TELEMAC-2D calibration and validation to the hydrodynamics of the Patos Lagoon (Brazil)

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Calibration and Validation of the TELEMAC-2D Model to the Patos Lagoon (Brazil)

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ABSTRACT

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Calibration and validation of the TELEMAC-2D model for the Patos Lagoon is presented. The model sensitivity is initially tested for variations in the friction coefficient, when applying the Manning, Chezy and Nikuradse laws of bottom friction, and for eddy viscosity and space discretization. The model calibration is carried out against field data from 27-29/10/1998 and reasonable agreement is achieved between measured and predicted longitudinal velocities at three stations in the estuarine area. A correlation of up to 0.93 is observed at Marambaia during the first day when applying the Manning law of bottom friction (m=0.010), while at Praticagem the correlation reaches 0.97 during the second day when applying the Chezy law of bottom friction (C=50). The use of friction varying according to the bed sediment grain size proved to be a further improvement towards the best reproduction of measurements. The model validation is carried out by comparing measurements and predictions from a reference station inside the estuary. Results indicate that the model can reproduce an independent water elevation data set (from 23/05-06/06/1998) with a Relative Mean Absolute Error (RMAE) of 0.16, indicating an excellent agreement between measurements and predictions. Modelling predictions are then used to study the general lagoon and estuarine circulation between the 27-29/10/1998, with the advantage of accurately filling the gaps in the velocities and water elevation time series measured during this period.

ADDITIONAL INDEX WORDS: *TELEMAC, model calibration, model validation, wind-driven flow, TELEMAC, coastal lagoon, Patos Lagoon.*

INTRODUCTION

Coastal lagoons and their estuaries are typically centres of population, commerce, industry, and recreation, and consequently are also sites for disposal of industrial, agricultural, and municipal wastes (CHENG *et al.*, 1993). The Patos Lagoon (Figure 1) is no exception. Important questions concerning beneficial uses of and potential changes to the lagoon and its estuary are left unanswered without a good understanding of hydrodynamic processes occurring on different time-scales. In the past decade, significant studies were carried out in the area regarding the wind-driven circulation, tidal and subtidal effects, and salinity behaviour (MOLLER, 1996; MOLLER *et al.*, 1996; MOLLER and CASTAING, 1999; FETTER, 1999; MOLLER *et al.*, 2001), but a further understanding of the physical processes involved in the Patos Lagoon proved to be necessary.

Located in the southern Brazilian coastline between 30-32°S and 50-52°W, the Patos Lagoon (Figure 1) is the largest choked coastal lagoon in the world (KJERFVE, 1986). With a length of 250 km 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 rivers that flow into the lagoon have a catchment area of 201,626 km^2. They exhibit a typical mid-latitude flow pattern of high discharge in late winter and early spring followed by low to moderate discharge through summer and autumn, with a large year-to-year discharge variation (MOLLER, 1996). The mean annual freshwater contribution in the north of the Patos Lagoon is 2000 m^3.s^{-1}. Seasonal variations can be observed, from 700 m^3.s^{-1} during summer (late December - March) up to 3,000 m^3.s^{-1} during spring (September - early December). MOLLER *et al.* (1991) observed river discharge peaks of 12,000 and 25,000 m^3.s^{-1} associated with the meteorological phenomena El Niño. During these high flood periods the lagoon can remain fresh for several months (PAIM and MOLLER, 1986). In the estuarine region, between Feitoria and the mouth (Figure 1), the Patos Lagoon connects to the South Atlantic Ocean via a channel 20 km long and 1 km wide.

Figure 1. The Patos Lagoon system and stations.

FERNANDES *et al.* (in press) presents a review of the Patos Lagoon hydrodynamics and main features.

A more detailed hydrodynamic study of the lagoon cannot be completely carried out based on field studies alone because of the large spatial and temporal variability. Such study would require a large number of field observations, and the costs associated with data collection are usually quite high. A possible solution to paucity of field data is the use of numerical models as sophisticated techniques for interpolation and extrapolation of field data in both spatial and temporal domains. Conversely, it is equally important to recognise that meaningful and realistic modelling results cannot be obtained without adequate supporting data (CHENG *et al.*, 1991). Thus, field data collection and numerical modelling must be considered as two inseparable and complementary elements of one integrated research programme.

The TELEMAC-2D model, developed by the Laboratoire National d'Hydraulique (EDF-Paris), was chosen for further numerical modelling of the Patos Lagoon hydrodynamics. However, before a numerical model can be applied in a reliable hydrodynamic study, it is necessary to carry out initial tests with the model. Firstly, the model sensitivity to variations in basic parameters as friction and viscosity should be investigated. Secondly, the model calibration should be carried out by adjusting parameters to compare results from the numerical model with field data. Thirdly, validation should be carried out by verifying that the model satisfactorily reproduces independently observed data sets. Only then can the model be used as a research tool for investigations of hydrodynamic processes in space and time (CHENG *et al.*, 1993).

In order to calibrate the TELEMAC-2D model for the Patos Lagoon, measurements of salinity, temperature, current speed and direction, water elevation, wind speed and direction and suspended matter were carried out simultaneously at three different stations along the estuarine area (Figure 1): Feitoria, at the top of the estuary; Marambaia, where the cross-section of the estuary changes; and Praticagem, at the mouth of the estuary. Measurements were carried out at the surface, middle depth and near bottom at approximately 30 min intervals in a field campaign between 27-29/10/1998, generating a limited data set. The limitations during the field measurements involve the size of the lagoon and the cost of personnel and shortage of equipment. The Rio Grande Pilots (Praticagem da Barra) supplied water level and meteorological data at the mouth of the estuary between 20-29/10/1998.

The aim of this paper is to present the calibration and validation the TELEMAC-2D model, with further application to study the Patos Lagoon hydrodynamics between 27-29/10/1998.

THE TELEMAC-2D MODEL

TELEMAC is a flow model based on finite element techniques developed by the Laboratoire National d'Hydraulique (EDF - Paris) to simulate the flow in estuaries and coastal zones. The TELEMAC-2D code solves the second order partial differential equations for depth-averaged fluid flow derived from the full three-dimensional Navier-Stokes equations, also called the Barre de Saint-Venant Equations (HERVOUET and VAN HAREN, 1994). 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 averaged form of the continuity equation is:

$$\frac{\partial h}{\partial t}+\frac{\partial(hU)}{\partial x}+\frac{\partial(hV)}{\partial y}=0 \tag{1}$$

The averaged form of the momentum equations is:

$$\begin{aligned}&\frac{\partial(hU)}{\partial t}+\frac{\partial(hUU)}{\partial x}+\frac{\partial(hUV)}{\partial y}=\\&-gh\frac{\partial Z}{\partial x}+\frac{\partial}{\partial x}\left(h\nu_e\frac{\partial U}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\nu_e\frac{\partial U}{\partial y}\right)+hF_x\end{aligned} \tag{2}$$

$$\begin{aligned}&\frac{\partial(hV)}{\partial t}+\frac{\partial(hUV)}{\partial x}+\frac{\partial(hVV)}{\partial y}=\\&-gh\frac{\partial Z}{\partial y}+\frac{\partial}{\partial x}\left(h\nu_e\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\nu_e\frac{\partial V}{\partial y}\right)+hF_y\end{aligned} \tag{3}$$

Where: U and V are the depth-averaged velocity components in the x and y Cartesian directions; h is the depth of flow; V_e is the coefficient of diffusion ($m^2\ s^{-1}$); g is the gravitational acceleration; t is the time; Z is the elevation of the free surface (m); F_x and F_y are the source terms of the momentum equation in U and V, respectively, which include friction, Coriolis and wind force.

The bed friction is represented as a quadratic function of velocity ($\vec{\tau}=(1/2)\rho C_f|u|\vec{u}$), where the friction coefficient (C_f) can be parameterised either in terms of the Chezy (C, in $m^{1/2}.s^{-1}$), Manning (m,: in $m^{1/3}.s^{-1}$), or Nikuradse (K_s, in mm) friction coefficients, by applying the respective equations

$$(C_f=g/C^2) \tag{4}$$

$$\left(C_f=\frac{gm^2}{h^{1/3}}\right) \tag{5}$$

$$\left(C_f=\left[\frac{1}{k}\ln\left(11.0\frac{h}{k_s}\right)\right]^{-2}\right) \tag{6}$$

In order to solve the basic equations TELEMAC-2D considers for the solid boundaries that: 1) no mass flux of water occurs through the bottom and closed lateral faces $(\vec{u}\vec{n}=0)$, where $\vec{n}$ is the unit normal vector of the boundary; 2) there is a free slip condition at the wall for all vectors tangent to the wall $\left(\frac{\partial(\vec{u}\cdot\vec{t})}{\partial n}=0\right)$; 3) the friction condition is written as $\left(\frac{\partial(\vec{u}\cdot\vec{t})}{\partial n}=\alpha(\vec{u}\cdot\vec{t})\right)$, where α is the friction coefficient. The water surface height is free and the surface boundary condition is a velocity calculated from the wind speed 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. Based on that, two situations were chosen: 1) prescribed flowrate and free surface elevation at the top of the lagoon; 2) free velocity and prescribed surface elevation at the ocean boundary.

TELEMAC-2D solves the equations on non-structured grids, with triangular (or quadrilateral) finite elements. The nature of the 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 Navier-Stokes equations are solved based on the Operator-Splitting method (MARCHUK, 1975), whose main principle is that the hyperbolic and parabolic parts of the Navier-Stokes equations should be treated separately, in order to use well-adapted numerical methods for each part. The solution involves two steps: 1) solution of advection terms; 2) solution of the propagation, diffusion and source terms. The Method of Characteristics has been applied to solve the advection of u and v (GALLAND *et al.*, 1991; BATES *et al.*, 1997; BATES *et al.*, 1998). The Streamline Upwind Petrov-Galerkin method (SUPG) has been applied to solve the advection of h (BROOKES and HUGHES, 1982). This method was implemented in TELEMAC-2D to ensure mass conservation and an oscillation free solution without excessive mesh refinement, or the addition of artificial diffusivity (BATES *et al.*, 1998). The propagation, diffusion and source terms are solved by the finite element method, where an implicit time discretization allows the elimination of non-linearities in the equations. Variational formulations and space discretisation transform the continuous equations into a linear discrete system where the values of h, u and v at the nodes are the unknown variables. This system is solved by an iterative conjugate gradient method (HERVOUET and VAN HAREN, 1994).

SENSITIVITY TESTS

Sensitivity tests were initially carried out in order to analyse TELEMAC-2D sensitivity to variations in the friction and eddy viscosity parameters, and to the Coriolis force. The model boundary conditions consisted of an imposed flowrate of 2000 $m^3.s^{-1}$ at the top end of the lagoon (mean annual value, BORDAS *et al.*, 1984), and a dynamic water elevation at the ocean boundary (data from Praticagem between 11-13/01/1992). Tests were carried using the finite element mesh presented in Figure 2.

In order to investigate the model sensitivity to different laws of bottom friction and to a range of values for the friction coefficient found in the literature, friction sensitivity tests were carried out by applying the Manning, Chezy and Nikuradse laws. Table 1 shows a summary of the friction sensitivity tests.

Table 1. *Friction sensitivity tests*.

Name of the test	Friction coefficient
Manning1	m=0.040
Manning2	m=0.025
Manning3	m=0.015
Chezy1	C=37
Chezy2	C=65
Chezy3	C=100
Nikuradse1	K_s=0.001 (smooth mud)
Nikuradse2	K_s=0.01
Nikuradse3	K_s=0.1 (sand)

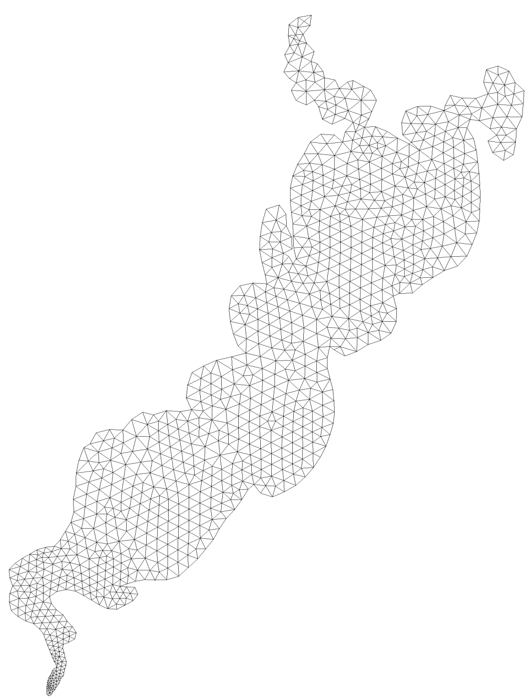


Figure 2. Finite element mesh with 1175 nodes and 2048 triangles.

Figure 3 illustrates the effect of varying the law of bottom friction and the value of the friction coefficient on the longitudinal velocity at Praticagem. It is clear that the overall variation of the longitudinal velocity is independent of which definition of bottom friction is assumed, although its magnitude is controlled by the magnitude of the friction coefficient.

Sensitivity tests on eddy viscosity were carried out based on the same initial and boundary conditions, and applying the Manning law of bottom friction (m=0.025). Very little difference was observed in the predicted circulation pattern for eddy viscosity coefficients varying from ν=0.01 to ν=100 $m^2.s^{-1}$. These results indicate that the eddy viscosity has little effect on the lagoon circulation, which seems to be mainly controlled by advective processes.

Although the Patos Lagoon is a huge water body, it is much longer than it is wide, and the Coriolis force is not expected to be significant. In order to analyse the Coriolis effect on the lagoon circulation, the Manning2 test (Table 1 - m=0.025) was repeated without taking into account the Coriolis force. No difference was observed when comparing velocity results, indicating that Coriolis force is not affecting the flow pattern.

MESH RESOLUTION TESTS

Bathymetry is probably the most important among the many factors that affect the flow properties in the environment, controlling the spatial variability of current magnitude and direction.

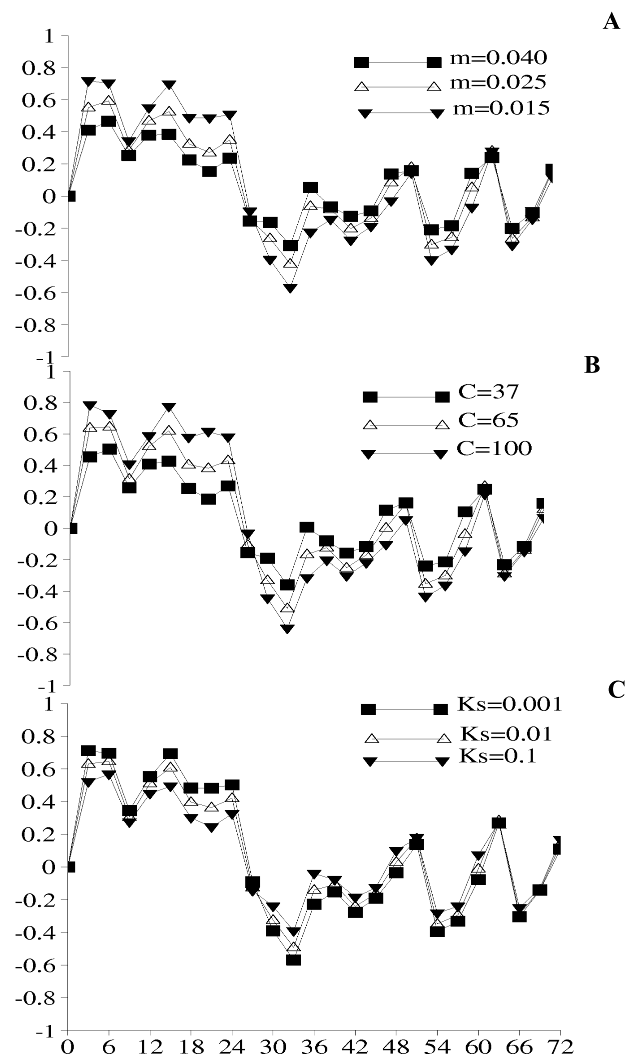


Figure 3. Longitudinal velocity at Praticagem (node 80) calculated using the (A) Manning, (B) Chezy, and (C) Nikuradse laws of bottom friction.

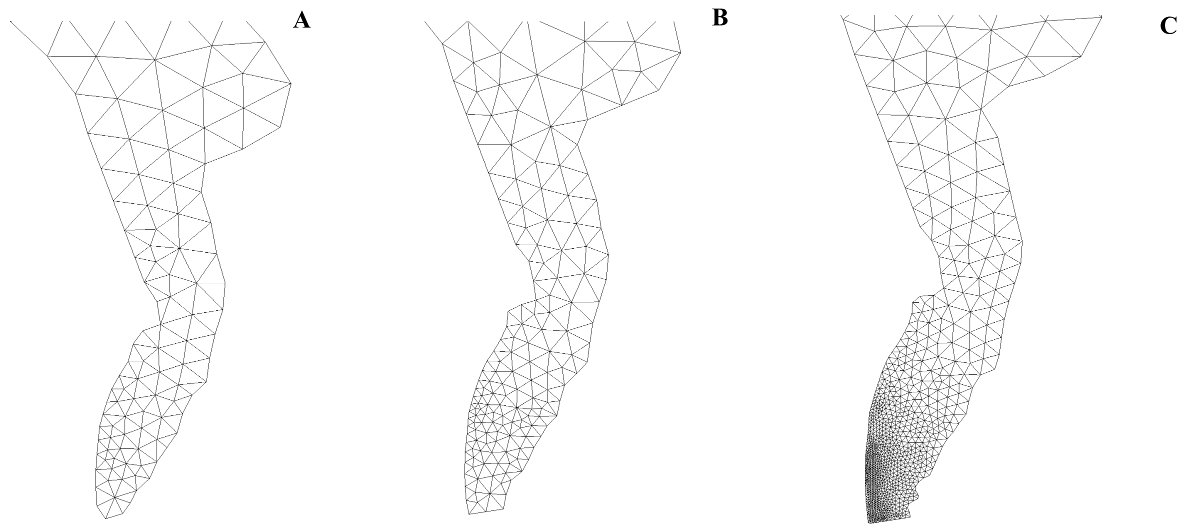


Figure 4. Estuarine space discretization at (A) low, (B) medium and (C) high resolution used for the mesh resolution tests.

An accurate bathymetric representation is one of the most important and fundamental requirements in successful modelling (CHENG *et al.*, 1991). This is particularly true for the Patos Lagoon estuary, where bathymetric variations are complex.

In order to analyse the effects of the mesh-size on the hydrodynamic results, three triangular finite element space discretization at low, medium, and high resolution were constructed. A low resolution was considered satisfactory within the lagoon, and refinement was carried out only in the estuarine area (Figure 4).

Figure 5 presents the effect of spatial discretization on the longitudinal velocity at Praticagem. Tests were carried out for the three different resolutions using the Manning law of bottom friction (m=0.020). Results indicate that when changing from a low- (Figure 5A) to a medium-resolution mesh (Figure 5B), the model reproduction of the longitudinal velocity is improved. A reasonable solution of the controlling equations is possible, even with a rather coarse discretization (LAGOA12), which can be improved with small computational cost when using the medium-resolution mesh (LAGOA14). No improvement was observed when changing from medium- to high-resolution (Figure 5C), and it is likely that the high-resolution mesh is over-specified regarding the density of the bathymetric data. However, the high-resolution mesh would probably give an improved performance if higher resolution topographic data were available. Further hydrodynamic simulations presented here use the low-resolution mesh in order to save computational time.

CALIBRATION OF THE MODEL

Following definition of the model sensitivity to friction, eddy viscosity, Coriolis and space discretization, the model was considered ready for calibration. During model calibration, some parameters have to be adjusted to give the best fit of the model results to field observations. However, there is a general lack of set guidelines for model adjustment. CHENG *et al.* (1991) commented that there is no standard procedure for model calibration and validation in modelling literature. Typically, the calibration is accomplished by qualitative comparison of short time series of water level or velocity produced by the numerical model with field data for the same location and period of time (CHENG *et al.*, 1993).

The TELEMAC-2D calibration was carried out with data measured at the Patos Lagoon estuarine area between the 27-29/10/1998. However, CHENG and WALTERS (1982) comment that meaningful comparison between models and measurements will not result unless the model and the measurements deal with processes that are controlled by the same time scales. Thus, in order to start the model with the same initial conditions that the Lagoon had when the main measurements started, a seven-day run based on measurements from Praticagem between 20-26/10/1998 was carried out using the mesh presented in Figure 2 and the set-up in Table 2. The model boundary conditions were an imposed flowrate of 2500 m3.s-1 at the top of the lagoon, and a dynamic water elevation at the ocean boundary (Figure 6A), and the model was forced with a time series of wind velocity (Figure 6B).

Results at the end of this seven-day run were then used as initial conditions for a three-day simulation of the current regime between 27-29/10/1998, which is the period when the main set of measurements were carried out in Patos Lagoon. The set-up of this run is presented in Table 2 (now using Number of time steps = 2880). The boundary conditions for the model were the prescribed flowrate of 2500 $m^3.s^{-1}$ at the top of the lagoon and a dynamic water elevation at the ocean boundary (Figure 6C). The time series of wind velocity used to force the model is presented in Figure 6D. As significant variations in the atmospheric pressure were observed during the field measurements carried out between 27-29/10/1998, spatially and temporally varying atmospheric pressure was also

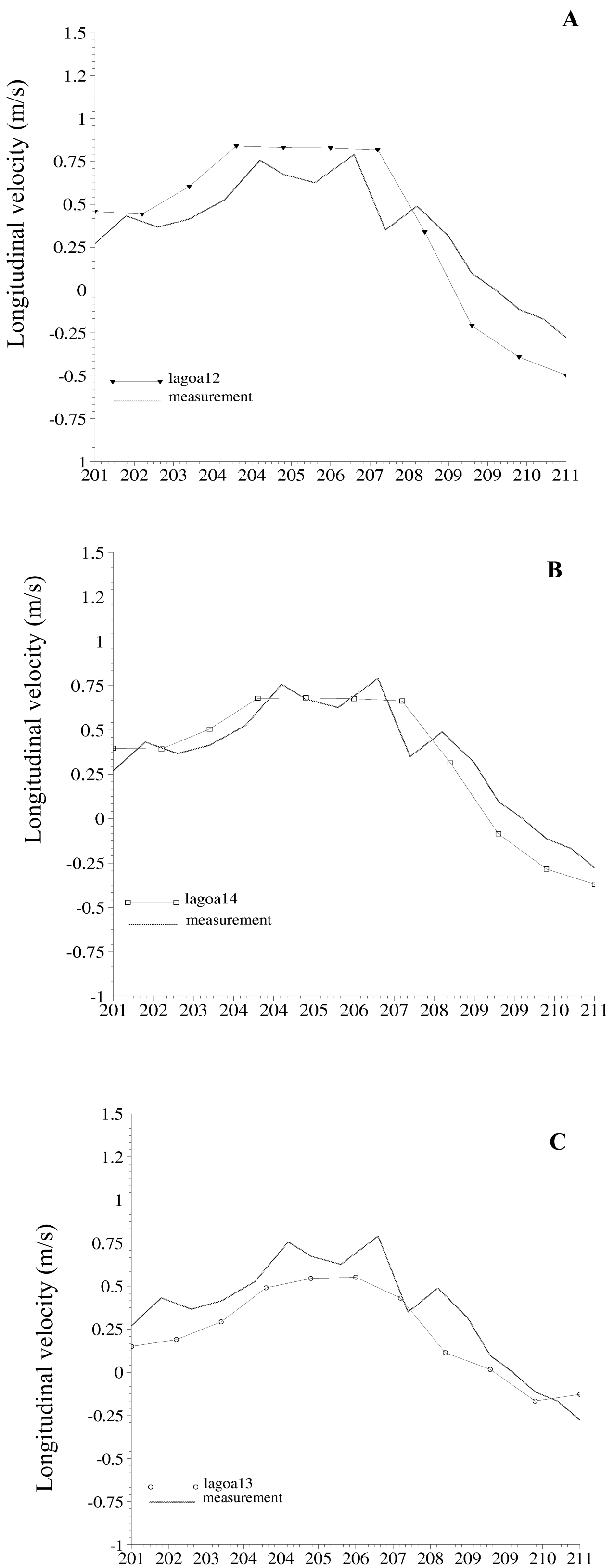


Figure 5. Calculated and observed longitudinal velocity at Praticagem for three different meshes: (A) lagoa12, (B) lagoa14, and (C) lagoa13.

used to force the model. As atmospheric pressure time series at different locations along the Patos Lagoon were not available, a single pressure gradient was established along the lagoon for each day based on synoptic charts for the area.

Table 2. *Set-up used for the seven-day run*.

Parameters	Values
Initial elevation	0.3 m
Time step	90 s
Number of time steps	6680
Coriolis	YES
Coriolis coefficient	-7.7×10^{-5}
Friction – Manning Law	m=0.020
Diffusivity	$10\ m^2 .s^{-1}$
Tidal flats	YES

Several tests were carried out using these initial and boundary conditions and varying the law of bottom friction and the friction coefficient in order to make predicted longitudinal velocities match measurements. Table 3 shows a summary of the calibration tests.

Table 3. *Calibration test*.

Test	Friction
Calibration1	m=0.010
Calibration2	m=0.015
Calibration3	m=0.020
Calibration4	m=0.025
Calibration5	m=0.030
Calibration6	C=20
Calibration7	C=37
Calibration8	C=50
Calibration9	C=65
Calibration10	C=80
Calibration11	K_s=0.008
Calibration12	K_s=0.01
Calibration13	K_s=0.03
Calibration14	K_s=0.05
Calibration15	K_s=0.08

The relation between predicted and measured longitudinal velocities for the same locations and period of time was initially evaluated by calculating the correlation coefficient between the two time series. This analysis is based on the covariance of the data sets divided by their standard deviations (DAVIES, 1973), which determines whether two data sets move together (positive correlation) or in opposition (negative correlation). Further evaluation of the relation between measurements and predictions was carried out using the Relative Mean Absolute Error (RMAE) comment by WALSTRA *et al.*, (2001) and SUTHERLAND (2001). The preliminary qualification for RMAE ranges suggested by WALSTRA *et al.* (2001) is presented in Table 4.

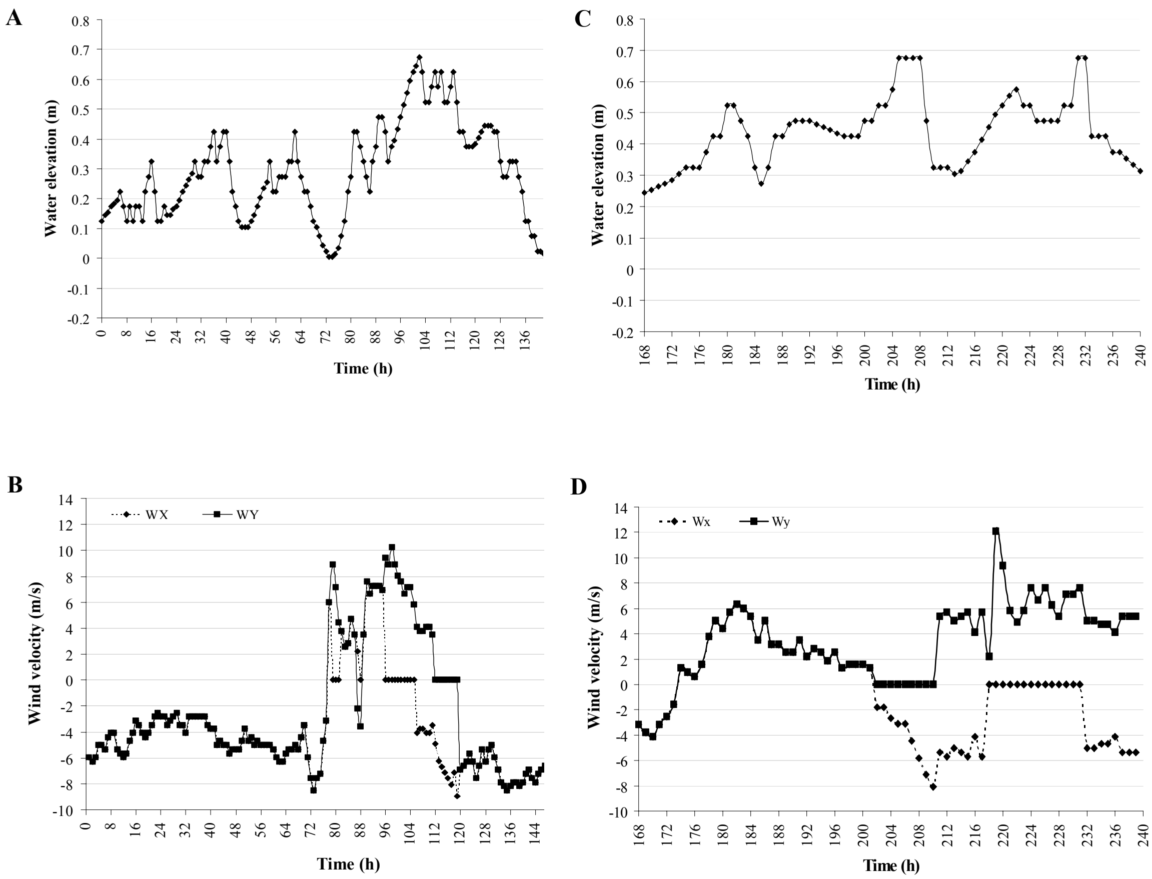


Figure 6 – Water elevation and wind data used to force the model between 20-26/10/1998 (A, B), and 27-29/10/1998 (C, D). WX is positive to the East and WY is positive to the North..

Table 4. *Qualification of error ranges for RMAE.*

Qualification	RMAE
Excellent	<0.2
Good	0.2 – 0.4
Reasonable	0.4 – 0.7
Poor	0.7 – 1.0
Bad	>1.0

Results from the calibration tests during the first day of simulation are shown in Figure 7. A range of Manning friction coefficients was tested. Results indicate that the higher the Manning friction coefficient, the lower the longitudinal velocity obtained. The best correlation between measured and predicted longitudinal velocity at Feitoria was 0.53 (Figure 7A), obtained with m between 0.020 - 0.030. At Marambaia the best correlation increased to 0.93 when using m=0.010. A time lag for the reversion of the longitudinal velocity was observed in both stations, reaching approximately 6 hours at Feitoria (Figure 7A) and 3 hours at Marambaia (Figure 7B). This is likely to be related to the establishment of the initial conditions in the model. Results from the calibration tests for the second day of simulation at Praticagem when using the three laws of bottom friction can be seen in Figure 8. The best reproduction of the measured longitudinal velocity magnitude was achieved with m=0.025 (Figure 8A), with a correlation of 0.93. When using the Chezy law (Figure 8B), the correlation increased to 0.97 for a friction coefficient C=50, whereas the Nikuradse law (Figure 8C) reaches a correlation of 0.96 either for K_s=0.008 and K_s=0.01. The range of friction coefficient values for each law was chosen based on literature and, although the ranges are not equivalent among themselves, the figure suggests that the Manning friction coefficient produces stronger longitudinal velocities then the Chezy and Nikuradse.

The third day of simulation was marked by poor reproductions, and although the model reproduces reasonably well the longitudinal velocity measured at the three stations during the first two days, it was not able to reproduce the observed lateral velocities (not shown). Several limitations in the model and data set can explain why a better reproduction was not achieved overall: 1) wind data was only measured at Praticagem but considered constant throughout the lagoon; 2) water elevation data was measured only during the day-time and interpolated for the night period; 3) the resolution of the bathymetric data and the distortion produced by the grid size; 4) salinity stratification was observed in the lower estuary during the measurements, but was not taken into account in the model; and 5) the model predicts depth-averaged velocities whereas measurements are for a particular depth.

Although it is known that, in principle, the friction coefficient should change according to the nature of the bed (ALDRIDGE and DAVIES, 1993), numerical models are generally run with uniform values of bed friction. SMITH and CHENG (1987) and CHENG *et al.* (1993) tested spatially varying friction by applying the Chezy and Manning laws of bottom friction, respectively. They both found that the introduction of depth dependent friction was necessary to achieve a best fit to the available field data.

The effect of varying bed friction in space as a function of bed composition is investigated here. The Nikuradse law of bottom friction was chosen because it prescribes the grain size at the bottom in the friction coefficient. The lagoon shallow areas have a sandy bed, the main lagoon has silt bed, and the deeper channels vary from fine silt to mud. Thus different friction coefficients were specified for specific depth ranges (Table 5). The distribution of the friction coefficient throughout the lagoon is presented in Figure 9.

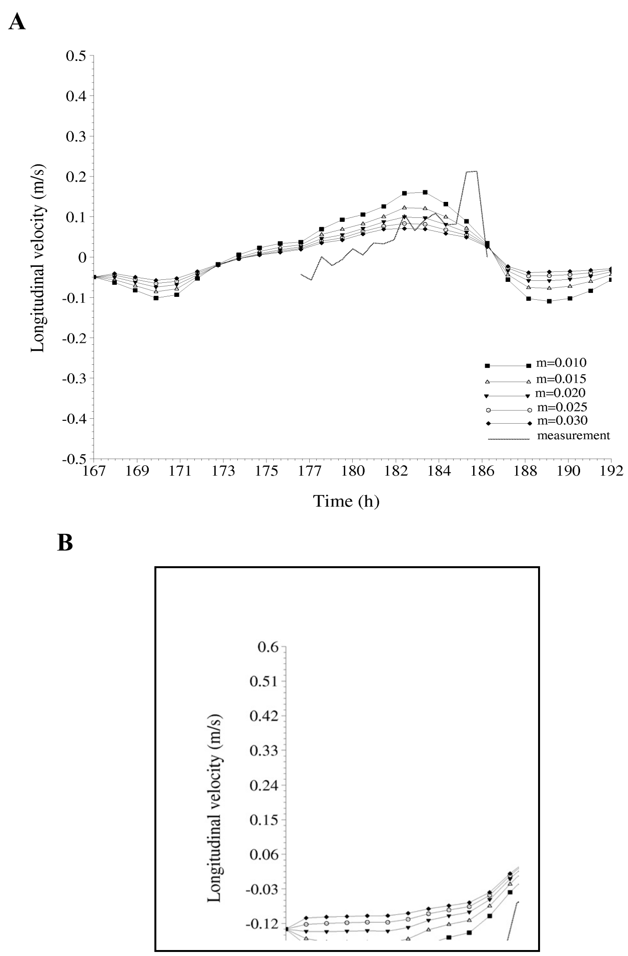


Figure 7. Results from the calibration tests for the first day of simulation at Feitoria (A) and Marambaia (B) when using the Manning law of bottom friction.

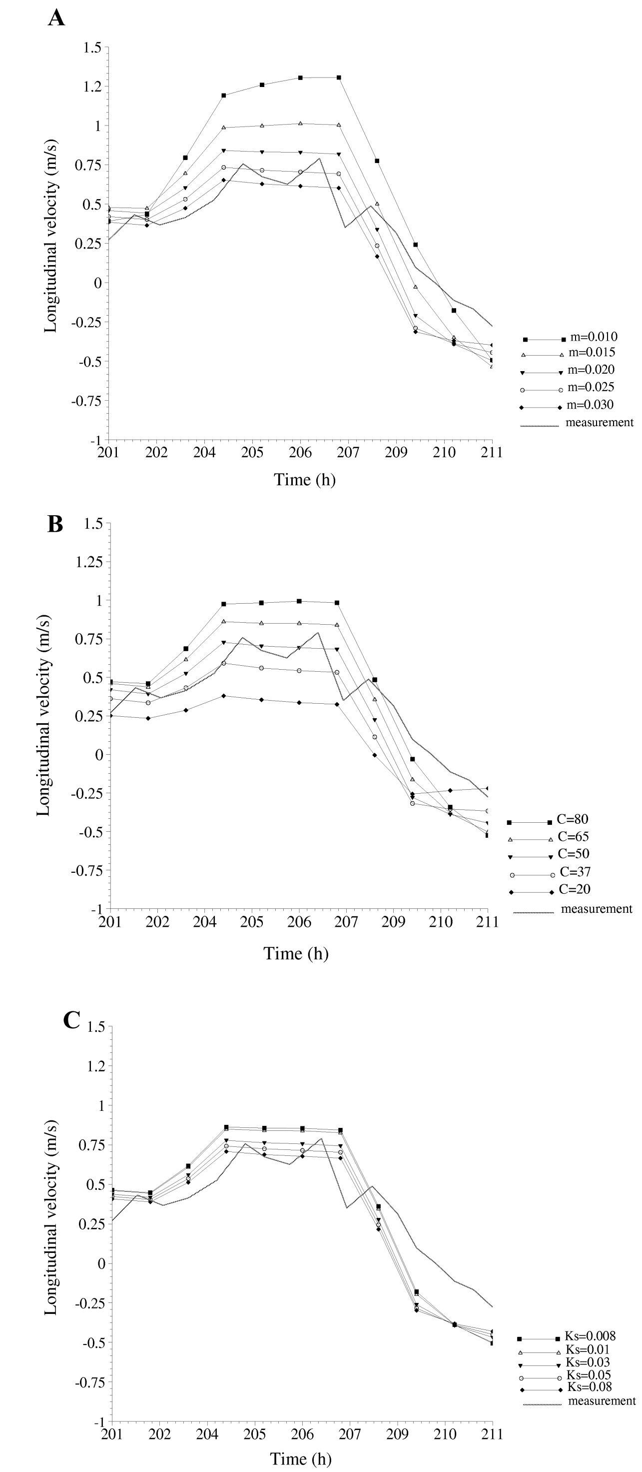


Figure 8. Results from the calibration tests for the second day of simulation at Praticagem when using the (A) Manning, (B) Chezy and (C) Nikuradse laws of bottom friction

The simulation applying friction varying in space was based on the same set-up used for the other calibration tests. However, the water elevation and wind data set previously used to force the model between 20-26/10/1998 (7-day simulation) and 27-29/10/1998 (3-day simulation) were combined into a time series from 20-29/10/1998, resulting in a 10-day simulation. In order to assess the effect of taking into account the bed composition of the lagoon, results from this simulation were then compared with measurements and results obtained with the same set-up and a constant bed friction (K_s=0.03).

Table 5 - Applied ranges for the spatially varying friction

Depth range (m)	Friction coefficient (K_s)	Type of bottom
$0 > h > -2$	0.25	medium/ fine sand
$-2 \geq h > -4$	0.13	fine/ very fine sand
$-4 \geq h > -6$	0.10	very fine sand
$-6 \geq h > -8$	0.06	coarse silt
$-8 \geq h > -12$	0.004	fine silt
$-12 \geq h > -20$	0.001	clay/mud

Figure 10 presents the predicted longitudinal velocity at Rio Grande (RG in Figure 1), and the inflow/outflow of water at the mouth produced when the model assumes constant friction (K_s=0.03), and friction varying according to the bed composition (Table 5). Results indicate that most of the time the use of a constant friction coefficient seems to over-estimate the velocity predictions, with differences between 5 – 7 cm s^{-1} for the longitudinal velocity and 3 – 5 cm s^{-1} for the lateral velocity. The use of constant friction also implies that more water is leaving/entering the lagoon during the simulation, with an over-estimation of approximately 400 $m^3 s^{-1}$ when t=102 h and 300 $m^3 s^{-1}$ when t=204 h, for example. Such results indicate that the use of friction varying according to the bed composition can produce more realistic predictions without increasing the computation time.

Assessment of the relation between measurements and predictions of the longitudinal velocity at Praticagem (Figure 11) was obtained by the RMAE technique. RMAE = 0.44 is obtained when using constant friction (K_s=0.03), indicating a reasonable agreement between the time series

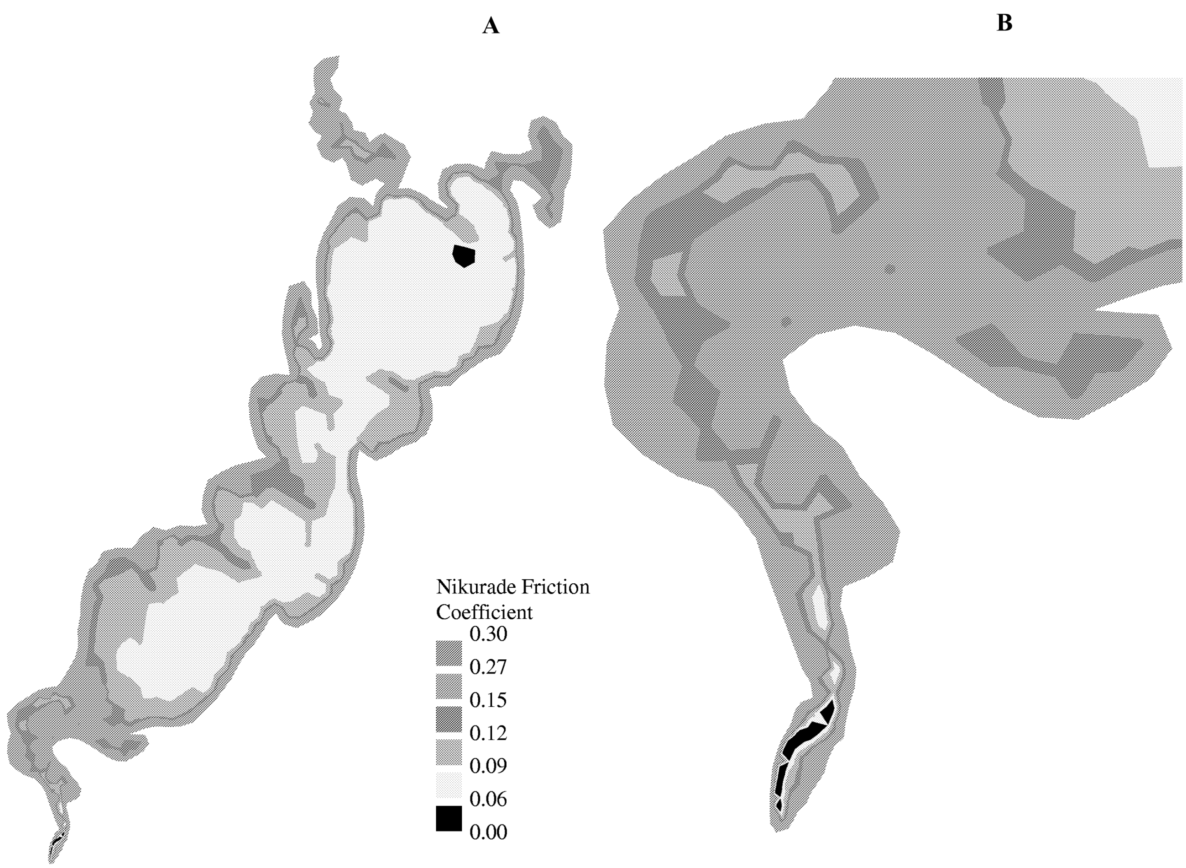


Figure 9. Bottom friction distribution for testing the spatially varying friction

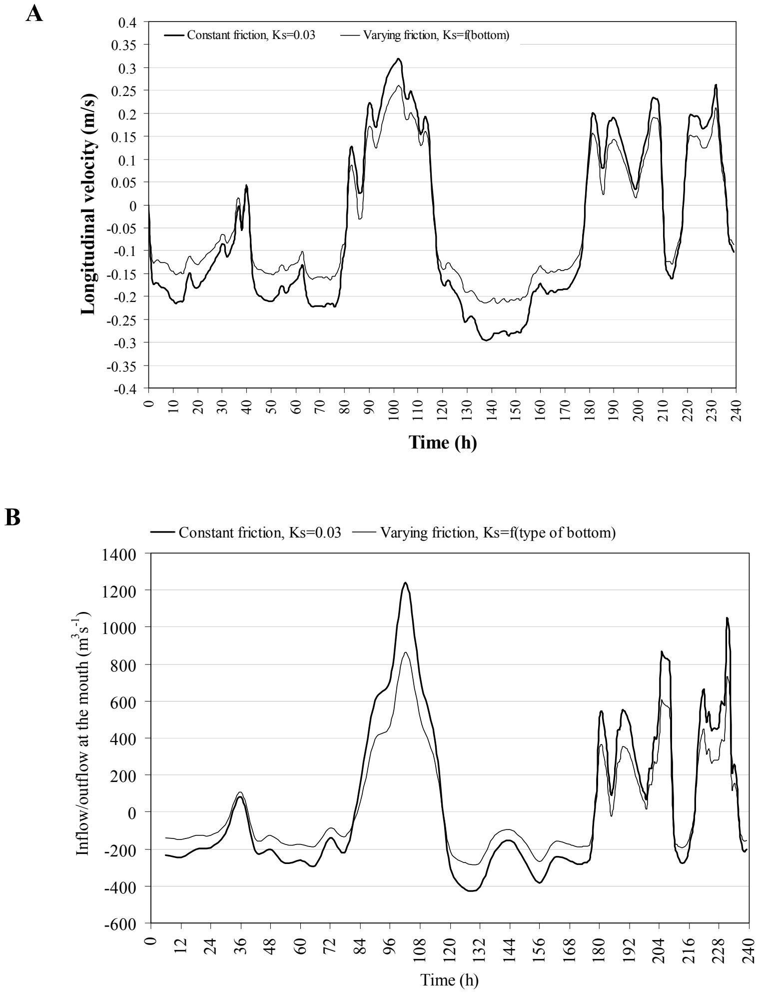


Figure 10. Comparison of (A) longitudinal velocities at Rio Grande and (B) inflow/outflow of water produced with constant and varying friction.

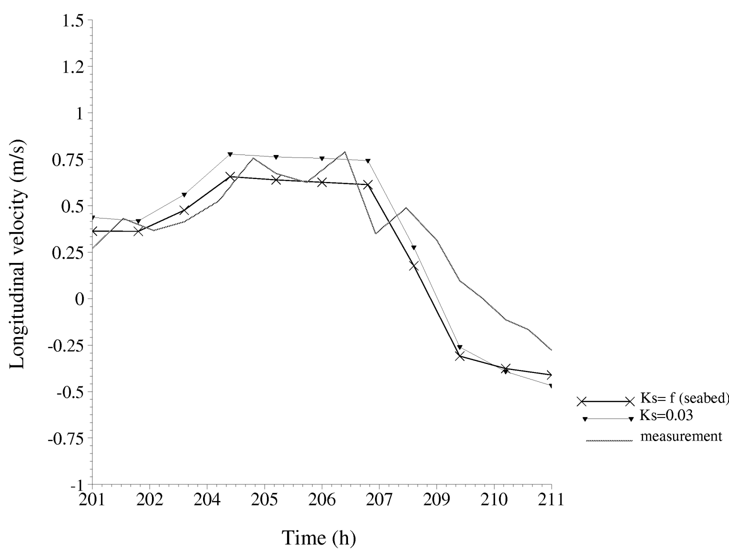


Figure 11. Comparison between measurements and predicted longitudinal velocities when using constant friction and friction varying according to bed sediment at Praticagem.

(Table 4). The use of friction varying according to the bed sediment produces a RMAE = 0.35, which indicates a good agreement between measurements and predictions (Table 4). Thus, although the use of friction varying according to the bed sediment is not essential, it proved to be an improvement in the reproduction of measurements in the model.

A summary of the calibration tests indicates that, when choosing not to apply friction varying according to the bed sediment, the best correlation are obtained using the Manning friction coefficient between 0.010 – 0.025, Chezy coefficient $C = 50$ or Nikuradse coefficient $K_s = 0.008$-0.01. However, the previous results are based on comparisons between measurements and modelling predictions from the estuarine area. The lack of measurements inside the lagoon requires the model calibration carried out in the estuary also to be applied in the lagoon.

VALIDATION OF THE MODEL

In order to validate the model against a second data set, measurements carried out at the Patos Lagoon estuary during an El Niño event (23/05 – 06/06/1998) by the Instituto Nacional de Pesquisas Hidráulicas (INPH) were used. The time series of water elevation available for Praticagem was used as the ocean boundary condition.

Simulations were based on a finite element mesh of 3697 triangles and the Nikuradse law of bottom friction was chosen. The model boundary conditions were an appropriate imposed flowrate of 5,000 $m^3.s^{-1}$ at the top end of the lagoon, and a dynamic water elevation at the ocean boundary (Figure 12A). Time series of wind velocity measured by the Rio Grande Pilots (Praticagem da Barra) for the same period of time (Figure 12B) were used to force the model.

Figure 13 shows a comparison between water elevation data measured at SJN (Figure 1) with results from the model for the same location and period of time. The model reproduction is excellent, with an RMAE=0.16. FERNANDES *et al.* (submitted) comment about similar validation tests carried out with higher freshwater discharge when simulating the Patos Lagoon hydrodynamics during the 1998 El Niño event.

Results show that the model calibration was successfully carried out against measurements from 27-29/10/1998, whereas the model validation, carried out with measurements from 23/05-06/06/1998, showed an excellent agreement between measurements and predictions at SJN station. Thus, after successfully applying the model to two different data sets, TELEMAC-2D can be considered calibrated and validated, and is now a new important tool for studying the Patos Lagoon hydrodynamics.

THE PATOS LAGOON HYDRODYNAMICS BETWEEN 27-29/10/1998

Although hydrodynamic measurements were carried out in the Patos Lagoon estuary between the 27-29/10/1998 in order to provide data to calibrate TELEMAC-2D, such measurements give a very localised and time limited picture of the estuarine circulation. Thus, the model can now be used as a tool to predict the general lagoon and estuarine circulation during this period. Results presented here are based on the set-up from the Calibration 3 test.

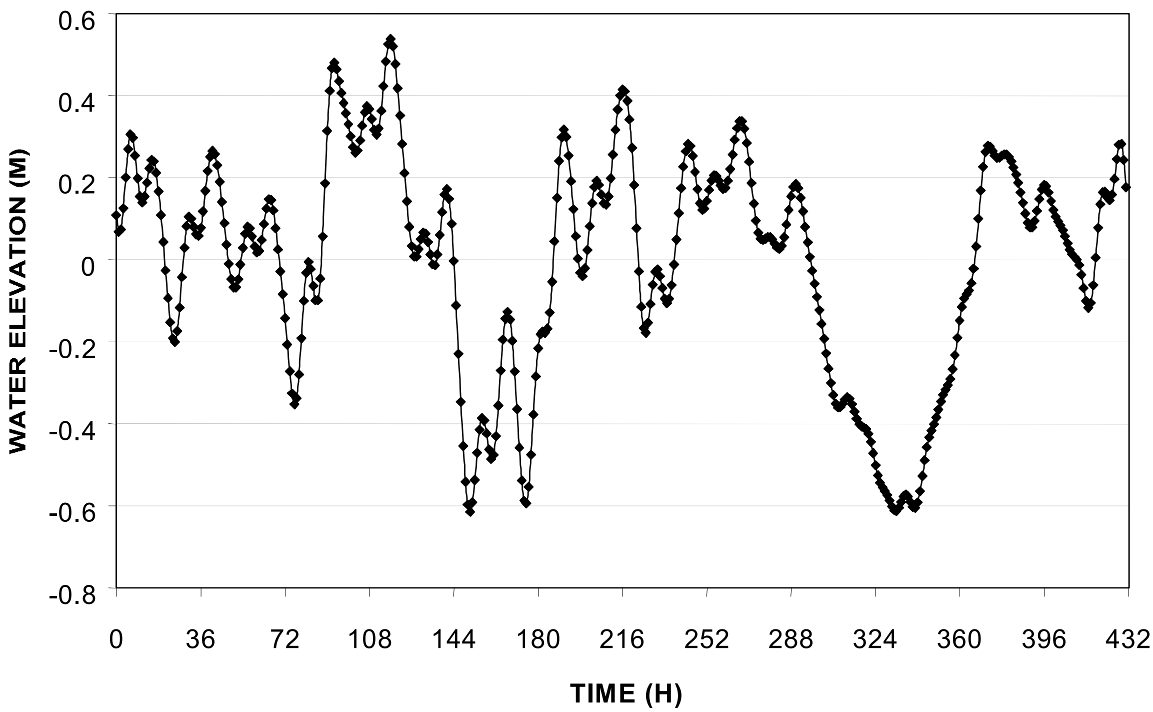
Predicted estuarine longitudinal and transverse velocities and water elevation time series between 27-29/10/1998 are individually presented for three locations in Figures 14, 15, and 16, respectively. The shaded areas in these figures show model predictions for velocities and water elevation for the same period when measurements were carried out in the estuarine area. Examples of the predicted circulation during the first, second, and third days of simulation are illustrated in Figures 17, 18, and 19.

During the first 11 hours of simulation (between t=167 and 178 hours) an ebb flow can be observed throughout the estuary (Figure 14), which is probably the result of 48 hours of NE wind between t=120 and t=168 hours (Figure 6B). The flow is weaker at Feitoria, with longitudinal velocities around -0.10 $m.s^{-1}$, and gets progressively stronger, reaching -0.65 $m.s^{-1}$ at Praticagem. As soon as the wind turns to SW (Figure 6D), the flow reverses and flood flow dominates the whole estuary. The longitudinal velocity at Praticagem varies from -0.65 to 0.65 m.s-1 in 5 hours (between t=175 and 180 hours of simulation) and gets weaker as it progresses landwards, reaching 0.10 m.s-1 at Feitoria. Figure 17 illustrates the lagoon and estuarine circulation at t=169 hours. The flow is clearly seaward everywhere and a set-up/set-down mechanism can be observed between Itapoã, Feitoria, and Praticagem, favouring the water outflow. The end of the first day was marked by the flood flow at Praticagem and Marambaia, although the flow reversed back to ebb conditions at Feitoria at t=187 hours.

The SW wind dominated the area for the next 30 hours (Figure 6D). The beginning of the second day of simulation (Figure 15) was thus marked by a flood flow throughout the estuary, with consequent increase in the water elevation. Figure 18 illustrates the lagoon and estuarine circulation at t=205 hours, where is clear that the lagoon is going through stagnation and the estuary is under the influence of a landward pressure gradient driving a water inflow. The wind changed to SE at t=210 (Figure 6D) favouring a strong outflow of water from the estuary to the coastal zone (Figure 15 B, C), reaching longitudinal velocities of –0.60 $m.s^{-1}$ at Praticagem. When the wind turned to S during the third day of simulation (t=217 hours, Figure 6D), the system immediately reverses back to a flood flow (Figure 16), reaching longitudinal velocities of almost 1 $m.s^{-1}$ at Praticagem and 0.3 $m.s^{-1}$ at Marambaia. The wind reversed back to SE at t=231 hours and the flood flow started to decrease in intensity. Figure 19 illustrates the circulation at t=233 hours, where the lateral set-up/set-down mechanism inside the lagoon forced by the SE wind effect is evident. The system gradually reverses the flow direction and finishes the simulation with an ebb flow at Praticagem and Marambaia.

A comparison between modelling predictions for the longitudinal and lateral velocities and measurements indicate that the model does reproduce reasonably well the system behaviour during this period of study, with the advantage of filling the gap in the measurements time series and also the possibility of plotting the circulation pattern at several time steps. However, although previous results show that TELEMAC-2D can be successfully calibrated and validated for the Patos Lagoon, some concern can still rise regarding the use

A



B

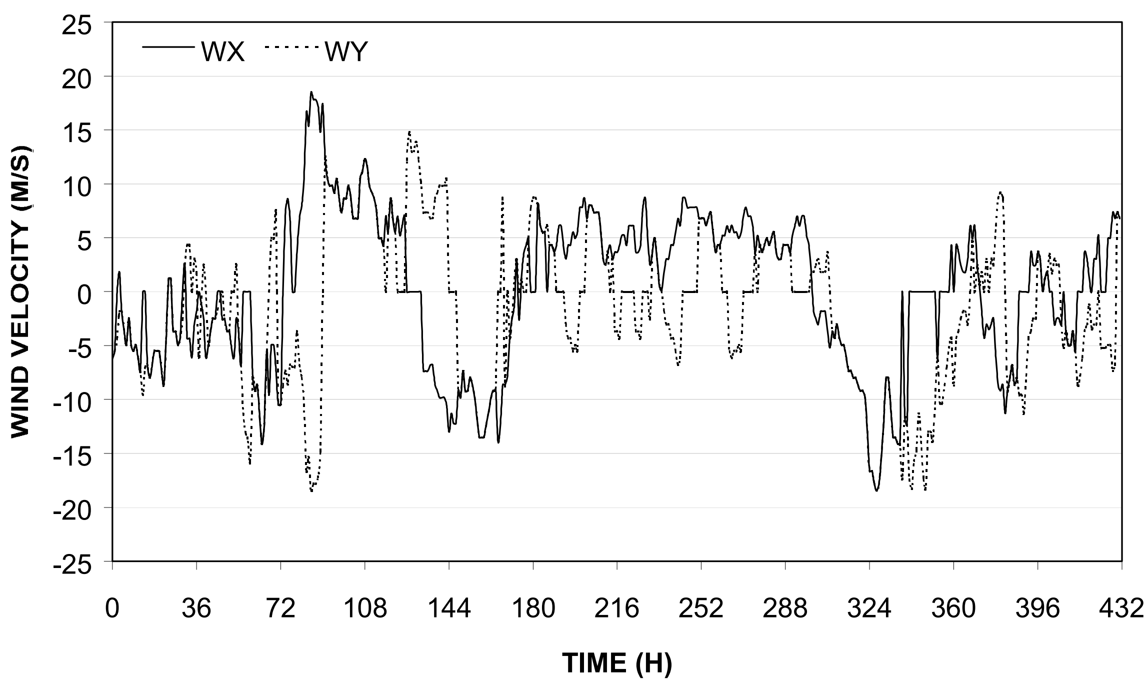


Figure 12. Water elevation (A) and wind velocity (B) time series used for the model validation simulation. WX is positive to the East and WY is positive to the North.

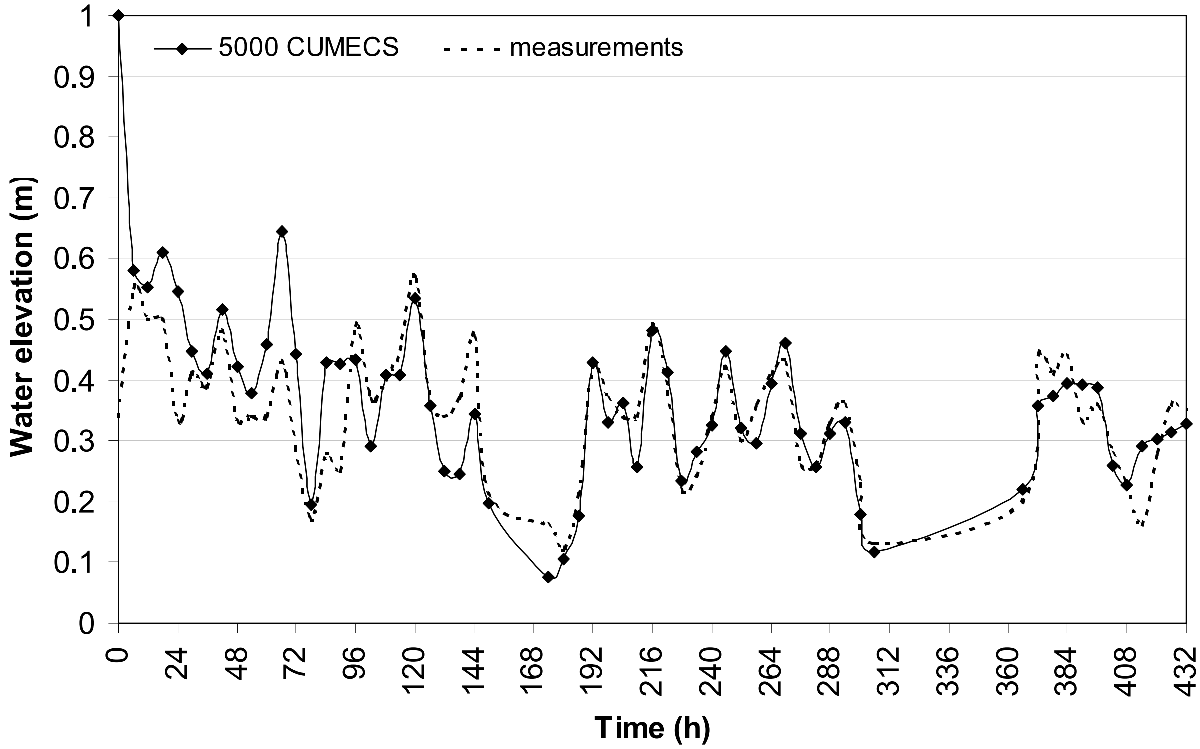


Figure 13. Comparison between measurements and modelling results at SJN.

of a two-dimensional depth-averaged model to predict wind-induced flow. HUNTER and HEARN (1987) comment that two-dimensional depth-averaged models of the hydrodynamic equations are satisfactory if the bottom stress can be adequately parameterised in terms of the depth-averaged velocity and if the non-linear advective terms are relatively small. Both requirements demand that the current is fairly homogeneous through the water column. Figure 20 shows a comparison between the observed depth-averaged (Figure 20A), surface (Figure 20B), middle depth (Figure 20C) and bottom (Figure 20D) longitudinal velocity at Praticagem against values calculated when using the Manning law of bottom friction (m=0.025). The observed longitudinal velocity through the water column at Praticagem seems fairly homogeneous, and the depth-averaged longitudinal velocity can be considered a reasonable reproduction of these measurements. Thus, the bottom stress can be parameterised in terms of the depth-averaged velocity, and the two-dimensional depth-averaged model TELEMAC-2D can be considered adequate for modelling the Patos Lagoon circulation in this case study. On the other hand, FERNANDES et al (in press) concluded that three-dimensional simulations are necessary to better understand the mechanism involved in the transverse circulation observed in the Patos Lagoon estuarine area.

CONCLUSION

Results from the sensitivity and calibration tests showed that, although the data and the space discretization have limitations, TELEMAC-2D can be adjusted to reproduce reasonably well measurements carried out in the Patos Lagoon. The validation test showed that TELEMAC-2D can reproduce an independent observed data set, and can then be used as a research tool to study the Patos Lagoon circulation and to predict velocities and water elevation. The procedure for model calibration and validation presented here for the Patos Lagoon takes modellers through the basic steps involved in numerical modelling, and can be used as a guideline for similar studies.

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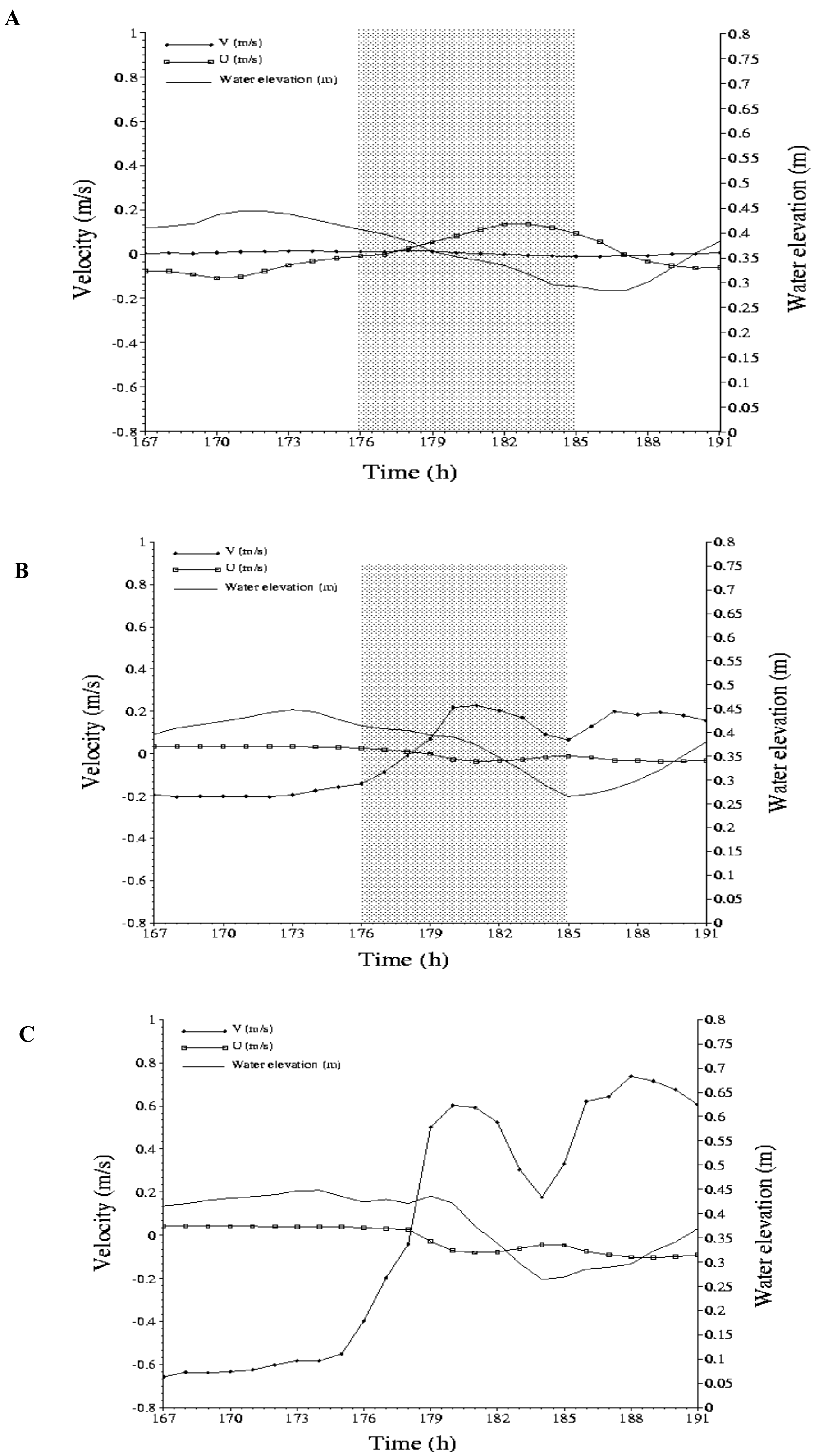

Figure 14. Predicted estuarine longitudinal and transverse velocities and water elevation time series (27/10/1998). (A) Feitoria, (B) Marambaia, (C) Praticagem.

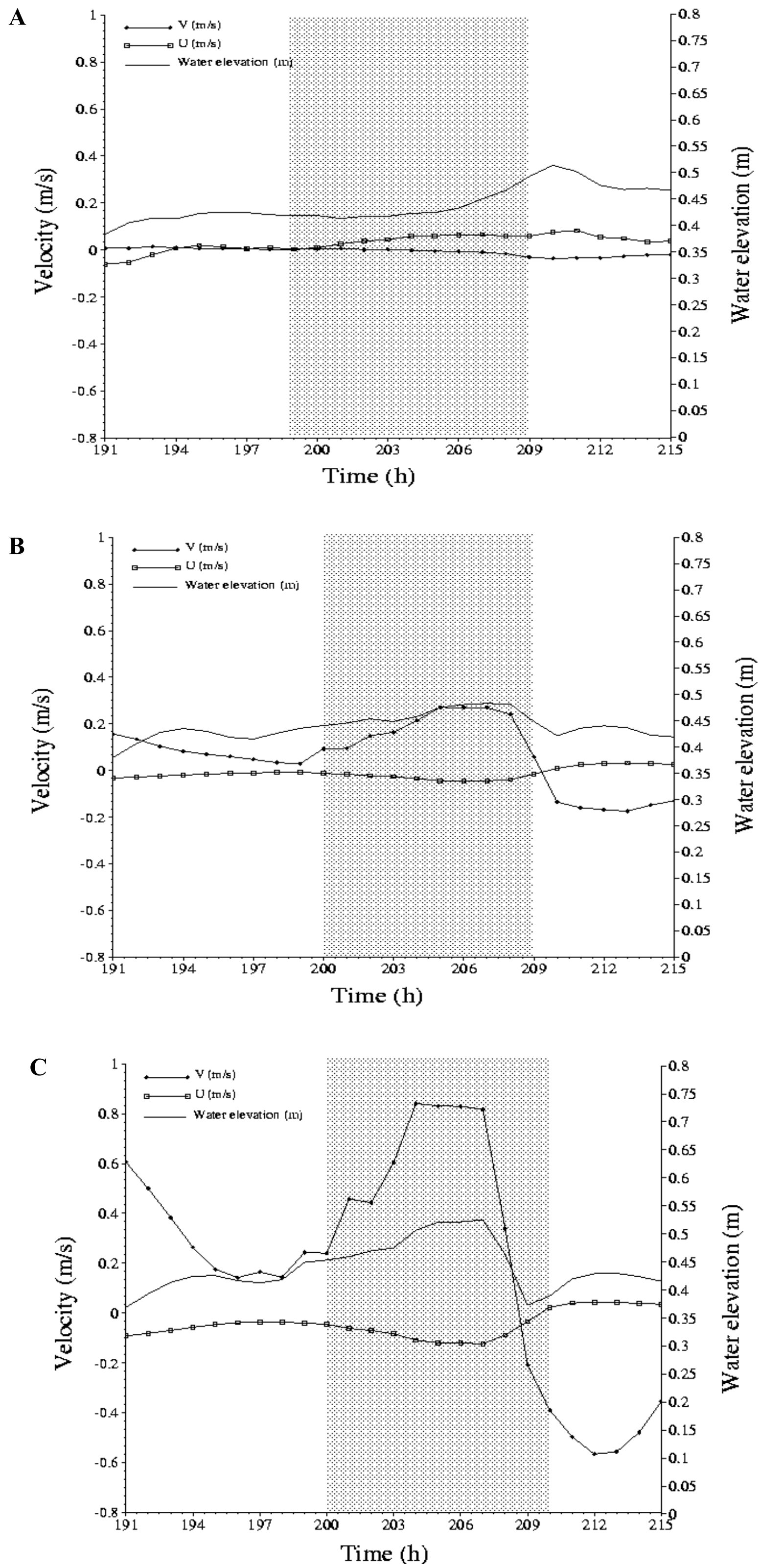

Figure 15. Predicted estuarine longitudinal and transverse velocities and water elevation time series (28/10/1998). (A) Feitoria, (B) Marambaia, (C) Praticagem.

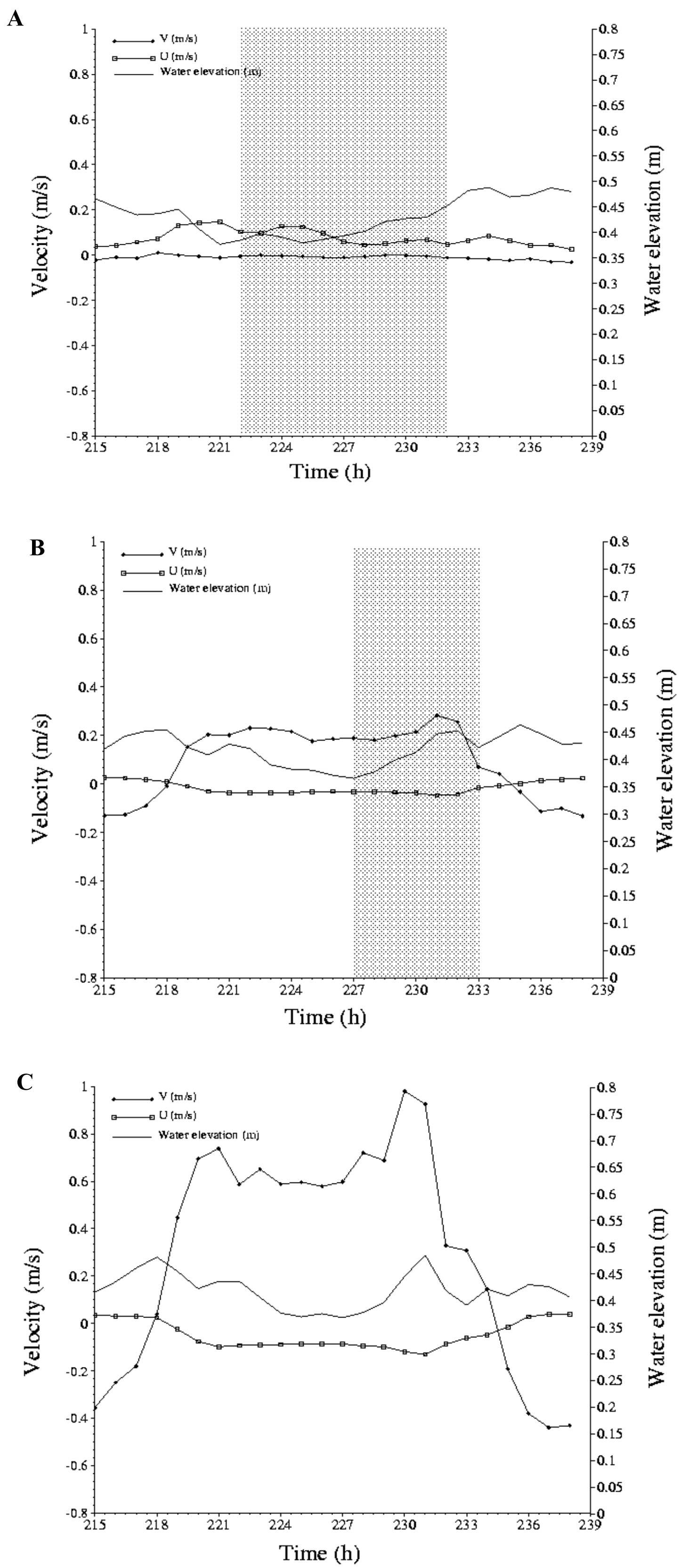

Figure 16. Predicted estuarine longitudinal and transverse velocities and water elevation time series (29/10/1998). (A) Feitoria, (B) Marambaia, (C) Praticagem.

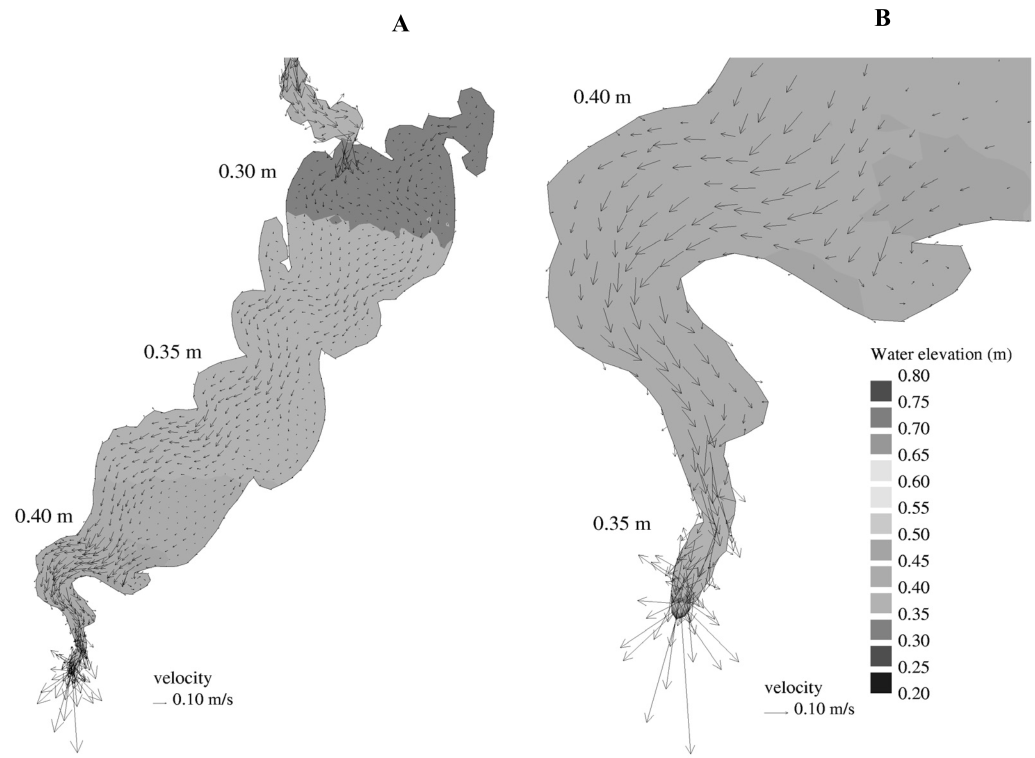

Figure 17. Predicted circulation during the first day of simulation at the lagoon (A) and estuary (B).

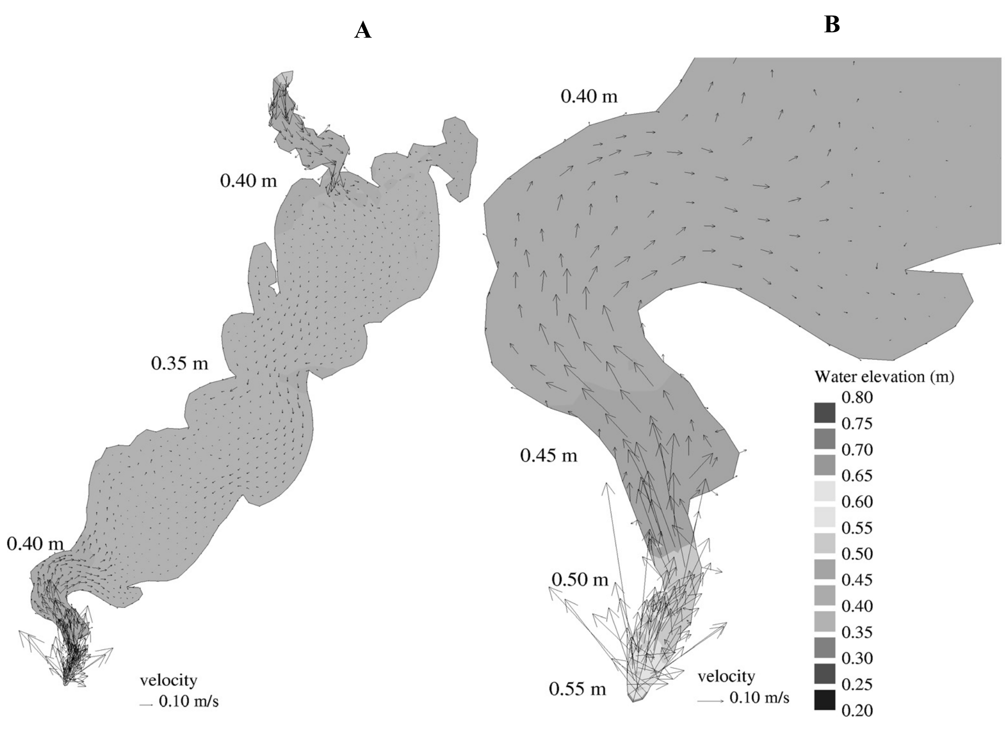

Figure 18. Predicted circulation during the second day of simulation at the lagoon (A) and estuary (B).

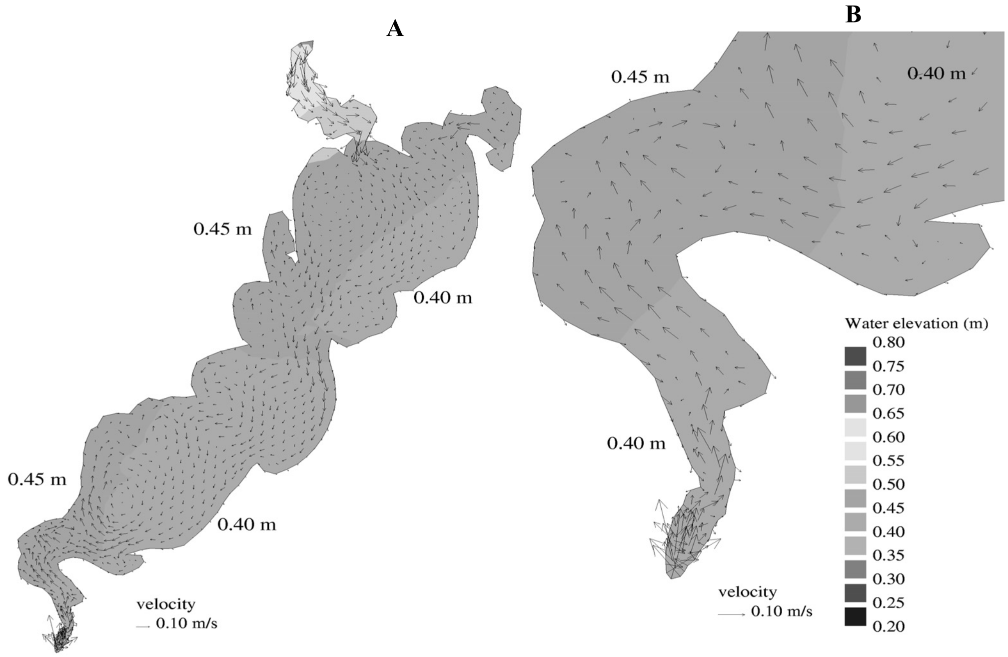

Figure 19. Predicted circulation during the third day of simulation at the lagoon (A) and estuary (B).

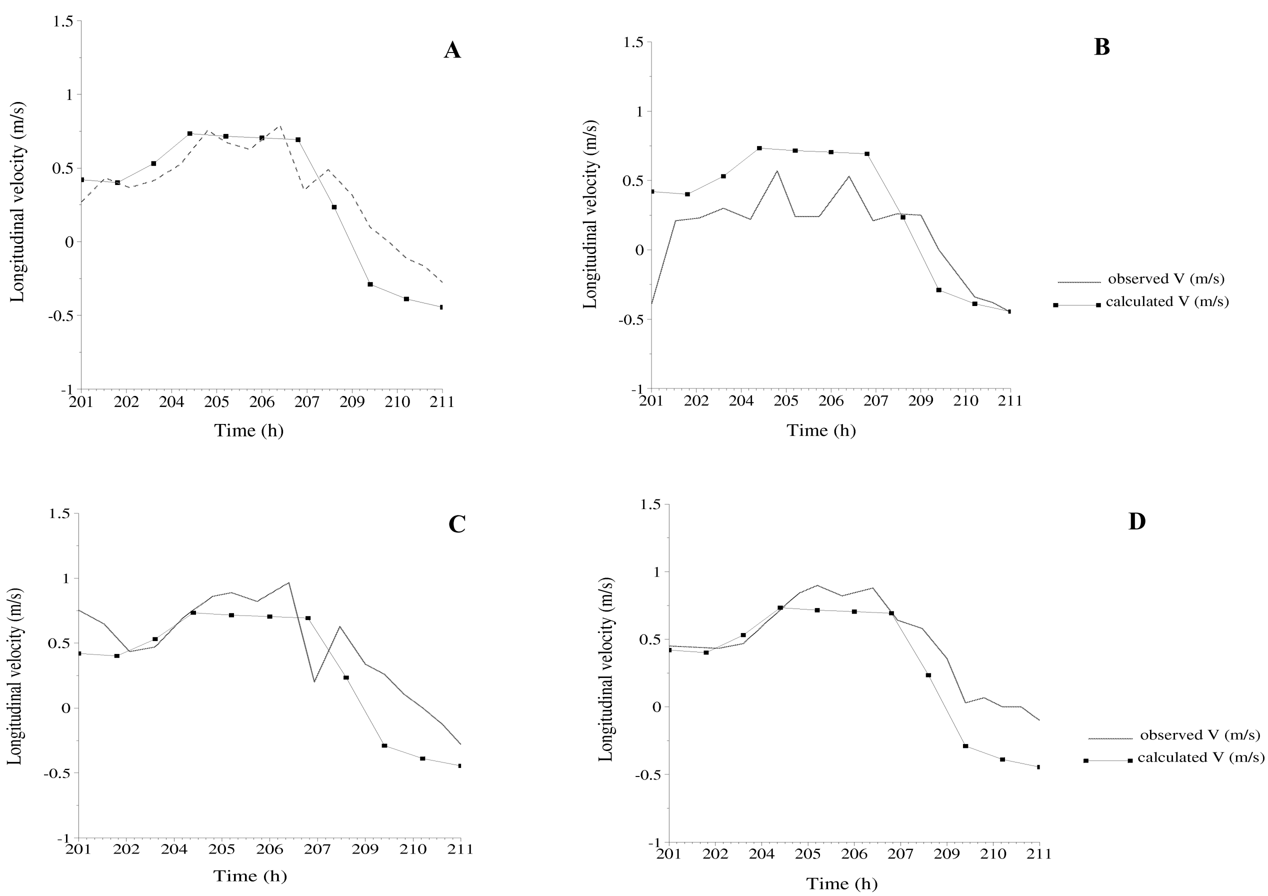

Figure 20. Comparison between the calculated longitudinal velocity (m=0.025) and the depth-averaged (A), surface (B), middle depth (C), and bottom (D) measurements at Praticagem (28/10/1998).

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