

Validation of the Hydrodynamic Module of a 3D Ecological Model for the Ria de Aveiro Lagoon (Portugal)

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Abstract: The purpose of this study is to validate a hydrodynamic module of a 3D ecological model. During the calibration, the parameters were adjusted so that the outputs match field data. The model is forced by considering tidal surface elevation at the open sea boundary and the river. The results show good agreement with the field data, for both the calibration and the validation experiments.

Keywords: Ria de Aveiro, lagoon, hydrodynamic flow model, validation

1. INTRODUCTION

Validated mathematical models for lagoonar coastal areas can be seen as tools for reconstruction real phenomena occurring in these systems. It is, therefore, required that numerical models for estuarine hydrodynamics should be calibrated and validated before used in practical applications. However, the procedures to perform these tasks are not widely accepted (Cheng et al., 1991). Calibration and validation methods appear in several forms, depending on data availability, water body characteristics and researchers opinion (Hsu et al., 1999). In the case of hydrodynamic modelling, the calibration is frequently made comparing short time series of predicted and measured data for the same location and period of time (Cheng et al., 1993). Another method consists in comparing the harmonic constituents generated from predicted and observed data (Smith, 1977).

2D models have been extensively applied in the study of the Ria de Aveiro hydrodynamics (Dias and Lopes, 2006; Lopes and Dias, 2006; 2007) and water quality (Lopes et al., 2006; 2008). The purpose of this work is to implement the hydrodynamic module of a fully 3D ecological model of the Ria de Aveiro lagoon by calibration and validation. The model calibration has been performed, as first approach, through a qualitative comparison of the simulated temporal evolution of SSE (sea surface elevation) with data for 1987/1988 on several locations of the lagoon. The validation procedure was performed using an independent data set of SSE values (1997). In the overall the model was evaluated using the minimum error involved in the calibration and the validation process.

Having the hydrodynamic model fully implemented, it will be used for future studies concerning the lagoon 3D hydrodynamics structure, namely the transport of salt, heat as well as non conservative biogeochemical particles.

2. Ria de Aveiro

Ria de Aveiro (Fig. 1) is a shallow lagoon situated in the Northwest Atlantic coast of Portugal (40°38'N, 8°45'W) which corresponds to a UTM-22 zone. The lagoon is 45 km long and 10 km wide and covers an area of 83 km² at high tide (spring tide), which is reduced to 66 km² at low tide. It is supplied with freshwater by two main rivers, the Antuã river (5 m³/s average flow) and the Vouga river (50 m³/s) (Dias et al., 1999), the last contributing the highest fresh-water input to the lagoon. Five other small rivers, with

average flow of $1\text{m}^3/\text{s}$, have small contributions to the overall freshwater budget of the lagoon.

Tides, which are semi-diurnal, are the main forcing of the circulation in the Ria de Aveiro lagoon. The estimated lagoon tidal prism is $136.7 \cdot 10^6 \text{ m}^3$ for maximum spring tide and $34.9 \cdot 10^6 \text{ m}^3$ for minimum neap tide (Dias, 2001). The bathymetry is probably the most important factor that affects the flow in shallow systems like Ria de Aveiro. The bathymetry controls the spatial variability of current magnitude and direction.

Numerical studies of the general circulation of the Ria de Aveiro show, that tides are strongly deformed in their propagation through the Ria de Aveiro, from the mouth to the far end of each channel, due to channels geometry and bathymetry (Dias et al., 2000). The general characteristics of the tidal wave in the lagoon are those of a damped progressive wave (Dias, 2001).

3. NUMERICAL SIMULATION OF THE RIA DE AVEIRO

3.1 Model Description

The three dimensional model presented here is based on finite volume techniques. This model was developed at the *DHI Water & Environment*. It is composed by a hydrodynamic module (*HD*) which is based on the numerical solution of the three dimensional continuity, momentum, temperature, salinity and density equations (*MIKE3-Flow Model*, 2005). The momentum equations are used in their incompressible *Reynolds* averaged version for the *Navier-Stokes* equations, involving the *Boussinesq* assumption and the hypothesis of the hydrostatic pressure in the vertical. The turbulence closure is affected using the *Smagorinsky* formulation for diffusion in the horizontal and the *k-ε* model in the vertical direction. In the horizontal plane both *Cartesian* and spherical coordinates can be used. The free surface is taken into account using a *sigma* coordinate transformation approach.

The physical model can be represented by the set of the basic equations referent to the hydrodynamic 3D mode:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial wu}{\partial z} = fv - g \frac{\partial \eta}{\partial x} - \frac{1}{\rho_0} \frac{\partial p_a}{\partial x} - \frac{g}{\rho_0} \int_z^\eta \frac{\partial \rho}{\partial x} dz + F_u + \frac{\partial}{\partial z} \left(\nu_t \frac{\partial u}{\partial z} \right) + u_s S \quad (1)$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial wv}{\partial z} = -fu - g \frac{\partial \eta}{\partial y} - \frac{1}{\rho_0} \frac{\partial p_a}{\partial y} - \frac{g}{\rho_0} \int_z^\eta \frac{\partial \rho}{\partial y} dz + F_v + \frac{\partial}{\partial z} \left(\nu_t \frac{\partial v}{\partial z} \right) + v_s S \quad (2)$$

$$\frac{\partial p}{\partial z} + \rho g = 0 \quad (3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (4)$$

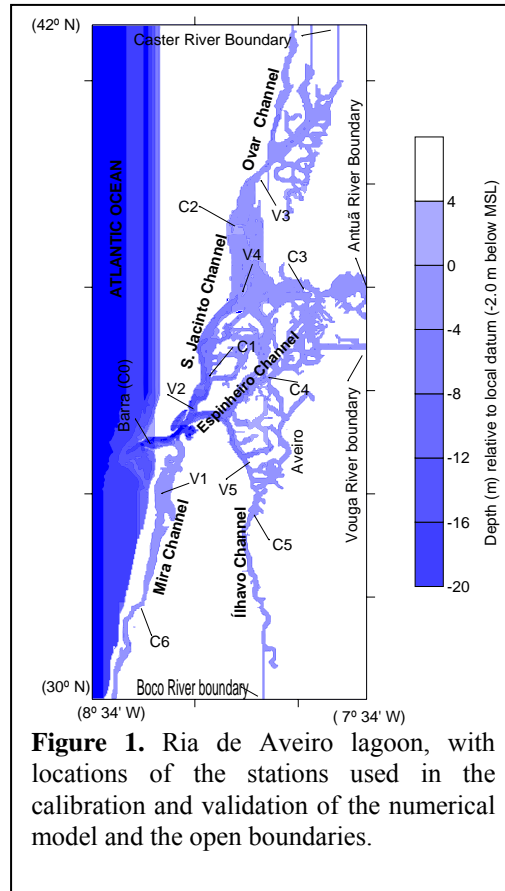


Figure 1. Ria de Aveiro lagoon, with locations of the stations used in the calibration and validation of the numerical model and the open boundaries.

where t is the time; x , y and z are the *Cartesian* co-ordinates; $h = \eta + d$, η is the surface elevation; d is the still water depth and h is the total water depth; u , v and w are the velocity components in the x , y and z direction respectively; $f = 2\Omega \sin \phi$ is the *Coriolis* parameter (Ω is the angular rate of the Earth and ϕ the geographic latitude); g is the gravitational acceleration; ρ is the density; ν_t is the vertical turbulent or eddy viscosity; p_a is the atmospheric pressure; ρ_0 is the reference density. SD is the magnitude of discharge due to point sources and (u_s, v_s) is the velocity by which water is discharged into the ambient water.

The vertical velocity is the velocity across a level of constant σ and is solved using a vertical sigma transformation and can be written as:

$$\omega = \frac{1}{h} \left[w + u \frac{\partial d}{\partial x'} + v \frac{\partial d}{\partial y'} - \sigma \left(\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x'} + v \frac{\partial h}{\partial y'} \right) \right] \quad (5)$$

At the bottom, the friction shear stress is imposed assuming a logarithmic velocity profile:

$$\frac{\bar{\tau}_b}{\rho_0} = C_d \bar{u}_b |\bar{u}_b| \quad (6)$$

Where C_d is the drag coefficient defined as:

$$C_d = \left[\frac{k \left(1 - \frac{\kappa_s}{30Z_b} \right)}{\log \left(\frac{30Z_b}{k_s} \right) - \left(1 - \frac{\kappa_s}{30Z_b} \right)} \right] \quad (7)$$

where k is the turbulent kinetic energy calculated farther (11), Z_b in the vertical extent of the bottom grid cell, $\bar{u}_b = (u_b, v_b)$ is the flow velocity above the bottom and κ_s is the bed roughness length scale. This expression has been obtained by assuming a logarithmic velocity profile at the bottom grid cell and depth averaging over the extent of the grid cell. At the free surface, the flux of momentum is also imposed in the form of a shear stress.

The transports of temperature, T , and salinity, s , follow the general transport–diffusion equations as:

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} + \frac{\partial wT}{\partial z} = F_T + \frac{\partial}{\partial z} \left(D_v \frac{\partial T}{\partial z} \right) + \hat{H} + T_s S \quad (8)$$

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} + \frac{\partial wS}{\partial z} = F_s + \frac{\partial}{\partial z} \left(D_v \frac{\partial S}{\partial z} \right) + S_s s \quad (9)$$

where T_s and s_s are the temperature and the salinity of the source, SD is the magnitude of discharge due to point sources, D_v is the vertical turbulent (eddy) diffusion coefficient, \hat{H} is a source term due to heat exchange with the atmosphere. F corresponds to the horizontal diffusion terms defined as:

$$(F_T, F_s) = \left[\frac{\partial}{\partial x} \left(D_h \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_h \frac{\partial}{\partial y} \right) \right] (T, s) \quad (10)$$

where D_h is the horizontal diffusion coefficient farther defined.

Turbulence is modelled using the eddy viscosity concept. The eddy viscosity is often described separately for the vertical and the horizontal transport. The hydrodynamic model has several turbulence models that we can apply: a constant viscosity, a vertically parabolic viscosity and a standard $k-\epsilon$ model.

Parameters and their units	Values
Time step (s)	6
Flood and drying depth (m)	0.2
Flooding depth (m)	0.4
Initial constant value for Surface elevation (m)	2.6
Bed roughness (m)	
κ_s	0.2
Turbulence (empirical constants)	
($c_{1\varepsilon}$, $c_{2\varepsilon}$, $c_{3\varepsilon}$)	(1.44, 1.92, 0)
Diffusion parameters	
(σ_k , σ_ε , σ_T)	(1, 1.3, 0.9)
k and ε lower limits (m^2/s^2 , m^2/s^3)	($1.0 \cdot 10^{-7}$, $5.0 \cdot 10^{-10}$)
Eddy viscosity limits (m^2/s)	
1 st range	($1.8 \cdot 10^{-6}$ - 12000)
2 nd range	($1.8 \cdot 10^{-6}$ - 12000)
3 rd range	($1.8 \cdot 10^{-6}$ - 30)
Background salinity (Psu)	32
Background temperature ($^{\circ}C$)	13

Table 1. Parameters values used in the hydrodynamic model calibration and validation.

In the k - ε model the eddy-viscosity is derived from turbulent variables, k and ε , as $\nu_t = c_\mu k^2/\varepsilon$ (Hartmut and Baumert, 2007; Burchard and Beckers, 2004), where k is the turbulence kinetic energy per unit mass (TKE), ε is the dissipation of the TKE . The horizontal and the vertical diffusion coefficients can be related to the eddy viscosity by $D_h = \nu_t / \sigma_k$ and $D_v = \nu_t / \sigma_\varepsilon$ respectively, where σ_k and σ_ε are *Prandtl-Schmidt* numbers and c_μ is an empirical constant defined in Tab. 1.

k and ε , are obtained from the following transport equations:

$$\frac{\partial k}{\partial t} + \frac{\partial uk}{\partial x} + \frac{\partial vk}{\partial y} + \frac{\partial wk}{\partial z} = F_k + \frac{\partial}{\partial z} \left(D_v \frac{\partial k}{\partial z} \right) + P + B - \varepsilon \quad (11)$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial u\varepsilon}{\partial x} + \frac{\partial v\varepsilon}{\partial y} + \frac{\partial w\varepsilon}{\partial z} = F_\varepsilon + \frac{\partial}{\partial z} \left(D_v \frac{\partial \varepsilon}{\partial z} \right) + \frac{\varepsilon}{k} (C_{1\varepsilon} P + C_{3\varepsilon} B - C_{2\varepsilon} \varepsilon) \quad (12)$$

where the shear production, P , and the buoyancy production, B , are given as:

$$P = \frac{\tau_{xz}}{\rho_0} \frac{\partial u}{\partial z} + \frac{\tau_{yz}}{\rho_0} \frac{\partial v}{\partial z} \approx \nu_t \left(\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right) \quad (13)$$

$$B = -\frac{\nu_T}{\sigma_T} N^2 \quad \text{and} \quad N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z} \quad (14)$$

$c_{1\varepsilon}$, $c_{2\varepsilon}$ and $c_{3\varepsilon}$ are empirical constants defined in Tab. 1.

The horizontal diffusion terms for turbulence are defined as:

$$(F_k, F_\varepsilon) = \left[\frac{\partial}{\partial x} \left(D_h \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_h \frac{\partial}{\partial y} \right) \right] (k, \varepsilon) \quad (15)$$

3.2 Discretisation

The numerical bathymetry used in this study was developed by the *Hydrographic Institute of Portuguese Navy (IH)*. The numerical grid must be sufficiently refined to resolve all variations of depth and geometry of the lagoon. This horizontal grid is composed by 266 X 654 cells, with dimensions of 60 X 60 meters. A time step as small as 6 s is required to satisfy the *Courant-Friedrichs-Levy* condition (*CFL*) and to avoid instabilities.

The spatial discretisation of the primitive equations is performed using a cell-centred finite volume method. In the horizontal plane an unstructured grid is used while in the vertical direction the discretisation is structured. The elements can be prisms or bricks whose horizontal faces are triangles or quadrilateral elements, respectively. A Riemann solver is used for computation of the convective fluxes, which makes it possible to handle discontinuous solutions. For the time integration a semi-implicit approach is used where the horizontal terms are treated implicitly.

3.3 Boundary conditions

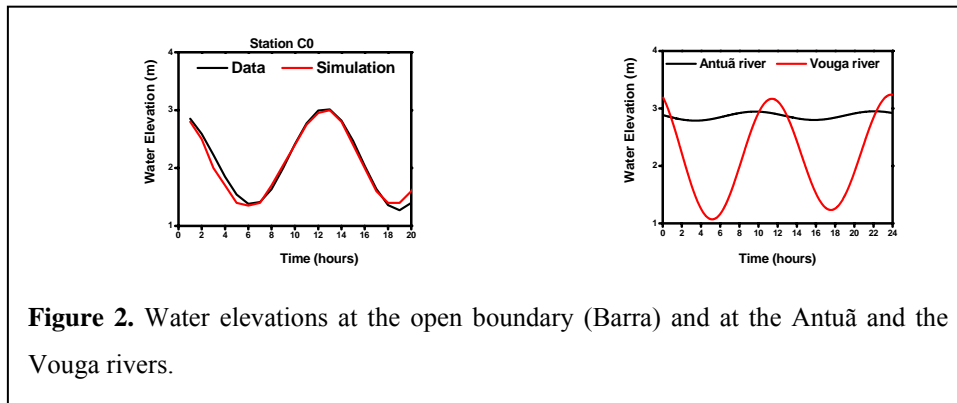


Figure 2. Water elevations at the open boundary (Barra) and at the Antuã and the Vouga rivers.

Several types of boundaries were used in this application: ocean and rivers open boundaries.

At the ocean open boundary the free surface elevation is specified whereas at the river boundaries the water flow or elevation can be imposed (Fig. 2). In this study the water elevation was specified at the river boundaries. No mass fluxes at the surface and bottom were considered.

The Ria de Aveiro lagoon system is affected by various natural and human stresses. The major natural stresses are tidal forces and variable recharge due to climatic variations. On the other hand it is also a place of discharge of domestic and industrial wastes, which flows do not contribute to the lagoon hydrodynamic (Dias et al, 1999).

3.4 Calibration and validation of the hydrodynamic model and sensitive analysis

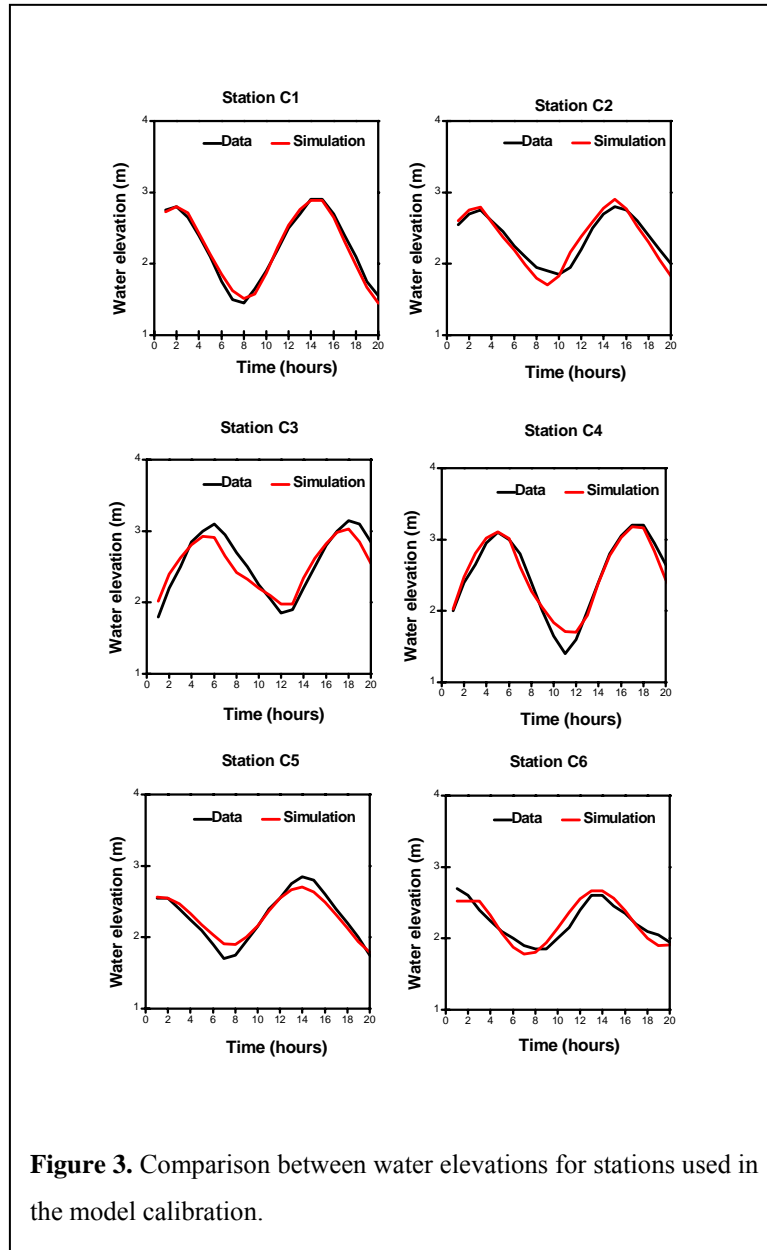
The hydrodynamic model calibration was carried out with sea surface elevation data for 1987/1988.

The results show that friction dissipates energy as the tidal wave propagates from the lagoon mouth towards the end of channels (Dias et al., 2006). This behaviour is a common feature in estuarine environments (Hsu et al., 1999) and was analyzed and quantified in Ria de Aveiro. Considering the lagoon geometry and the tidal range at the mouth, the

magnitude of the bottom friction coefficient determines the tidal range variation along the lagoon channels (Dias et al., 2006).

In many studies the procedure adopted to calibrate the model consisted in spatially varying the bottom roughness coefficient, by assuming *Manning's* values to specific regions of the numerical domain. In this study the model is not very sensitive to the bottom roughness, but rather to the water depth and rivers flow. The bottom roughness has been kept constant and equal to 0.2 m in the simulation. It is known that the water depth strongly influences the bottom stress. This parameter is introduced into the calculations of shear stress.

Fig. 3 shows the comparison between data and computed water elevations time series for six stations used in the model calibration (this procedure involved 22 stations).



The assessment of the relation between data measured and the model of SSE was performed with the help of *RMS* error defined as:

$$RMS = \left\{ \frac{1}{N} \sum_{i=1}^N [\xi_0(t_i) - \xi_m(t_i)]^2 \right\}^{1/2} \quad (16)$$

where $\zeta_0(t_i)$ and $\zeta_m(t_i)$ are the observed and modelled data of *SSE*, respectively, and N is the number of measurements in the time series.

Although the calibration involved 22 stations, only 6 stations are presented. Tab. 2 summarizes the *RMS* error between the model and data. In general there is a good agreement between the simulations and data, for all stations. The minimum *RMS* error was obtained for station *C1* and *C5* (0.099 m and 0.89 m respectively), whereas a maximum *RMS* error of 0.15 m was calculated for station *C3*. The higher *RMS* errors observed for *C3* as well as for *C6* may be explained by bathymetry effect, the shallowness of the area (see Fig. 1) and the uncertainties related to the river flows. The agreement between simulated and observed data from station *C0* (Barra, see Fig. 2) was not perfect, as *RMS* error of 0.1 m was found for this station. Indeed, this error may be explained by the fact that the boundary where the tide is imposed is located far western of *C0*.

Nevertheless, in overall, the 22 stations used in the calibration, show *RMS* values lower than 0.15 m, which corresponds to a relative error, for the water level, of the order of 6%. Considering the above results, it can be considered that the model is calibrated.

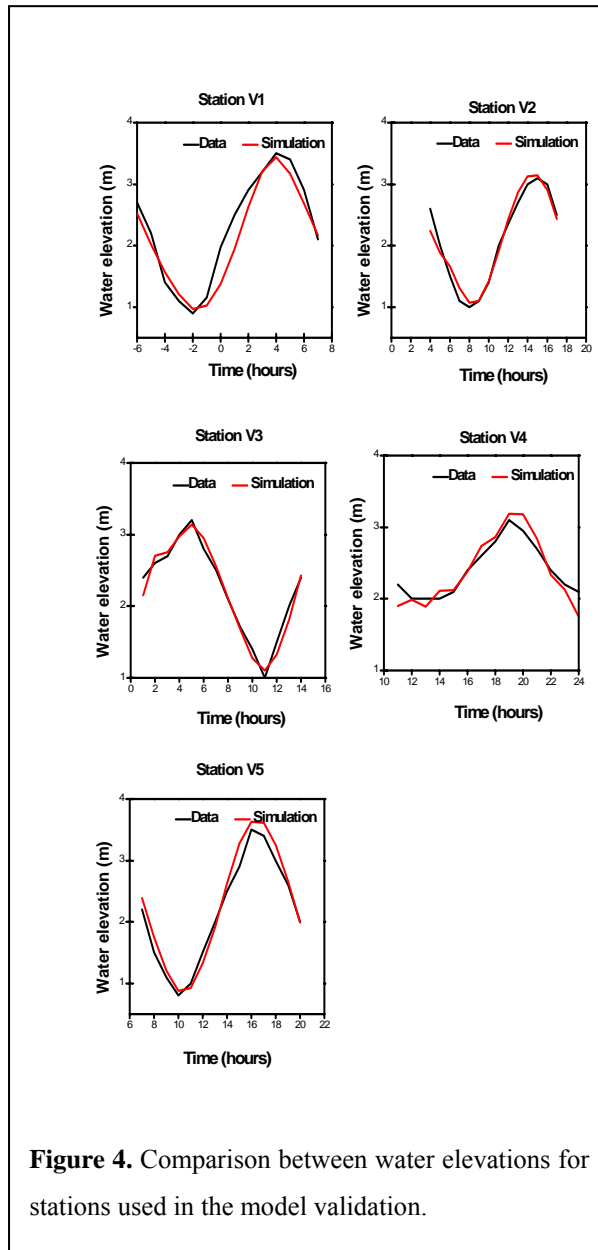


Figure 4. Comparison between water elevations for stations used in the model validation.

	Station C1	Station C2	Station C3	Station C4	Station C5	Station C6
RMS error	0.10 m	0.11 m	0.15 m	0.11 m	0.09 m	0.13 m

Table 2. Estimated *RMS* error for the model calibration.

The model validation is defined as a procedure consisting in comparing the model output with field or laboratory data to prove the model efficiency (Dias et al., 2006). The measurements used in the validation have to be independent from the set used in the calibration.

The validation corresponds to a very wet period during June 1997 where the model performance was evaluated by comparing the *RMS* error between modelled and observed data of *SSE*. These conditions were used to study the model's response to the interaction of tidal forcing and varying river discharge.

Fig. 4 shows results concerning the model validation for water elevation for five stations. Tab. 3 summarizes the *RMS* error between simulation and data. A good agreement can be observed, as in general the *RMS* values are low.

The highest value was found at station *V1* with the *RMS* error around 0.15 m. From these results it may be concluded that the hydrodynamic model for the Ria de Aveiro has been successfully validated.

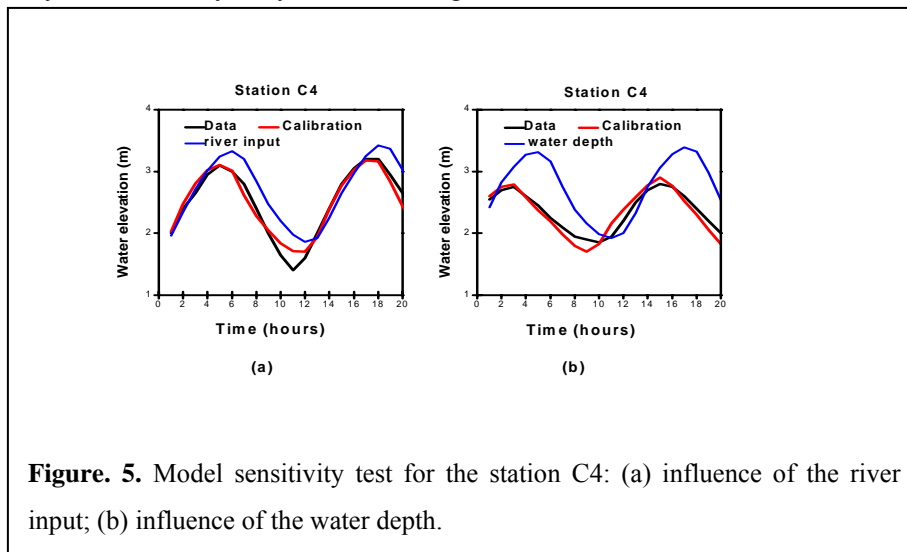
	Station V1	Station V2	Station V3	Station V4	Station V5
RMS error	0.146 m	0.050 m	0.041 m	0.055 m	0.062 m

Table 3. Estimated *RMS* error for the model validation.

The methodology of the sensitivity tests consisted in the assessment of the effect of the most sensitive parameters/processes involved in the calibration procedure, allowing variations of their values within a range of 10-30%.

During the calibration it was found that concerning the influence of the bottom stress, the model was more sensitive to the small variations of the water level than to the roughness length scale. It was also found that for stations situated near the far ends of the lagoon, the most important process was the river inputs.

Fig. 5 presents the sensitivity test concerning these two processes for the station *C4*. The case (a) compares the calibration to a situation for which the river flow was increased by a value of the order of 20%, whereas the case (b) compares the calibration to a situation for which the water depths at the area corresponding to station *C4* were increased by a value of the order of 30% relatively to the original bathymetry. In both cases it can be observed the deviations of the amplitude and phase lag relatively to the calibration/data. The inaccuracy in the bathymetry definition has, therefore, important repercussion in the tidal wave propagation inside the lagoon, namely at the shallow areas. The results show as well that the definition of an accurate river flow at the rivers boundaries is also important to correctly simulate the hydrodynamic of the lagoon.



4. Conclusions

The hydrodynamic model was successfully applied for the Ria de Aveiro lagoon. The results show that the calibration and validation of the hydrodynamic model was successfully carried out, revealing a good agreement between data and predictions. They show that inaccuracies in the bathymetry definition of the shallow areas, associated with the complex structure of the lagoon, composed by several very narrow channels, which are not well resolved by the horizontal grid, are crucial for the accurate simulation of the lagoon hydrodynamic.

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