

***MID TERM SIMULATION OF SUSPENDED SEDIMENT TRANSPORT
AND BED EVOLUTION FOR THE PATOS LAGOON ESTUARY***
**SIMULAÇÃO DE MÉDIO PRAZO DO TRANSPORTE DE
SEDIMENTO SUSPENSO E EVOLUÇÃO DO FUNDO PARA O
ESTUÁRIO DA LAGOA DOS PATOS**

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Abstract: Worldwide harbors are settled inside estuarine areas due the protection function of these environments against oceanic waves and therefore are subjected to the hydrodynamic processes that provide morphodynamic changes in sediment distribution and bed evolution. Understanding the dynamic of sediments and the bed evolution at estuaries is of crucial importance on maintenance of fairways and harbor docks. The aim of this study is to model the suspended and cohesive sediment transport at the Patos lagoon estuary, southern Brazil, from 2003 to 2007, in order to point out the possible problems that sediment transport can cause at the harbor zone of Rio Grande. Therefore, a hydrodynamic model, TELEMAC 3D, and a morphodynamic, Sisyphé, were applied in order to acquire the bed evolution and sediment distribution of the area using different data sources for the oceanic, atmospherical and continental boundary conditions. The results show that clay is being deposited at deeper parts of the channel. Bed evolution results indicate siltation process where silt is being deposited. Sedimentation rates were calculated based on the bed evolution results.

Keywords: Telemac 3D. Sisyphé. Cohesive sediment. Suspended load. Bed evolution.

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1 Introduction

Estuaries are coastal transitional environments by which sediment is transported from high lands, by the rivers, to the sea. The relative shallow waters and harbor conditions that most estuaries present make them useful environments for human activities like installation of harbors, and shipyards and the maintenance of navigable fairways due offshore logistic of goods and oil.

Estuaries present a complex sediment dynamic related to the estuarine circulation. In many estuaries the suspended sediment concentration (SSC) increases in the upstream direction where a turbidity maximum zone (TMZ) is found at the head of the salt intrusion, forced by the entrance of sea water in the system (DYER, 1995). The distribution and magnitude of the TMZ are affected by seaward and landward sediment supply summed with variations in river discharge. Changes on natural patterns of both SSC and TMZ can affect sediment distribution and the morphodynamics of the environment. Moreover, human interventions, like deepening and widening of natural channels and land reclamation, can impact the natural distribution of the TMZ, resulting in ecological and infrastructural impacts (de Jonge et al., 2014).

Although siltation and erosion of fairways are natural processes of an equilibrium environment, they can be altered by human interventions. Dredging, can change the local sediment dynamics, affecting the natural patterns of sedimentation/erosion and affecting the SSC dynamics as well (MONGE-GANUZAS; CEARRETA; EVANS, 2013; van Maren et al., 2015; ZHU et al., 2014; PAARLBERG et al., 2015; WANG et al., 2015; van Maren et al., 2016).

Modeling of sediment transport and bed evolution of coastal environments are a difficult challenge, mainly because of the various different scale processes that need to be consider (PUTZAR; MALCHEREK, 2014). With the improvement of morphological models and the advance of computational resources, morphological modeling became a relevant alternative to understand the consequences of sediment transport in estuarine systems and its interactions with the hydrodynamics (LIU; HSU; KUO, 2002). Many morphological processes that earlier were assisted in an empirical approach can now be modeled by different proposed models, from sediment distribution and bed evolution to SSC and TMZ behavior (van Maren et al., 2015).

Bed evolution and sediment flux are also important features used to understand the

interactions between hydro and morphodynamics. The use of morphological models provide fast approach to assist the estuarine environment and it is many different scale variables and processes. Studies in different sandy estuaries already prove the reliability of morphological models and its contributions for different studies in the civil engineering and oceanographic fields of study (DAVIES; BROWN, 2007; GUILLOU; CHAPALAIN, 2010; MARQUES et al., 2010; ROBINS; DAVIES, 2010; XIE et al., 2013; ZHOU et al., 2013).

Therefore, the aim of this study is to simulate 13 years of sediment transport and bed evolution of the Patos Lagoon estuary. For then, test a dredge operation model for the harbor zone of the city of Rio Grande, located inside the estuary. Complementary analysis will be carried out regarding the effects of estuarine flow on the circulation and sediment distribution along the estuarine channel.

2 Modeling structure

This study applied three dimensional numerical modeling of the estuarine flow and sediment transport using the open TELEMAC-MASCARET system (<<http://www.opentelemac.org>>). The modeling procedure was conducted using two modules of the TELEMAC-MASCARET system: Telemac3D and Sisyphe. The first computes the flow regime which is needed to calculate the forcing data for sediment dynamics computed by the second. Hence, Telemac 3D and Sisyphe are constantly exchanging information about water and bed levels and flow velocities.

Telemac3D was already validated for the Patos lagoon estuary in previous studies about the hydrodynamic of the estuary and associated currents (FERNANDES et al., 2002); (MARQUES et al., 2010); (Marques, W. C., Fernandes, E. H. L., Malcherek, A., and Rocha, 2012); (KIRINUS; MARQUES, 2015). The module Sisyphe is been applied for the first time in this area.

2.1 Telemac3D model

This hydrodynamic model solves the Navier-Stokes equations, which are used to describe the motion of viscous fluids. It can calculate the velocities of the flow and the motion of physical properties such as temperature and salinity. For the vertical component of Navier-Stokes equations, a hydrostatic approach is applied so the pressure over a certain point is due

the atmospheric pressure and the weight of the water column above it. The three dimensional property of this model help us to model the vertical interactions inside the estuarine region as also the saline intrusion dynamics.

2.2 Morphodynamic numerical model

The morphodynamic model Sisyphe calculates the sediment transport in the form of bed load, suspended load and total load (bed + suspended). The bed load equation chosen for this study was the Meyer-Peter and Muller, which is validated for the grain diameter used in this study: $6.2 \times 10^5 \mu\text{m}$ for silt and $3.9 \times 10^6 \mu\text{m}$ for clay. The suspended load is computed by an advection-diffusion equation of the suspended sediment concentration in the water column. Finally, the bed evolution is calculated by the Exner equation, Eq.(1), which result the changes in bed levels caused by the sediment transport.

$$(1 - n) \frac{\partial Z_f}{\partial t} + \nabla \cdot Q_b = 0 \quad (1)$$

Where: n is the porosity of the non-cohesive bottom, Z_f is the bottom elevation and Q_b is the transport of solid volume (bed load) per unit width ($\text{m}^2 \cdot \text{s}^{-1}$). Details of these equations can be found at the Sisyphe user's manual (TASSI; VILLARET, 2014).

2.3 Numerical Domain and Boundary Conditions

The spatial domain is represented by an unstructured mesh composed by 93050 nodes varying distance from 10 km in oceanic domain up to 20 m at interested areas (waterway and near the groins of the inlet). The bathymetry interpolated into the mesh, varies from -0.5 m inside the estuary (sand banks) to almost -4000 m at the most end of the oceanic boundary Fig.1. Fifteen sigma levels spaced from the surface to bottom of the water column were discretized in the three dimensional domain.

For the liquid oceanic boundary condition we forced data of current velocities (u and v), water temperature and salinity, obtained from the HYCOM project (<<https://hycom.org>>). For the liquid continental boundary, river discharge data from the Guaíba and Camaquã rivers and the São Gonçalo's channel were obtained from the National water agency (ANA) (<<http://www3.ana.gov.br>>). At the free surface of the mesh, NOAA (<<https://www.esrl.noaa.gov>>) data were forced to simulate the exchange of atmospheric and oceanic processes. The data used were composed by air temperature, wind velocity (u and v) and atmospheric pressure Fig.2. Annual means of SSC were forced at the rivers as initial boundary condition, using data calculated by (JUNG, 2017).

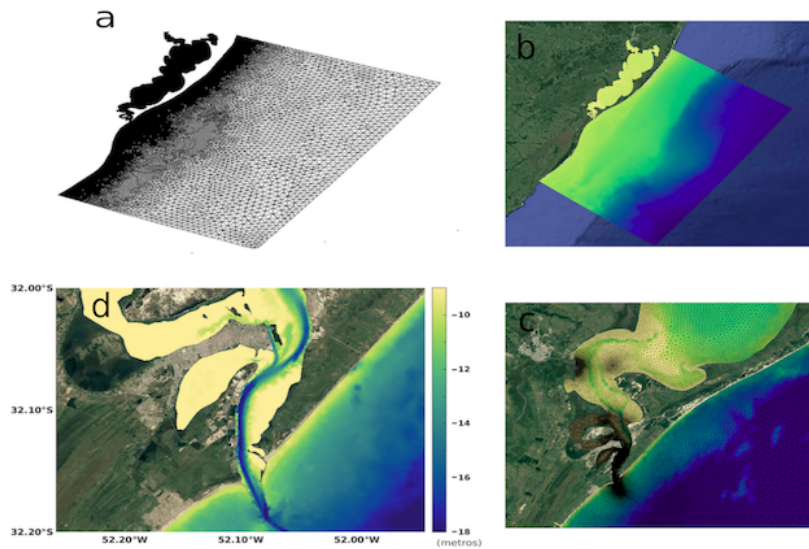


Figure 1: a) mesh generated using the BlueKenue software; b) Interpolated bathymetry in the mesh; c) zoomed view of the mesh inside the estuary; d) bathymetry inside the estuary.

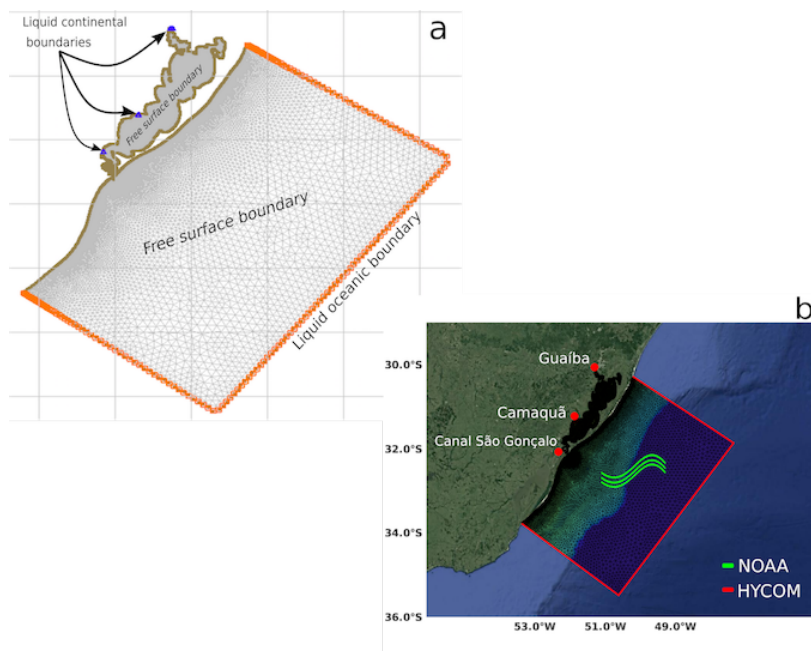


Figure 2: a) Location of the superficial and liquid boundary conditions used on the mesh; b) identification of the data used in each boundary. The NOAA data is applied at the free 2D surface of the mesh, while the HYCOM data is applied in the 15 layers of the 3D mesh.

3 Model validation

Salinity and current velocity modeled inside the estuary, at the Praticagem's station, were validated using *Conductivity and Temperature (CT)* and *Acoustic Doppler Current Profiler (ADCP)* data. The *in situ* data was collected by the LOCOSTE-IO FURG laboratory. The

validation represents a period of one year (01/01/2011 to 01/01/2012) (Fig.3). The statistical results of this validation are presented in Table1.

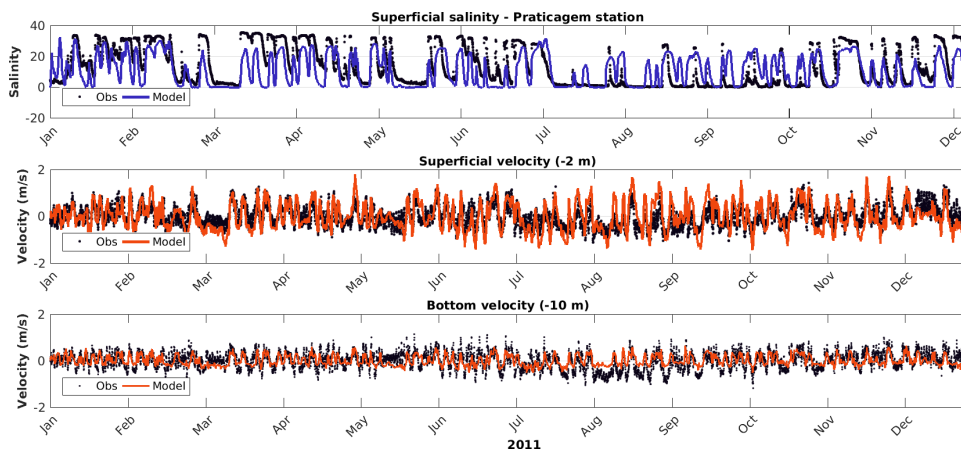


Figure 3: The upmost graph shows the validation for salinity at -2 m of depth. The other two graphs represent the superficial and bottom current velocities at -2 and -10 m respectively.

Table 1: Statistical results from the validation procedure for the salinity and superficial and bottom velocities.

	Parameter	in situ data	TELEMAC 3D
Salinity	Standard Deviation	12.580	9.851
	Absolute Error		8.229
	Root Mean Square Error		10.704
Superficial Velocity	Standard Deviation	0.325	0.299
	Absolute Error		0.203
	Root Mean Square Error		0.257
Bottom Velocity	Standard Deviation	0.233	0.111
	Absolute Error		0.158
	Root Mean Square Error		0.195

The analysis of Fig.3 gives us a perspective that the modeled data is correctly representing the physical parameters of the estuarine region. Salinity and both the superficial and bottom velocities modeled by Telemac3D follow the tendency of the ADCP data. The statistical parameters presented in Table1, show that the standard deviation of the salinity data is higher than the superficial and bottom velocities. yet, it is acceptable for this study. The salinity parameter is the one that showed the highest absolute error, 8.229.

Furthermore, we also validated the free surface elevation inside the lagoon with observed data of water levels provided by ANA. Fig.4 shows how the model correctly represented the tendency of the real water level data. These three stations were chosen because they are located at the west margin of the lagoon, the most affected by the wind and river discharges, correctly representing the variations of the surface for this environment.

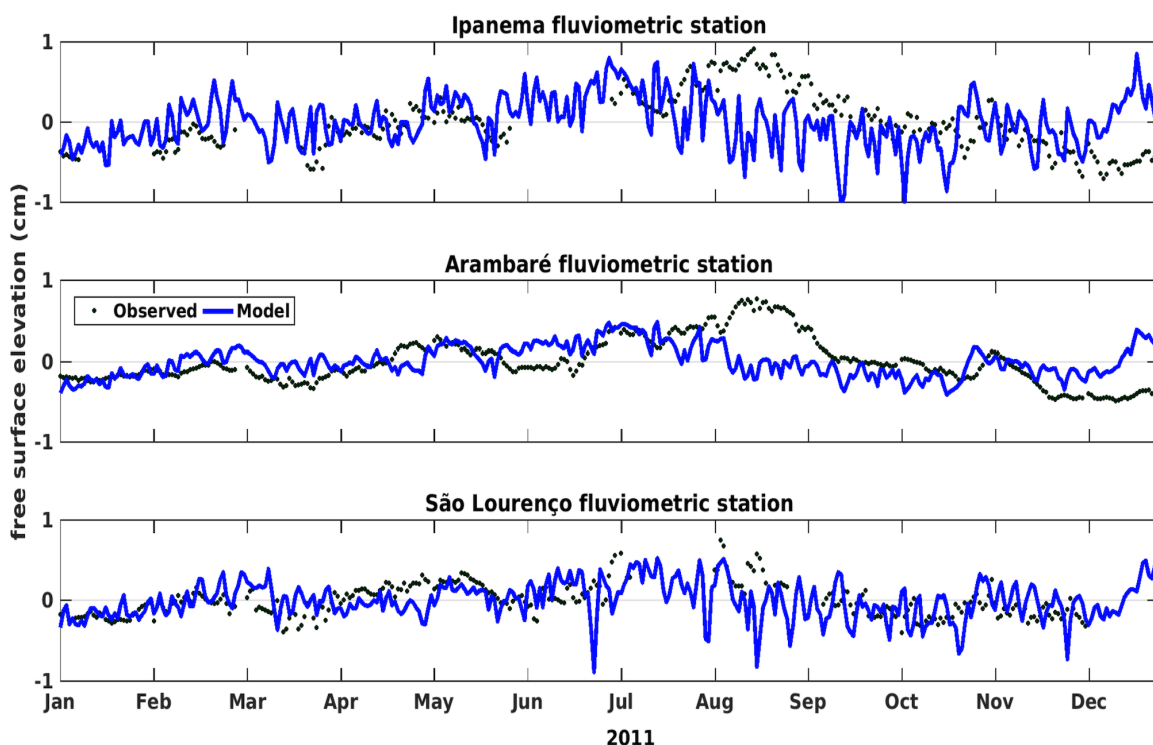


Figure 4: Validation procedure for water level inside the Patos Lagoon. From north to south we have the Ipanema, Arambaré and São Lourenço stations.

The amount of gaps in the real data of ANA limited the statistical results, but, the absolute error presented by Table2 are acceptable and represent well the surface elevation of the water inside the lagoon. The absolute error for the ANA data calculated in this validation procedure were 0.528, 0.607 and 0.735 for the Ipanema, Arambaré and São Lourenço stations respectively.

Table 2: Statistical results from the validation procedure for the water level data inside the Patos lagoon.

	Parameter	ANA data	TELEMAC 3D
Ipanema station	Mean	0.736	1.158
	Standard Deviation	0.364	0.318
	Absolute Error	0.528	
Arambaré station	Mean	0.545	1.130
	Standard Deviation	0.293	0.194
	Absolute Error	0.607	
São Lourenço station	Mean	0.425	1.173
	Standard Deviation	0.2004	0.230
	Absolute Error	0.735	

4 Results and Discussion

1005 days of suspended sediment transport were modeled at the estuary channel of the Patos Lagoon. Fig.5 show the suspended sediment transport rate versus current velocity. The velocity was obtained from the 2D simulation, so it represents the whole water column flux as one velocity only. We can see that suspended sediment transport rate increase with increasing velocity, that is because the flux resuspend the deposited sediment from the bottom, adding it again in the flux.

Fig.6 represent the concentration of suspended sediments, with silt at the left y-axis and clay at the right y-axis, versus the flow velocity for the same three points analyzed before. We can notice that clay suspended concentration at the Bacia do Porto Novo (BPN) point are higher than the silt ones, indicating that clay is been transported all over the water column, while silt can be found deposited at the bottom. At higher velocities both sediment classes initiate movement in the water column. For the points SP1 and SP2, at the estuarine channel, we notice less suspended clay, which indicates that it is deposited at the bottom. Again, with higher velocities we can see that both clay and silt are been transported by the flux.

Figure 7 shows the estuary bed evolution, sedimentation rate and sediment distribution, after 1005 days of simulation. It is clear that the evolution is remarkable along the estuary channel due shear stress of currents. Following, we present a detailed description of the bed evolution behavior along the estuary channel and analyzing other physical processes that explain the modeled results.

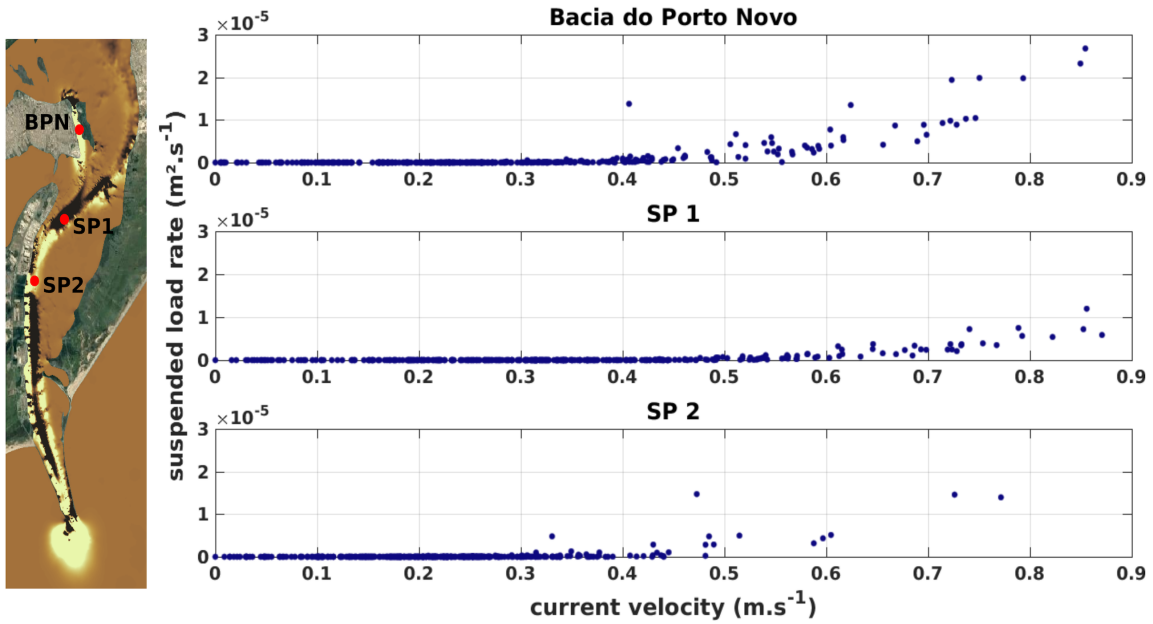


Figure 5: Current velocity versus suspended load rate for 3 points inside the estuarine channel. The points BPN, SP1 and SP2 represent the timeseries graphs on the right for the Bacia do Porto Novo, SP1 and SP2, respectively.

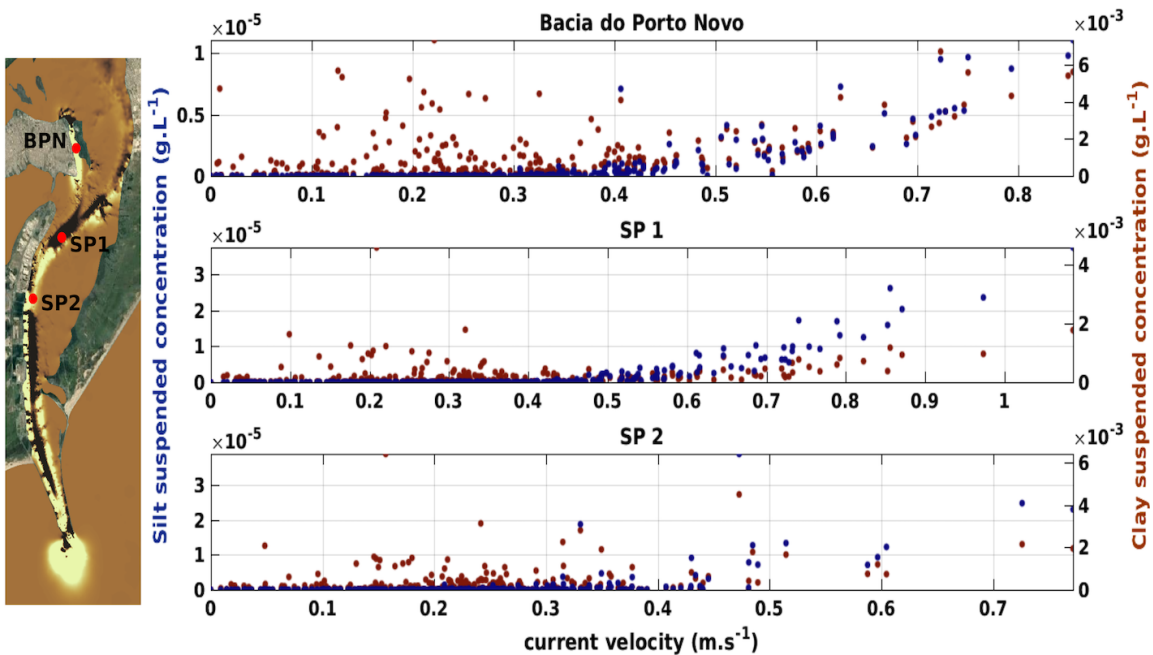


Figure 6: Graphs representing the relation between current velocity (x-axis) and suspended sediment concentration in g.L^{-1} . The right y-axis represents the clay suspended concentration, while the left y-axis represent the silt concentration.

The BPN region is known to present a positive depositional pattern, presenting positive bed evolution with smooth oscillations along time (MARTINS, 1971). Here, current velocities are slower than the rest of the estuary and make it possible for some fine sediment particles to

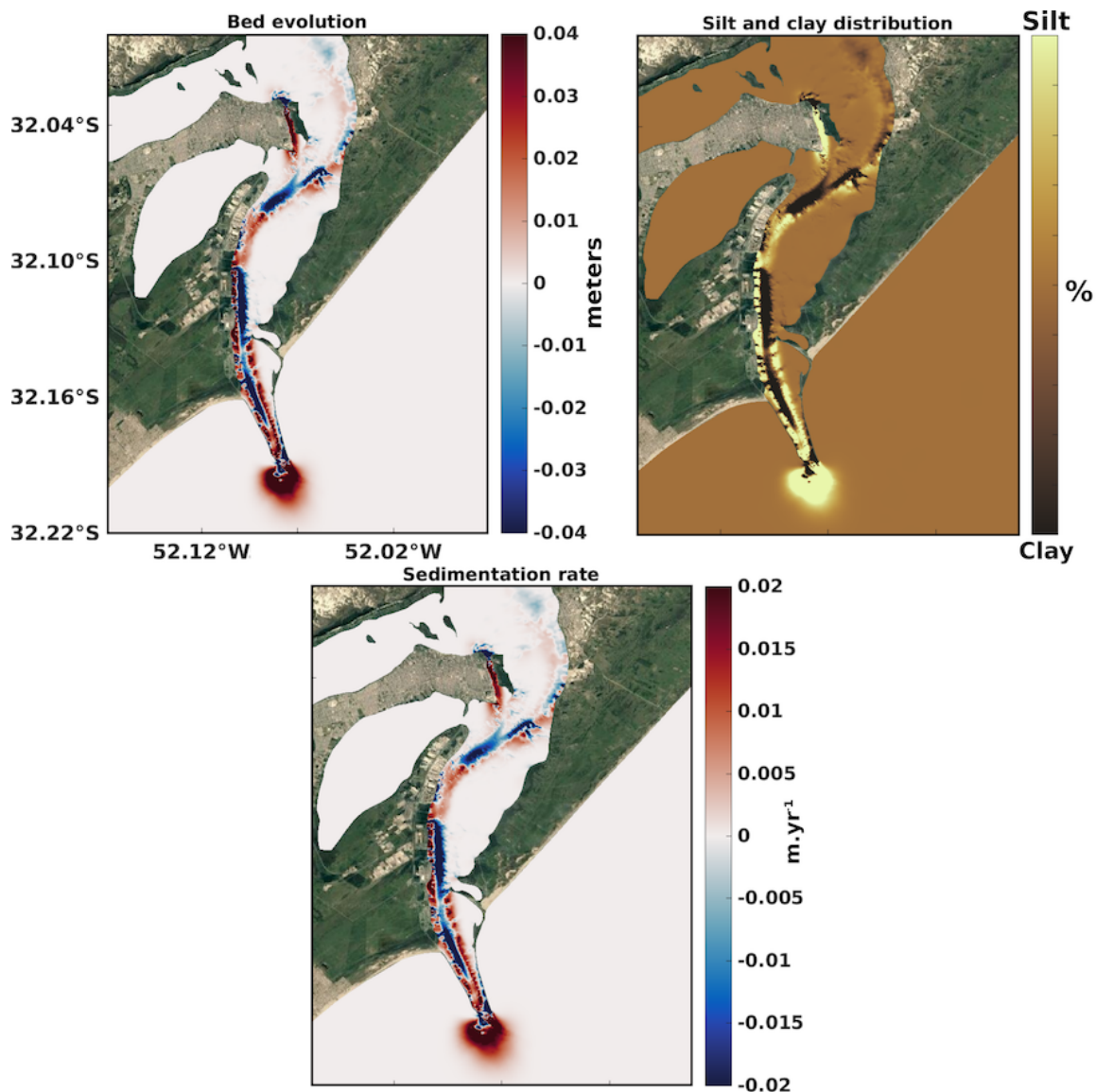


Figure 7: Bed evolution of the Patos Lagoon estuary. Dark red and dark blue indicate positive and negative bed evolution, respectively.

settle.

(CALLIARI et al., 2009) and (ANTIQUERA; CALLIARI, 2005) pointed out that the BPN have a depositional tendency due different processes that make the sediment particles settle in this region. The authors states that temperature, salinity and current velocity are the main forces to induce sediments to silt inside the BPN. Although the first 300 meters of the BPN present intense erosion at the end of the simulation, the rest of the basin present positive bed evolution Fig.???. We found -0.12 m, 0.0002 m and 0.05 m of bed evolution for the north, central and south part of the BPN, respectively. Along the 2.000 m of docks, the central part

presented the highest positive evolution of the basin, 0.22 m.

(Da Silva, 2016), unpublished, found the same pattern along the BPN and the docks when calculating sedimentation rates for the region, based on bathymetric data collected before each dredge operations. The author calculated a sedimentation rate of 405.8 mm.yr^{-1} , while we estimated a 11 mm.yr^{-1} . This difference in the results could be associated with the fact that Sisyphé did not simulated mud consolidation, underestimating our results.

The rest of the channel present a dominant erosional pattern at the middle of the channel, while the outer and inner margins present positive evolution. No literature was found to compare with our modeled results. Therefore, this is the pattern of siltation and erosion that we present for the estuary channel after 1005 days simulated.

We can also see that at the mouth of the estuary, inside the jetties Fig.7, a positive evolution tendency. This can be associated with an axial sany bank that is present at the right margin of the channel. This bank can be the source of the sediments that make this evolution to be positive at this site. More details about this bank can be found in (CALLIARI et al., 2009).

The sedimentation rates for the BPN, SP1 and SP2 sectors were estimated based on the bed evolution results by the time simulated. In Fig.7 they are represented in mm.yr^{-1} . For the BPN and SP1, we found sedimentation rates of 11 mm.yr^{-1} and $-11.84 \text{ mm.yr}^{-1}$, respectively. For the BPN sector, (Da Silva, 2016),unpublished, found a sedimentation rate of 405.8 mm.yr^{-1} . That difference in results can be associated with the fact that our simulation does not consider siltation and mud consolidation processes, underestimating our results.

For the SP2 sector, we found a positive sedimentation rate at the right margin and a negative rate at the left margin. That is conditioned by the geometry of the channel, that cause current velocities to be greater at the left margin, conditioning a erosive pattern at the left margin. The left and right margin present sedimentation rates of -40 mm.yr^{-1} and 8 mm.yr^{-1} , respectively.

The results of sediment distribution of clay and silt are in accordance with (TOLDO et al., 2006) when the author states that the coarse sediments deposit on the margins of the lagoon because of the high hydrodynamics that do not permit the fine particles to settle. Therefore, the

finer sediments are found all over the central lagoon bottom and the estuary deep channel. Silt and clay distribution results are shown in Fig.7.

At the BPN, the results present mainly silt deposited. That is because the clay is in suspension in this region as we saw in Fig.6. (CALLIARI et al., 2009) pointed out that the mixture of clay and silt inside the BPN can be the result of the saline intrusion that reaches this region during flood scenarios. The mix between salt and fresh water creates an attraction force between sediment particles, known as Wander Walls forces, which induce the sediment particles to flocculate, increasing its density and consequently the settling velocity.

We only modeled silt and clay because of the computational demand that more sediments classes would require. Therefore, sandy sediments were not modeled here. Thus, our results do not present the marine and transitional domain proposed by (MARTINS, 1971). The author states that the marine and transitional domains of the estuary (from the jetties to the Saco da mangueira entrance) are mainly covered with silty-sand and clayey-sand, because of the marine input of coarser sand sediments. The author also characterized the rest of the estuary as a lagoon domain, where the BPN would be covered by clayey-silt mixtures. Our results agree with the lagoon domain proposed by (MARTINS, 1971).

The morphological simulation corroborate with the sediment distribution proposed by the sedimentological literature of the region: (MARTINS, 1971);(TOLDO et al., 2006);(ANTIQUEIRA; CALLIARI, 2005) and (CALLIARI et al., 2009). Although we did not modeled sandy sediments mixtures, silt, the coarser class module, is being deposited in the outer and inner margins of the channel, that are the shallowest parts. Clay can be found at the deepest parts of the channel. Estuarine marginal bottoms did not present significant difference of both classes. That may be because of the short period simulated and the absence of sand in the simulation.

5 Conclusions

1005 days of morphodynamic at the Patos Lagoon estuary were simulated using finite elements numerical modeling. The results indicate positive bed evolution at the estuary channel margins as well at the BPN. Consequently, negative bed evolution is found major along the deeper center of the channel and at the north of the BPN. The SP2 sector, at the curvilinear part

of the channel, present intense positive bed evolution. Therefore, this region present a more need of dredge operations than the SP1 sector (negative evolution only), for example.

The suspended sediment transport results indicate that clay is deposited at the deeper parts of the channel while silt is found at the shallow and low hydrodynamic parts, like the margins of the channel and the BPN, respectively.

Mud consolidation and flocculation processes should be included in future morphodynamic simulations, as also adding more sediment classes, like fine sand. Therefore, the sedimentation rates would be more reliable to assist dredge operations and the presence of fine sand in the simulations would make evident the marine input of sediment inside the estuary.

Finally, Sisyphé had a good representation of the sedimentological and morphodynamic processes inside the estuary. Improvements of the model for this region could be of great value for future research and engineering studies such as dredge, land reclamation and navigability of the channel.

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