

Primary production of the benthic microalgae in the bottom sediments of Ria de Aveiro lagoon

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ABSTRACT

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The Ria de Aveiro is a mesotidal coastal lagoon located in the north coast of Portugal. It has a complex irregular geometry characterized by large intertidal areas and several freshwater tributaries, which are the main sources of nutrients into the lagoon. The dynamics between the tidal propagation and the landward nutrient sources modulates the primary production within the lagoon. Here, primary production may have two main contributors: the chlorophyll in the water column and the benthic microalgae in the bottom sediments.

In this work, a new methodology to compute microalgae in the bottom sediments is presented, consisting in coupling a numerical module of the benthic layer to a biophysical model. To perform the study, three schematic scenarios were implemented: Scenario 1 is the reference case, where typical nutrient load values were considered; Scenario 2 doubles the nutrient load concentrations at ocean and river boundaries; Scenario 3 reduces to half the nutrient values.

The results show that an increase in nutrient load (Scenario 2) causes a reduction of benthic biomass, while a decrease causes an increase of benthic biomass, impacting the lagoon's primary production. In general, an increment of nutrient concentration in the water column favors the phytoplankton growth, which increases biomass. This will lead to an attenuation of the light intensity reaching the bottom sediments, resulting in a decrease of benthic primary production. The opposite pattern is observed for Scenario 3 in response to nutrient concentration.

ADDITIONAL INDEX WORDS: *Ria de Aveiro, Benthic microalgae, Primary production, Sediments.*

INTRODUCTION

Benthic microalgae as microphytobenthos are important primary producers in estuarine and coastal ecosystems, forming highly dense and productive organisms on the upper layers of the intertidal sediment flats (MacIntyre *et al.*, 1996; Underwood and Kromkamp, 1999). A key issue in the assessment of the functional role of these communities is the estimation of the microalgae biomass accumulating in the photic layers of the sediment, which contribute to the rate of ecosystem production (Serôdio *et al.*, 2009).

The large microalgae biomass which is present in the photic zone of the bottom sediments (upper layers), is the most important cause for the high production rates observed in intertidal areas, and the main factor determining the community-level photosynthesis on short-term time scales (Serôdio *et al.*, 2001).

Estuarine systems, as Ria de Aveiro, in general have 3 main limiting factors affecting the growth of benthic microalgae: (i) nutrients, (ii) light and (iii) water temperature. Nutrients are involved in reactions of photosynthesis, wherein carbon, phosphorus and nitrogen are considered the most important

nutrients affecting the growth and mortality of these organisms. The water temperature influences the metabolic rates of organisms and their photosynthetic capacity, while the light is the source of energy used by benthic organisms to generate primary production. In the case of benthic organisms, light availability can be a major limiting factor in the promotion of their growth. Additionally, tidal propagation and estuarine currents are also very important in the benthic communities distribution (Leal *et al.*, 2015).

In estuarine systems the study of benthic microalgae spatial and temporal distributions is a highly challenging task, since these systems are extremely variable in terms of nutrient and granulometry spatial distribution. The biophysical models are actual and sophisticated tools that can be used to overcome this challenge and obtain accurate and useful information about benthic microalgae distributions.

The main objective of this study is to present the first results of a novel implementation of MOHID, comprising a coupled circulation and biogeochemical model, including a new module that computes benthic biomass generation (Ascione, 2014). Moreover, a new methodology to simulate the benthic primary production in Ria de Aveiro will be implemented to assess how the model responds to changes in ocean and river forcing's.

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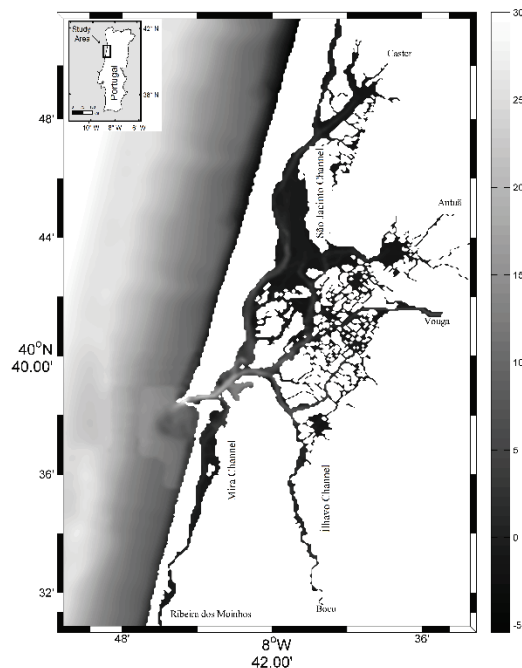


Figure 1. Location of study area, the Ria de Aveiro lagoon, and its bathymetry in meters.

STUDY AREA

The Ria de Aveiro (Figure 1) is a shallow coastal lagoon located in the northwest coast of Portugal, separated from the Atlantic Ocean by a sand dune barrier. It has an irregular geometry, and its only connection with Atlantic Ocean is through an artificial channel constructed in 1808 (Dias, 2001, Dias and Mariano, 2011).

The lagoon has a maximum width of 8.5 km and a length of 45 km, being constituted by four main channels, which act like independent sub-systems, conferring to the lagoon a high complexity in terms of its physical features (Dias, 2001).

The main forcing factor driving water circulation in Ria de Aveiro is the tidal propagation, which has mesotidal characteristics, presenting an average amplitude at the inlet of 2 meters, and amplitudes of 0.6 meters in neap tides and 3.2 meters in spring tides (Dias 2001; Araújo *et al.*, 2008). Several authors evaluated the tidal prism for the Ria de Aveiro lagoon through different numerical models (considering different bathymetries), and several values were obtained. For maximum spring tide Dias (2001) and Lopes *et al.* (2006) estimate $136.7 \times 10^6 \text{ m}^3$, Picado *et al.* (2010) $86.3 \times 10^6 \text{ m}^3$ and Lopes *et al.* (2010) $87.5 \times 10^6 \text{ m}^3$ and for minimum neap tide Dias (2001) and Lopes *et al.* (2006) estimated $34.9 \times 10^6 \text{ m}^3$, Picado *et al.* (2010) $31.0 \times 10^6 \text{ m}^3$ and Lopes *et al.* (2010) $28.9 \times 10^6 \text{ m}^3$. These values are much higher than the total freshwater input in a tidal cycle. Moreira *et al.* (1993) projected an input of nearly $1.8 \times 10^6 \text{ m}^3$. The tidal prism of each channel relative to its value at the mouth

is 35.4% for S. Jacinto channel, 25.6% for Espinheiro channel, 10.0% for Mira channel and 13.5% for Ilhavo channel (Dias and Picado, 2011). Likewise, the semidiurnal tides are the main factor influencing the hydrodynamics of the lagoon (Dias *et al.*, 2000). Thus, the most important harmonic constituents in Ria de Aveiro are M_2 and S_2 , corresponding of about 88% and 10% of total tidal energy, respectively (Dias, 2001).

The lagoon has five main rivers discharging in each main channel: Vouga, Antuã, Caster, Boco and Ribeira dos Moinhos, being the most important the Vouga river. According with Ria de Aveiro Polis Litoral program, which considered the data present in the Plano de Bacia Hidrográfica (www.arhcentro.pt), the mean freshwater inflows are $60.0 \text{ m}^3\text{s}^{-1}$ for Vouga river, $4.5 \text{ m}^3\text{s}^{-1}$ for Antuã, $1.6 \text{ m}^3\text{s}^{-1}$ for Caster, $1.0 \text{ m}^3\text{s}^{-1}$ for Boco and $3.6 \text{ m}^3\text{s}^{-1}$ for Ribeira dos Moinhos.

According with Fortes *et al.*, (2015), the distribution of phytoplankton concentration in the lagoon evidences maximum concentrations located between the second half of the lagoon channels and their heads. On the other hand, the minimum values are observed at the lower channels close to the lagoon mouth as well along the S. Jacinto channel. In the central areas of the lagoon was found a well typified concentration gradient, characterizing the transition between the ocean and the rivers boundaries.

METHODS

In this work, a new methodology to compute microalgae in the bottom sediments is presented, consisting in coupling a numerical module of the benthic layer to a biophysical model (MOHID, www.mohid.com). MOHID solves the three-dimensional incompressible primitive equations. Hydrostatic equilibrium is assumed as well as the Boussinesq and Reynolds approximations. A detailed derivation of the model equations was presented in several studies and can be consulted in Vaz (2007), for example.

The equations for momentum and mass balance are:

$$(1) \frac{\partial u_i}{\partial t} + \frac{\partial(u_i u_j)}{\partial x_j} = -\frac{1}{\rho_0} \frac{\partial p_{atm}}{\partial x_i} - g \frac{\rho(\eta)}{\rho_0} \frac{\partial \eta}{\partial x_i} - \frac{g}{\rho_0} \int_{x_3}^{\eta} \frac{\partial \rho'}{\partial x_i} dx_3 + \frac{\partial}{\partial x_j} \left(\nu \frac{\partial u_i}{\partial x_j} \right) - 2\varepsilon_{ijk} \Omega_j u_k$$

$$(2) \frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} = 0$$

where u_i are the velocity vector components in the horizontal Cartesian x_i directions, u_j are the velocity vector components in the three Cartesian directions x_j , p_{atm} is the atmospheric pressure and ν is the turbulent viscosity. ρ is the specific mass, ρ' is its anomaly, ρ_0 is the reference specific mass, η is the free surface level, $\rho(\eta)$ represents the specific mass at the free surface, g is the acceleration of gravity, t is the time, Ω is the Earth's velocity of rotation and ε is the alternate tensor. Integrating the mass balance equation over the whole water column (between the free surface elevation and the bottom), is obtained the free surface equation:

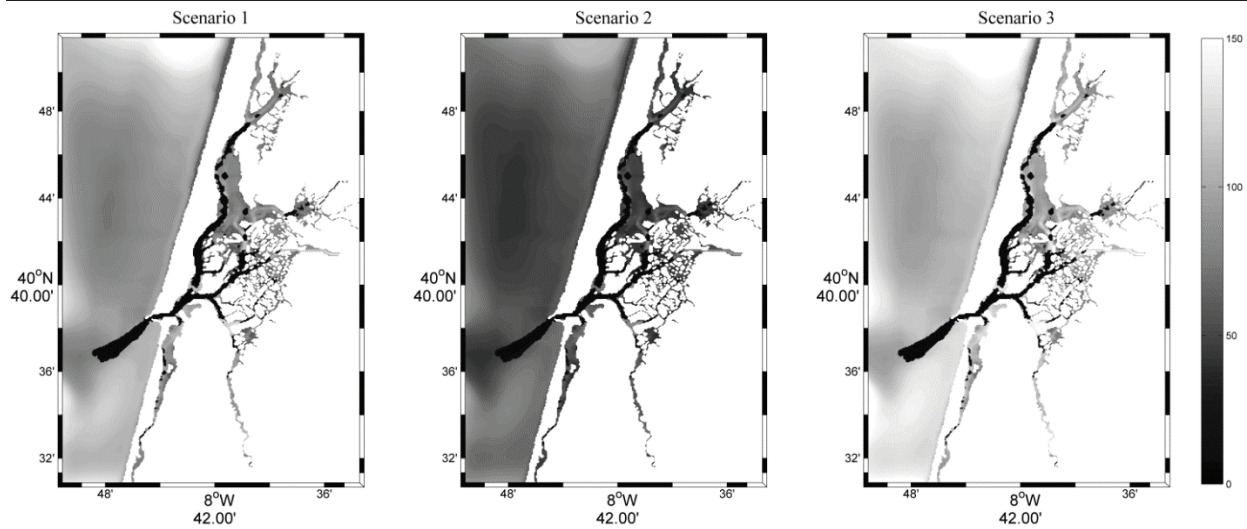


Figure 2. Microalgae concentration for three scenarios, expressed in g(Chl a)/m².

$$(3) \frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x_1} \int_{-h}^{\eta} u_1 dx_3 - \frac{\partial}{\partial x_2} \int_{-h}^{\eta} u_2 dx_3$$

where h is water depth.

The bottom shear stress, $\bar{\tau}$, is represented as a quadratic function of velocity and the drag coefficient (C_D) can be parameterized in terms of Manning's friction coefficient (n):

$$(4) \bar{\tau} = C_D |\vec{v}| V$$

$$(5) C_D = gn^2 H^{1/3}$$

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

Beyond the hydrodynamic model, this modeling system comprises the water column ecological model, which calculates the nutrients and primary production in the water column (Mateus *et al.*, 2008) coupled with the benthic ecological model, which computes biomass in sediment surface (Ascione, 2014).

A general equation of population growth, which accommodates most of the limiting processes in a closed system, has been formalized:

$$(6) \frac{dX_j}{dt} = \sum_{i=1}^m (e_{ij} \tau_j p_{ij} f_{ij} X_j) - (\mu_j + \varphi_j + \rho_j) X_j - \sum_{k=1}^m (\tau_k p_{jk} f_{jk} X_k)$$

where e_{ij} is the assimilation efficiency of species j using resource i ; τ_j is the maximum specific ingestion/uptake rate of species j ; p_{ij} is the preference of species j for resource i ; f_{ij} is the limitation of ingestion/uptake of resource i by species j ; μ_j is the specific loss rate due to natural mortality; φ_j is the specific loss rate due to excretion; ρ_j is the specific loss rate due to respiration.

Model implementation

Disregarding boundary conditions, the bathymetry is the most important factor affecting the flow in systems such as Ria de Aveiro. The bathymetry controls the spatial variability of the current in terms of their magnitude and direction, constituting a specific feature which guarantees the realism of the numerical model (Cheng *et al.*, 1991; Dias and Lopes, 2006). The simulations of the Ria de Aveiro model were performed using a rectangular grid with a spatial resolution of 100 meters.

At the ocean boundary, the hydrodynamic model was forced by the tide. At the landward boundaries, freshwater inputs for the 5 main rivers discharging in the Ria de Aveiro (Vouga, Antuã, Boco, Ribeira dos Moinhos and Cáster) are imposed using time series predicted by the SWIM model (Krysanova *et al.*, 2000). On the water surface, time series of measured data for relative humidity, atmospheric pressure, air temperature, wind velocity and direction, solar radiation and cloud cover are also applied as atmospheric inputs.

Regarding to the water column and benthic layer modules, the inputs are mainly water temperature, salinity, nutrients, organic matter and pelagic and benthic microalgae. As in hydrodynamic model, all these parameters are imposed at the ocean and river boundaries, and represents typical spring values.

In order to assess the model performance, three schematic scenarios were defined: Scenario 1, considered as reference, where typical spring nutrient load values were considered; Scenario 2 doubles the nutrient load concentrations at ocean and river boundaries; Scenario 3 reduces to half these values.

RESULTS

In Figure 2 are depicted the results for the microalgae benthic biomass in the Ria de Aveiro, for scenarios 1, 2 and 3, respectively. The results are expressed in grams of chlorophyll a per m². These results suggest a biomass spatial gradient

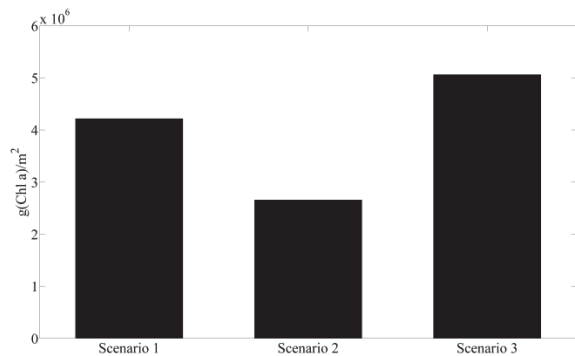


Figure 3. Total benthic microalgae concentration for Ria de Aveiro for each Scenario.

within the lagoon, with very low concentrations near the tidal inlet, with values ranging from 5 to 8 g(Chl a)/m², and in the deeper areas of the main canals, increasing gradually until the river mouths (typical values of spring season).

At the inlet, there are no major differences between the three established scenarios, with values of about 6 g(Chl a)/m². On the other hand, the areas with the highest benthic biomass concentration are found close to the river mouths. The highest concentrations were identified for all the three scenarios near the Vouga River mouth at the upstream region of the Espinheiro Channel, with values around 88.81, 54.79 and 107.65 g(Chl a)/m² for scenarios 1, 2 and 3, respectively. Close to the Antuã river mouth, the concentrations are lower than in the Vouga region, as expected, with values of 73.61 g(Chl a)/m², 47.81 and 92.72 g(Chl a)/m² in scenarios 1, 2 and 3, respectively. Close to Boco river mouth the values are quite similar, despite the higher inflow from Antuã. The concentrations are 74.90, 52.75 and 92.39 g(Chl a)/m² for scenarios 1, 2 and 3, respectively.

At the channels margins, *i.e.* at the intertidal areas, the biomass is much higher than at in the center of the channels (deeper regions), revealing the importance of the incoming radiation in the microalgae growth. For example, this process is clearly evident in S.Jacinto channel. At the channel's axis, the microalgae biomass is about 6 g(Chl a)/m² (concentrations similar to those found at the inlet area), while in the intertidal areas the concentrations are 81.15, 48.40 and 100.04 g(Chl a)/m² for scenarios 1, 2 and 3, respectively.

DISCUSSION

The results shown in Figure 2 highlight two clearly patterns: a spatial gradient in benthic microalgae concentration, with values increasing gradually from the inlet to the upstream areas of the lagoon; and a negative feedback process, where higher nutrient concentrations in the water column and surface sediment induce a decrease in the benthic biomass.

The highest benthic biomass concentrations are found at the upstream areas of the lagoon, close to the rivers mouths, as the load of nutrients and organic matter in Ria de Aveiro is through the rivers, in particular its main tributary (Vouga river). Additionally, these are shallow areas and therefore the light availability also favors the photosynthesis development.

It is also observed that in the channels margins, *i.e.* at the intertidal areas, the benthic biomass concentration is much higher than at the center of the channels. In those areas, the light availability is very high and consequently the conditions for photosynthesis development are also favorable.

The main patterns found in this study are consistent with the findings by Fortes *et al.* (2015), and Mateus *et al.*, (2008) for the Ria de Aveiro lagoon and the Tagus estuary, respectively.

The comparison between the results obtained for the three scenarios suggests that an increase of pelagic and benthic nutrients and organic matter leads to a decrease of benthic biomass concentration. Figure 3 represents the total benthic biomass for Ria de Aveiro for the three scenarios (determined as the sum of biomass for all cells of the numerical grid), and therefore the total of chlorophyll a concentration at the benthic layer of the Ria de Aveiro.

The total biomass in scenario 1 is 4.22×10⁶ g(Chl a), while in Scenarios 2 and 3 the total biomass is 2.68×10⁶ and 5.06×10⁶ g(Chl a), respectively. The comparison between scenarios 1 and 2 results show that a duplication of total nutrients and organic matter (Scenario 2) causes a decrease of 36.88% on the benthic biomass. Conversely, when reducing to half the nutrient input (Scenarios 1 and 3) is predicted an increase of 19.96% of benthic microalgae. These results reveal that nutrients and organic matter rise has more influence in the system that its reduction. This suggests that the Scenario 2 inputs exceed the consumption by the microorganisms.

According with Hagerthey and Kerfoot (1998), when nutrients are a limiting factor, the benthic primary producers have advantage in a competition between benthic and pelagic microbiota, because they have access to nutrients from the sediments. The access to water column nutrients is restricted for the benthic microalgae due to a boundary through which nutrients slowly penetrate in the benthic layer (Riber and Wetzel, 1987). Therefore, increased nutrient concentrations in the water column typically favour phytoplankton (pelagic), which increase biomass. This obviously causes a reduction in the light intensity reaching the benthic habitat and consequently benthic microalgae growth may become light limited (Havens *et al.*, 2001).

CONCLUSIONS

The MOHID modelling system, integrating the hydrodynamic model coupled with the pelagic and benthic ecological models has been used to study primary production of the benthic microalgae in the bottom sediments of Ria de Aveiro lagoon. This modelling tool has been successfully developed and implemented in order to achieve the main goal of this study.

The results show that an increase of nutrient load (Scenario 2) causes a reduction of benthic biomass. An increment of nutrient concentration in the water column favors phytoplankton, which increases biomass. This will lead to an attenuation of the light intensity reaching the bottom sediments, resulting in a decrease of benthic primary production. The opposite pattern is observed for a decrease of nutrient load (Scenario 3).

In summary, the biophysical model was successfully implemented and it is able to reproduce the interactions between water column and bottom sediment.

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