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Numerical modeling of Ria Formosa tidal dynamics

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ABSTRACT

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The tidal dynamics of shallow estuaries and lagoons is a complex matter, which has attracted the attention of a large number of researchers over the last few decades. The main purpose of the present research is to study the tidal dynamics of the Ria Formosa lagoon, which is located in Algarve, south of Portugal. This lagoon exhibits an extremely complex geometry and is characterized by large areas of salt marshes and sand flats. The methodology followed in this study comprises the application of a two-dimensional depth-integrated mathematical model (ELCIRC), in order to determine the spatial distributions of amplitude and phase of the main harmonic constituents. The tidal asymmetry and the tidal dissipation were also studied for this environment.
The analysis of the model results show that the tidal amplitude decreases with the distance from the lagoon inlets, while the phase lag increases, revealing a strong deformation of the tidal wave inland. The tidal asymmetry results also revealed a considerable tidal distortion along the Ria Formosa, and were found both flood and ebb dominance areas in the lagoon. The tidal dissipation results showed higher values in areas where the tidal currents are stronger, as well as in the areas of transition from the sea to the lagoon.
According to the results, most of the characteristics of the tidal propagation in Ria Formosa can be related to changes in the lagoon geometry and depth. In shallow areas there is a strong attenuation of M_2 tidal constituent and the opposite occurs for the M_4, which undergoes strong amplification, thus inducing tidal asymmetry in these areas. There is also a significant phase delay as the tide propagates into these shallow areas.

ADITIONAL INDEX WORDS: *ELCIRC, harmonic analysis, tidal dissipation, tidal asymmetry*

INTRODUCTION

Investigating tidal dynamics has been the focus of a large number of recent numerical modeling studies. This has lead to significant advances in the field of mathematical modeling of physical processes in shallow estuarine waters over the last few decades. The models produced can be used as reliable and useful tools to study tidal dynamics in shallow estuaries. There are several recent studies devoted to investigating the tidal dynamics of shallow estuaries motivated by the use of hydrodynamic models, such as: DIAS *et al*. (2000) in Ria de Aveiro (Portugal), BURLING *et al*. (2003) in Shark Bay (Australia), CANHANGA and DIAS (2005) in Maputo Bay (Mozambique) or MIRFENDERESK and TOMLINSON (2007) in Gold Coast Broadwater (Australia).

The Ria Formosa is a large mesotidal, coastal lagoon extending along the eastern part of the south coast of the Algarve, Portugal (36º56'N, 8º02'W to 37º03'N, 7º32'W, see Figure 1). It is a large multi-inlet barrier island system (50 km long; 110 km^2 of surface area), presently with six tidal inlets. The embayment is characterized by a large area of salt marshes and sand flats and by a complex net of natural and partially dredged channels. The average depth of the navigable channels is 6 m, although most areas are less than 2 m deep (SALLES *et al*., 2005). NEVES (1988) has modeled the submergence and emergence period for the western part of the lagoon as a function of the tides, showing that large areas of mudflats are exposed at low water and submerged at high water.

The major transport mechanisms within the Ria Formosa are tidally driven (SALLES *et al*., 2005) and therefore the tidal regime will be an important component in a hydrodynamic study of this lagoon.

In this work, is studied the tidal dynamics of Ria Formosa, through the application of the hydrodynamic model ELCIRC and consequent exploitation of results.

The present paper follows a previous study, where the ELCIRC model was calibrated and validated in order to study the relocation of one of the inlets of Ria Formosa (DIAS *et al.*, in press).

HYDRODYNAMIC MODEL

The hydrodynamic model used in this study is the ELCIRC (ZHANG *et al*, 2004). This model uses a finite-volume/finite difference Eulerian-Lagrangian algorithm to solve the shallow water equations. Because the equations are solved using an unstructured grid in the horizontal, ELCIRC is particularly adequate for cases involving complex bathymetries and geometries. This model solves the free surface elevation and the 3D water velocity, using a set of four hydrodynamics equations based on the Boussinesq and hydrostatic approximations. Because the study area is shallow and well mixed (SALLES, 2001), a single

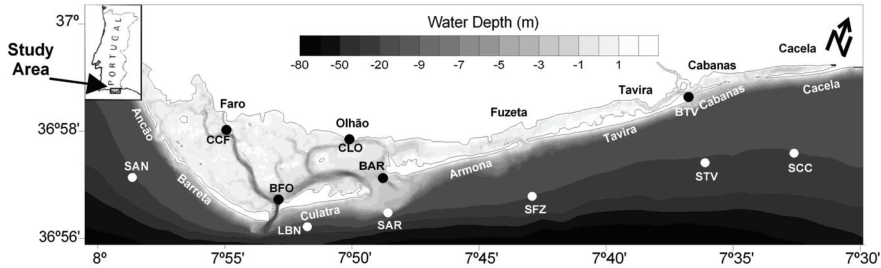

Figure 1. Location of the Ria Formosa lagoon, with the representation (circles) of the stations used to calibrate and validate the numerical model.

vertical layer is used, so ELCIRC reverts two dimensions (equations 1-3).

The equations solved in this model express the conservation of mass and momentum, and are written in the following form:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial [HU]}{\partial x}+\frac{\partial [HV]}{\partial y}=0 \quad (1)$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=fV-g\frac{\partial \zeta}{\partial x}+\frac{C_D}{H}\sqrt{U^2+V^2}U \quad (2)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-fU-g\frac{\partial \zeta}{\partial y}+\frac{C_D}{H}\sqrt{U^2+V^2}V \quad (3)$$

where $h(x,y)$ is the water depth; ζ is the surface water elevation; H is the total water depth ($H(x,y,t)=h(x,y)+\zeta(x,y,t)$); g is the acceleration of gravity; t is the time; U and V are the depth-averaged velocity components in the x (eastward) and y (northward) direction; and C_D is the bottom drag coefficient. Due to the relatively reduced dimension of the domain in the N-S direction, a constant Coriolis factor was used (f=9.3×10^{-5} rad/s).

The bottom drag coefficient is computed through the following equation:

$$C_D=\frac{gn^2}{\sqrt[3]{H}} \quad (4)$$

where n is the space-dependent Manning coefficient.

The temporal discretization of the equations is done with a semi-implicit scheme: the barotropic pressure gradient in the momentum equation and the flux term in the continuity equation are treated semi-implicitly; the bottom boundary condition for the momentum equations is treated fully implicitly; and all other terms are treated explicitly.

The ELCIRC model was previously implemented and calibrated for the entire Ria Formosa. The calibration was performed comparing the measured and predicted time series of sea surface elevation (SSE) for 11 stations distributed throughout the lagoon (Figure 1), and comparing the harmonic constants of the tides generated by the model to the respective values of the field data (DIAS *et al.*, in press). As an example of the model calibration results, the amplitude and phase of the M_2 constituent determined by harmonic analysis are shown in Figure 2. The comparison between predicted and observed values shows that the amplitude of the M_2 constituent may be considered well represented by the numerical model for the entire lagoon, with average differences lower than 2 cm and an average delay of about 4 minutes. The model validation consisted in comparing the modeled and measured velocity values and tidal discharges. The validation results show that the model adequately reproduces the hydrodynamic behavior of the Ria Formosa.

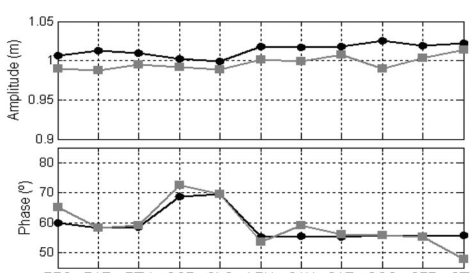

Figure 2. Distributions of tidal amplitude and phase for M_2 harmonic constituent for each measurement site (■ data; • model).

METHODOLOGY

Once the numerical model is considered calibrated and validated, much useful information can be derived from its application.

In this study the model was used keeping the parameters defined during the calibration and validation (DIAS *et al*., in press). It was only forced by the tides at the ocean boundary, with 12 tidal constituents (Z_0, M_{sf}, O_1, K_1, N_2, M_2, S_2, MN_4, M_4, MS_4, M_6, $2MS_6$), and were performed 30 days of simulation.

The spatial distribution of the harmonic constants of the major tidal constituents was determined from harmonic analysis applied to SSE time series numerically computed for each grid element.

In order to evaluate the flow pattern and characterize its flood or ebb dominance, the tidal asymmetry was also studied. Different definitions were found for tidal asymmetry in the literature, relating flood and ebb amplitudes. For the purposes of this study, the conventions using the M_2 harmonic constituent and its over-tide M_4 are used (FRIEDRICHS and AUBREY, 1988). Consequently, the ratio of M_4 to M_2 amplitude in SSE (asymmetrical coefficients) is used to indicate the magnitude of the tidal asymmetry generated within the lagoon. Similarity, the relative phase of M_2 and M_4 determines the type of asymmetry. The asymmetrical coefficients (amplitude ratio A_r and relative phase φ) are defined as follows:

$$A_r=\frac{A_{M_4}}{A_{M_2}} \quad (5)$$

$$\varphi=2\theta_{M_2}-\theta_{M_4} \quad (6)$$

where A is the amplitude, θ is the phase, and subscripts M_2 and M_4 indicate the tidal constituents. The flow is flood dominant if $0º<\varphi<180º$ and ebb dominant if $180º<\varphi<360º$.

"Flood dominance" indicates that the duration of falling tides exceeds that of rising tides, producing longer lags at low water than at high water, and leading to a tendency for stronger flood than ebb tidal currents. "Ebb dominance" refers to the opposite situation.

The mean rate of dissipation of energy per unit area, due to bottom friction is also estimated for Ria Formosa in this study, from the application of the following equation BURLING *et al*. (2003):

$$\varepsilon = \frac{1}{T}\int_0^T C_D \rho (U^2 + V^2)^{3/2} dt \qquad (7)$$

where C_D is the bottom friction used in the calibration of the model (DIAS *et al.,* in press) and U and V are the x and y components of the current, respectively. The fortnightly modulation of tidal forcing changes the amount of energy dissipated inside the lagoon, contributing to the tidal mixing of the water column. In this study, the integration presented in equation (7) was taken over 1 tidal cycle, for neap and spring tide cases, respectively. Calculations were performed on the half-hourly depth-averaged currents.

RESULTS AND DISCUSSION

Tidal propagation was analyzed along Ria Formosa. The semidiurnal constituents have the highest amplitudes, followed by the diurnal. The results for M_2 can be considered representative of the tide in Ria Formosa lagoon, since it has most of the tidal energy. The following analysis is based on the amplitudes and phases of the M_2 and M_4 tidal constituents (Figure 3), although the main patterns are common to the majority of the constituents.

The tides propagate into the lagoon and are altered by its geometry and bathymetry. The tide propagates faster at the beginning of the inlets, especially in the Faro, Armona and Tavira Inlets. There are rapid phase changes as the tide propagates along the lagoon channels, especially in shallow areas, where there is a

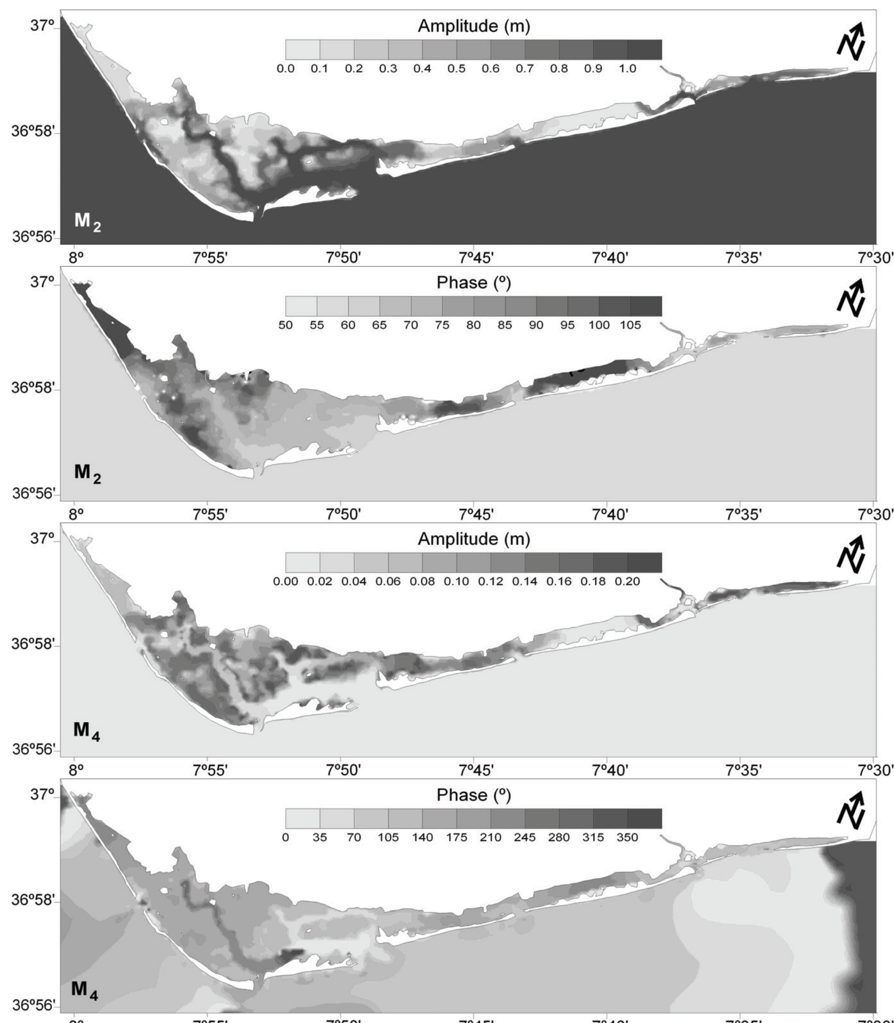

Figure 3. Amplitude and phase distributions for the M_2 and M_4 constituents.

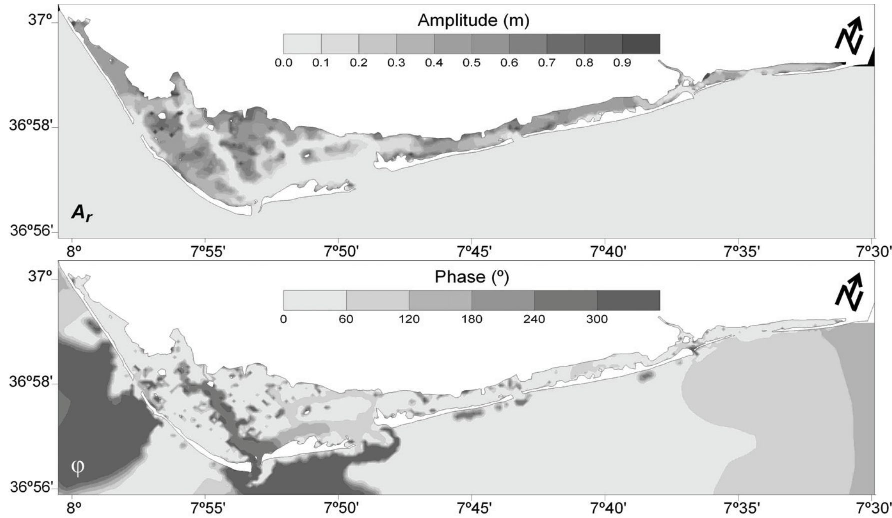

Figure 4. Amplitude ratio (A_r) (upper) and relative phase (φ) (lower).

rapid phase change due to an increase in the friction. For instance, for the M_2 constituent the phase lag from the Faro Inlet to Faro city is of the order of 35º, which corresponds to 1.2 hours of delay.

Figure 3 shows a similar phase pattern between the M_2 and M_4 constituent. In general, the time of propagation of M_4 from the inlets into the far end of the channels is about 1 hour, which corresponds to longer time delays of propagation than those of the principal tides. The relationship between the M_2 and M_4 patterns suggests an ebb and flow dominated asymmetry in the tidal flow at the region close to the inlets. BURLING *et al*. (2003) found similar results for Shark Bay (Australia).

There is strong attenuation of the M_2 constituent along the shallow regions and the opposite occurs for the M_4 tidal constituent, which undergoes strong amplification. The amplitudes of these shallow water tides are very small and show little spatial variation, except for a perceptible decrease away from the channels head, indicative of generation within the lagoon. This constituent is essentially locally generated, in shallow regions where non-linear interactions are important. Its major generating mechanisms are due to bottom friction effects, flow curvature and to the reduced tidal amplitude comparing to the water depth (PUGH, 1987).

As tidal waves propagate into a shallow region, shallow water tides usually increase, thus inducing tidal asymmetry (Figure 4). The tidal asymmetry is also measured by the water-surface relative phase, which is an indicator of the type of flow dominance and plays an important role in the dynamics of non-cohesive sediments (FRIEDRICHS and AUBREY, 1988).

The analysis of the amplitude ratio (A_r) and relative phase (φ) in Figure (4) shows that neither parameter exhibits a clear trend in Ria Formosa. In other words, the results reveal an interesting feature, showing that there are both ebb and flood dominated areas, as well as areas where asymmetry does not exist. In general, the A_r growth is not significant (from 0 to 0.1 for all inlets), revealing that in theses areas there is no tidal asymmetry. The amplitude ratio increases inside the lagoon (shallow regions), revealing that tidal asymmetry is maximum at these areas.

The relative phase decreases inside the lagoon, suggesting clear flood dominance in Ancão, Armona, Fuzeta and Cacela inlets and ebb dominance in the other inlets. These results are in disagreement with the findings of SALLES *et al*. (2005) for the Ancão and Armona inlets. This can be due to the fact that the duration of flood or ebb is not a determinant factor for flow dominance. Longer flood (ebb) may be associated with flood (ebb) dominance, due to the existence of strong residual circulation between inlets. In fact, larger flood (ebb) discharge in a shorter period does not necessarily lead to stronger flood (ebb) currents. But, the flood (ebb) dominance has an important impact on the sediment dynamics, promoting the inflow of the sediments into (out of) the lagoon.

Figure 4 also shows a strong distortion of the tide within the lagoon, which is the result of dissipation due to friction and nonlinear spectral energy transfer. Dissipation is responsible for the weakening of the mean velocity field, for third-diurnal, fourth-diurnal and for fortnightly components (DWORAK and GÓMEZ-VALDÉS, 2003). With this purpose Figure 5 shows the spatial tidal distribution of average dissipation in neap and spring tides, respectively.

The results show one order of magnitude difference between spring and neap tides in the effective tidal mixing energy input, which is consistent with the observed change in current amplitudes (DIAS *et al.,* in press), implying a considerable fortnightly change in the balance between stratifying and mixed terms. This pattern is in accordance with the results obtained for the Shark Bay (BURLING *et al*., 2003) and for the Maputo Bay (LENCART E SILVA, 2007), where the tidal dissipation calculated for neap tides is considerable lower than for spring tides.

In Ria Formosa, during neap tides the channels of the lagoon become very shallow, that is, the water column height is low during the majority of the tidal cycle and tidal currents are weak, contributing to a low dissipation of energy from the principal harmonic constituents to their sub-harmonics, as normally occurs with M_2 (AUBREY and SPEER, 1985).

During spring tides, the tidal dissipation is about 0.2-0.4 $W.m^{-2}$ over a large proportion of the Ria Formosa and the maximum tidal dissipation (1 $W.m^{-2}$) is found through the Faro channel. Dissipation is also high in Armona inlet, where the tidal currents

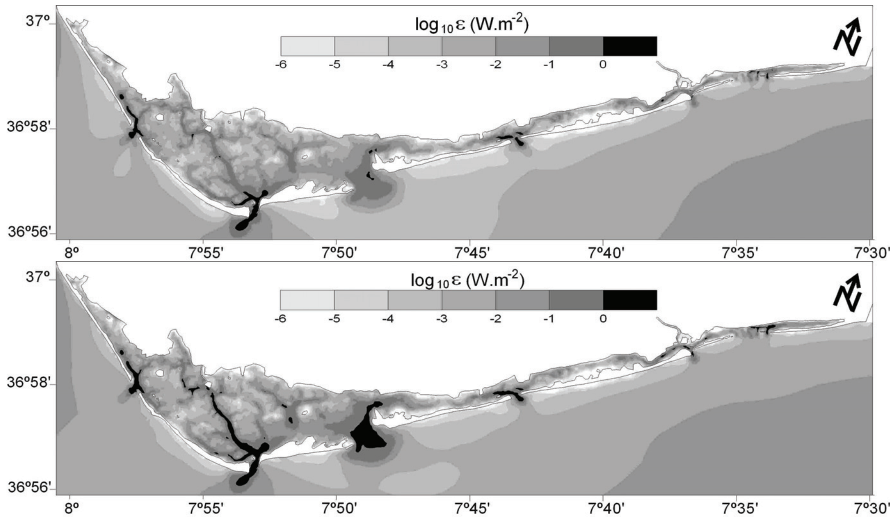

Figure 5. Spatial-logarithmic distribution of the average dissipation in neap (upper) and spring tides (lower).

are strong, as well as in the zones of transition from the sea to the lagoon.

CONCLUSIONS

The tidal dynamics of Ria Formosa has been successfully resolved through the application of the ELCIRC model.

The model results showed that the tidal amplitude decreases with the distance from the inlets while the phase lag increases, and that the shallow depths distort the tidal wave along its propagation through the lagoon channels. Tidal asymmetry parameters indicate flood dominance in Ancão, Armona, Fuzeta and Cacela inlets and ebb dominance in the other inlets. The results for the tidal dissipation showed that the dissipation is higher in areas where the tidal currents are stronger and in transition zones from the sea to the lagoon. The tidal dissipation is considerably higher during spring versus neap tides.

In conclusion, most of the characteristics of the propagation in Ria Formosa can be related to the variations in the lagoon geometry and bathymetry. In the shallow areas the M_2 tidal constituent is strongly attenuated, while the opposite occurs for the M_4, which is strongly amplified, thus inducing tidal asymmetry. The phase delay is also significant as the tide propagates into these shallow areas.

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