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# Biological response of a coastal plain estuary to torrential episodes: a modelling study

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**ABSTRACT**

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Estuaries are highly dynamic systems with an important impact on biogeochemical cycles and primary production, which may be affected and modified in a climate change context, namely due to extreme rainfall events. This study aims to research chlorophyll-a (Chl-a) and nutrients dynamics in the Tagus estuary under extreme freshwater discharge in a climate change context, using a 2D biophysical model. Three scenarios were set changing the inputs from the main tributaries – Tagus and Sorraia rivers. First, a scenario with one day of extreme discharge for both rivers was considered. Next, and in order to understand the importance of each river, two more scenarios were set considering the extreme discharges separately. Results show that Chl-a concentrations follow the same trend as the imposed discharges, however with a delay of one day. The results also reveal that the biogeochemical characteristics of the Tagus estuary are mainly influenced by the Tagus River inflow. Moreover, in the scenario where the extreme discharges are imposed for both rivers, Chl-a levels increase in the entire estuary and consequently a decrease in nitrate concentrations is observed. Otherwise, phosphate concentrations slightly increase. This suggests primary producers inside the estuary preferentially consumes nitrate, at a higher rate than it is being loaded.

**ADDITIONAL INDEX WORDS:** *Chl-a concentration, nutrients, biogeochemical model, Tagus estuary.*

## INTRODUCTION

Estuaries are unique environments where sea water meets freshwater, dictating the interactions between land and sea. Among the most important processes occurring in these systems are biogeochemical cycles and primary production. All these interactions and reactions affect life in a large scale and are becoming progressively threatened over the years due to human and natural stresses. Given the vast influence that biogeochemical cycles have on phytoplankton growth/decay and primary production, and on marine life in general, the study of the threats that they are facing or will face in the next years becomes a matter of great interest. Primary production carried out by phytoplankton is the first level of the trophic chain. All the other levels depend on it and their evolution and follow its trends. Primary production in marine environment is the result of the water masses movement coupled to nutrient and light availability. These elements can also limit production, either by absence or excess, making the study and the attempt to predict these processes highly relevant to become aware of the threats faced by estuaries. One of the main actual threats is climate change, which has a direct impact in the mean sea level and especially in the freshwater discharging into estuaries, which modulates the nutrient cycles and generation of phytoplankton, dictating primary production in these environments. In this setting, this study aims to research the biological response of Tagus estuary to extreme freshwater discharge induced by torrential episodes in a climate change context.

The Tagus Estuary (Figure 2 - D3) is the largest estuarine system in Portugal, being located near Lisbon (38°44' N, 9°08' W). It has a total surface area of 320 km$^2$, a mean volume of $1900\times10^6$ m$^3$ and is a relatively shallow mesotidal estuary dominated by a semi-diurnal tidal regime with a mean tidal amplitude of 2.2 m (Mateus and Neves, 2008; Mateus *et al.* 2012; Valentim *et al*., 2013). About 20 to 40% of the estuarine area is intertidal, composed mainly by mudflats (Mateus and Neves, 2008; Valentim *et al*., 2013). The hydrodynamic conditions are determined by the balance between the inflow of saline water from the Atlantic Ocean and the riverine discharges from the three contributors (Vaz *et al*. 2011): Sorraia, Trancão and Tagus Rivers (Figure 2 - D3). The Tagus River is the most significant in terms of freshwater flow, with an annual average of 400 m$^3$s$^{-1}$ (Neves, 2010), and integrates urban, industrial and agricultural effluent discharges. Sorraia and Trancão rivers are comparatively small, with average annual discharges of 35 and 2.5 m$^3$s$^{-1}$, respectively.

The interaction between meteorological conditions and riverine inputs induces high seasonality to the hydrodynamic and biogeochemical estuarine conditions (Mateus and Neves, 2008). Primary production limiting nutrients are known to be nitrogen and silica, but they are usually available inside the

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estuary (Mateus, 2012). Nutrient limitations may be found significant only in lower estuarine areas and mostly during summer. Consequently, light is believed to be the main factor controlling the primary production on Tagus Estuary (Mateus and Neves, 2008).

## METHODS

The numerical model MOHID (Martins *et al*., 2001) was used to study the impact of extreme freshwater events on Chl-a and nutrients distribution along the Tagus estuary.

Initially, a simulation covering the period from April 2003 to December 2004 was performed and the biogeochemical properties, including ammonia, nitrate, Chl-a and oxygen concentration, were qualitatively compared with measured data at four stations distributed along the NE-SW direction of the estuary (S1, S2, S3 and S4: Figure 2 - D3). The data used for this comparison are described in Mateus *et al*. (2012) and Mateus and Neves (2008). Only the results for S2 are presented herein (see Figure 3).

As the main goal of this study consists in researching the biological response of Tagus estuary to extreme freshwater discharge induced by torrential episodes, three scenarios were set defining extreme values to the main tributaries flow: Tagus and Sorraia. Trancão river was not included in these scenarios considering its flow negligible and consequently without impact in the estuary biogeochemistry. Primarily, a scenario considering one day of extreme discharge for the Tagus (6000 $m^3s^{-1}$) and Sorraia (200 $m^3s^{-1}$) rivers was considered (Scenario #1). Next, in order to assess the impact on the estuarine biogeochemistry of the freshwater discharge from each river separately, two more scenarios were defined: one considering only high discharge from Tagus (Scenario #2) and other only high discharge from Sorraia (Scenario #3).

Freshwater discharges considered in this study are depicted in Figure 1 and were set based on fluvial regime climatology: between days 6 and 8 discharges from both rivers linearly increase from a base flow (250 $m^3s^{-1}$ for Tagus and 25 $m^3s^{-1}$ for Sorraia) to a peak value (6000 for Tagus and 200 $m^3s^{-1}$ for Sorraia), remaining constant during a day (from day 8 to 9) and then decreasing, during a day, to the base flow again. This pattern was defined to assess the estuarine response to a torrential episode and evaluate its behaviour under the relaxation period. All simulations were performed for 20 days periods, to evaluate Chl-a and nutrients concentration distribution and temporal evolution as well as the relaxation period to extreme discharges. From numerical predictions, Chl-a and nutrients (nitrate and phosphate) maxima concentrations were computed for each cell of the estuarine numerical grid for three different periods: before the flow peak (A), during the peak (B) and after the peak (C) (see Figure 1).

### Model description and set up

MOHID (Martins *et al.* 2001) is a three-dimensional baroclinic finite volume model, designed for coastal and estuarine shallow water applications (Valentim *et al*., 2013). The model solves the three-dimensional incompressible primitive equations and assumes the hydrostatic equilibrium as well as Boussinesq and Reynolds approximations (Valentim *et al.* 2013).

Along the Portuguese coast, MOHID has been previously successfully applied to coastal lagoons: Ria de Aveiro (Vaz *et al*., 2005, Picado *et al*. 2013) and Ria Formosa (Martins *et al*., 2004) and to estuaries: Sado (Martins *et al*., 2001) and Tagus (Vaz *et al*., 2011, Vaz and Dias 2014), showing a good performance when simulating flows in shallow water systems. Regarding the biogeochemical processes, a few works were carried out with MOHID. For instance, Mateus *et al*. (2012) studied the influence of physical, chemical and environmental parameters on the biogeochemistry of the Tagus estuary.

In this study, a coupled circulation and biogeochemical model was implemented through a downscaling methodology, which consists on simulating hydrodynamics and water quality on a local scale based on information provided by large-scale models, considering three nested domains (Figure 2). In the first domain (D1) is used a 2D barotropic tidal driven model forced by FES2004 global solution, which covers up most of the Atlantic Coast (from 33 to 50ºN and 0 to 13ºW) and has a horizontal resolution of ~6 km. The time step used was 180 s. The second domain (D2) comprises a region from 8º30' to 10º30'W and 36 to 40ºN, with a horizontal resolution of ~1.6 km and a time step of 60 s. Finally, the third domain (D3) includes Tagus estuary area (from 38º30' to 39ºN and 8º42'W to 9º30'W). It has a numerical grid with 335×212 cells with a horizontal resolution of 200 m. The time step was set to 15 s and the horizontal viscosity to 5 $m^2$ $s^{-1}$. D3 is forced by the tide from D2. Both D2 and D3 are two-dimensional barotropic models.

Tagus River discharges were provided by Sistema Nacional de Informação de Recursos Hídricos (SNIRH, www.snirh.pt). Due to the lack of data for Sorraia and Trancão rivers, climatological values were imposed. Atmospheric forcing consisting in wind, radiation, air temperature, relative humidity and precipitation data was imposed with hourly temporal resolution. These data were measured at a nearby meteorological station: Estação Meteorológica da Guia (http://www.mohid.com/tejo-op/ ).

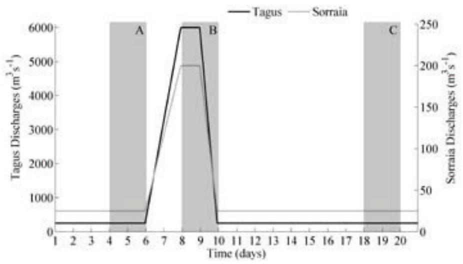


Figure 1. Discharges ($m^3s^{-1}$) imposed on Tagus and Sorraia rivers. A, B and C represent the periods for which the results are evaluated.

The biogeochemical model was only considered in the D3 domain, through the module Life (Mateus, 2012). Life is a multi-parameter biogeochemical model that is coupled to MOHID and simulates nutrients, primary producers, secondary producers and decomposers. The model has a decoupled carbon-nutrients dynamics with explicit parameterization of carbon, nitrogen, phosphorus, silica and oxygen cycles. It considers two major groups of producers, diatoms and autotrophic flagellates, and also the microbial loop dynamics and organic matter components (Mateus *et al*., 2008). Chlorophyll synthesis is simulated according to Geider *et al.* (1997) and the threshold for limitation is defined by the Redfield ratio (Mateus *et al*. 2008).

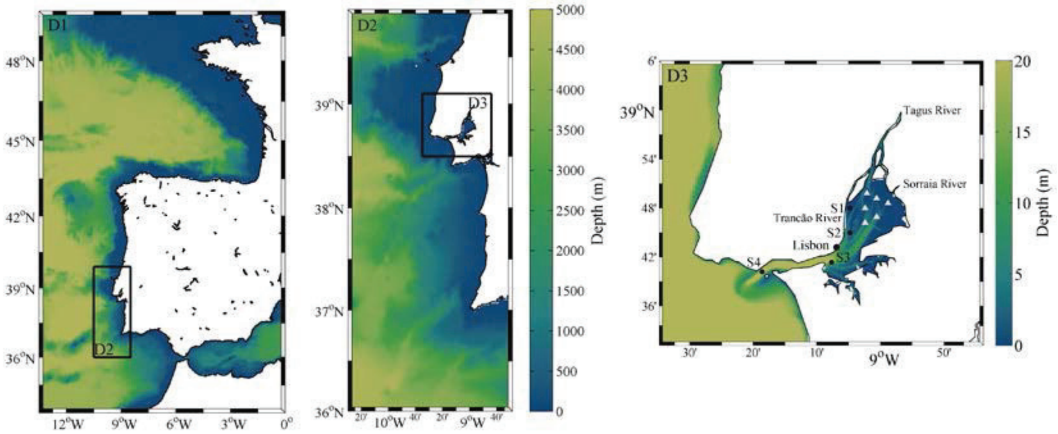


Figure 2. Three nested domains used for the numerical simulations, with bathymetry in meters. Location of the calibration stations (S1, S2, S3 and S4) and location of the local station of time series analysis (white triangles).

**Model validation**

The implementation of the hydrodynamic model used in this study was already validated in Mateus *et al*. (2012), and therefore it was assumed that physical parameters are being correctly simulated. Thus, only the biogeochemical parameters are qualitatively compared with measurements. Results are presented in Figure 3,
where the grey area comprises the daily maximum and minimum model prediction for each property and the dark grey line the daily mean. Measured data are represented by the dots.

Model predictions show strong seasonality of ammonia concentration, with high values in winter and low in spring and summer (see Figure 3), showing good agreement with observations and demonstrating that observed trends are correctly reproduced by the model. However predictions are slightly lower than the observations, meaning that model captures ammonia dynamics. Model nitrate concentrations also show a marked seasonality, with higher values in winter (>1 mg $m^{-3}$) than in summer (0.5 mg $m^{-3}$). According to Figure 3 it can be concluded that model represents well the nitrate dynamics, but slightly overestimating observations. In general, predicted oxygen reproduces well the data, with the exception of the first measurement. Finally, the predicted Chl-a concentration also shows high seasonality, with high values occurring in late spring/early summer, with maximum values of 4 mg $m^{-3}$.In this case, model results are, in general, lower than observations. The same data set was used by Mateus and Neves (2008) to validate a different implementation of MOHID in the study area and similar results were achieved.

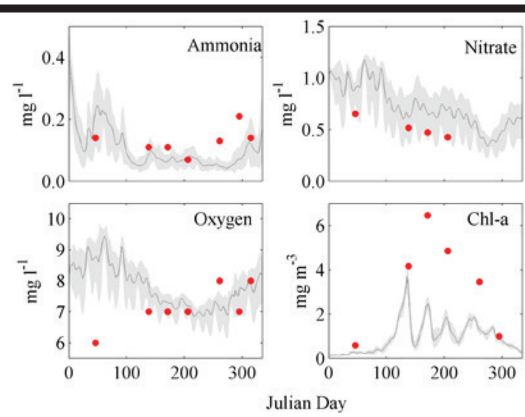


Figure 3. Comparison between ammonia, nitrate, oxygen (mg $l^{-1}$) and Chl-a (mg $m^{-3}$) model predictions (grey area and line) with observation (dots), for S2 station. The days are referred to 2004.

## RESULTS

The results are primarily analysed in terms of Chl-a time series, once this variable is assumed as a natural bio-indicator considering its complex and rapid response to changes in environmental conditions (Livingston, 2001).

Figure 4 depicts the mean Chl-a concentration time series at six stations located in the central estuary (triangles in Figure 2 - D3). Chl-a concentration follows the same trend as the imposed discharges for Scenarios #1 and #2, however a time delay close to one day was found (discharges increase from day 6 and Chl-a from day 7 – Figure4). Two days after the imposed discharge, Chl-a levels remain high, oscillating around 4 mg $m^{-3}$ during approximately 3 days, then it decrease to the base value, with concentrations lower than 0.5 mg $m^{-3}$ after seven days. It is noteworthy that the mean values of Chl-a concentration after the relaxation period are slightly lower than the ones observed before the imposed extreme discharges. For Scenario #3, when an extreme discharge is imposed only in Sorraia River, the pattern is completely different: Chl-a concentration slightly increase from day 7 to the end of simulation.

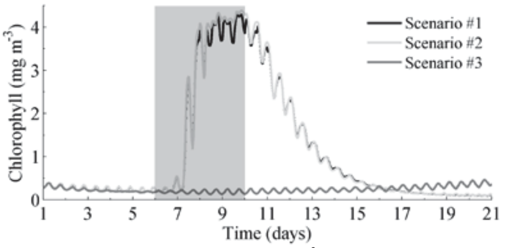

Figure 4. Mean time series of Chl-a (mg $m^{-3}$) for the Scenario #1, #2 and #3. The shaded area represents the period of extreme discharges.

Based on these results, Chl-a and nutrients (nitrate and phosphate) maxima were assessed only for Scenario #1 and for three periods (see Figure 1): one before the high discharge (A), other during the peak (B) and a third period after the relaxation period (C).

Before the extreme discharge (period A) were found low maxima Chl-a concentrations in the whole estuary (Figure 5 – upper panel A), with values ranging from 0.2 mg $m^{-3}$ on the middle estuary to 1.0 mg $m^{-3}$ on the upper estuary (right next to the Tagus River mouth) and on the estuary mouth. As the Chl-a concentrations are low, nutrients (nitrate and phosphate) are expected to be high. Indeed, high nitrate concentrations are found in the whole estuary, with the highest values (2.0 mg $m^{-3}$) detected near Sorraia mouth (where Chl-a is lower). Phosphate concentrations are relatively uniform along the estuary, with mean values about 0.8 mg $m^{-3}$. These results are in accordance with Mateus *et al*. (2012), which found relatively low concentrations during winter in the estuary and concluded that the nutrient concentrations tend to be low with the increased distance from the upper estuary areas.

For period B, a significant rise of the Chl-a maxima was observed (Figure 5, top panel, B), with values ranging from 3.5 to 5.0 mg $m^{-3}$ on the entire estuary, except for the lower areas where minor values are observed (between 1.0 and 1.2 mg $m^{-3}$). At this period the nitrate concentration (Figure 5 - middle panel, B) decreases significantly on the upper estuary (from values higher than 1.0 to 0.5 mg $m^{-3}$), next to Tagus River mouth, exactly on the same areas where Chl-a concentration increase. Otherwise, the maxima phosphate concentrations (Figure 5 - bottom panel, B) slightly increase in the middle estuary (approximately 0.15 mg $m^{-3}$), relative to the maxima found for period A, and at the mouth of the estuarine channel (more than 0.4 mg $m^{-3}$).

Finally, after the relaxation period Chl-a maxima concentrations (Figure 5 – top panel, C) drop to values lower than the those observed before the extreme discharge, ranging from 0.2 at the Tagus River mouth to 0.5 mg $m^{-3}$ at the estuary mouth. Regarding the nitrate, the maxima concentrations drop along the entire estuary, except next to Tagus River mouth, where an increase of approximately 0.2 mg $m^{-3}$ is observed. Otherwise, no significant changes are observed in phosphate concentrations from period B to C.

## DISCUSSION

The transfer of nutrients, organic matter and other materials from terrestrial to estuarine systems is a key feature governing the ultimate source of productivity (Jickells, 1998; Granskog *et al*., 2005). In the Tagus estuary, river discharge can be considered the major input of nutrients into the system, carrying higher concentrations of nitrate than phosphate (Ferreira *et al*. 2003).

According to the previous results achieved for Tagus estuary the freshwater inflow is a key driver of Chl-a and nutrients distribution along the entire estuary.

Moreover, results also suggest that Tagus River discharge has greater influence in nutrients and Chl-a patterns than Sorraia. These results are corroborated by Mateus and Neves (2008), that based on measured data analysis found a clear influence of the Tagus River discharge in the estuary biogeochemistry.
Additionally, when extreme discharges are imposed on Tagus and Sorraia rivers, maxima Chl-a concentration clearly rise in the entire estuary and consequently the nitrate values drop, suggesting that the nitrate is being consumed at an higher rate than it is being loaded. Otherwise, a slightly increase in the phosphate concentrations after the imposed extreme discharge is observed, suggesting that the primary producers inside the estuary preferentially consumes nitrate.

## CONCLUSIONS

Three scenarios were designed and their results analysed to study the influence of torrential episodes and consequent extreme fluvial discharges on the biogeochemistry of the Tagus estuary. Results demonstrate that Chl-a concentration evolution depends essentially on extreme discharges from Tagus River, with a time response of approximately one day after the maximum freshwater flow and a relaxation time of seven days. Under extreme discharge from Sorraia River, Chl-a slightly increased along time, but with concentrations much smaller than achieved under Tagus discharge. Therefore, it may be concluded that the biogeochemical characteristics of the estuary are mainly influenced by the Tagus River discharge, while Sorraia River do not induce major changes in the assessed properties.

Under extreme discharges from Tagus River was found that after the relaxation period Chl-a maxima concentration drop to values lower than observed before this event, while nitrate slightly increases. This may be due to the decrease of phytoplankton transported from rivers and/or to its mortality. The phytoplankton mortality increases the dissolved organic and particulate organic materials, which attenuate the light penetration in the water column. Consequently, although there are nutrients available, Chl-a decreases to such low values as light is the main factor limiting primary production in Tagus estuary (Mateus and Neves, 2008).

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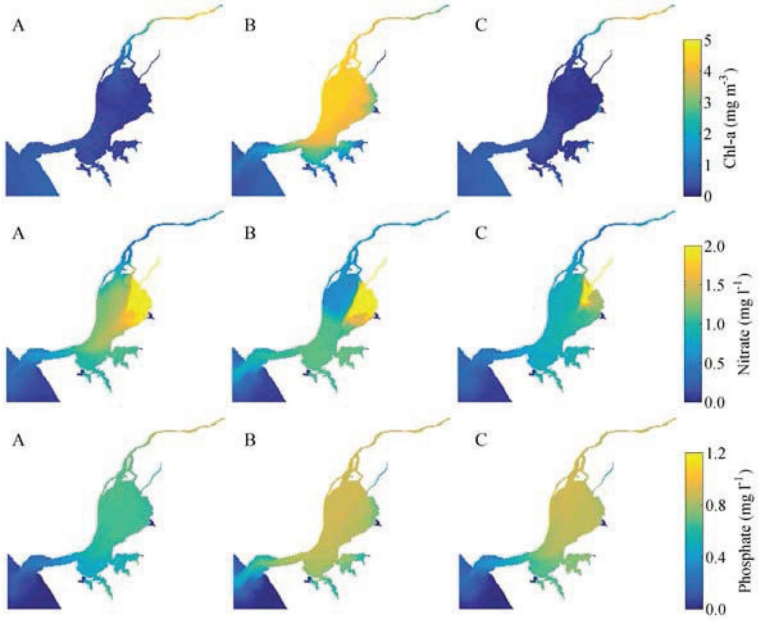


Figure 5. Maxima Chl-a (top panel), nitrate (middle panel) and phosphate (bottom panel) concentration for Scenario #1, for periods A, B and C (Figure 2).

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