Journal of Coastal Research	SI 39	1556 - 1559	ICS 2004 (Proceedings)	Brazil	ISSN 0749-0208

Morphologically Induced Changes in the Circulation of the Patos Lagoon Estuary Brazil

R.V. Schiller†; R.O. Cecilio‡ and E.H.L. Fernandes∞

Fundação Universidade Federal do Rio Grande
Departamento de Física, Laboratório de Oceanografia Física.
Av. Itália, Km 8, CP 474, Rio Grande, RS, Brasil
†rafaelschiller@bol.com.br
‡r.cecílio@bol.com.br
∞e.fernandes@furg.br

ABSTRACT

SCHILLER, R.V.; CECILIO, R.O. and FERNANDES, E.H.L., 2006. Morphologically induced changes in the circulation of the Patos Lagoon estuary. Journal of Coastal Research, SI 39 (Proceedings of the 8th International Coastal Symposium), 1556 - 1559. Itajaí, SC, Brazil, ISSN 0749-0208.

The Patos Lagoon estuary has one of the most important harbor complexes in Brazil. The increasing navigational activities observed in the last decade enhanced the dredging demand in the access channel of the lagoon. Developments have been proposed for the area, which include an extension of the jetties at the entrance of the estuary, as well as deepening the existing access channel.

The objective of this study is to investigate the effect of the proposed developments on the circulation pattern of the estuary. Three scenarios are the focus of this study: a) original channel geometry and jetties length; b) original channel depth and extension of the jetties; c) modification of the channel depth and extension of the jetties. The TELEMAC flow model, based on the finite elements method, was used to carry out two-dimensional depth-averaged simulations to investigate the effect of such alterations on the hydrodynamics of the area.

Results showed that the extension of the jetties would reduce flood and enhance ebb fluxes in the estuary. The scenario with the extension of the jetties without dredging, however, would lead to stronger velocities at the access channel causing stronger shear stresses over the bottom and potentially reducing the demand for dredging. The scenario considering the extention of the jetties with dredging would lead to weaker velocities, which could promote the siltation of the access channel. Moreover, the extension of the jetties seems to reduce salt-water intrusion, which could affect the entrance of commercial fish and shrimp species, harming the local fishery production.

ADDITIONAL INDEX WORDS: *Numerical modeling, TELEMAC model, dredging, Patos Lagoon.*

INTRODUCTION

Located in the southernmost part of Brazil, between 30-32°S and 50-52°W, the Patos Lagoon (Figure 1, upper) is the largest choked coastal lagoon in the world (KJERFVE, 1986). With a length of 250 km in the main NE-SW axis and average width of 40 km, the lagoon has a surface area of 10,360 km^2, and can be classified as a shallow lagoon since it has an average depth of 5 m. The lagoon connects to the South Atlantic Ocean through a single inlet, which is 20 km long and less then 1 km wide. Several hydrodynamic studies carried out in the lagoon and in its estuarine area during the last decade present a thorough investigation of the main forces controlling the dynamics of the system (FERNANDES *et al.*, 2001; 2002; *in press*; MOLLER *et al.*, 1996; 2001).

The Patos Lagoon estuary (Figure 1, lower left) extends approximately 60 km inland and has one of the most important harbor complexes in Brazil (Rio Grande Harbor). The increasing navigational activities observed in the area during the last decades enhanced the dredging demand and the necessity of developments in the Patos Lagoon access channel. Recent developments have been proposed, which include the extension of the east and west jetties at the entrance of the estuary by 500 and 900m, respectively, as well as deepening the existing access channel from 14 to 20m and correcting its geometry. The objective of this study is, therefore, to investigate the effect of the proposed developments on the circulation pattern of the Patos Lagoon estuary.

METODOLOGY

The proposed hydrodynamic study of the estuary cannot be completely carried out based on field studies alone because of the large spatial and temporal variability of the area. Thus, the TELEMAC-2D model was used to carry out two-dimensional depth-averaged simulations to investigate the effect of the proposed developments on the hydrodynamics of the area.

The TELEMAC-2D model

TELEMAC is a flow model based on the finite element technique developed by the Laboratoire National d´Hydraulique (EDF, France) to simulate the flow in estuaries and coastal zones (HERVOUET and VAN HAREN, 1994; 1996). The TELEMAC-2D code solves the second order partial differential equations for depth-averaged fluid flows derived from the full three-dimensional Navier-Stokes equations. This gives a system consisting of an equation for mass continuity and two force-momentum equations, where the only assumption is that the fluid should be Newtonian. The equations at constant density are averaged over the vertical by integrating from the bottom to the surface. The source terms of the momentum equations include friction, Coriolis and wind force, with the bed friction being represented as a quadratic function of velocity and the parameterized friction coefficient being chosen by the user.

In order to solve the equations TELEMAC-2D considers for the solid boundaries that no mass flux of water occurs through the bottom and closed lateral faces and there is a free slip condition at the wall for all vectors tangent to it. The water surface height is free and the surface boundary condition is a stress calculated from the components of the wind velocity and the coefficient of wind influence. For the liquid boundaries, the user can define for each of the principal variables, if there is a prescribed or a free value at each point of the mesh. The model solves the equations on non-structured grids, with triangular finite elements. The nature of finite element mesh allows the fitting of various sized elements within a specified boundary, which allows high resolution in areas of increased bed slope or narrow channels and low resolution in areas where detail is not required.

The model has the option of using salinity (kg/m^3) as a tracer, taking density effects into account. The prescribed numerical

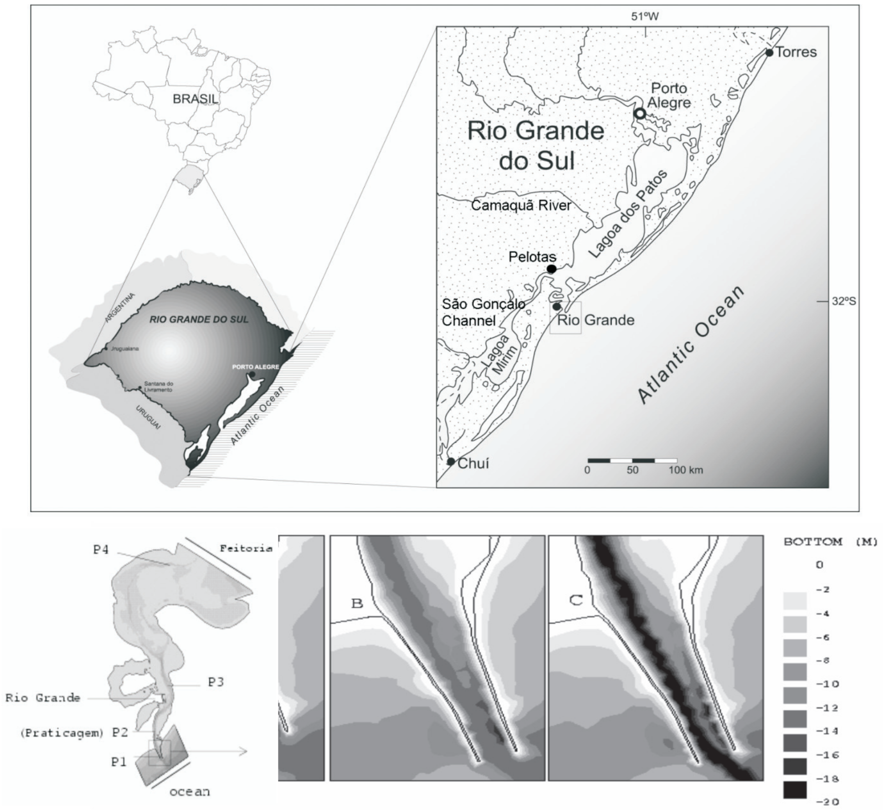

Figure 1. Location of the Patos Lagoon (upper, from Toldo and Dillemburg (2001)), estuarine area with chosen points for results presentation (P1, P2, P3 and P4) (lower left) and the three different scenarios under investigation (lower right).

value of salinity is an average over the vertical. The tracer represents a physical quantity that does not change or modify the flow. The evolution of the tracer with the flow depends on the advection and diffusion processes.

Model Set-up

Measurements carried out at Praticagem (Figure 1, lower left) between May and October 1999, were used to simulate the dynamics of the whole lagoon using a finite element mesh of 8,000 elements. The dynamic surface boundary condition was a stress calculated from the components of the wind velocity. The effect of incoming freshwater at the top of the lagoon was represented by a prescribed time series of sea surface elevation measured at the top of the lagoon (National Water Agency - ANA). Results from this simulation were then used to provide a time series of sea surface elevation used as the upper estuary boundary condition at Feitoria (Figure 1, lower left) for the estuarine simulations.current velocity (m/s)

Simulations for the estuarine area were then carried out using the same data set, but concentrating on a month period (between 07/99 and 08/99), representing the typical winter scenario: high river discharge and the passage of strong weather fronts over the area. Three different meshes with approximately 10,500 elements were used to represent the scenarios under investigation (Figure 1, lower right): A) maintenance of the original channel geometry and jetties length; B) maintenance of the original channel depth and extension of the jetties; C) modification of the channel depth and extension of the jetties. Measurements of sea surface elevation carried out at Praticagem (P2) were extrapolated for the three ocean open boundaries and used as the dynamic ocean boundary condition, as suggested by Moller *et al.* (2001).

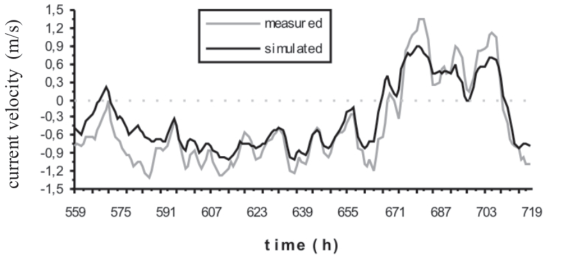

Figure 2. Comparison between measured and simulated current velocity at Praticagem (P2) for the last 160 hours of the period under investigation.

The TELEMAC-2D model was previously calibrated and validated for the Patos Lagoon using measurements of sea surface elevation and wind speed and direction from Praticagem (Fernandes *et al.*, 2001; 2002). The relation between measurements and modeling predictions was evaluated by calculating the relative mean absolute error (RMAE) proposed by Walstra *et al.* (2001), which indicated excellent agreement (Fernandes *et al.,* 2002).

In order to validate the model for this particular study of the estuarine dynamics, measurements of current velocity carried out at Praticagem during the period under investigation (07/99 08/99) were compared with modeling predictions for the same point and time interval (Figure 2). The model reproduction was also classified according to the method proposed by Walstra *et al.,* (2001), where the calculated RMAE=0.31 indicates a good agreement between measurements and predictions. This comparison indicates that the TELEMAC-2D model can be

Table 1. *Mean values (% relative to scenario A) for P1.*

	A	B	C
Flood flux ($m^3 s^{-1}$)	2761	2582 (-6.5%)	2590 (- 6.2%)
Ebb flux ($m^3 s^{-1}$)	-4149	-4443 (+7.1%)	-4578 (+10.3%)
Flood currents ($m s^{-1}$)	0,34	0,31 (-6.5%)	0,27 (-18.6%)
Ebb currents ($m s^{-}$)	-0,52 (+3.2%)	-0,54 (-4.8%)	-0,49

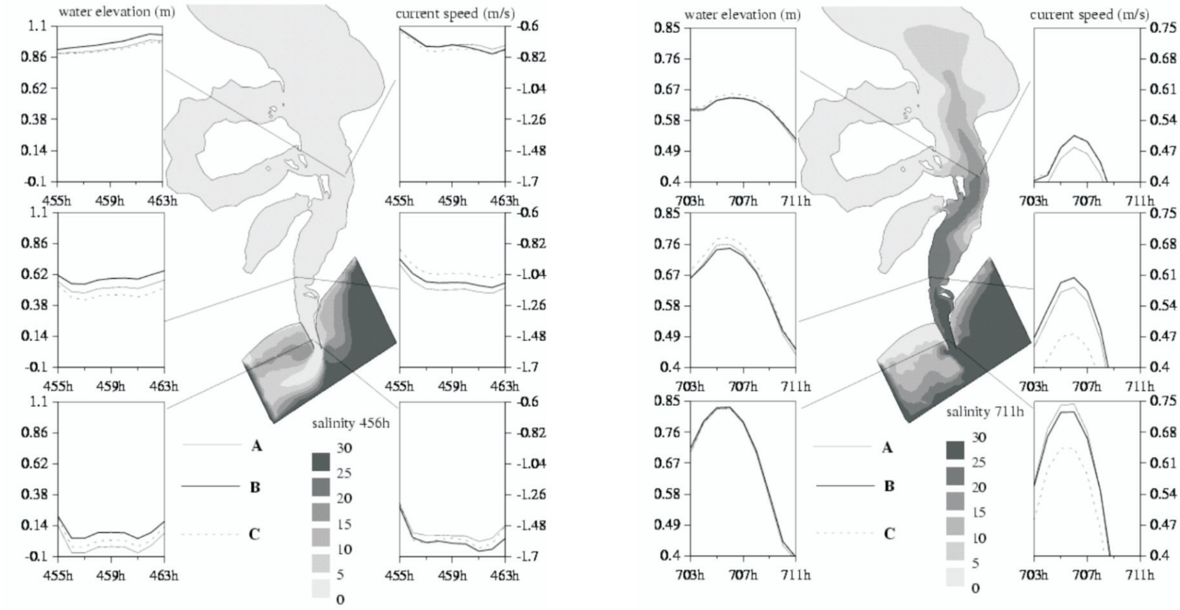

Figure 3. Water elevation and current velocity at P1, P2 and P3 for the investigated scenarios during 8h of a NE (left) and a SW wind event (right). Results considering salinity as a tracer are presented for scenario A.

Used as a reliable tool to study the dynamics of the estuarine area.

Results indicate stronger flood fluxes and currents for scenario A, while B and C had similar flood fluxes. Smaller flood currents were observed for scenario C due to the increase in the cross-sectional area. The ebb flux presented the opposite behavior, being stronger for scenario C. The ebb currents were stronger for scenario B, followed by A and C. Thus, the extension of the jetties tends to reduce the flood and enhance the ebb fluxes.

In order to study the dynamics of the estuarine area in more detail, predictions illustrating the two predominant wind situations in the area (winds from NE and SW) were selected from the studied period.

The period between 455 and 463 h of simulation (Figure 3, left) illustrates a NE wind event. The calculated sea surface elevation throughout the estuary indicates that the combined effect of the local and non-local wind establishes a barotropic pressure gradient towards the ocean, favoring flushing of the estuarine mixing zone to the coastal area for the three studied scenarios. These results also indicate the different behavior for the three scenarios. Although the water level was reduced at the ocean boundary, the funneling effect produced by scenario B seemed to retain water near the mouth, pilling up water in the area and generating an elevation 10 cm higher than in scenario A. A similar behavior was observed for scenario C, although in a smaller scale due to the presence of a deeper channel. The difference in current speeds between P2 (B and C < A) and P1 (B and C > A) showed fluid acceleration for B and C due to the extended jetties.

The period between 703 and 711 h of simulation (Figure 3, right) illustrates a SW wind event. The calculated sea surface elevation throughout the estuary indicates that the combined effect of the local and non-local wind establishes a barotropic pressure gradient towards Feitoria , favoring the occurrence of flood fluxes and the penetration of salt water. The salt-water intrusion is illustrated for scenario A. The overall results for the tracer (not shown) indicate that for low salinity values (1-5), the isolines for B and C had almost the same incursion distance. For high salinity values (20-30), however, the incursion distances for B and C was shorter. The shorter intrusion is directly related to the weaker flood fluxes previously observed for scenario B and C, suggesting that, the salinity distribution is dominated by advection in the access channel. Moller and Castaing (1999) observed a similar behavior. Finally, the current speed for C showed acceleration between P2 (C << A) and P3 (C = B >A) due to the reduction of the cross sectional area at the end of the deeper access channel.

Results for P4 are not shown because all scenarios presented similar results of water elevation and velocity in both events, suggesting that the dynamics of this area is not affected by morphological changes at the estuary entrance.

CONCLUSIONS

The numerical experiments indicate that the proposed developments in the morphology of the Patos Lagoon access channel could modify the circulation pattern of this area, although further investigation needs to be carried out in order to establish the relevance of such modifications

The extension of the jetties would reduce flood and enhance ebb fluxes. The extension of the jetties without dredging, however, would lead to stronger velocities at the access channel, generating stronger shear stresses over the bottom and potentially reducing the demand for dredging. The extension with dredging would lead to weaker velocities, potentially promoting siltation.

Besides that, the extension would also cause intensification of the funneling effect, generating higher water elevations inside the estuary. Salt-water intrusion could be reduced, making the entry of important commercial fish and shrimp species more difficult and affecting fishery production.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil, for sponsoring this research under the contract no. 540467/01.

LITERATURE CITED

TOLDO, E. E. and DILLENBURG, S. R., 2001. Swash bar migration at the inlet of the Lagoa dos Patos Lagoon, Brazil. *Journal of Coastal Research*, 34, 489-492.

FERNANDES, E.H.L; DYER, K.R. and NIENCHESKI, L.F.H., 2001. TELEMAC-2D calibration and validation to the hydrodynamics of the Patos Lagoon (Brazil). *Journal of Coastal Research,* ??, 470-488.

FERNANDES, E.H.L.; DYER, K.R.; MOLLER, O.O. and NIENCHESKI, L.F.H., 2002. The Patos Lagoon hydrodynamics during an El Niño event (1998). *Continental Shelf Research* 22: 1699-1713.

FERNANDES, E.H.L.; MARIÑO-TAPIA, I.; DYER, K.R. and MOLLER, O.O. (in press). The attenuation of tidal and subtidal oscillations in the Patos Lagoon estuary. *Ocean Dynamics*.

HERVOUET, J. M. and VAN HAREN, 1994. TELEMAC-2D Principle Note. Electricité de France. Technical Report HE-43/94/051/B.

HERVOUET, J. M. and VAN HAREN, 1996. Recent advances in numerical methods for fluid flows. In: *Floodplain Processes*. Anderson, M. G.; Walling, D. E. and Bates, P. D. (Eds.). Pp. 183-214.

KJERFVE, B., 1986. Comparative oceanography of coastal lagoons. In: *Estuarine variability*, Wolfe, D.A., (Ed.), pp. 63-81. Orlando, Florida: Academic Press.

KJERFVE, B. and KNOPPERS, B.A., 1991. Tidal chocking in a coastal lagoon. In: *Tidal Hydrodynamics*. Parker, B.B.(Ed). Pp. 169-181.

MOLLER, O. O.; LORENZZETTI, J. A.; STECH, J. L. and MATA, M. M., 1996. The Patos Lagoon summertime circulation and dynamics. *Continental Shelf Research*, 16, 335-351.

MOLLER, O. O. and CASTAING, P., 1999. Hydrografical characteristics of the estuarine area of Patos Lagoon. In: PERILLO, G.M.E.; PICCOLO, C.M. and PINO, M.(eds.) *Estuaries of South America. Their geomorfology and dynamics*. Springer-Verlag, Berlin, pp.83-99.

MOLLER, O.O., CASTAING, P., SALOMON, J.C. and LAZURE, P., 2001. The influence of local and non-local forcing effects on the subtidal circulation of Patos Lagoon. *Estuaries* 24: 275-289.

WALSTRA, L.C.; VAN RIJN, L.C.; BLOGG, H.; and VAN ORMONDT, M., 2001. Evaluation of a hydrodynamic area model based on the COAST3D data at Teignmouth 1999, Report TR121 EC MAST Project No. MAS3-CT97-0086. HR Wallingford, UK.