Journal of Coastal Research	SI 64	1086 - 1090	ICS2011 (Proceedings)	Poland	ISSN 0749-0208

Hydrodynamic study of bay beaches – a case study of Itapocorói Bay, Brazil

L. M. Leite∞, J.M. Dias‡, J.M.B. Carvalho§, A.H.F. Klein†

∞Departamento de Física, Universidade de Aveiro, 3810-193 Aveiro, Portugal
luisleite@ua.pt

‡ CESAM, Departamento de Física, Universidade de Aveiro, 3810-193 Aveiro, Portugal
joao.dias@ua.pt

§ Centro de Ciências Tecnológicas da Terra e do Mar, Universidade do Vale do Itajaí, Itajaí, SC. Cx. P. 360. CEP 88302-202, Brasil
carvalho@univali.br

†Universidade Federal de Santa Catarina, Centro de Filosofia e Ciências Humanas Departamento de Geociências, Campus Universitário Trindade - Florianópolis SC Brasil CEP 88.040-970
klein@cfh.ufsc.br

ABSTRACT

Leite, L. M., Dias, J.M., Carvalho, J.M.B., Klein, A. H. F. 2011. Hydrodynamic study of baybeaches – a case study of Itapocorói Bay, Brazil. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 1086 – 1090. Szczecin, Poland, ISSN 0749-0208.

The hydrodynamic understanding of Bay Beaches is an essential feature in the coastal management, since it constitutes the base required to the development of future projects and studies, and has many applications in different areas (e.g. coastal erosion, water quality, ecology, etc). An investigation that could explain the hydrodynamic behaviour, the vortex formation, the circulation pattern of currents and their interaction with the tide and local wind inside the bay beaches, was held on the shores of Itapocorói's Bay (Alegre and Piçarras), in the north-central coast of Santa Catarina – Brazil. In this context, several campaigns were carried out to measure the tide, current at different depths and study the behaviour of the local wind. These data were used as 3D model forcing to characterize the circulation patterns on the bay and verify the existence of a vortex during the data collection period. Scenarios with different characteristic winds (constant and uniform) were then simulated and the conditions in which these structures formed were determined. The model results have enabled to make a characterization of the general pattern of currents in Itapocorói Bay and revealed the vortex formation in the southern part. Those structures can have clockwise or counter-clockwise gyre depending on the direction of the incident wind. The simulations show a vortex located in the south area of the bay with a counterclockwise gyre when the winds are coming from the South and Southeast quadrant. With northeast winds, sporadic and short vortices with clockwise can be formed.

ADDITIONAL INDEX WORDS: *hydrodynamic model, vortex generation, coastal circulation*

INTRODUCTION

The headland bay beaches or embayed beaches represent about 50% of the world's coastline (Short and Masselink, 1999) hence, their understanding is essential to coastal sciences.

These beaches can have different configurations, various sizes and shapes, and despite several studies have already been performed about their geography and geology (eg, Yasso, 1965; King, 1972; Carter, 1988), their hydrodynamic was only considered by a small number of scientists and engineers.

Authors such as Short and Masselink (1999), Klein and Menezes (2001) and Klein (2004) acknowledge that studies conducted in the bay beaches are scarce. In short, this is still an open field of environmental science to be explored in relation to hydrodynamic processes, sediment transport and morphodynamics.

Recently, Valle-Levinson and Mogara-Opazo (2006) and Valle-Levinson *et al.* (2000) studied the pattern of currents in two inlets of Chile and observed the formation of vortices, resulting from the interaction of the currents with the local geography of these bays. However, these vortices had already been detected using numerical models in the work of Allen (2000), Klink (1996) and Gan *et al.* (1997), and were associated with the interaction of flows to coastal submarine canyons or the geometry of the shoreline of the bay beaches. Moreover, several studies have found currents response to the local wind and tide (Pattiaratchi *et al.*, 1997; Masselink and Pattiaratchi, 1998; Sedrati and Anthony, 2007), which could have influence on the generation of these vortices. Thus, since there are not many studies on this type of beaches, a new research study that attempt to explain the formation of vortices in bay beaches, the establishing of currents and their interaction with the tide and local wind, would be useful to increase the knowledge about this topic.

STUDY AREA

The Itapocorói Bay is located in north-central coast of Santa Catarina, Brazil, and includes Piçarras and Alegre's beaches (Figure 1). Piçarras's beach is located in Balneário de Piçarras and is considered a bay beach, with 8 km long. It is bounded on the north by the Itajuba Headland and on south by the Piçarra's river. Between Piçarras and Iriri's river is Alegre's beach, which is about 1 km long.

The wind regime in this area is predominantly from the Northeast throughout the year, however the effect of local sea breezes is also observed. These prevailing winds are very influenced by the spread of extra tropical cyclones, which intensify in the months of winter and spring, changing the local

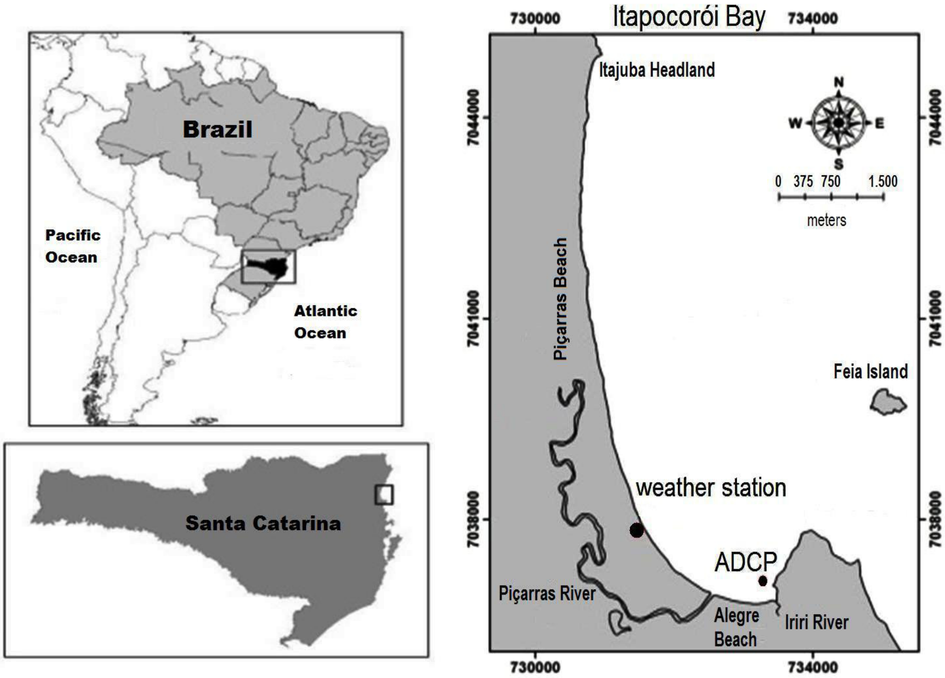


Figure 1. Study area. UTM Datum SAD-69 coordinates.

weather and increasing the importance of South winds (Truccolo, 1998)

Numerical modelling studies by Van den Heuvel *et al.* (2008) show that due to the Piçarras Beach geometry its South part is protected from South and Southeast swells. Therefore is created a shadow zone, located south of the beach, which is less exposed to swells than the northern area. Finally, they found that due to diffraction the wave height decreases in the area that is protected by the Feia's Island and in the South part of the bay.

According to the classification of Davies (1964), a system of micro-tidal mixed tide predominantly semi-diurnal is described for the region. The average tidal amplitude is 0.8 m, with a minimum of 0.3 m during f neap tides and a maximum of 1.2 m during the spring tides (Schettini *et al.*, 1996). These authors also claim that the meteorological tides, under extreme conditions, exert great influence in regional coastal dynamics and can reach an elevation of 1 m over the values of the astronomical tides.

METHODS

To study and simulate the vortex formation inside Itapocorói Bay the hydrodynamic FIST3D model of SisBAHIA was used in its three dimensional mode. However, before carrying out these simulations, and in order to obtain an approximate characterization of the currents pattern in the Bay, a 2DH model application was performed. Different scenarios with constant and uniform wind forcing were simulated for the period of time between 1 and 31 of July 2009. At this stage the tide was theoretically calculated by SisBAHIA. These simulations allowed the understanding of the hydrodynamic behaviour of currents in Itapocorói Bay for different incident wind directions and of the formation of different vortices.

These previous results were used to define a sample point where an ADCP (Acoustic Doppler Current Profiler) have been anchored and sea level elevation data was collected during 45 days (between July 10^{th} and August 24^{th}). A weather station was also installed at the beach to record the wind data for the same period of time. The results of this monitoring were subsequently used as boundary conditions for the 3D model, applied to study the formation of vortices in Itapocorói Bay and the interaction between currents, tides and local winds. The period between July 10 and August 24 was simulated by the 3D model and some vortices were identified.

Then, different scenarios with constant and uniform wind were created, to study in which conditions the vortices are formed and analyze the local hydrodynamic.

Hydrodynamic model

The barotropic hydrodynamic module of SisBAHIA modeling system (Sistema Base de Hidrodinâmica Ambiental) was used to study the hydrodynamics of Itapocorói Bay. The SisBAHIA is a set of hydrodynamic and transport models that has been widely evaluated and tested for coastal studies (Rosman, 1987, 2001, 2003) and was developed at the Coastal and Oceanographic Engineering Group of the Federal University of Rio de Janeiro, Brazil. The hydrodynamic module solves the momentum and continuity equations for a homogeneous fluid, considering the Boussinesq and the hydrostatic approximations. Spatial discretization of the modelling domain is done through sub-parametric Lagrangian finite elements, with the geometry defined by linear Lagrangian polynomials. The flow variables and the domain parameters are defined by quadratic Lagrangian polynomials, considering a quadrangular mesh (Rosman, 2001).

Turbulent stress is parameterized according to filtering techniques derived from the approach known as large eddy simulation (LES) (Rosman, 2009) and is self adjustable in the sub-grid scale.

The model solves the two-dimensional shallow water equations in their depth-integrated form:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial\left[U\left(h+\zeta\right)\right]}{\partial x}+\frac{\partial\left[V\left(h+\zeta\right)\right]}{\partial y}=0 \qquad (1)$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-g\frac{\partial \zeta}{\partial x}+\frac{1}{d}\left[\frac{\partial}{\partial x}\left(\frac{d\tau_{xx}}{\rho_r}\right)+\frac{\partial}{\partial y}\left(\frac{d\tau_{xy}}{\rho_r}\right)\right]+fV+\frac{\tau_x^s}{d\rho_r}-\beta U \qquad (2)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-g\frac{\partial \zeta}{\partial y}+\frac{1}{d}\left[\frac{\partial}{\partial x}\left(\frac{d\tau_{yx}}{\rho_r}\right)+\frac{\partial}{\partial y}\left(\frac{d\tau_{yy}}{\rho_r}\right)\right]-fu+\frac{\tau_y^s}{d\rho_r}-\beta V \qquad (3)$$

In (2) and (3):

$$\beta=\frac{C_f\left|U^2+V^2\right|^{1/2}}{d} \qquad (4)$$

where: $d(x,y,t) = h(x,y)+ \zeta (x,y,t)$; $\zeta (x,y,t)$ is the free surface elevation with respect to the mean water level; $h(x,y)$ is the water depth, $d(x,y,t)$ is the total water depth; U and V are the depth-averaged components of the horizontal velocity; τ_{ij} represents the turbulent stresses components, f is the Coriolis parameter, and ρ_r is a reference density. The bottom friction coefficient, C_f, is written in terms of the Chezy coefficient (C) according to

$$C_f=\frac{g}{C^2} \text{ with } C=18\log\left(\frac{6d}{\varepsilon}\right), \qquad (5)$$

where ε is the amplitude of the equivalent bottom roughness that corresponds to double the roughness height. According to Daily and Harleman (1966), the surface stresses may be expressed as follows:

$$\tau_i^s=\rho_{air}C_D U_{10}\cos x_i\,, \qquad (6)$$

where C_D is a wind drag coefficient (Wu, 1982); U_{10} is the wind speed 10 m above the free surface, θ_i the angle between the wind velocity vector and the x_i direction, and ρ_{air} is the air density.

The bathymetry of Itapocorói was determined with the aid of a vessel, an echo sounder of Odom and a Trimble's RTK that mediates the depth, informed the instantaneous position and correct the water level. For smaller depths, and because it has greater mobility, a jet ski with a Garmin's echo sounder probe was used for measuring the depth and location, and a GPS correct the position given by the probe. The numerical grid for the hydrodynamic model was developed using the Kriging interpolator. It consists of 1144 quadratic elements with a resolution increasing from the open border (300 meters) to the study area (150 meters).

The time step of the numerical applications was 1200 seconds, the wind in the open boundary was constant and uniform in space and time (the direction and intensity varied in each simulation), the Von Karman constant was 0.404 and the bottom had a roughness value of 0.03 meters. The turbulent viscosity was calculated internally by the model and the flow of Piçarras and Iriri Rivers were discarded.

Data collection

The 2DH model results for the currents field allowed the identification of the generation of different vortices with different direction gyres. The ADCP was installed in the vortices generation area and was moored at (733299, 7037124 UTM), about 100 meters from the harbour on the right side of Alegre's beach, in the northwest direction. This place was chosen because, according to the 2DH model results, different directions of wind generate unequal currents and eddies intersecting that area. The ADCP (Argonaut-XR SonTek -1500 kHz) was used with a 1200 seconds acquisition interval and an average sample of 120 seconds. This average helped to remove the effect of ripple and high noise frequency. In the definitions of the ADCP, six cells for data acquisition were selected and different depth values of current direction and intensity, as well as free surface level data were recorded. The ADCP was moored during the period between 10 July and 24 August 2009, and weekly campaigns were performed to verify the equipment.

During the same period of time acquisition of wind data in the study area was performed. To record the speed and wind direction, a weather station (Weather Monitor II Complete) was installed in Piçarras. Thus, a tripod was installed to fix the weather station and the anemometer was elevated to approximately 10 meters high, using the U.S. Army Corps of Engineers' (Thompson and Leenknecht, 1994) standards to reduce the influence of the boundary layer. In the settings of the station was selected a data acquisition every 10 minutes.

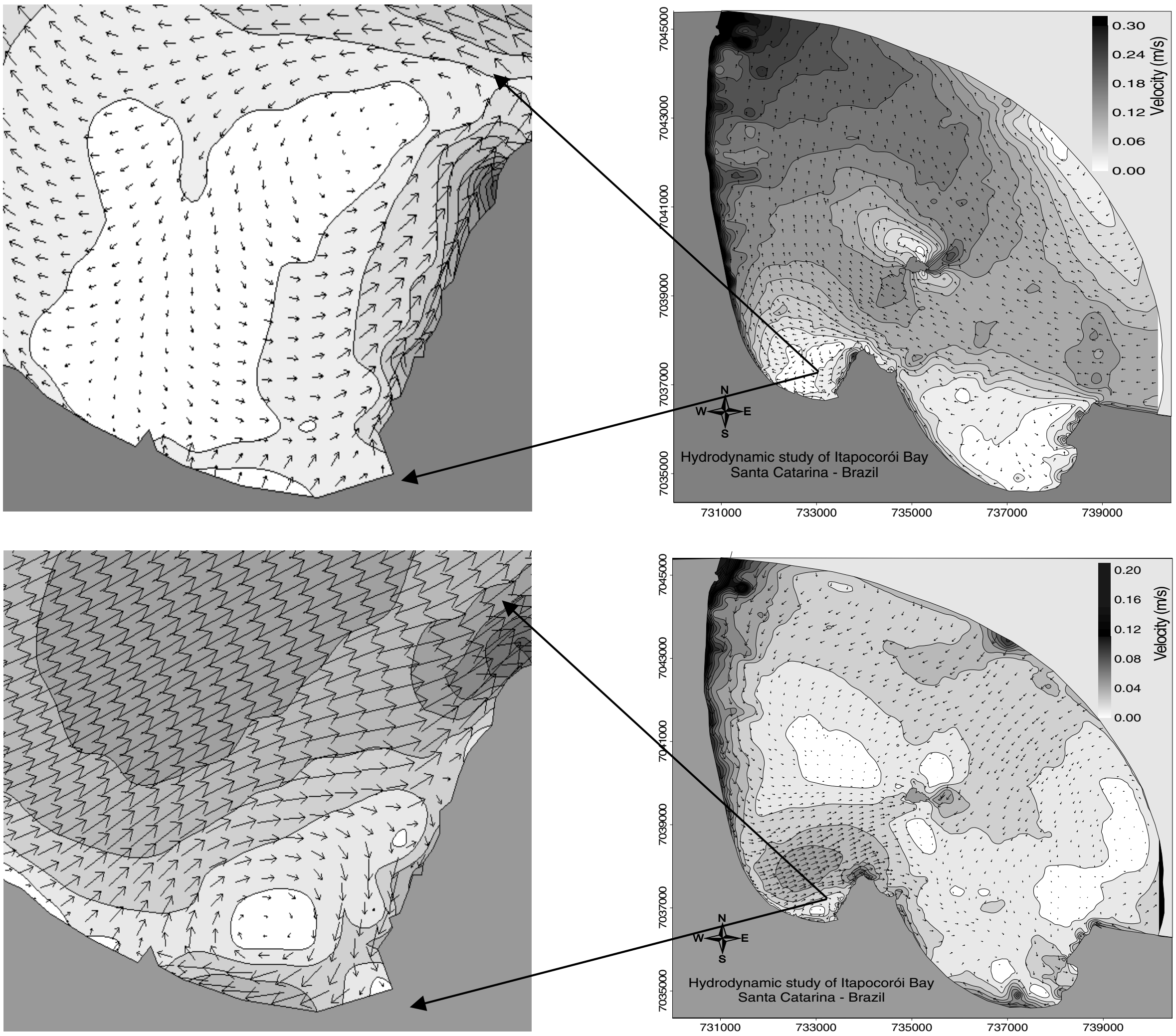
RESULTS AND DISCUSSION

The results presented in this section are separated in three main themes:

- Validation of the hydrodynamic model;
- Hydrodynamic characterization of Itapocorói Bay carried out from the 3D model results, with the wind and tide collected in the period between July 10th and August 24th 2009 were used as boundary conditions;
- Model results for scenarios with different wind forcing and the consequent creation of vortices with specific gyres.

Validation of the hydrodynamic model

Although the hydrodynamic model used (SisBAHIA) has mechanisms for self calibration that depend only on the input data and provide consistency between actual and predicted values of the water levels (typically better than 90%) and of the flow direction and velocity (usually better than 70%), comparisons between model results and the data measured by ADCP were also performed in this work in order to define the model skill. To quantify the differences between the measurements and model predictions two statistical formulas were used: the normalized root mean square error (NRMS) and the skill (Wilmott, 1981; Warner *et al.*, 2005). To analyze the accuracy of the 3D model a comparison between the tide measured by the ADCP and that predicted by the model for the same location was performed. Values of 0.7% for NRMS and 0.99 for skill were obtained, showing the excellent model accuracy to represent the elevation of the sea surface elevation. The comparison between observed and predicted north-south and east-west velocity components show values of 28% and 18% for NRMS, respectively. For the *skill* were found values of 0.43 and 0.5, respectively, revealing a lower adjustment between predictions and measurements.



a)

b)

Figure 2. a) Example of a Counter-clockwise vortex formed with Southern winds. b) Example of a clockwise vortex formed with Northern winds.

Hydrodynamic characterization of Itapocorói Bay

Different currents patterns at Itapocorói Bay were analysed from the hydrodynamic model results. It was found that the south part of the Bay has less intense currents than the northern area and a temporary vortex was identified in the southern (and sheltered) area. There were several days when the formation of these structures was observed, especially during the reversal of the tide, however those vortices had a poorly defined structure and their presence was recorded for a short period of time, disappearing in less than an hour. The vortices identified are possibly formed by the influence of tide and wind and the direction of rotation depends on the incident wind direction.

As it had been found in Valle-Levinson and Moraga-Opazo (2006) these structures result directly from the local wind and the currents forcing. However, the different geography of the bay and the fact that a coastal current have not been included may cause a formation of one single vortex, unlike previous studies which identified the formation of two vortices, with inverse circulations (Gan *et al*., 1997; Hickey *et al*., 2003).

Scenarios with different wind forcing

To the wind conditions that induce the vortex generation and study the wind and tidal influence on circulation patterns, several simulations were made. Steady and uniform wind was imposed on the open boundary and different incident wind directions were tested.

Northeast winds

Figure 2 shows an example of a vortex generated by northeast winds. This vortex has a small size, was formed during a short period of time and has been generated during the tide inversion. Thus, Northern winds may cause temporary vortices with clockwise circulation in the south part of Itapocorói Bay. The current patterns is fairly uniform across the bay, with just a small shadow zone caused by Feia Island.

South and southeast winds

South or southeast winds induce a vortex generation in the south part of the Bay (Figure 2). This vortex with a counterclockwise gyre is formed by the combination of wind and tide. The currents pattern show an area located in the south of the Bay where current velocity is lower than at the northern bay.

Other incident winds

The winds from other incident directions do not generate well defined vortices despite surface currents respond to local incident winds. For westerly winds was found that the velocity has values lower than for the remaining study area at the south of the Bay. For Eastern winds the currents have a lower intensity along the entire coast of Itapocorói Bay.

CONCLUSIONS

It was possible to have a better understanding of the hydrodynamic of Itapocorói Bay from the study of previous works on vortices, the measurement of wind, free surface level and currents data and the application of the numerical model SisBAHIA. The 3D simulations of SisBAHIA revealed the generation of short period vortices. Those structures were found to have their origin in the interaction between the tide and incident wind. Different scenarios with constant and uniform winds have been simulated and the wind directions inducing vortices generation have been identified. The model predictions show a vortex located in the south area of the bay for South and Southeast wind. With northeast winds, sporadic and short duration vortices can be formed. The vortices at Itapocorói Bay were found to be counterclockwise and generated during the tide inversion for south and southeast winds and clockwise when the winds are from the northeast. For other incident wind directions, was observed a current response to the wind forcing, but vortices were not identified.

The velocity patterns determined for Itapocorói Bay revealed that for south and west winds the current has lower values at the south part of the Bay than in the northern area. It was also found that the current intensity increased between Feia island and the south part of the Bay due to the narrowing of this area. For low intensity and unsteady winds the currents are essentially induced by tidal forcing.

ACKNOWLEDGEMENT

The authors would like to thank the financial support of the field activities received from the Conselho Nacional de desenvolvimento Científico e Tecnológico do Brasil (CNPq) [Proc. No.575008/2008-3], [Proc. No. 471068/2008-0].

LITERATURE CITED

Allen, S.E., 2000. On subinertial flow in submarine canyons:effect of geometry. *Journal of Geophysical Research* 105, 1285-1297.

Carter, R.W.G., 1988. *Coastal Environments: An Introduction to the Physical, Ecological and Cultural Systems of Coastlines*. Academic Press, London, 617p.

Daily, J.W. and Harleman, D.R.F., 1966. *Fluid Dynamics*. Addison- Wesley, Reading, MA.

Davies, J.H., 1964. A morphogenetic approach to world shorelines, *Z. Geomorphol.*, 8, 127-142.

Gan, J.; Grant, R.; Ingram, R.G. and Greatbatch, R.J., 1997. On the unsteady separation/intrusion of the Gaspé Current and variability in aie des Chaleurs: Modeling Studies. *Journal of Geophysical Research* 102, 15567-15581.

Hickey, B.M.; Dobbins, E. and Allen, S.E., 2003. Local and remote forcing of currents and temperature in the Central Southern California Bight. *Journal of Geophysical Research*, 108(C3): 3081, doi:10.1029/2000JC00313.

King, C.A.M., 1972. *Beaches and Coasts*, 2nd ed. Edward Arnold, London. 573p.

Klein, A.H.F. 2004. *Morphodynamics of Headland Bay Beaches*. PhD thesis, Universidade do Algarve, Faro, Portugal. 450p.

Klein, A.H.F. and Menezes, J.T. 2001. Beach morphodynamics and profile sequence for a headland bay coast. *Journal of Coastal Research,* 17 (4), 812-835.

Klinck, J.M., 1996. Circulation near a submarine canyon: a modeling study. *Journal of Geophysical Research* 101 (C1), 1211-1223.

Masselink, G. and Pattiaratchi, C. B., 1998. The effect of sea breeze on beach morphology, surfzone hydrodynamics and sediment resuspension. *Marine Geology* 146 (1-4), 93-113.

Pattiaratchi, C.; Hegge, B.; Gould, J. and Eliot, I., 1997. Impact of sea-breeze activity on nearshore and foreshore processes in southwest Australia. *Cont. Shelf Res*. 17 (13), 1539-1560p.

Rosman, P.C.C., 1987. *Modeling Shallow Water Bodies Via Filtering Techniques*. PhD thesis. Department of Civil Engineering, Massachusetts Institute of Technology, Massachusetts, USA.

Rosman, P.C.C., 2001. *A computational system for environmental hydrodynamics*. In: da Silva, R.C.V. (Ed.), Métodos Numeéricos Em Recursos Hídricos, first ed. ABRH, Rio de Janeiro, RJ, Brasil (chapter 1).

Rosman, P.C.C., 2003. Final report—modeling thermal plumes around Itaorna Cove, Bayof Ilha Grande, RJ. Technical report COPPETEC - PENO – 3991, 1–69.

Rosman, P. C. C., 2009. Referência Técnica do SisBaHiA – Sistema Base de Hidrodinâmica Ambiental. Report COPPETEC-PENO-565. COPPE/UFRJ. 213p.

Schettini, C.A.F.; Carvalho, J.L.B. and Jabor, P. 1996, Comparative hydrology and suspended matter distribution of four estuaries in Santa Catarina State – southern Brazil. *In:* Workshop on comparative studies of temperate coast estuaries, Bahia Blanca. Bahia Blanca: [s.n.]. 29-32.

Sedrati, M. and Anthony, E.J., 2007. Storm-generated morphological change and longshore sand transport in the intertidal zone of a multi-barred macrotidal beach. *Marine Geology,* 244, 209-229.

Short, A.D. and Masselink, G., 1999. Embayed and structurally controlled beaches. In: Short, A.D. (Ed.), *Handbook of Beach and Shoreface Morphodynamics*. Wiley, New York, 230-249p.

Thompson E. F. and Leenknecht D. A., 1994. Wind Estimation for coastal modeling applications. *Journal of Coastal Research*, 10(3), 628-636.

Trucolo EC. 1998. *Maré Meteorológica e Forçantes Atmosféricas Locais em São Francisco do Sul – SC*. MSc thesis, Universidade Federal de Santa Catarina, Santa Catarina Brasil.100p

Valle-Levinson, A. and Moraga-Opazo, J., 2006. Observation of bipolar residual circulation in two equatorward-facing semiarid bays. *Continental Shelf Research*, 26, 179-193.

Valle-Levinson, A.; Moraga, J.; Olivares J. and Blanco J. L., 2000. Tidal and residual circulation in a semi-arid bay: Coquimbo Bay, Chile. *Continental Shelf Research, 20,* 2009-2028.

Van den Heuvel S.; Hoekstra, R.; Zeeuw, R., and Zoon, A., 2008. Case Study Piçarras Beach – Erosion and Nourishment of a Headland Bay Beach Final Report - Master project Hydraulic Engineering, Technical University of Delft. 249p.

Warner, J.C.; Geyer, W.R., and Lerczak, J.A., 2005. Numerical modeling of an estuary: a comprehensive skill assessment. USA. *Journal of Geophysical Research* vol. 110, 13p.

Willmott, C.J., 1981. On the validation of models. *Physical Geography 2*, 184–194.

Wu, J., 1982. Wind–stress coefficients over sea surface from breeze to hurricane. *Journal of Geophysical Research,* 87 (12), 9704–9706.

Yasso, W.E., 1965. Plan geometry of headland bay beaches. *Journal of Geology*, 73, 702-714.