1. Introduction

A mathematical model can be considered as an approximate reconstruction of a real phenomenon. All parameterizations and approximations used in models lead to deviations of the model results from nature. It is an accepted requirement that a numerical model of estuarine hydrodynamics should be verified, calibrated and validated before used in a practical application. 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 mass characteristics and researchers’ opinion (Hsu et al., 1999).

In this work, the Mohid-2D model implementation for the Ria de Aveiro lagoon is presented, describing its assessment through calibration and validation against several different data sets. Due to the lagoon complex geometry and the large number of calibration stations used, this goal constitutes a very challenging task.

The model is calibrated using as a first approach a qualitative comparison of the temporal evolution of sea surface elevation (SSE) data measured in 1987/1988 at several locations. When a good match is obtained for all stations, the model’s accuracy is evaluated through the determination of the root mean square (RMS) error and also through the comparison between amplitude and phase of the main tidal constituents determined from harmonic analysis of the observed and computed data. The validation procedure is performed using two independent data sets, which includes observations of current velocities and SSE values (1997 data) and measured water fluxes at the lagoon’s inlet for the period of October 2002.

2. The study area

Ria de Aveiro (Fig. 1) is a shallow mesotidal lagoon located in the Northwest coast of Portugal (40°38’N, 8°44’W). It is 45 km long and 10 km wide, being characterized by narrow channels and by the existence of large intertidal areas. In spring tide the water covers an area of 83 km² at high tide reducing to 66 km² at low tide (Dias et al., 2000). Ria de Aveiro receives freshwater mainly from two rivers:
Antuã (5 m³ s⁻¹ average flow) and Vouga (50 m³ s⁻¹ average flow) (Dias et al., 1999). Vouga River is responsible for ~66% of the freshwater input into the lagoon (Dias et al., 1999). Tides, which are semi-diurnal, are the main forcing of circulation within the lagoon.

A prior hydrological characterization lead to the conclusion that Ria de Aveiro can be considered vertical homogeneous during dry seasons (Dias et al., 1999).

3. The numerical model

The numerical model used in this study is Mohid (Martins et al., 2001), a three-dimensional finite volume model with the ability to simulate flows in shallow systems like Ria de Aveiro. Due to the lagoon’s characteristics the model equations were discretized with only one layer in order to simulate the lagoon’s hydrodynamic.

The model solves the three-dimensional incompressible primitive equations. Hydrostatic equilibrium is assumed as well as the Boussinesq approximation. The momentum and mass balance equations are

\[
\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho_0} \frac{\partial p_{\text{atm}}}{\partial x_i} - g \frac{\rho(\eta)}{\rho_0} \frac{\partial \eta}{\partial x_i} - \frac{g}{\rho_0} \int_{-h}^{0} \frac{\partial \rho'}{\partial x_i} \, dx_3 + \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_j} \right) - 2e_{ijk} \Omega_j u_k, \tag{1}
\]

where \( u_i \) are the velocity vector components in the horizontal Cartesian directions \( (i = 1, 2) \), \( u_j \) are the velocity vector components in the three Cartesian directions \( x_j \) \( (j = 1–3) \), \( v \) is the turbulent viscosity and \( p_{\text{atm}} \) is the atmospheric pressure. \( \rho \) is the specific mass, \( \rho' \) is its anomaly, \( \rho_0 \) is the reference specific mass, \( \rho(\eta) \) represents the specific mass at the free surface, \( g \) is the acceleration of gravity, \( t \) is the time, \( \Omega \) is the Earth’s velocity of rotation and \( e \) is the alternate tensor. Integrating Eq. (2) over the whole water column (between the free surface elevation \( \eta(x, y) \)) and the bottom \( -h \), the free surface equation is obtained:

\[
\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x_1} \int_{-h}^{0} u_1 \, dx_3 - \frac{\partial}{\partial x_2} \int_{-h}^{0} u_2 \, dx_3, \tag{3}
\]

where \( h \) is the depth.

The bottom shear stress, \( \tau_b \), is represented as a quadratic function of velocity (Eq. (4)) (Dronkers, 1964) and the drag coefficient \( (C_D) \) can be parameterized in terms of Manning’s friction coefficient \( (n) \), by applying Eq. (5):

\[
\tau_b = C_D |\vec{V}| V, \tag{4}
\]

\[
C_D = gn^2H^{1/3}, \tag{5}
\]

where \( \vec{V} \) is the horizontal velocity vector and \( H \) \( (H = h + \eta) \) is the total depth of the water column.

The model discretization is fully described in Martins et al. (2001).

Due to the lagoon’s complex geometry a grid with variable spatial step was developed. This grid has 429 by 568 cells, with dimensions of 40 by 40 m in
the central area of the lagoon (Fig. 1) and 40 by 100 m in the north and south areas of the lagoon. At the sea open boundary, water elevation over the reference level was imposed using tidal harmonic constituents determined using T_TIDE package (Pawlowicz et al., 2002). The initial conditions were null free surface gradients and null velocity in all grid points. At the solid boundaries, a null normal velocity was imposed and a free slip condition was assumed.

4. Hydrodynamic model calibration

In most of the estuarine systems, SSE observations reveal tidal energy damping, due to friction, as the tidal wave propagates upstream (Hsu et al., 1999). In Ria de Aveiro, this behavior was analyzed by Dias and Fernandes (2006). The magnitude of the bottom friction coefficient determines changes in the tidal wave propagation within the lagoon. Thus, the model parameter subjected to adjustments in the calibration process is the Manning bottom friction coefficient \( n \) (Eq. (5)). The model’s calibration was performed adjusting manually the bottom friction coefficient for the entire lagoon. In general, the model results are not very sensitive to the absolute values of \( n \). However, it is known that the water depth strongly influences the bottom stress. This “influence” is introduced into calculations by allowing Manning’s coefficient values to vary as a function of water depth. In this study the best adjustment between model results and field observations was achieved through bottom roughness parameterized from Manning’s coefficients ranging between 0.022 and 0.045.

Fig. 2 shows the comparison between computed and observed SSE time series for 9 stations used in the model calibration (this procedure involved 24 stations). The RMS errors are discussed as % of the local amplitude of each variable, which means that relative errors are discussed throughout this note.

In general, the disagreement between computed and observed SSE is low with values lower than 5% of the local tidal range. The highest disagreement was found for stations P, T and U, with RMS errors around 10% of the tidal range. The errors occurred at stations P and U (RMS = 0.243 m and RMS = 0.218 m, respectively) are probably due to an integrated effect of bathymetry errors in terms of the water volume arrested in the tidal flats during the flood. At station T an RMS error of 0.234 m was computed. This difference may be due to several factors, such as the distance to the lagoon mouth (~12 km), the fact that this station is placed close to the Vouga River mouth or the small width and depth of the channel (~40 and ~2 m, respectively). At the end of Ilhavo Channel (stations X and Y) the RMS error is ~7% of the local tidal range. These disagreements may be explained by a narrow section where strong current occurred. This region is very difficult to represent in the numerical bathymetry, even with cells of 40 m wide.

Harmonic analysis (Pawlowicz et al., 2002) was performed on 1 month length time series for both
observed and computed SSE for all the stations. Results for the three major semi-diurnal tidal constituents, which represent ~90% of the tidal energy in Ria de Aveiro ($M_2$, $S_2$ and $N_2$) are presented in Fig. 3.

For the $M_2$ constituent, which has the major amplitude, the mean difference of the amplitudes is about 3 cm and the standard deviation is ~7 cm. The mean phase difference for all the 24 stations is ~3° and the standard deviation is ~6°. One error of 1° corresponds to about 2 min departure in the arrival of high tide for a semi-diurnal constituent, which means that the average difference between field and model data is about 6 min for the $M_2$. Results for the other semi-diurnal constituents as well for the diurnal ones (not shown), are not so accurate as for the $M_2$ constituent. However, they reveal a good agreement between the computed and observed constants. The comparison between these values reveals that the amplitude of the major semi-diurnal constituents is well reproduced by the model for the entire lagoon, with averaged differences lower than 5 cm.

5. Hydrodynamic model validation

As previously referred, the model was validated comparing model predictions and hourly measurements of SSE (not shown) and current velocity at 11 and 10 stations, respectively. The validation procedure was carried out without changing the friction coefficients used during the calibration. At the ocean open boundary the tide synthesized for the considered periods of measurements was imposed.

When assessing velocities point by point some discrepancies can be found (Fig. 4). The RMS errors are very high, ranging from ~6% of the current amplitude in the case of the better adjustment (station D) to more than 50% at station F. At stations B, C and D (near the lagoon’s mouth), the phase errors are lower than 10 min. These stations are located in the center of wide channels and therefore it can be considered that the measured velocities are representative of the current speed in an area correspondent to a grid cell. At stations F, H and M the model results are not so accurate, the phase difference between predicted and measured values is about 1 h, revealing a degradation of the predicted velocity.

The model was also validated using computed and observed data of the water fluxes between the lagoon and the ocean in a monthly time scale. The observed water fluxes were determined using measurements of electrical potential difference (MIV) between the shores as described in Nolasco et al. (2006). The tidal evolution in the Ria de Aveiro is essentially determined by the lunar constituents. They represent more than 90% of the tidal energy. Thus, only the observed and computed water flow induced by the lunar constituents ($M_2$ and $O_1$) and by $M_4$ (essentially generated inside the lagoon) will be compared.

The spectra of these time series are presented in Fig. 5A. The higher energy peaks correspond to $M_2$, but $M_4$ and $O_1$ are also present in the spectra of MIV and model results. The direct comparison (for a short period) between the water flow computed by
the model and obtained from MIV measurements is shown in Fig. 5B. The agreement between the two series is rather good. At spring tide, the average value of water flow passing across the bar during the flood is 4124.8 (model) and 4586.1 m$^3$/s (MIV), and during the ebb is 4136.3 (model) and 4696.2 m$^3$/s (MIV). At neaps, the average values during the flood is 2320.5 (model) and 2659.7 m$^3$/s (MIV), and during the ebb is 2721.2 (model) and 3170.3 m$^3$/s (MIV). The relative errors of the average values computed by the model related to the average MIV values are about 10–12%.

6. Summary

In Ria de Aveiro, tides are distorted as they progress from the mouth toward the end of the channels. The general characteristics of the tidal wave are those of a damped progressive wave, presenting a decrease of the tidal amplitude and an increase of the phase lag due to bottom friction.

According to the results obtained, Mohid-2D was successfully implemented, revealing an accurate reproduction of the tidal propagation within Ria de Aveiro. Therefore, the model can be used in future studies concerning the lagoon’s hydrodynamics.
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References


