

# Sensitivity Analysis of an Ecological Model applied to the Ria de Aveiro

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## ABSTRACT

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Ecological models can be useful tools for understanding the dynamics of the estuarine and coastal ecosystems. However, the application of these models in real systems requires the specification of many empirical input parameters, which are in general difficult to quantify for a specific site. This study presents a sensitivity analysis on the input parameters of the model ECO-SELFE applied to the Ria de Aveiro. ECO-SELFE is a three-dimensional, unstructured grid, fully-coupled hydrodynamic-ecological model. The sensitivity analysis is based on a previous analysis using the zero-dimensional ecological model, where one parameter was varied with the others being held constant. Results show that phytoplankton growth rate and zooplankton excretion and mortality rates are the parameters that influence the results the most. The degree of influence of these parameters depends on the local concentrations of zooplankton and phytoplankton. These two ecological variables are also most affected by the variations in the input parameters.

**ADDITIONAL INDEX WORDS:** *Ecological Models, Input Parameters, Sensitivity Analysis, Coastal Lagoon*

## INTRODUCTION

Ecological models are very useful tools for estuarine and coastal management. Duly validated, these models can be used to help understand processes, to diagnose the status of the system and to predict its evolution, or to evaluate management scenarios.

The first ecological models were very simple (e.g. Riley, 1946). Commonly, these models considered only one phytoplankton group and one single nutrient for phytoplankton growth. The increase of the computational power contributed significantly for the growing complexity in ecological modeling and, presently, several complex three-dimensional ecological models are available, like NEMURO (KISHI *et al.*, 2007), and ECO-SELFE (RODRIGUES *et al.*, 2008; RODRIGUES *et al.*, in review).

SNOWLING and KRAMER (2001) verified that the sensitivity of the ecological models increased with their complexity, due to the structure of the interactions between parameters and variables, and the larger number of degrees of freedom. The higher complexity of the models entails a larger number of processes represented and, consequently, more input parameters are needed to establish the model. These parameters are often poorly known for a specific site. Thus, one of the major difficulties associated with the use of complex ecological models is the definition of the input parameters.

Sensitivity analyses, which allow the estimation of the change in the model solution due to the change in the input parameters, have an important role in the implementation of ecological models. Several questions can be addressed by sensitivity analyses, as highlighted by CARIBONI *et al.* (2007):

Which are the input factors that influence the outputs the most?

If the uncertainty of one input factor could be eliminated, which one should be chosen to minimize the variance of the output?

Are there some input factors whose effect on the output is so low that they can be confidently fixed anywhere in their ranges of variation?

Several methods are available to perform sensitivity analyses (e.g. HAMBY, 1994). These methods can be *quantitative* or *qualitative* (CARIBONI *et al.*, 2007). They can also be *local*, when the effect of the variation of a single factor is evaluated, or *global*, otherwise (CARIBONI *et al.*, 2007), and have been widely applied to different ecological models (e.g. YOSHIE *et al.*, 2008).

The aim of this paper is to perform a sensitivity analysis on the input parameters of ECO-SELFE. Previous studies with the zero-dimensional version of the model showed the importance of some parameters, namely those related to phytoplankton growth and zooplankton dynamics (RODRIGUES *et al.*, 2008). Here, the sensitivity analysis is performed to the three-dimensional model applied to a real system, the Ria de Aveiro, where ECO-SELFE was previously validated (RODRIGUES *et al.*, in review).

## METHODOLOGY

### Study area

The Ria de Aveiro is a shallow temperate coastal lagoon located on the Northwest (NW) coast of Portugal (40°38'N, 8°45'W). This lagoon is the habitat of several species of flora and fauna, and plays an important ecological role.

The lagoon is about 45 km long and 10 km wide (Figure 1), and has an average depth of about 1 m (DIAS *et al.*, 2000). It is connected to the ocean by an artificial tidal inlet about 20 m deep. This channel connects to the four main branches of the lagoon, through which the main sources of freshwater are supplied to the lagoon: the Mira, Ílhavo, Espinho and S. Jacinto channels (Figure 1). The major sources of freshwater to the lagoon are the

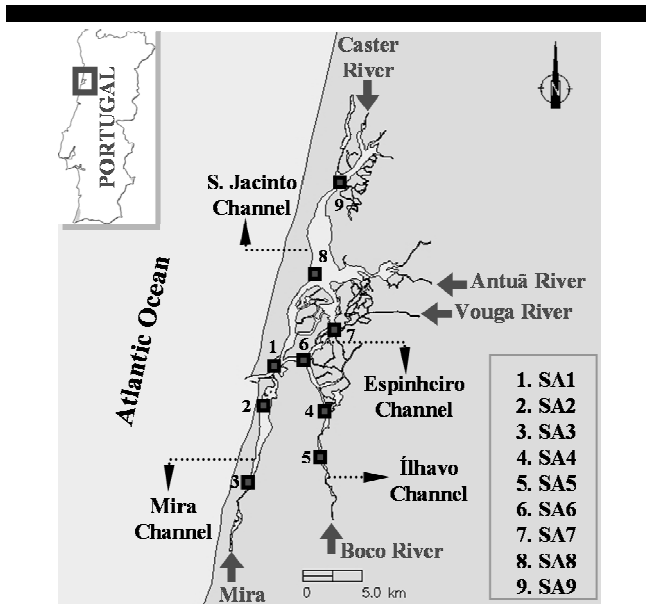


Figure 1. General overview of the Ria de Aveiro and stations used in the sensitivity analysis (SA stations).

ivers Vouga and Antuã (DIAS *et al.*, 2000). Smaller sources of freshwater also flow into the system, namely the rivers Boco, Caster and several small others in the Mira channel. Tides at the mouth of the lagoon are semi-diurnal, with a mean tidal range of about 2 m (DIAS *et al.*, 2000).

### Model description

ECO-SELFE (RODRIGUES *et al.*, 2008), couples the three-dimensional hydrodynamic model, SELFE (ZHANG and BAPTISTA, 2008, available at [www.stccmop.org/CORIE/modeling/selfe/](http://www.stccmop.org/CORIE/modeling/selfe/)) and an ecological model. SELFE is an unstructured grid model, which solves the three-dimensional shallow-waters equations for the free-surface elevation, the water velocity, the salinity and the temperature. This model includes a user-defined transport module, allowing the solution of the transport equation for any user-defined tracer:

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + w \frac{\partial c}{\partial z} = \frac{\partial}{\partial z} \left( \kappa \frac{\partial c}{\partial z} \right) + F_c + \Lambda c \quad (1)$$

where  $c$  is a generic tracer,  $(u, v, w)$  is the velocity,  $\kappa$  is the vertical eddy diffusivity,  $F_c$  is the horizontal diffusion and  $\Lambda c$  are the sources and sinks terms, calculated by the ecological model.

The ecological model was extended from model EcoSim 2.0 (BISSET *et al.*, 2004, available at [www.myroms.org/](http://www.myroms.org/)) to account for the simulation of several groups of zooplankton (RODRIGUES *et al.*, 2008). The model includes the cycles of carbon, nitrogen, phosphorus, silica and iron. Besides zooplankton, the model can simulate several phytoplankton groups, bacterioplankton, dissolved and particulate organic matter, inorganic nutrients and dissolved inorganic carbon (Figure 2).

The coupled model is based on a finite-element/finite-volume numerical scheme. The domain is discretized horizontally with unstructured triangular grids and vertically with hybrid coordinates ( $S$ -coordinates and  $Z$ -coordinates), allowing for high flexibility in both vertical and horizontal directions.

The parallel version of the coupled model (version v2.0f) was used in this study, which allowed a significant improvement of the computational times. To improve computational efficiency, the

optimal number of processors was previously evaluated. For this application this optimum number is about 20-24 processors (Figure 3).

### Model set-up

The simulations were performed with a horizontal grid of about 21000 nodes (Figure 4) and a vertical grid with 7  $S$  levels. Six open boundaries (one oceanic and five riverine) were considered. At the ocean boundary the model was forced by tidal elevations from the regional model of FORTUNATO *et al.* (2002). Salinity and temperature at the ocean boundary were set as 36 and 15 °C, respectively. At the river boundaries, the flows used were: 31.3 m<sup>3</sup>/s (Vouga), 10.3 m<sup>3</sup>/s (Antuã), 8.5 m<sup>3</sup>/s (Caster), 4.5 m<sup>3</sup>/s (Boco) and 4.5 m<sup>3</sup>/s (Mira). At these boundaries, salinity was set to 0 and temperature was set to: 14.0 °C (Vouga), 15.4 °C (Antuã), 18.3 °C (Caster), 17 °C (Boco) and 15.5 °C (Mira). The simulations were done for a period of 30 days, using a time-step of 90 s and a warm-up period of 2 days.

### Input parameters influence analysis

The sensitivity analysis was performed for 20 input parameters, selected based on the results of the sensitivity analysis performed previously. Based on the previous approach (RODRIGUES *et al.*, 2008) most parameters were changed in a range of -50% and

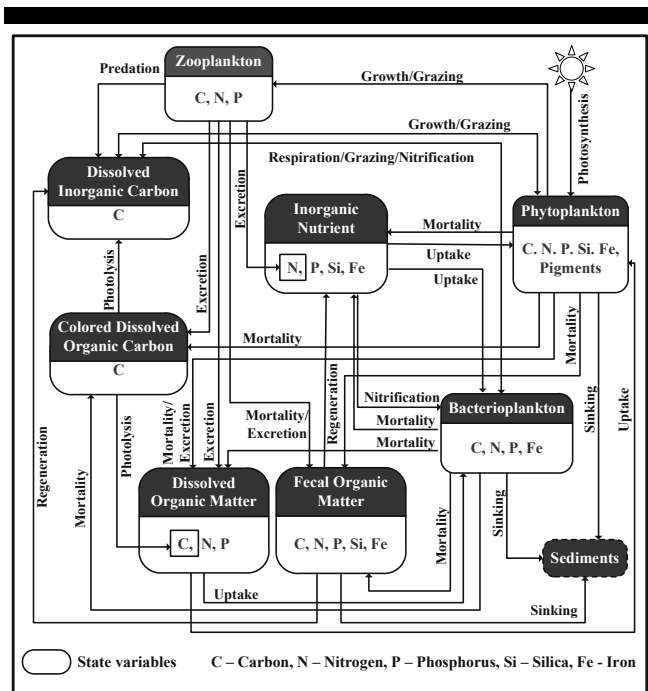


Figure 2. Sources and sinks of the ecological model.

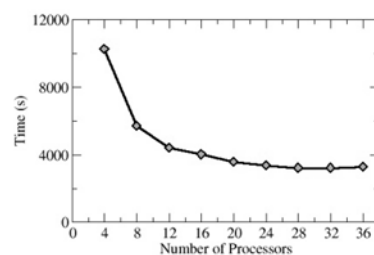


Figure 3. Computational times vs. number of processors in the MEDUSA cluster (for SELFE).

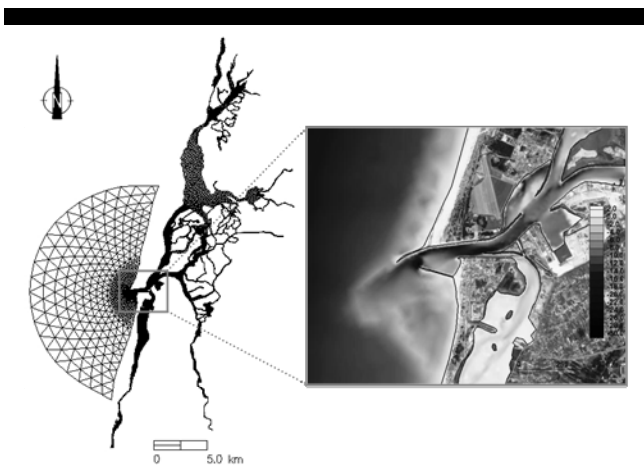


Figure 4. Horizontal grid and detail of the inlet bathymetry.

+100% from a base value (generating 3 different values for each parameter), while the other parameters remained constant. However, this range was unrealistic for some parameters. Hence, base temperature for phytoplankton growth was changed between 20 °C and 30 °C and the proportions of material released to organic and inorganic pools were changed such that their sum is always 1. The availability of prey to predator was changed between 0.5 and 1. The base values are listed in Table 1.

The analysis was performed for the average values of the ecological tracers in each branch and in the whole lagoon. A group of hypothetical stations (SA stations) located along the lagoon was also used to analyze the results (Figure 1). The analysis was performed with the results of the last 15 days of simulation.

The influence of an individual parameter was calculated based on the rate of variation  $\partial C/\partial X_p$ , where  $C$  is the normalized state variable and  $X_p$  is the input value of the parameter  $p$  (see Table 1). These values were normalized as:

$$C = \frac{c_{final} - c_{initial}}{c_{initial}} \quad (2)$$

$$X_p = \ln x_p \quad (3)$$

where  $c_{initial}$  and  $c_{final}$  are, respectively, the initial and the final concentrations of the ecological variable, and  $x_p$  is the input parameter value used in the sensitivity analysis.

The total influence of the input parameters in the results of each state variable ( $\Delta Y$ ) was evaluated as:

$$\Delta Y = \sum_p \frac{\partial C}{\partial X_p} \Delta X_p \quad (4)$$

where  $\Delta Y$  is the total influence of the input parameters on the state variable  $C$  and  $\Delta X_p$  is the variation in the parameter  $p$  given by:

$$\Delta X_p = \frac{\Delta x_p}{x_b} \quad (5)$$

where  $\Delta x_p$  is the difference between the highest and the lowest values for the input parameter  $p$ , and  $x_b$  is the base value.

## RESULTS AND DISCUSSION

Phytoplankton concentration is mostly influenced by the parameters that control its growth rate and the ones related to zooplankton excretion and mortality rates. This behavior occurs throughout the lagoon (Figure 5), but not uniformly. Phytoplankton growth rate parameters are more influential in the

Mira and Ílhavo channels and zooplankton loss parameters are more influential in the Espinheiro and S. Jacinto channels.

A more detailed analysis shows that zooplankton mortality rate is the input parameter which influences phytoplankton concentration the most in all SA stations, with the exception of stations SA3 and SA5 located in the Mira and Ílhavo channels, respectively (Figure 6). At these two stations, phytoplankton concentration depends mostly on base temperature for growth and on phytoplankton maximum growth rate. Zooplankton concentrations in SA3 and SA5 are smaller (about 0.06 mg C/l) than in the other SA stations (about three times larger on average) and phytoplankton concentration is of the same order of magnitude (about 1 mg C/l on average). Since phytoplankton mortality depends on zooplankton biomass, these results suggest that the magnitude of the influence of the phytoplankton growth rate and zooplankton loss parameters depends on the local concentrations of these two ecological variables. Consequently, for higher zooplankton concentrations, zooplankton mortality and excretion rates affect phytoplankton concentrations more. For smaller zooplankton concentrations, the most influential parameters in phytoplankton concentrations are related to its growth rate.

Because the Espinheiro and S. Jacinto channels occupy a large fraction of the lagoon area, the influence of zooplankton loss parameters in phytoplankton concentrations is dominant when considering the Ria de Aveiro as a whole (Figure 7). These results are consistent with those observed for zooplankton, which is mostly affected by its excretion and mortality rates (Figure 5 and Figure 7). Zooplankton and phytoplankton are the ecological variables most affected by the inputs parameters (Table 2).

Table 1: Sensitivity analysis: input parameters and base values

Parameter <sup>1</sup>	Value
1. Half-saturation for NO <sub>3</sub> uptake (mmol NO <sub>3</sub> .m <sup>-3</sup> )	0.824
2. Half-saturation for NH <sub>4</sub> uptake (mmol NH <sub>4</sub> .m <sup>-3</sup> )	0.414
3. Half-saturation for SiO <sub>2</sub> uptake (mmol SiO <sub>2</sub> .m <sup>-3</sup> )	1.82
4. Half-saturation for PO <sub>4</sub> uptake (mmol PO <sub>4</sub> .m <sup>-3</sup> )	0.0515
5. Maximum phytoplankton growth rate (d <sup>-1</sup> )	3.7
6. Base temperature for exponential growth (°C)	27
7. Phytoplankton temperature factor (°C <sup>-1</sup> )	0.0633
8. Fraction of dissolved organic matter released by phytoplankton (n.d.)	0.333
9. Fraction of particulate organic matter released by phytoplankton (n.d.)	0.333
10. Inorganic matter released by phytoplankton (n.d.)	0.333
11. Phytoplankton excretion rate (d <sup>-1</sup> )	0.005
12. Phytoplankton natural mortality rate (d <sup>-1</sup> )	0.01
13. Fraction of dissolved organic matter released by zooplankton (n.d.)	0.333
14. Fraction of particulate organic matter released by zooplankton (n.d.)	0.333
15. Fraction of inorganic matter released by zooplankton (n.d.)	0.333
16. Availability of prey to predator (n.d.)	1
17. Half-saturation for zooplankton's food ingestion (mmol C.m <sup>-3</sup> )	1.04
18. Assimilation efficiency of zooplankton's predators	0.5
19. Zooplankton excretion rate (d <sup>-1</sup> )	0.05
20. Zooplankton mortality rate (d <sup>-1</sup> )	0.046

<sup>1</sup>n.d. – non-dimensional

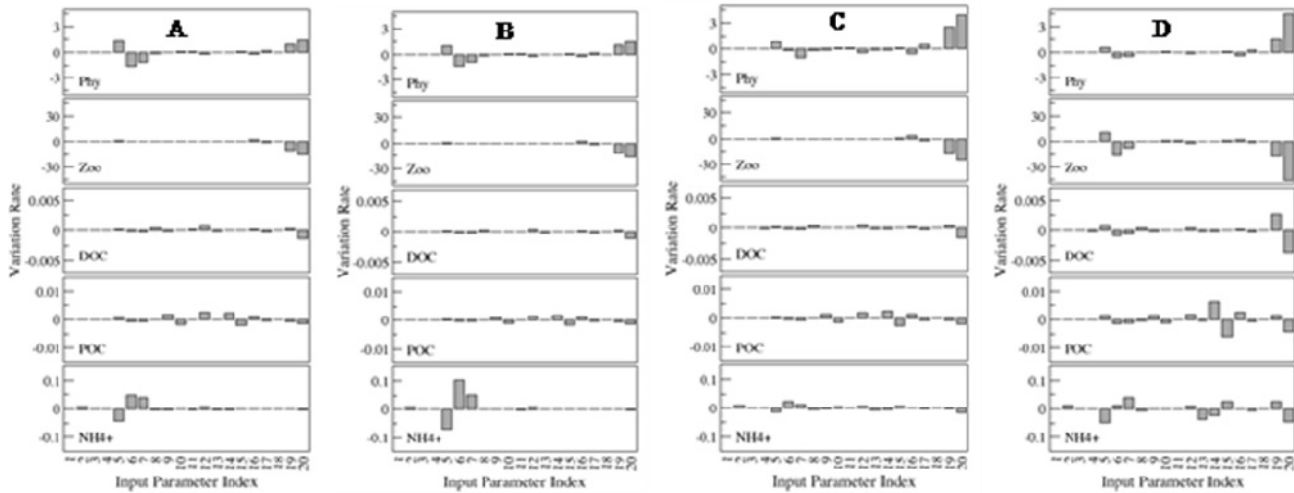


Figure 5. Influence of the input parameters in: A) Mira channel, B) Ílhavo channel, C) Espinheiro channel and D) S. Jacinto channel (Phy: Phytoplankton; Zoo: Zooplankton; DOC: Dissolved Organic Carbon; POC: Particulate Organic Carbon; NH<sub>4</sub><sup>+</sup>: Ammonium).

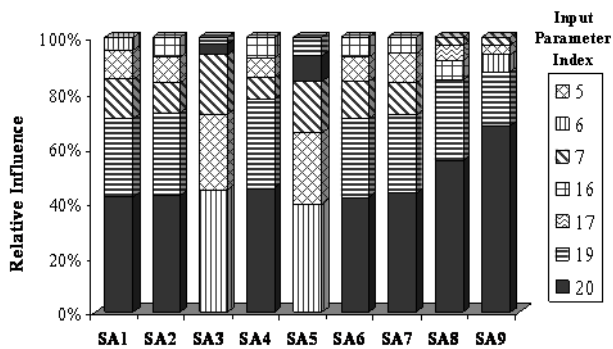


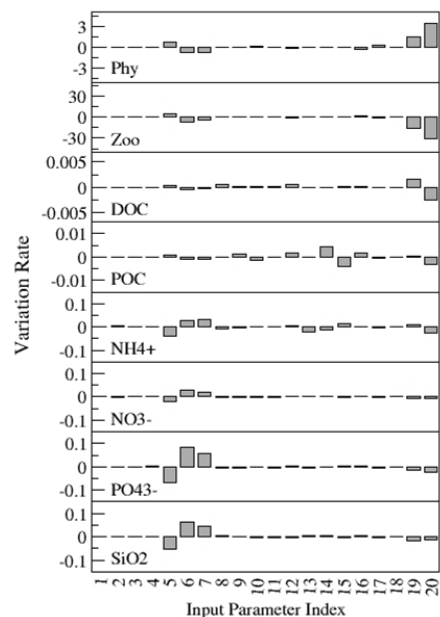
Figure 6. Relative influence of the top-five most influential input parameter of phytoplankton concentration in each SA station.

Ammonium concentrations are mostly influenced by phytoplankton growth parameters in the Mira and Ílhavo channels (Figure 5A and 5B). In the S. Jacinto channel, where zooplankton concentrations are larger, zooplankton loss terms also influence significantly ammonium (Figure 5D). In the Ria domain, the other nutrients are also influenced by phytoplankton growth terms (Figure 7), which shows the dependence between phytoplankton and nutrients concentrations, since phytoplankton growth depends on nutrient availability.

Dissolved organic carbon (DOC) and particulate organic carbon (POC) are, together with nutrients, the variables less affected by the input parameters (Table 2). These two ecological variables are slightly affected by the parameters related to zooplankton and phytoplankton mortality rates (Figure 5 and Figure 7). POC is also influenced by the fractions of material released by zooplankton, which are the ones that affect this variable in the S. Jacinto channel the most (Figure 5D).

As environmental conditions vary seasonally, for some of the most influent parameters, some additional tests were performed for environmental conditions characteristic of summer periods, where river flows are lower and boundary temperatures are higher.

In these simulations, the flows and the temperatures considered at the boundaries were: 3.92 m<sup>3</sup>/s and 19.2 °C (Vouga), 1.3 m<sup>3</sup>/s and 19.9 °C (Antuã), 1.1 m<sup>3</sup>/s and 22.6 °C (Caster), 0.6 m<sup>3</sup>/s and 20.4 °C (Boco) and 0.6 m<sup>3</sup>/s and 22.4 °C (Mira). Averaging over the whole Ria, the results show that zooplankton mortality rate has a higher influence on phytoplankton concentration than phytoplankton maximum growth rate, for both types of river flows (Figure 8). They also highlight the effect that zooplankton concentrations have on the magnitude of the influence of these parameters: during lower river flows periods, local concentrations of zooplankton are higher, which decreases the influence of phytoplankton maximum growth rate (Figure 8A) and increases the influence of zooplankton mortality rate (Figure 8B).



Phy: Phytoplankton; Zoo: Zooplankton; DOC: Dissolved Organic Carbon; POC: Particulate Organic Carbon; NH<sub>4</sub><sup>+</sup>: Ammonium; NO<sub>3</sub><sup>-</sup>: Nitrate; PO<sub>4</sub><sup>3-</sup>: Phosphate; SiO<sub>2</sub>: Silicate

Figure 7. Influence of the input parameters in the Ria de Aveiro

Table 2: Total influence ( $\Delta Y$ ) of the input parameters in the ecological variables (RA: Ria de Aveiro; CM: Mira channel; CI: Ílhavo channel; CE: Espinho channel; CSJ: S. Jacinto channel)

Variable	$\Delta Y$				
	RA	CM	CI	CE	CSJ
<b>Phytoplankton</b>	0.37	0.15	0.19	0.47	0.45
<b>Zooplankton</b>	-3.8	-2.0	-2.3	-3.3	-5.2
DOC	$-1.6 \times 10^{-5}$	$-1.3 \times 10^{-5}$	$-9.8 \times 10^{-6}$	$-1.7 \times 10^{-5}$	$-2.4 \times 10^{-5}$
POC	$-1.4 \times 10^{-4}$	$-6.7 \times 10^{-6}$	$-5.7 \times 10^{-5}$	$-8.5 \times 10^{-5}$	$-2.1 \times 10^{-4}$
<b>Ammonium</b>	$-2.0 \times 10^{-3}$	$5.7 \times 10^{-4}$	$2.4 \times 10^{-4}$	$-8.6 \times 10^{-4}$	$-3.8 \times 10^{-3}$
<b>Nitrate</b>	$-9.4 \times 10^{-4}$	$3.2 \times 10^{-5}$	$-3.1 \times 10^{-4}$	$-3.2 \times 10^{-4}$	$-2.0 \times 10^{-3}$
<b>Phosphate</b>	$-2.4 \times 10^{-3}$	$3.2 \times 10^{-4}$	$-4.8 \times 10^{-4}$	$-4.1 \times 10^{-4}$	$-7.4 \times 10^{-3}$
<b>Silicate</b>	$-1.7 \times 10^{-3}$	$3.0 \times 10^{-4}$	-	$-1.8 \times 10^{-4}$	$-4.1 \times 10^{-3}$

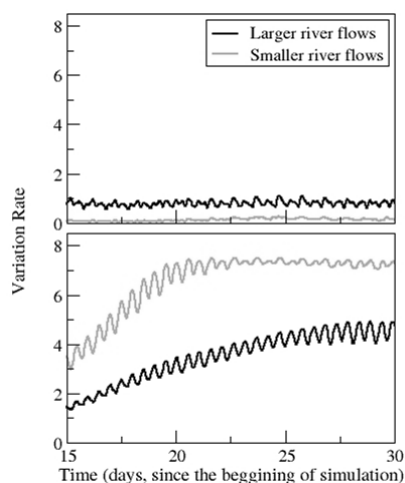


Figure 8. Effects of the variation of A) phytoplankton maximum growth rate and B) zooplankton mortality rate in phytoplankton concentration for different environmental conditions, averaging over the whole Ria de Aveiro

## CONCLUSIONS

This study highlighted the most influent parameters when implementing sophisticated ecological models in a real system. The parameters related to phytoplankton growth and zooplankton losses (mortality and excretion rates) are the ones that influence the results the most. These findings are similar to those achieved with the sensitivity analysis of the zero-dimensional ecological model (RODRIGUES *et al.*, 2008). However, the three-dimensional model sensitivity analysis also evidenced that the influence of these parameters on phytoplankton concentration depends on the local concentrations of zooplankton. These results suggest that the simple model can be used in this type of analyses, providing that different phytoplankton and zooplankton concentrations are evaluated.

Similar studies with other ecological models also showed the larger influence of zooplankton and phytoplankton parameters on the final results of the model (e.g. YOSHIE *et al.*, 2007). In particular, the larger influence of zooplankton mortality found here agrees with the findings of STEELE and HENDERSON (1992), which showed that the definition of this parameter can have a larger influence on the ecological models' dynamics. Thus, when implementing these models in real systems, phytoplankton and

zooplankton parameters should be as accurate as possible, using site-specific data whenever it is available.

Future exploitation of the model sensitivity should account for the simultaneous variation of the input parameters, to evaluate their combined influence and, in particular, the feedback of the phytoplankton growth and zooplankton loss parameters on phytoplankton and zooplankton concentrations.

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