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Semidiurnal and spring-neap variations in the Tagus Estuary: Application of a process-oriented hydro-biogeochemical model

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ABSTRACT

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The main objectives of this work are the presentation of a hydro-biogeochemical model for the Tagus estuary and the study of the interaction between tides and river discharge. Special emphasis will be given to hydrographic, fine sediment dynamics and biogeochemical variations at two different time scales: the tidal cycle and the fortnight cycle. The numerical model validation was performed comparing harmonic analysis results of measured and model predicted sea surface height for 12 stations covering the whole estuary. For the M_2 constituent the difference is less than 5% of the local amplitude for almost all the stations. Differences in phase are small, with an average value of 5º. The results show strong salinity and suspended sediments gradients which are advected up and downstream according to the tidal cycle. Moreover, the estuary is divided in three main regions: a marine, a mixing and a freshwater influence area. The suspended sediments and chlorophyll concentrations reveal strong fortnight time dependence near the estuary mouth. Higher concentrations of fine sediments are found during spring tides that on neaps, which induces a decrease (increase) in the chlorophyll concentration during spring (neap) tides. This study presents the first results of the Tagus estuary predictive model, which are consistent with observations and with previously knowledge about the estuary. Preliminary outcomes obtained with this high resolution numerical modeling system are very encouraging to pursuit the development of a numerical tool suitable to deliver products that can be used both in scientific endeavors and in estuarine management, in order to assess the ecological estuarine quality.

ADDITIONAL INDEX WORDS: *Salinity, Suspended sediments, Chlorophyll, River inflow,Ttides*

INTRODUCTION

Estuaries are heavy populated interface areas subject to an enormous natural and anthropogenic stress. The knowledge of their physical and biogeochemical characteristics and their relation with the main driving mechanisms is a very important and actual issue. The lack of available in-situ data covering the whole area of an estuary limits this research, but it may be overcome by the development and use of high-resolution numerical models.

In a first approach these models are used to study the basic hydrodynamic features of an estuary, as performed by Fortunato *et al.* (1997) for the Tagus estuary and Dias *et al.* (2000), Vaz *et al.* (2009a) and Picado *et al.* (2010) in their studies in Ria de Aveiro lagoon. Then, the coupling of robust biogeochemical models increases the models potential and integrated studies of these ecosystems are being performed. In the last years, this integrated approach has been used worldwide. Baretta *et al.* (1995) presented a complex marine ecosystem model called European-Regional-Seas-Ecosystem-Model (ERSEM), launching the basis for recent ecological models. Baird *et al.* (2001) studied the interaction effects of several water properties and the nutrient uptake in the phytoplankton growth evaluating the model skill to reproduce this processes. More recently, Lopes and Silva (2006) studied the temporal and spatial variability of dissolved oxygen in a coastal lagoon using a modeling approach; Saraiva *et al.* (2007) studied the nutrient loads in several Portuguese estuaries and Duarte *et al.* (2008) implemented an integrated watershed and biogeochemical model for the Ria Formosa (Algarve, Portugal), analyzing the effects induced by changes in the lagoon bathymetry, evaluating the importance of land drainage and water exchanges for nutrient and suspended sediment dynamics. Mateus and Neves (2008) evaluated the light and nutrient limitations in the control of phytoplankton production in the Tagus estuary and the results suggest that light is the controlling factor of the ecosystem. Banas *et al.* (2009) used a four-box model of planktonic nutrients cycling, coupled to a circulation model, to evaluate how an estuarine plume shapes the phytoplankton biomass patterns and productivity in a regional scale. Also, Arndt *et al.* (2010) use a 2D model approach in order to quantify the biogeochemical transformations and fluxes of carbon and nutrients along the mixing zone of the Scheldt (Belgium/Holland), revealing that the balance between highly variable estuarine nutrient inputs and physical constrains exert an important control on the magnitude and succession of the ecosystem structure.

In this study, it is described the implementation and first results of a 2D hydro and biogeochemical model for the Tagus estuary. The main focus will be the implementation of the model, tidal propagation and fine sediments and biogechemical variations in the tidal and spring-neap cycles.

STUDY SITE

The Tagus Estuary is coastal plain system located near Lisbon (Portugal). Tides are semidiurnal with amplitude ranging from 1 to 4 m (over the local datum). With a surface area of about 320 km^2 and an average volume of 1900×10^6 m^3, it is the largest Portuguese estuarine system (Figure 1). Intertidal areas, composed mainly by mudflats, occupy an area between 20 and 40% of the total estuarine area.

The hydrography of the estuary is modulated by the tidal propagation and fluvial discharge from the major tributaries (Tagus, Sorraia and Trancão Rivers). These interconnected forcings induces the appearance of sharp gradients of salinity (and other variables) inside the estuary with the formation of three distinct regions: a marine region (lower estuary), a mixing region (middle estuary) and a region where the freshwater inflow dominates (upper estuary). This is consistent with the observations by Vaz and Dias (2008) for another Portuguese estuarine system, where they spatially characterized the salinity gradients of a tidal channel under different tidal forcing and river inflow conditions. In general, the system is well-mixed and has an average tidal prism of 600×10^6 m^3.

The major source of freshwater is the Tagus River, with an annual average inflow between 300-400 m^{3}s^{-1}. The estuary also receives effluent discharges, mainly from several urban, industrial and agricultural sources.

The wind regime in the region exhibits a marked seasonal pattern, presenting south southwest predominant winds during the wet seasons, rotating to north/northwest during the dry season. The seasonal variability of meteorological conditions and river inflow induces a strong seasonal variability in the estuary hydrography and biogeochemical conditions (Mateus and Neves, 2008).

Several groups of primary producers can be found in the Tagus ecosystem with diatoms being the predominant (Cabrita *et al.*, 1999). Other relevant primary producers in the system include microphytobenthos (Serôdio and Catarino, 2000) and salt marsh vegetation (Caçador *et al.*, 1996).

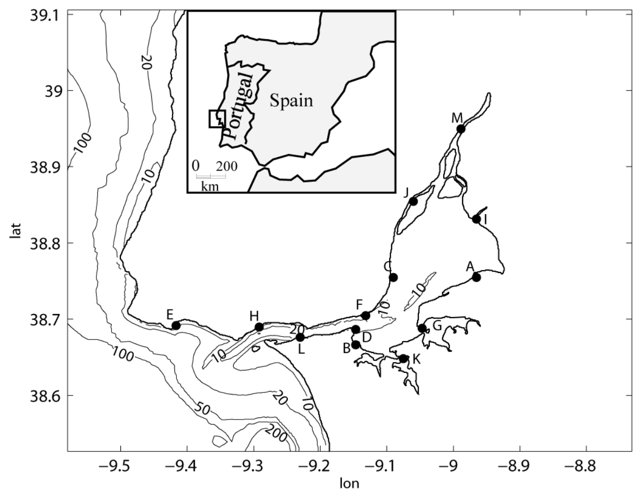

Figure 1. The Tagus estuary: location, station names and bathymetry (isolines (in meters) relative to the local datum).

THE TAGUS MODEL

The Tagus Estuary predictive model is an implementation of Mohid (www.mohid.com) for the study area. The model is a baroclinic finite volume model, designed for coastal and estuarine shallow water applications, like Tagus estuary, where flow over complex topography, flooding and drying of intertidal areas, changing stratification or mixing conditions are all important. Mohid allow an integrated modeling approach of physical and biogeochemical processes. A complete description of the model's physics can be found in the work by Leitão *et al.* (2005).

Given the intense vertical mixing of the estuary, the model was set in a 2D mode. The numerical grid encompasses the whole extension of the Tagus estuary, having 335×212 cells of 200 m each. This resolution was considered adequate to simulate hydro and biogeochemical processes inside the estuary. Tides, meteorological variables and variable river inflow are the main forcing mechanisms for the circulation. On the open ocean boundary, the model input is the tidal forcing from a 2D tidal model (Vaz *et al.,* 2009b). Meteorological forcing (from the Guia meteorological station, http://www.mohid.com/tejo-op/atm_data.asp) and river discharge from the major tributaries (www.snirh.pt) are imposed at the surface and landward boundaries, respectively. Atmosphere-water interactions (e.g. heat fluxes, solar radiation and wind stress) and the interaction between the estuary bottom and the water column (e.g. cohesive sediments re-suspension and deposition) are handled by the model.

The model was spun-up for 2 years (January 2008 to December 2009) with a time step of 15 s and a horizontal viscosity of 5m^{2}s^{-1}. Also a value of 5 m^{2}s^{-1} was adopted for both salt and heat diffusion coefficients. Initial conditions for the hydrodynamic model are null free surface gradient and null velocity in all points. For the transport model, constant values for the whole estuary were imposed. The spin-up was three months (prior to 2008) in order to achieve a proper bottom sediment pattern inside the estuary.

The ecological model (Mateus, 2006) was coupled to the circulation model as a zero dimensional water quality/ecological model with an Eulerian formulation. The model has an explicit parameterization of carbon, nitrogen, phosphorus, silica and oxygen cycles. Synthesis of chlorophyll-a is simulated, allowing for a temporal and spatial variation of C:Chla ratios in producer populations. Light penetration in the water column is affected by chlorophyll and cohesive sediment concentrations and is computed within the model system. The ecological model iterates every 3600 s and runs for two years.

Details on the ecological model formulation and on a prior application for the Tagus Estuary can be found in Mateus (2006) and Mateus and Neves (2008).

RESULTS

Sea Surface Height

A first validation of the numerical model was performed through comparison of harmonic analysis (Pawlowicz *et al.*, 2002) results of sea surface height measurements and model predictions for the stations depicted in Figure 1. The data used in this process was measured in 1972 covering the whole estuary. Figure 2 depicts the amplitude and phase difference for the two major constituents (M_2 and O_1) in the Tagus estuary.

For the M_2 tidal constituent, the difference between measured and predicted amplitudes is less than 5% of the local amplitude for almost all the stations. Differences in phase are small, with an average value of 5º, which represents an average delay of 10

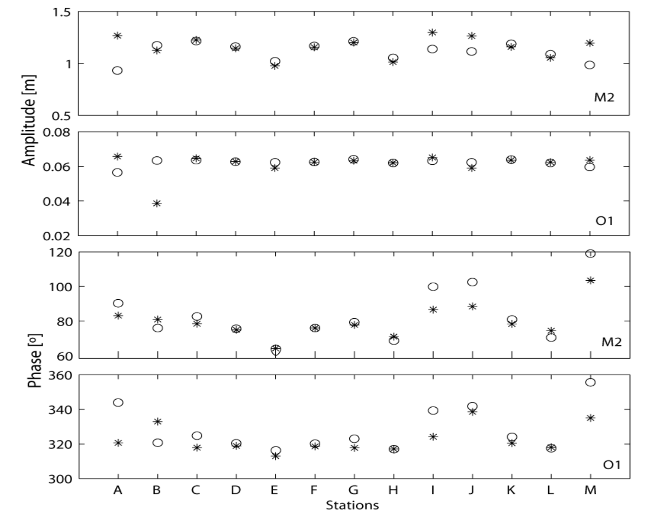

Figure 2. Comparison between amplitude and phase of the larger semidiurnal (M_2) and diurnal (O_1) tidal constituents determined in all stations throughout the Tagus estuary. o – measurements and * - model predictions.

minutes. The exceptions are the stations located at the upstream region of the Tagus estuary, close to the river mouth (stations I, J and M). At these locations, the difference ranges from 10 to 15% of the local tidal amplitude, representing a degradation of the results.

The major diurnal constituent here presented has very similar amplitude in all the stations of the Tagus estuary analyzed. Concerning the model skill in reproducing this constituent differences in amplitude and phase are small (about 5% of the local values).

The results show that the M_2 amplitude is much higher than the O_1 amplitude, which means that the tides in the estuary are semidiurnal with a small diurnal inequality.

One of the main features of the Tagus estuary is related to the amplification of the tidal wave in the middle region of the estuary. In fact, the M_2 amplitude presents the highest values at stations C, F, J, and K. This amplification of the tidal amplitude is consistent with the results presented by Fortunato *et al.* (1997) and may be related to the reflection of the tidal wave at the upstream region of the estuary. As the tidal wave reaches the upstream region of the estuary, it is reflected in this shallow region turning back and meets the wave that is still propagating upstream. This process induces a resonance mode with a period close to twelve hours in the estuary, as described by Oliveira (1993). This effect enhances the amplitude of the tidal wave at the mixing region of the estuary.

In general, the results show a fair comparison between model results and observations, revealing that the model can accurately reproduce the observed tidal propagation.

Tidal cycle analysis

The Tagus estuary is a coastal plain estuary where the combination between the tidal and river inflow forcings induces the formation of estuarine properties spatial gradients, which propagate up and downstream according to the tidal stage. Figure 3 show the horizontal patterns of salinity and suspended sediments at two distinct moments of the tidal cycle: low and high tide. The salinity and suspended sediment patterns are found similar, revealing a strong spatial gradient throughout the estuary.

At high tide (Figures 3b and c) it is noticeable the division of the estuary in three main regions: a marine regions extending from the estuary mouth to ~10-15 km upstream with salinity values ranging between 30 and 36 psu, a mixing region which includes the central region of the estuary, presenting salinities between 10 and 30 psu, and a fluvial region, where the freshwater effect is dominant. These regions are considering characteristic of several estuarine systems, and the results found are consistent with the observations by Vaz and Dias (2008) for Ria de Aveiro, revealing the model skill in reproducing typical estuarine patterns.

As previously referred, the suspended sediment concentration presents similar patterns. The major source of suspended sediment in the estuary is the Tagus river inflow. The major concentrations of sediment are visible near the upper estuary (between 30 and 35 mgL^{-1}), where the river effect is dominant, decreasing downstream toward the mouth (close to 0 mgL^{-1}). During the low tide, the river effect extend its influence downstream, and the estuary presents concentrations between 30 and 35 mgL^{-1} until a region of 8 km downstream of the river mouth.

From low-to-high tide, it is visible an upstream migration of high saline waters (as expected since the tide is rising). This water migration has an extension of about 15 km upstream during a spring tide (Figures 3, b and d), being smaller during neaps (~8-10 km, not shown).

Spring-neap analysis

The study of the suspended sediment dynamics is very important since its variation along the estuary modulates the behavior of several biogeochemical variables (e.g. chlorophyll). In a recent paper, Valente and Silva (2009) studied the turbid plume of the Tagus estuary, revealing its spring-neap modulation.

Figure 4 shows a 1 month time series of cohesive sediments and chlorophyll-a for the outer monitoring stations in the Tagus estuary (Stations H and E) for April 2009, when the Tagus river inflow has an average value of ~150 m^3s^{-1}, in order to capture different patterns of fine sediments near the Tagus estuary mouth.

For station E (far from the estuary mouth, Figure 4b), the suspended sediment concentration ranges from 1 to 1.5 mgL^{-1}. This concentration of suspended sediments is consistent with the results of Jouanneau *et al.* (1998). They present suspended

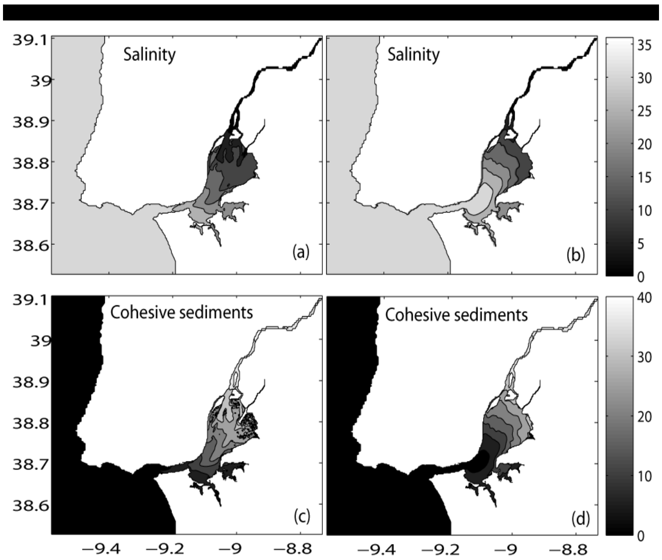

Figure 3. .Horizontal patterns of salinity and cohesive sediments [mgL^{-1}] in the Tagus estuary, during low tide (a, c) and high tide (b, d). Spring tide period in April 2009.

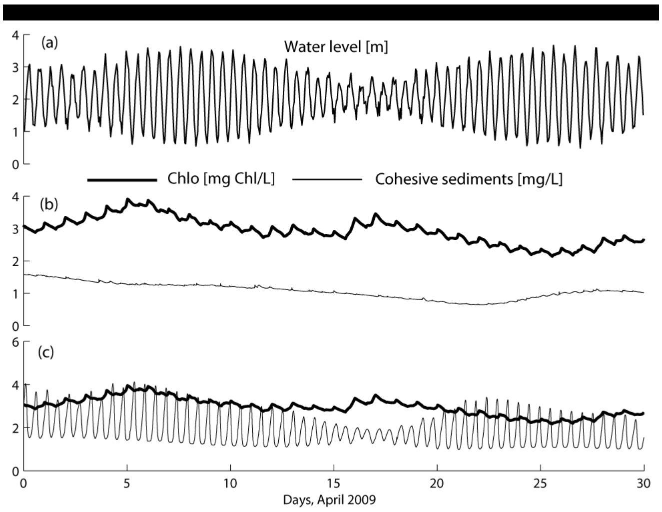

Figure 4. .(a) Water level at station E for April 2009; (b) represents the time evolution of suspended sediments (thin black line) and chlorophyll concentrations (thick black line) for station E; (c) represents the same as b) for Station H (closer to the Tagus estuary mouth). The suspended sediment and chlorophyll units are depicted in the figure.

sediment concentrations of 0.8-1.0 ftu (1ftu – Formazine Turbidity Unit - ~1.7 mgL^{-1}) for the region near the Tagus estuary mouth. For station H (closer to the estuary mouth, Figure 4c), the suspended sediment concentration ranges between 1.5 and 4 mgL^{-1} during spring tides, decreasing to concentrations between 1.5 and 2.2 during neaps. This monitoring station is closer to the estuary mouth and the concentrations are more influenced by the estuarine discharge. The concentration of suspended sediments inside the estuary is higher and the advection during spring tides is enhanced due to the large tidal currents. In both stations is noticeable a marked fortnight cycle, with higher concentrations during spring tide and lower during neaps. This is a direct consequence of the influence of the estuarine discharge to the near-shelf.

Analyzing the chlorophyll concentration, the results show that slightly higher concentrations are computed in station H (close to the Tagus mouth, Figure 4c). Despite this small difference, the chlorophyll time series present the same pattern at both stations. During spring tides the chlorophyll concentration decreases while during neaps the concentration increases. This is quite visible in Figure 4c (thick line) and reveals a spring-neap modulation of the chlorophyll in the region outside the Tagus estuary. During spring tides this decrease of the chlorophyll concentration is directly related to the increase of suspended sediments in the water. The available light is lower and the production is also lower. On the other hand, during neaps, the suspended sediments concentration decreases, there is more availability of light and the production is higher. These patterns are consistent with the results presented by Mateus and Neves (2008), where a higher concentration of chlorophyll is found when the availability of light is higher

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CONLUSIONS

In this work, the first results of a coupled hydrodynamic and biogeochemical model of the Tagus estuary are presented. The model implementation is based on the Mohid marine model which has been used to study other estuarine systems in Portugal. The effort of study coupled hydro and biogeochemical features of the Tagus estuary is part of an integrated study of several estuarine-coastal system.

The first results reveal that the model can reproduce the tidal propagation along the estuary with small differences between predicted sea level height and observations. For almost all the stations it was achieved a good validation of the tidal propagation. The exceptions are the locations at the upstream region of the estuary, and the differences computed may be due to an inaccurate numerical bathymetry.

The computed biogeochemical variables also present results which are consistent with observations and results presented in the literature. The cohesive sediments spatial patterns reveal high spatial and temporal variations. A significant spatial gradient is visible in the simulations, with high concentrations in the upper estuary (> 30 mgL^{-1}) and lower values near the estuary mouth (< 5 mgL^{-1}). The cohesive sediment concentration inside the estuary is determined by the freshwater inflow from the river, presenting high concentrations during the wet season (due to the high freshwater discharge) and low concentrations during the dry season.

The chlorophyll concentration inside the estuary is directly dependent on the suspended sediment concentration, because it controls the light availability which is essential for the chlorophyll growth. The spatial distribution of chlorophyll inside the estuary follows the same patterns found by Mateus and Neves (2008). In the winter, there is a clear spatial gradient ranging from low concentrations at the middle and upper estuaries to higher concentrations at the lower (or marine) estuary (~3.5 mg ChL^{-1}), whilst during the summer the spatial gradient reverses, presenting lower concentrations near the estuary mouth.

Tidally driven sediment resuspension and riverine input are important mechanisms affecting the suspended matter concentrations in the Tagus estuary. These mechanisms affect the light availability inside the estuary. Thus, even when the nutrient concentration is high, the light availability is a key factor (limitation) which controls the estuary in terms of chlorophyll concentration.

In Summary the main conclusions of this study are:

- The model results for sea level height reveal small differences with observations. In almost all the stations these differences are lower than 5% of the local variation, both in amplitude and phase. Therefore an accurate validation of the tidal propagation was achieved.
- An amplification of the M_2 tidal constituent was found in the central region of the estuary. This amplification is due to the reflection of the tidal wave in the upstream region of the estuary. This result is consistent with results by Oliveira (1993) and Fortunato *et al.* (1997).
- The model predicts strong salinity and suspended sediment concentration spatial gradients inside the estuary, which are advected back and forth according to the tidal stage.
- Due to its length, the Tagus estuary may be divided in three distinct and very well marked regions: a lower and saline estuary; a mixing area located in the central area of the estuary and an upper region dominated by the freshwater inflow from the Tagus River.
- The results for the stations near the mouth of the estuary show a strong fortnight modulation: during spring tides, the suspended sediment concentration increases, leading to a decrease of the light

availability and consequently to a decrease of the chlorophyll concentrations. During neaps the suspended sediment concentration decreases leading to the increase of the chlorophyll concentration. These results are consistent with the results presented by Valente and Silva (2009).

As previously referred, the preliminary results of this coupled hydro and biogeochemical model are very encouraging. This model implementation will allow the development of several products, which can be used by scientists and managers to increase the knowledge on estuarine processes, contributing to a more efficient management of the complex and sensible ecosystem inside the Tagus estuary.

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