at the Outfall of the São Francisco River

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ABSTRACT: *The hydrodynamics of the waters of a river that flows to the sea establish important control in the volume and direction of the watercourse. The study was carried out in the area of the mouth of the São Francisco River between the municipalities of Propriá / SE and Piaçabuçu / AL under São Francisco. For the calibration of the hydrodynamic model, the simulations were adjusted based on the parameters of a field campaign carried out on September 26 and 27, 2015, at the end of the quadrature tide and beginning of the tide of syzygy at which time the waters in oscillations are higher, closing a 12-hour cycle. In the hydrodynamic scenario, the influence of the tide on the flow of the river in areas above Piaçabuçu / AL was observed, which may allow changes in the environmental dynamics and alteration of water quality characteristics in detriment to the control of the flows released by the Hydroelectric Power Plant Cursed*

Key words: *Hydrodynamics, Flow, Marine current.*

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I. INTRODUCTION

The hydrodynamics of the estuaries represent a determining factor in the processes and dynamics of the local environment. The hydrodynamic oscillations in estuarine areas allow the sea to mix with the river waters, establishing exchange and energy circulation processes of the aquatic ecosystem.

The dynamics of estuaries are basically governed by tidal action and freshwater flow. For [1] this process of mixing between the waters from the coastal zone and the waters from the river, allows the transport of sediments and aquatic biogeochemistry. [2] further add that estuaries are highly variable in physical terms and biological properties, and that the estuarine hydrodynamic system is the response to the change in freshwater flow.

In conjunction with the estuarine system there is a river mouth that is fundamental to the population and the balance of natural resources. However, nowadays, a good part of its marginal course and river discharge are affected by strong anthropogenic effects, of environmental degradation in these spaces. These changes compromise the sustainability of large rivers, among which we can mention the hydrographic basin of the São Francisco River, which currently has a good part of its tributaries in risky conditions.

One of the risk factors is the process of regularization of the flows attributed to the construction of dams along the course of the São Francisco River [3]. According to [4] dam installation causes changes in the integrity of rivers, [5] argue that their environmental and social impacts are unquestionable, but already exceeds in 800,000 the number of dams in the world. Dams are defined as structures in a permanent or temporary course of water [6] For [7] the dams often cause flooding of productive land areas and all social and ecological system culminate together.

One fact observed in the construction of dams along the São Francisco River, which were responsible for natural and social changes in this environment, led to problems that were not dimensioned during the installation period. According to [8] one of the most notable modifications in the construction of river dams is the regularization of the flow, aiming at a water supply necessary for the generation of electric energy, causing a great reduction in the natural flow, causing an energy imbalance between the river and the sea.

In this context, the present work has the objective of analyzing hydrodynamic changes in the area of the São Francisco River mouth by means of hydrodynamic modeling.

II. METHODOLOGY

2.1 Area of study

The São Francisco river basin has 639.219km2 of drainage area, whose main bed is 2,700km long with an average flow of 2,850m3s-1, covering the states of Bahia, Pernambuco, Alagoas, Sergipe, Goiás and the Federal District [9].

According to the National Water Agency (2005), this basin is divided into four physiographic regions: Upper, Middle, Sub-Middle and Lower São Francisco, that for the purpose of planning, these areas were subdivided into thirty-four small basins, and 12,821 micro basins with the purpose of outlining the main rivers of the region. The study was carried out in the area of the São Francisco river mouth between the municipalities of Propriá / SE and Piaçabuçu / AL (Figure 1). The climate of the region is divided into tropical semi-arid and tropical semi-humid. Evapotranspiration can vary from 600 to 700mm in the wet season and 750mm to 800mm in the dry season, annual precipitations can decrease from the coast. There is occurrence of hydromorphic soils, including organic, gley and alluvial soils, which in their natural state are subject to periodic flooding, exhibit fertility limitation, and are more prone to rice cultivation [10].

The coastal strip dips beneath the ocean and advances as a substrate of the continental border and the rocks of the sedimentary basin constitute the geological substrate of the final stretch of the São Francisco river-sea system [11].

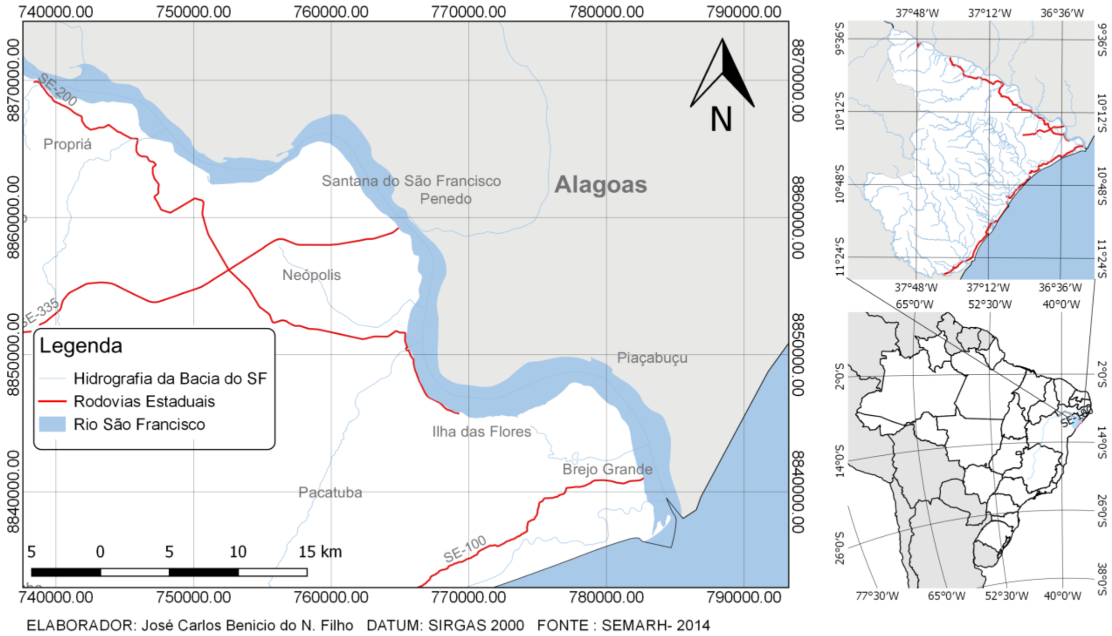


Figure 1: Location map of the study area between the municipalities of Own / SE to Piaçabuçu / AL.
Source: SEMARH / SE

2.2 Hydrodynamic model

Hydrodynamic modeling was performed using the Environmental Hydrodynamic Basis System (SisBahia), version 9.1, which satisfactorily represents the phenomenon of interest. Moreover, the interface of this system is considerable, friendly and has been constantly refined through research. The main input data of the SisBaHiA are: flows, wind velocity, river bathymetry, harmonic constants, finite element mesh, outline map of land and water, roughness, precipitation, among others. The access to this software is free through a term of responsibility acquired by COPPE / UFRJ allowed its scientific use and for the management of water resources.

In the hydrodynamic model, calibration processes are minimized due to spatial discretization via finite elements, allowing to maximize data reliability and can be used to simulate various scenarios involving rivers, estuaries, coastal zones, bays, canals, lakes, ponds and reservoirs [12].

SisBahia has a hydrodynamic model called FIST3D (Filtered in space and time), optimized for natural water bodies with free surface where turbulence modeling is based on filtering techniques, with similarities to those applied in the Large Vortex Simulation Eddy Simulation), considered the state of the art for geophysical flow turbulence (ROSMAN et al., 2001).

The hydrodynamic model FIST3D of the SisBaHiA consists of two modules: the first averaged in the vertical or two-dimensional horizontal (2DH), by means of which the free surface elevation and current

velocities (2DH) averaged in the vertical are calculated, module named 3D calculates the field of three-dimensional velocities through two possible options.
a) Totally numeric 3D model, attached to a 2DH module. FIST3D is a complete 3D model for homogeneous fluids.
b) Analytical-numerical 3D model to obtain the velocity profiles in the horizontal flow field. This option is more efficient in computational terms, but only considers the advective acceleration in the 2DH module. Therefore, it gives less accurate results in regions where advective accelerations vary significantly along depth. In this option, the velocity profiles are computed through a solution that is a function of the velocities 2DH averaged in the vertical, free surface elevation, equivalent background roughness of the 2DH module, and the wind velocity acting on the free surface of the water.

The mathematical formulation of the hydrodynamic model comprises the Navier-Stokes equations, fundamental for representing any body of water. The results of the simulation can be represented by 3D or 2DH using the input data. 2D models predominantly have two-dimensional flow and require considerable numbers of parameters, which need to be well known to avoid generating inaccuracy in results. In this research the 2DH module was used, fulfilling the requested objective, the summary of the 3D governing equations are in Figures 27 and 28.

Spatial discretization was performed by means of 601 fourth-order quadrangular elements. The vertical discretization of the water column was done through finite differences with sigma transformation. The time pace used in the hydrodynamic simulations was 30 seconds, with a maximum Courant of 3.0.

2.3 Initial data for modeling

The elaboration of the area geometric outline of the Sào Francisco River was based on the nautical chart of the mouth of the São Francisco do Norte river, elaborated by the Department of Hydrography and Navigation (DHN) and coordinates defined by means of images taken from the Google Earth satellite program. This stage is considered important, to structure the spaces and the representation of the simulated environmental phenomena.

The nautical chart was inserted in the Surfer program, version 12, for the elaboration of land and sea outline and then imported to the model. The land outline represented the dry part limiting the main banks of the São Francisco, Paraúna and Potengy rivers, as well as the islands Criminosa, Fitinha and Negra, and the Parapuca channel. Figure 2 shows the representation of the outline of land and sea, with the blue color indicating the sea, open area, and the brown color the outline of land, the white part on the map indicates the modeling domain.

The bathymetric data of the study area were taken from the DHN charts (nº 1002 and 22300), bathymetric surveys conducted by the GeoRioMar research department, Federal University of Sergipe and data provided by region's nautical vessels, data that will complement areas that the nautical charts did not present information.

The equivalent background roughness value adopted ε[1] was 0.020m, with predominance of fine and medium sand, based on the granulometry analysis of the bottom sediments carried out at the ITPS (Technological Research Institute of the State of Sergipe). Followed by the values suggested for effective amplitude of background roughness without wave effects between 0.0070m to 0.0300m (Abbot and Basco, 1989 apud Rosman, 2015). The bathymetric map represents the depth profile distributed throughout the evaluated channel, as shown in Figure 2.

[1] ε Significa amplitude

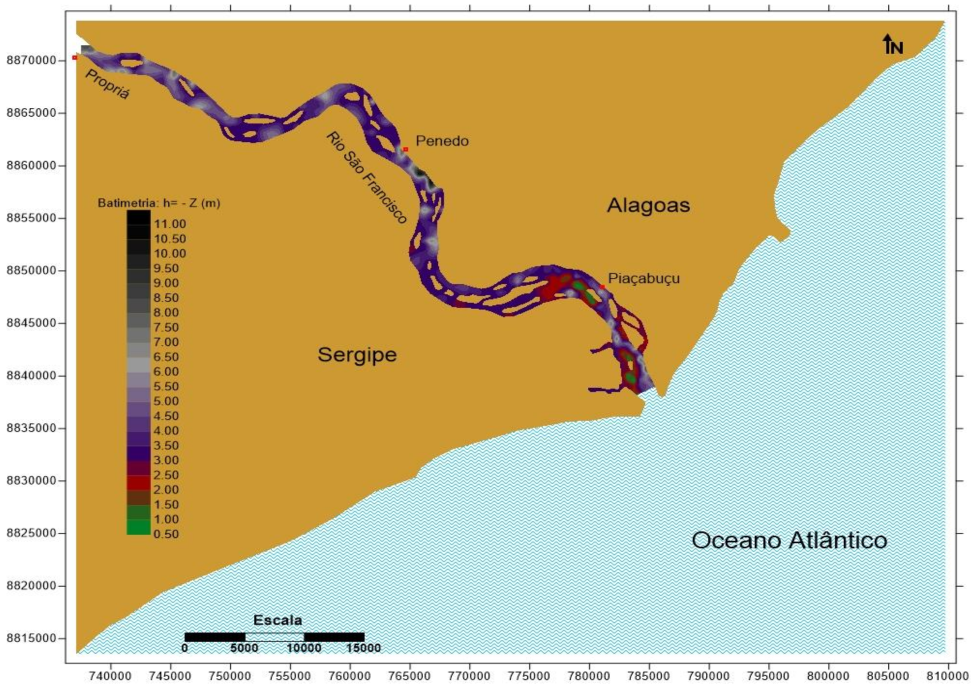


Figure 2: Bathymetry used in the modeling domain of the São Francisco river mouth**.**

The spatial discretization of the modeling domain was done through a finite element mesh, representing the main configurations of the stretch of the mouth to the municipality of Propriá / SE. The discretization mesh has 1,854 nodes in the horizontal plane and 1,053 vertical levels, totaling 2,907 points of calculations, 128.9km2 of area and an average depth of 4.36m (Figure 3).

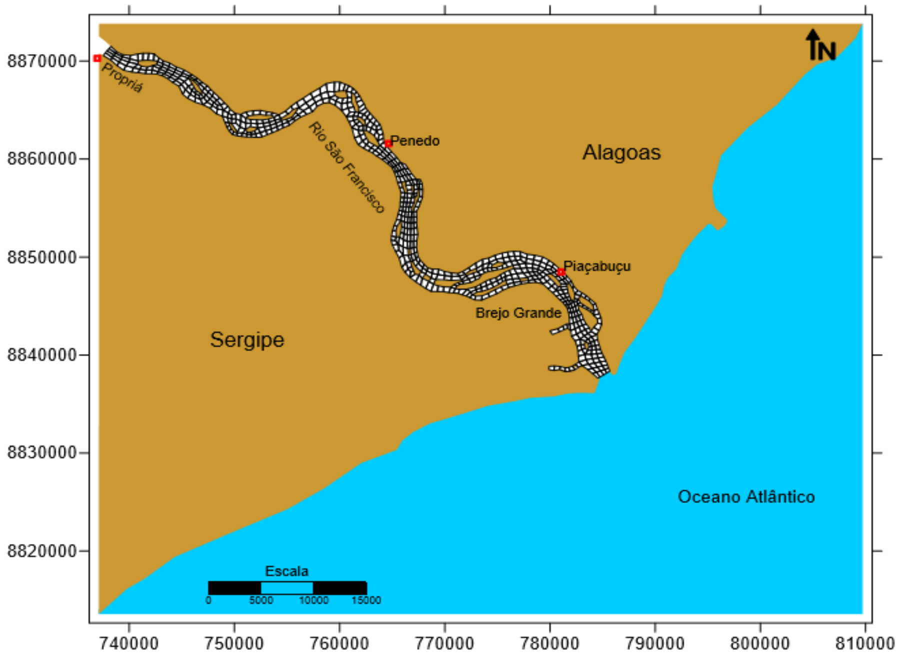


Figure 3: Finite element mesh of the modeling domain.

2.4 Model Forcings

The harmonic constants used to represent the tidal forcing were based on Cabeço's tide station (Station 127), located in the mouth of the São Francisco River in front of the lighthouse, controlled by the Foundation for Sea Studies [13]. In order to verify the variations of the flow and its behavior in the course of the water bed in the region of the mouth of the São Francisco River, a 39-year time series of the fluvial discharges (Qf) of the monthly averages was analyzed. The average of the flow released by the Xingó hydroelectric power plant in the municipality of Propriá for the simulated year was considered constant around $952m^3.s^{-1,}$ evaluating the year 2015 to 2016, data were obtained through the National Water Agency (ANA).

2.5 Simulations of scenarios

For the monitoring of the simulated scenarios six points were defined along the course of the river. Point 1 refers to Criminal Island with approximately 4km distance from the mouth, point 2 Piaçabuçu / AL with distance of 10km, point 3 is located in the municipality Ilha das Flores / SE 16km, point 4 Penedo / AL 30km, point 5 Saúde / SE 37km, point 6 Propriá / SE with 57km distance from the mouth, according to Figure 10. It is highlighted that the points were directed by the location of the main channel of the river, causing records of points in the state of Sergipe and Alagoas, according to Figure 6.

III. RESULTS AND DISCUSSION

3.1 Calibration of the hydrodynamic model

For the calibration of the hydrodynamic model, the simulations were adjusted based on the parameters of the 6th field campaign held on September 26 and 27, 2015, at the end of the quadrature tide and beginning of the tide of syzygy, at which point the waters in vertical oscillations are higher, closing a cycle of 12 hours. This cycle characterized the existing tidal regime at the mouth of the São Francisco river, which is considered semidiurnal with an interval of 12.4 hours, a classification detailed by Miranda, Castro and Kjerfve (2002), by calculation presented by number of form (Nr) in which the result obtained had a value of 0.16, thus classifying the tide type of the study area.

The validation of the model, checking the variations of the tide level and then the velocities of the currents, is part of the methodology suggested by Rosman, Cunha e Cabral (2013), in the modeling process. Initial checks showed that bathymetry, velocity and simulated flow rates corresponded to the data measured in the field. The velocity data were extracted from the monitoring report of the São Francisco Hydroelectric Company [14] which monitored a point located 4 km from the mouth, with coordinates UTM 24L 784605 and 8841266.

Pearson's correlation was used to analyze the results at the sampling point, [15] emphasizes that, after the calibration of the model, errors related to water levels should be less than 5%, velocity and flows less than 20%. Based on these values, the correlation presented with 97.98% and 94.28% indicating a strong correlation with the simulated data (Figure 5 and 6). In all, 8 calibrations were performed, the latter being considered with adequate behavior, being the best percentage of calibration.

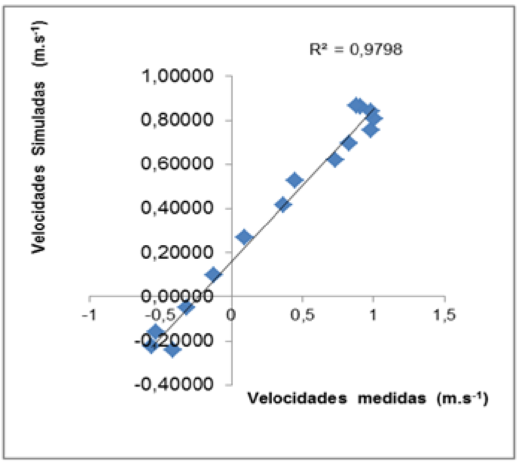


Figura 4: Análise da correlação entre a velocidade de corrente da água medida e simulada no dia 17/12/2009 das 15:00h as 22:00h

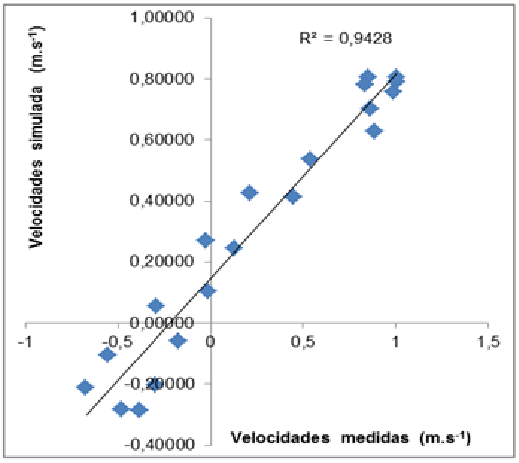


Figura 5: Análise da correlação entre a velocidade de corrente da água medida e simulada no dia 18/12/2009 das 01:00h as 10:30h.

It is understood that the SisBahia hydrodynamic model already contains self-calibration mechanisms requiring only the input data, providing consistency between the actual and predicted values at 90% water levels and flow direction and winds around 70%. The simulation occurred with a space of 13 days, closing a tidal cycle of syzygy.

3.2 Hydrodynamic scenario at the São Francisco River mouth

For the analysis of the behavior of the river flow dynamics and the expansion of the tidal displacement in Figure 6, it is shown that only in the municipality of Propriá and Penedo the values of the river discharge are within the limit of the value recorded by the fluviometric station. The other points present values above the registered one, indicating the entrance of the sea current in these regions, the point of the Criminal Island standing out with greater incidences.

According to [16], the behavior of the encounter of the fluvial waters with the one of the sea transported by the tide extending upstream is a characteristic event of the estuarine environments. However, the data reveal the expansion of the influence of the tide to the municipality of Ilha das Flores due to the recording of fluvial forcing above $1500m^3.s^{-1}$ according to Figure 6.

It is observed that in point 1, the largest variations occurred, that reached -6000 m^3s^{-1} in the tidal flood and -4000 m^3s^{-1} in the flood with quadrature tide. At another point in the ebb tide, the flows ranged from 8000 m^3s^{-1} at low tide to 5595 m^3s^{-1} at the quadrature tide. Point 1 is the largest representation of tidal amplitudes among the other points assessed, reinforcing the tide flow domain over the river flow (Figure 6). Results from the monitoring report carried out by CHESF in 2009 in the region of the São Francisco river mouth indicated mean flows around 2,097 m^3s^{-1}, during a tidal period of quadrature and syzygy, with these levels it was verified that the flow of the river reacts to the expansion of tidal propagation in the estuary.

However, currently with values of regularized flows around 900 m^3s^{-1} the scenario is reversed. According to [15] the practice of a 900 m^3s^{-1} defluence was necessary due to the lowering of the Sobradinho / BA reservoir. For [8], the effect of dams allowed the regularization and decrease in the magnitude of flows along the São Francisco River, drastically reducing its flood pulses. Note also the influence of the tide in point 2 and point 3, but with less intensity than point 1.

It is observed that in P6, the variations in the quadrature and systolic tide present between 930 and 970 m^3s^{-1}, reaffirming the phenomenon of regularization of the flows maintained by the Xingó HPP (Figure 21). Figure 7 shows the velocity of currents in the water column, where the mean value ranged from 0.04 $m.s^{-1}$ in the municipality of Penedo / AL to 0.14 m.s-1 in the Propriá / SE region. The maximum values for the ebb period were 0.17 $m.s^{-1}$ and for the flood period of 0.19 $m.s^{-1}$.

Figure 6: Simulated velocities in the hydrodynamic model region in the São Francisco River mouth.

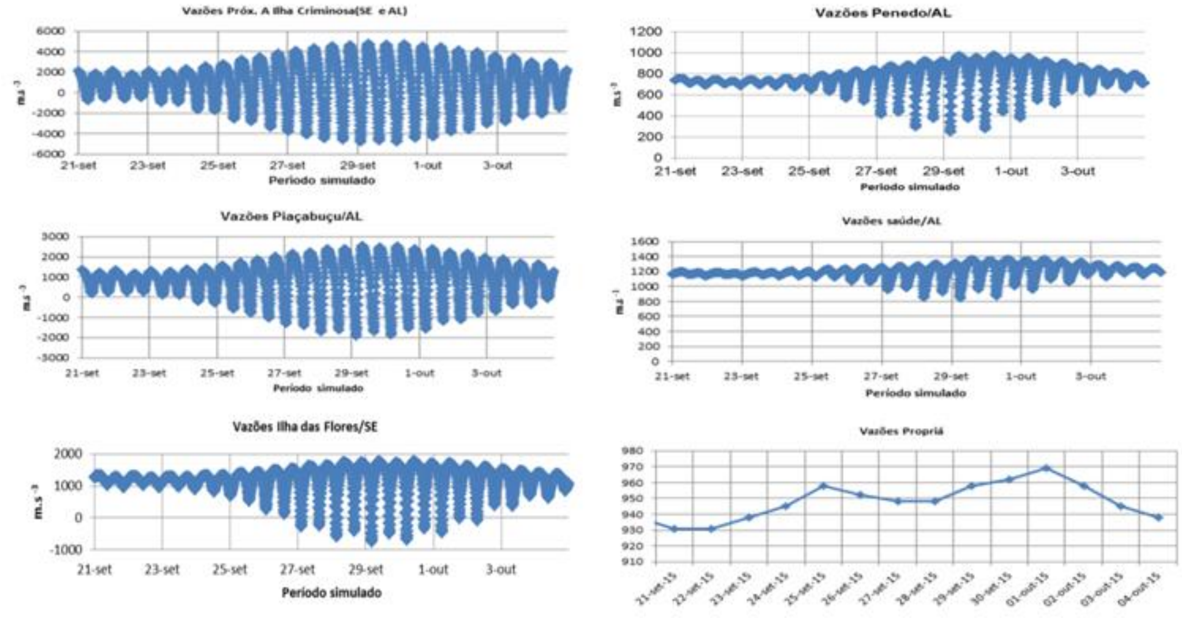
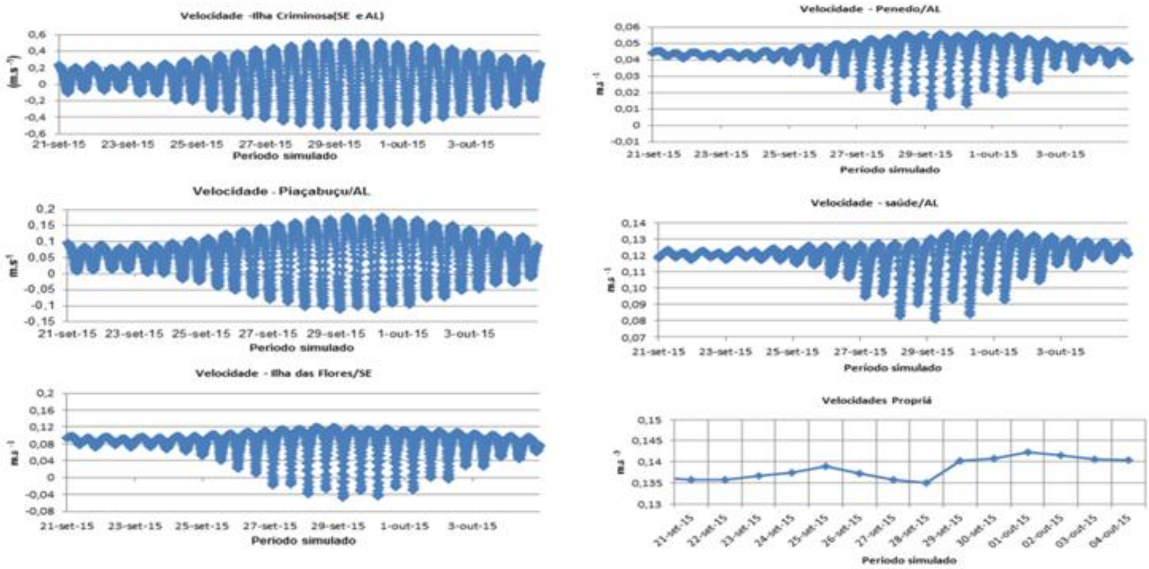


Figure 7: Simulated flows in the hydrodynamic model region in the Foz region of the São Francisco river.



Throughout the simulations for pre-wave hydrodynamic circulation, we observed the well-defined vortices formed by the velocity of the circulation of the sea current above the municipality of Piaçabuçu / AL, being limited below the municipality of Penedo / AL. At the moment of the low sea, the vortices indicate a linear flow towards the sea, this behavior indicates that the low sea oscillations do not interfere in the fluvial force in the main section of the channel of the mouth. However, Vortices are noted in continent direction entering the channel of the Parapuca. [17] analyzing the hydrodynamics in the Santos estuary, it has been found that the most intense velocities occurred in the preamar, indicating the predominance of the tidal effect in the renewal and water exchange of the system (Figure 8).

In the simulations of floods, it records that in the mediations of the municipality of Penedo / AL the limitation of vortices on the action of the sea current occurs, this scenario indicates a stability between the pulse of the river and the force of the sea current (Figure 8). However, with effluent simulation, the vortices of sea current action are not evidenced (Figure 9). The mixing zone occurs before the municipality of Penedo / AL, occurring the mixing of fresh water with sea water. According to [16] the mixing zone is the region where the mixing of fresh water with sea water is predominant. These results confirm that the hydrodynamics of an estuarine are the results fof the interaction between the estuarine basin morphology, the river flow and the tidal regime [18].

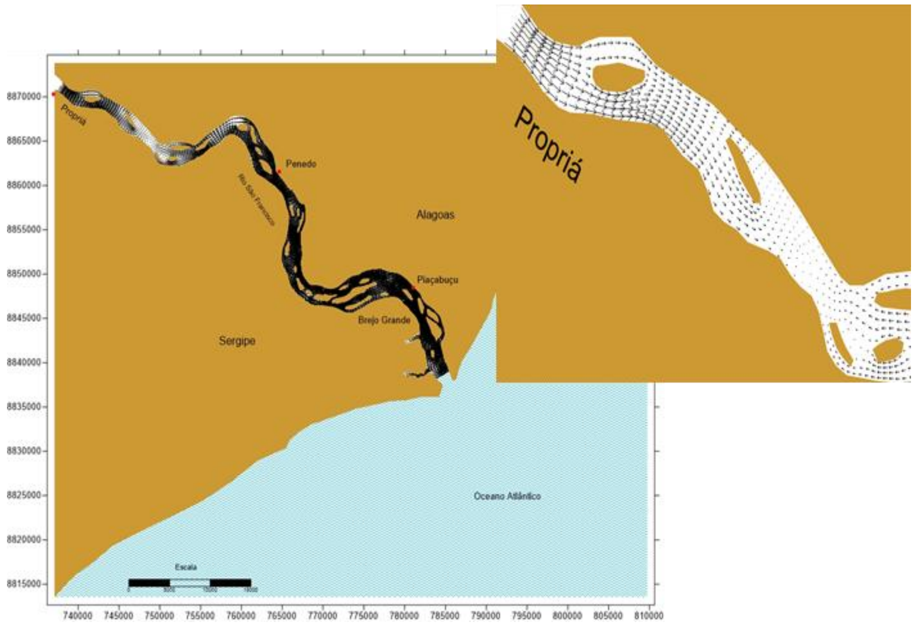


Figure 10: Simulation of the flood velocity hydrodynamics (A). (B) Speed above the municipality of Saúde and below the municipality of Propriá / SE.

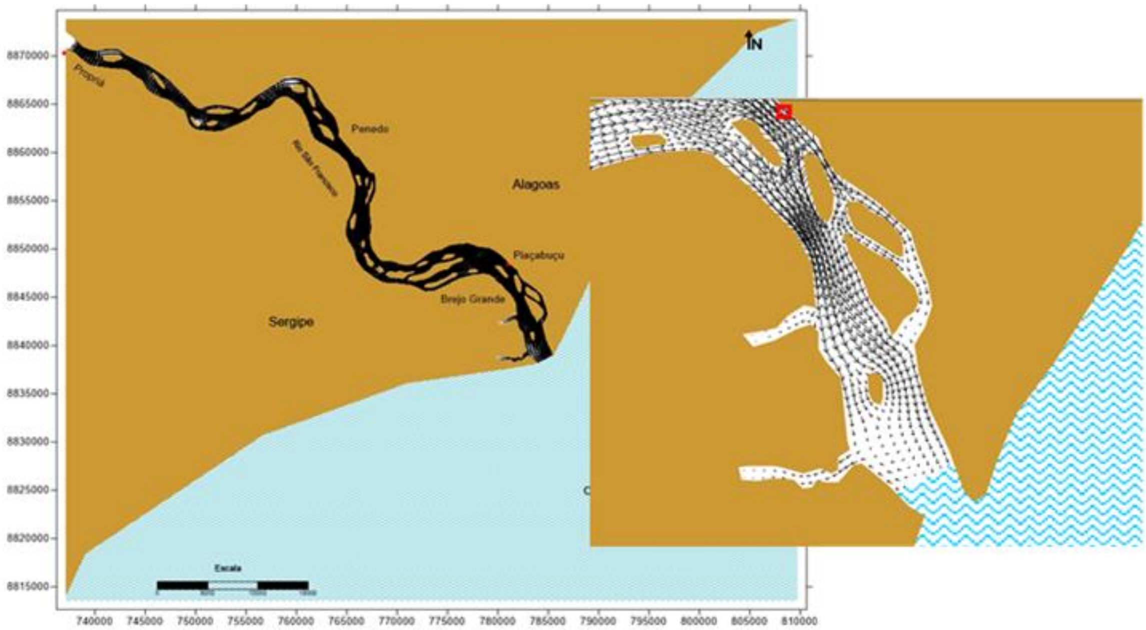


Figure 11: Simulation of the effluent velocity hydrodynamics (A). (B) Speed Foz a Piaçabuçu.

IV. CONCLUSION

The use of the hydrodynamic environmental model made it possible to understand the hydrodynamics existing at the São Francisco River mouth. The simulations presented the dynamics of the flows and the profile of the velocity in the period of ebb and flood of the river.

In the hydrodynamic scenario, the influence of the sea current on the flow of the river in sections above Piaçabuçu / AL was observed, which can allow change in the environmental dynamics and alteration of the water quality characteristics, in detriment to the decrease in the useful volume of the existing reservoirs downstream of the São Francisco River.

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