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Modelling the influence of nutrient loads on Portuguese estuaries

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Abstract The effects of implementing Directive 91/271/EEC of 21 May 1991 (Waste Water Treatment Plan Directive) and Directive 91/676/EEC of 12 December (Nitrates Directive) are analysed in 7 Portuguese estuaries (Minho, Lima, Douro, Mondego, Tagus, Sado and Guadiana) and two coastal lagoons (Ria de Aveiro and Ria Formosa), with a modelling approach. MOHID Water Modelling System was used to perform simulations with three nitrogen load scenarios for each system: a reference scenario, a 50% nitrate removal by agriculture scenario and another with a 100% nutrients removal by waste water treatment plants (WWTP). It is shown that the interaction between hydrodynamic and ecological processes is an important feature to study trophic problems in estuaries. Ecological processes such as primary production only occur inside the system if the residence time of water is high enough to enable organismal activity and if the adequate conditions are found (e.g. light, nutrients, temperature). From the model results it is possible to conclude: (i) in systems with short residence time a reduction in nutrient load will only produce a decrease in nutrient transit and will not affect the system's global ecological status (e.g. Douro Estuary); (ii) in systems with long residence time the effects will range from significant, when primary production is mostly limited by nutrients (e.g. Ria de Aveiro), to non-significant, when primary production in the system is light-limited (e.g. Tagus Estuary).

Keywords Modelling · European Directives · Nutrient loads · Coastal waters · Primary production · Eutrophication

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Towards an integrated knowledge and management of estuarine systems

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Introduction

The European Directive 2000/60/EC of 23 October 2000 is the most recent framework for environmental legislation on protection of several types of aquatic systems. One of the key concerns regarding the management of coastal waters is the artificial and problematic acceleration of the eutrophication phenomena and it's a key aspect in this directive. Eutrophication can be defined as an increase in the rate of supply of organic matter to an ecosystem (Nixon, 1995a, b), which can represent an increase in organic matter mineralization and consequently a depletion in oxygen concentrations (Nixon, 1995a, b; Flindt et al., 1999; Smith et al., 1999; Havens et al., 2001; Grall & Chauvaud, 2002). The extent of an eutrophication event is a result from the combination of several factors and processes occurring in the system, including flushing time, turbidity and the input and concentration gradient of nutrients (De Jonge & Elliott, 2001; De Jonge et al., 2002).

With the objective of reducing the risk of eutrophication two council directives introduce the concepts of *Sensitive Areas* (Directive 91/271/EEC of 21 May 1991; Urban Waste Water Treatment Directive) imposing restrictions for urban discharges and *Vulnerable Zones* (Directive 91/676/EEC of 12 December; Nitrates Directive) imposing restrictions against pollution caused by nitrates from agricultural sources. The areas classified as *Sensitive* or *Vulnerable* have important restrictions in terms of human uses, therefore it becomes important to verify if applying the directives will really improve the system's global ecological status.

The dynamics of shallow estuaries and coastal waters is, in general, very complex, in the sense that its environmental conditions depend on hydrodynamic and ecological processes, as well as interactions between them. Hydrodynamics determine nutrient availability through transport processes, light penetration through transport and deposition/erosion of particulate matter and, above all, determine how long will a water mass stay in a certain place or, in other words, the water specific residence time (Deleersnijder et al., 2001; Braunschweig et al., 2003). Ecological processes such as primary production only occur if adequate conditions are found (e.g. light, nutrients, temperature) and if there is enough time for organismal activity to occur. Systems with long residence times are particularly susceptible to developing algal blooms when nutrient loads increase (Schramm, 1999) and strong water currents usually prevent eutrophication by flushing nutrients out of the system (Grall & Chauvaud, 2002). Thus, assessing the nutrients input effects on coastal systems requires a detailed study of hydrodynamic and ecological conditions of that particular system. The complex interaction between these different processes and the need to quantify these interactions lead to the development of numerical models, which are able to compute the evolution of several properties over space and time. Coupling primary production models to physical models describing tidal transport promotes the development of sophisticated modelling tools to support coastal areas management. The explicit consideration of hydrodynamics in the ecological calculations makes the model applicable to all estuaries, despite the fact that the relative importance of processes varies among them.

In this paper, a modelling approach is used to assess the impact of two EU directives application (Directive 91/271/EEC and Directive 91/676/EEC) on 7 Portuguese estuaries and two coastal lagoons. This work is part of a national project lead by Portuguese National Water authority (INAG) to assess the water quality status in major Portuguese estuaries, in view of the water directives. The modelling task, presented here, uses a coupled hydrodynamic-biogeochemical model to achieve this goal. The results of this work have thus produced a set of information that can be used by competent authorities to characterize the systems.

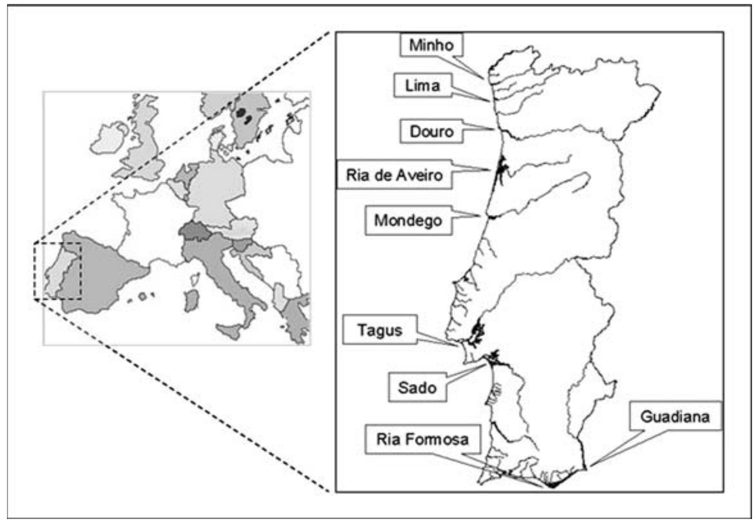
Methodology

Study areas

Seven estuaries—Minho, Lima, Douro, Mondego, Tagus, Sado and Guadiana—and two coastal lagoons—Ria de Aveiro and Ria Formosa—were studied (Fig. 1).

Generally, in the northern part of Portugal estuaries are narrow and rivers have high flow discharges. In the southern estuaries, rivers have irregular discharges characterized by long periods of small flow interrupted by short and strong episodes of storm flow. Coastal lagoons also present significant differences: Ria de Aveiro receives large amounts of fresh water from Vouga river and its connection to the ocean is narrow; Ria Formosa does not have permanent fresh water sources and is connected to the ocean through seven inlets.

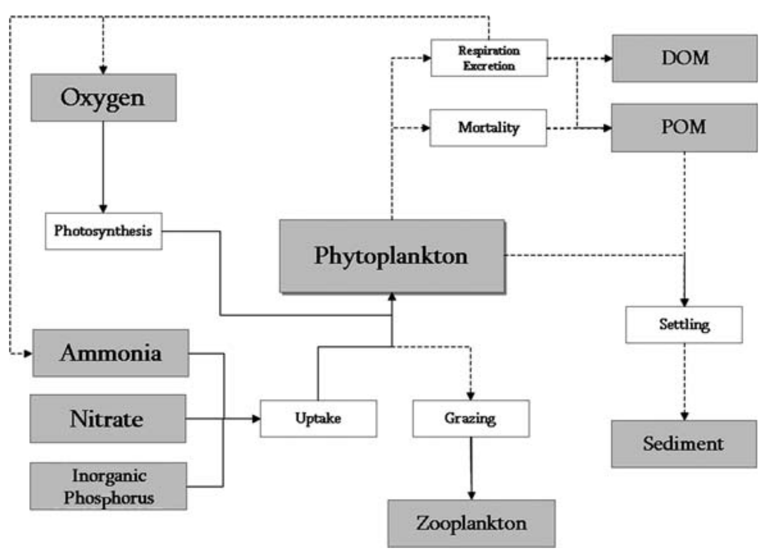
Fig. 1 Geographic location of the studied estuaries and coastal lagoons



Model description

MOHID Water Modelling System (2004) was used to perform the simulations. MOHID Water consists of a set of coupled models, based on the finite volume concept, including hydrodynamic, eulerian and lagrangian advection–diffusion, sediment transport and ecological models. With the hydrodynamic model solving the 3D incompressible primitive equations (Martins et al., 2001), MOHID Water is prepared to simulate properties such as temperature, salinity, cohesive sediments, phytoplankton, zooplankton, nutrients, contaminants, etc., in the marine environment. These properties can either be relative to elements dissolved in water, therefore following the currents, or in a particulate phase, thus being subject to settling. This approach enables particulate properties to deposit in the bottom and thus become a part of the sediments compartment. Ecological processes, implemented in the form of sinks and sources terms of the transport model, are computed in the Water Quality Module (0D), giving the desired flexibility to be coupled to either a Lagrangian or an Eulerian approach (Pina, 2001). Nitrogen and phosphorus

Fig. 2 MOHID Water Quality Module: phytoplankton main processes



biogeochemical cycles are simulated explicitly and constant Carbon:Nitrogen:Phosphorous (C:N:P) ratios are assumed for organic matter and plankton. The parameterization of ecological processes in the water column (pelagic system) is mainly adapted from EPA (1985), including phytoplankton, zooplankton, dissolved nutrients and dissolved and particulate phases of organic matter as state variables. Figure 2 represents the main processes assumed by the Water Quality Module to compute the evolution of phytoplankton concentration.

MOHID Water Modelling System (2004) has been applied to different estuarine ecosystems including: Tagus estuary (Portela, 1996; Pina et al., 2000; Pina, 2001; Braunschweig et al., 2003; Pina et al., 2003), Guadiana estuary (Cunha et al., 2000), Douro estuary (Pina et al., 2003), Sado estuary (Martins et al., 2001), Ria Formosa (Martins et al., 2004), Ria de Aveiro (Trancoso et al., 2005) and Ria de Pontevedra (Galicia) (Villarreal et al., 2002).

Model Simulations: Residence Time

Residence time can be defined as the time required for renewing the water in the estuary. Since processes with time scales longer than the residence time can not take place in its interior, it can be a key aspect for understanding the fate

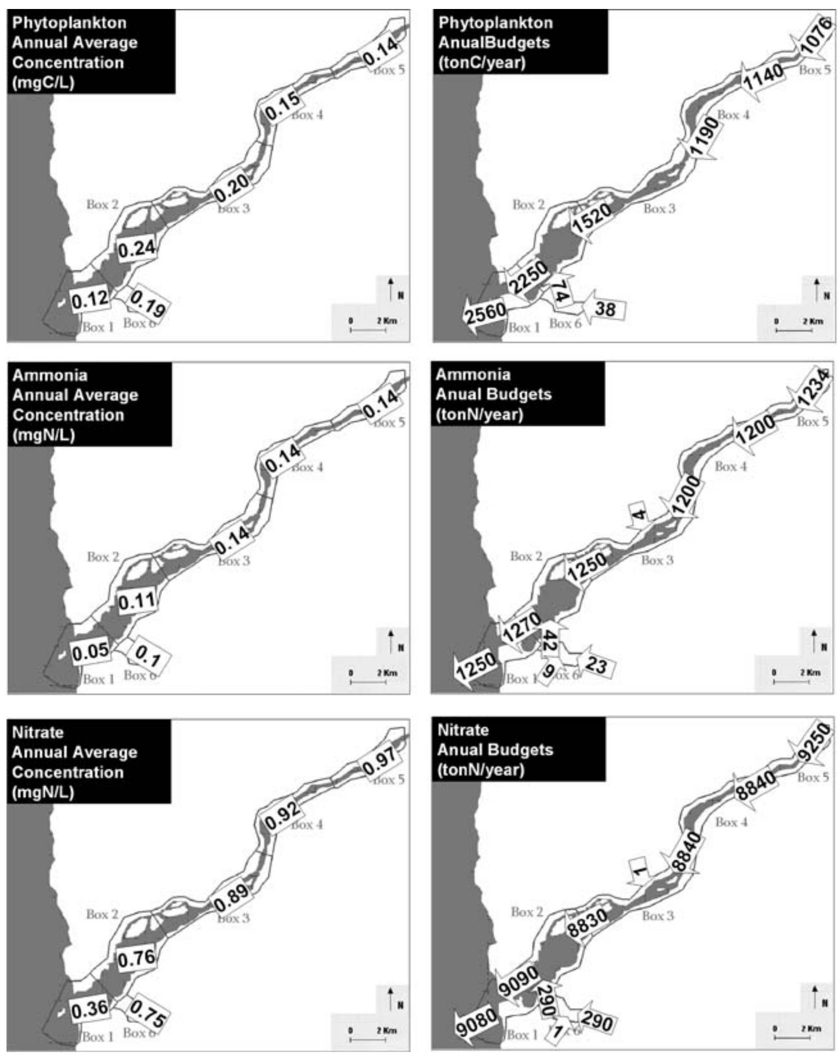


Fig. 3 Minho estuary: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

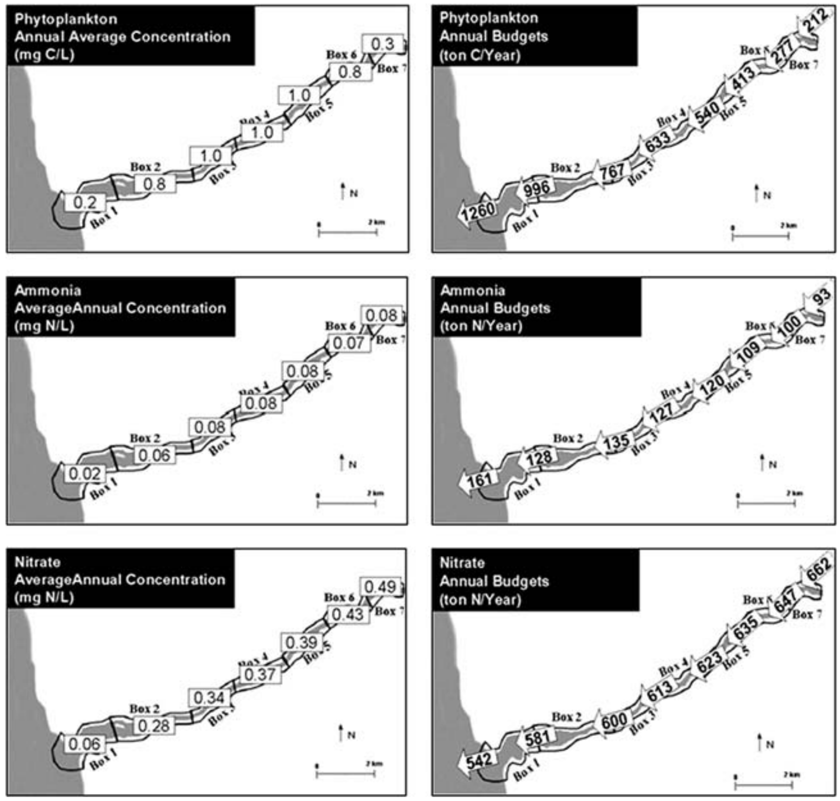


Fig. 4 Lima estuary: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

of estuarine loads. From the ecological point of view, estuaries with a short transit time will export nutrients from upstream sources more rapidly than estuaries with longer transit times. As a consequence, estuaries with short residence time are expected to have algae blooms less pronounced than estuaries with long residence time (Schramm, 1999; Braunschweig et al., 2003). Thus, the longer the flushing time, the more vulnerable the system is to nutrient enrichment, as primary producers have a greater period available to use excess nutrients (De Jonge & Elliot, 2001; De Jonge et al., 2002). Different renewal time scales can thus be used to generally characterize an estuary, to compare different estuaries in respect to the transport processes, or to aggregate field data in ‘‘easy to use’’ parameters. In this study, residence time computation uses the concept of lagrangian tracers to label the water inside the estuary (or coastal lagoon) and assumes residence time as the time required by 80% of the water to leave the estuary (or coastal lagoon). Residence time was computed performing the following steps, using the methodology described by Braunschweig et al. (2003): (i) Computation of hydrodynamics forced by tide and mean annual river inflow; (ii) Splitting of the estuary into boxes filled with lagrangian tracers, having the volume, spatial coordinates and the number of the box where they were released as associated properties; the total amount of tracers and their initial distribution in each box are calculated so that the total volume of tracers inside the box matches its water volume, and (iii) Calculation of residence time as the ratio between instantaneous tracers volume and initial tracers volume over time.

Model simulations

Ecological simulations

For each system, a reference simulation representing current system conditions was done. The conditions imposed to simulate this reference

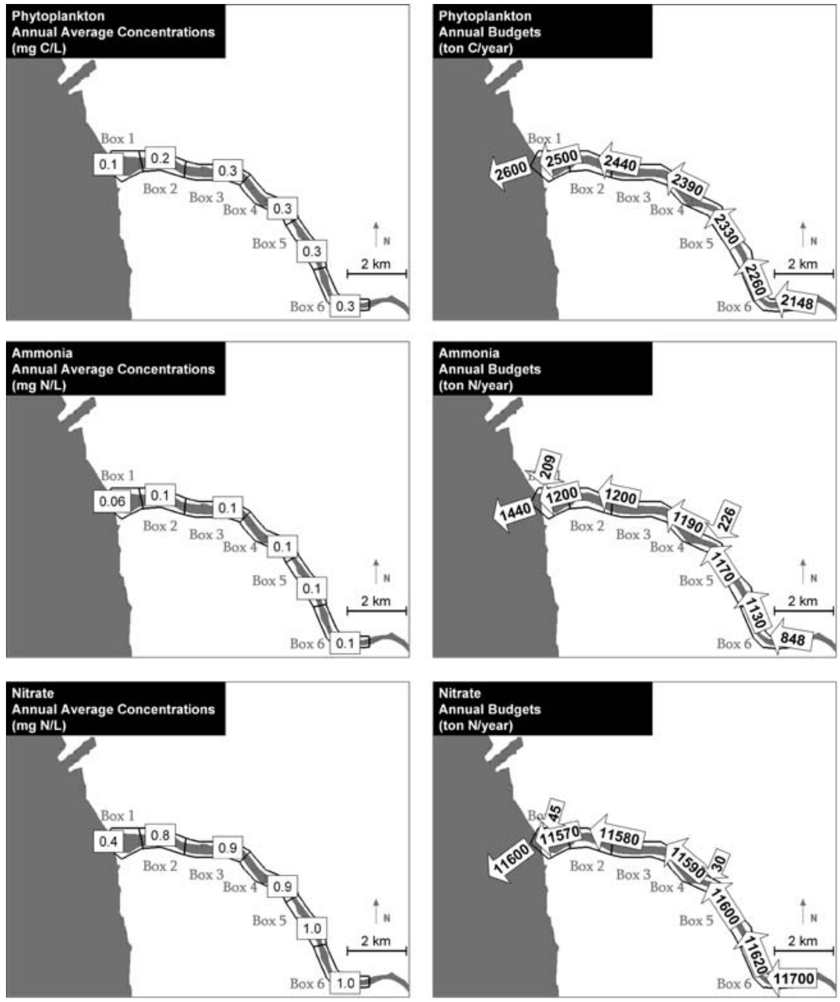


Fig. 5 Douro estuary: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

scenario were performed using the most recent information available for each system including field data from INAG, historical data and data from specific projects developed in the systems. To evaluate the effects of reducing the nitrate discharge from agriculture and nutrient removal by wastewater treatment plants (WWTP) two reduction scenarios were simulated and compared with the reference situation. In the first case, a 50% reduction in the nitrate river load was used, maintaining all other conditions. This simulation is based on the assumption that agriculture is the major source of nitrate and in the fact that phosphorus is not the main limiting nutrient to primary production in estuaries (Valiela, 1995; Day et al., 1989; Marsili-Libilli, 2003). By comparing model results in this scenario with those of the reference simulation, it becomes possible to determine the effects of considering the particular area as *Vulnerable Zone*, according to Directive 91/676/EEC. To study the effects of considering the coastal water as *Sensible Area* (Directive 91/271/EEC), an extreme scenario of completely removing the discharge of all urban loads was tested. The scenarios were tested in terms of phytoplankton, ammonia and nitrate total balance in the systems, using the concept of integration boxes.

Integration boxes concept

MOHID Water Modelling System (2004) is able to produce several types of results. The use of

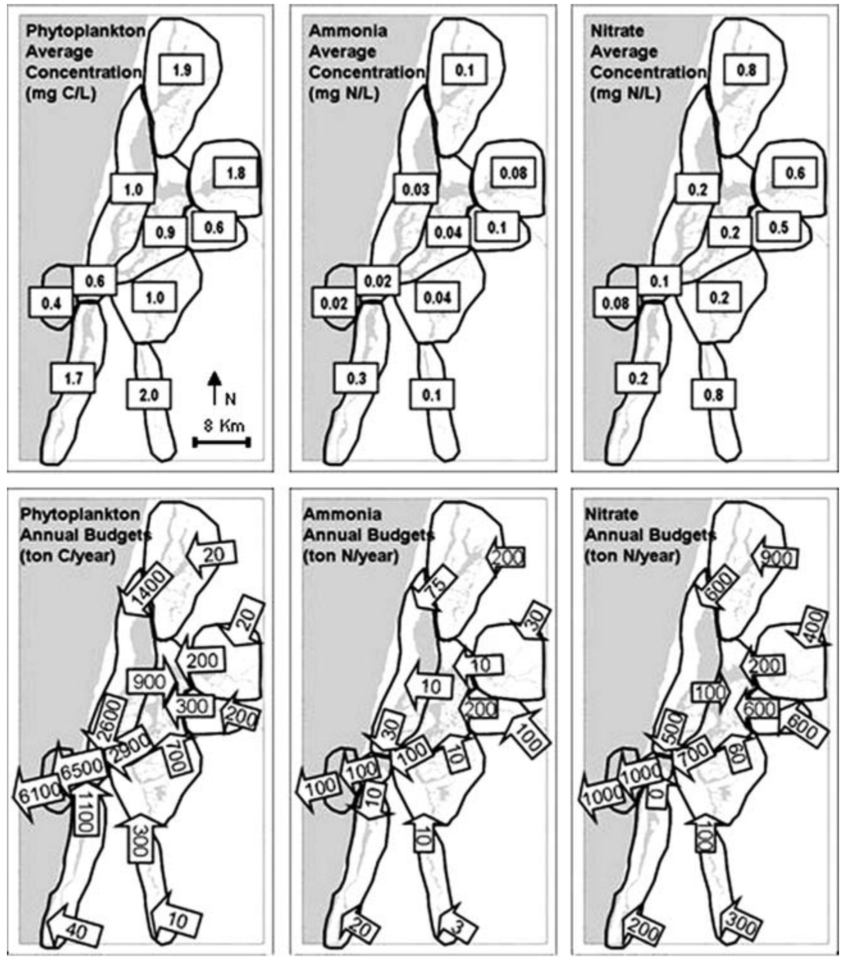


Fig. 6 Ria de Aveiro: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

point time series results, considering a specific grid cell, can be very useful to validate the model simulation by comparing data field values with model results. Nevertheless, the use of this kind of results to characterise spatial and temporal variation in the system can raise some difficulties, such as choosing which area is represented by a unique cell or which field data should be compared with a cell time series computed by the model. The association of time series to larger areas (Integration Boxes) and the computation of fluxes across the boundaries merge temporal and spatial variability, simplifying the analysis of results. Integration Boxes represent areas of the system that have similar conditions regarding hydrodynamic and ecological processes. Concentration values in each box were obtained by spatially integrating model results for all the cells inside the box and fluxes were obtained by integrating the solution along the box boundary. Both spatially averaged values inside the box and fluxes across boxes boundaries were used to build time series and compute annual net fluxes and average concentrations. Integration boxes are particularly useful for testing the model solution in different scenarios, making comparisons simpler and more objective.

Results and discussion

Reference situation

Figures 3–11 represent the annual average concentration and the total annual phytoplankton,

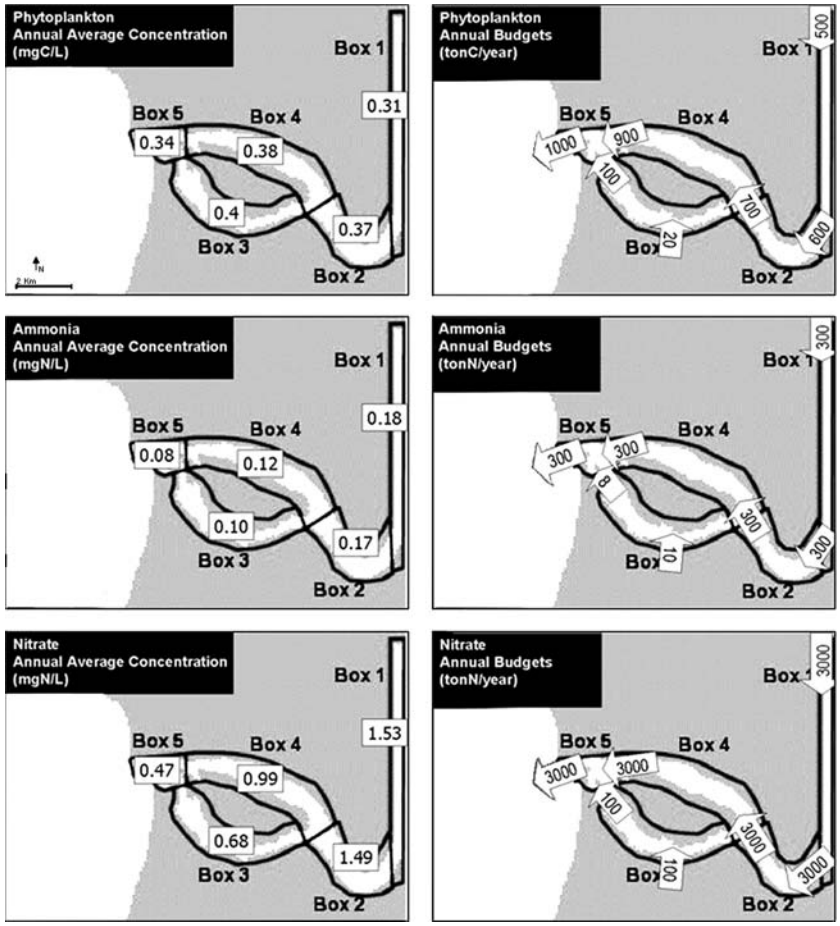


Fig. 7 Mondego estuary: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

ammonia and nitrate transports between boxes for the areas studied.

The total annual balance of phytoplankton, ammonia and nitrate in the reference situation is presented, for each system, in Table 1. The balances were computed as differences between output and input annual fluxes of properties (thus resulting positive for net output).

Most systems behave as phytoplankton exporters to the coastal zone, having a positive total balance (Table 1), with Sado estuary as the only exception. The finding that this system imports phytoplankton from the sea can be justified by a significant production of phytoplankton near the estuary's mouth, in front of Troia peninsula, fuelled by nutrients from deep areas off the estuary plateau and also by nutrients discharged by the estuary that had previously entered the estuary during flooding.

The net production of phytoplankton inside the systems is followed by a net consumption of nitrate. In terms of ammonia, most systems present a net consumption, but in some results show ammonia exportation to the sea, following net production of phytoplankton, particularly in the case of the Tagus estuary. In fact, processes related with deposition and mineralization of particulate organic matter in shallow intertidal areas in addition to organismal excretions can constitute important sources of ammonia in the system, when residence time is enough to allow the development of these processes (e.g. Tagus estuary and, to some extent, Lima estuary). In Douro estuary, because the residence time is short and phytoplankton production is consequently low, the exportation of ammonia from the estuary is more probably related with anthropogenic loads of nutrients.

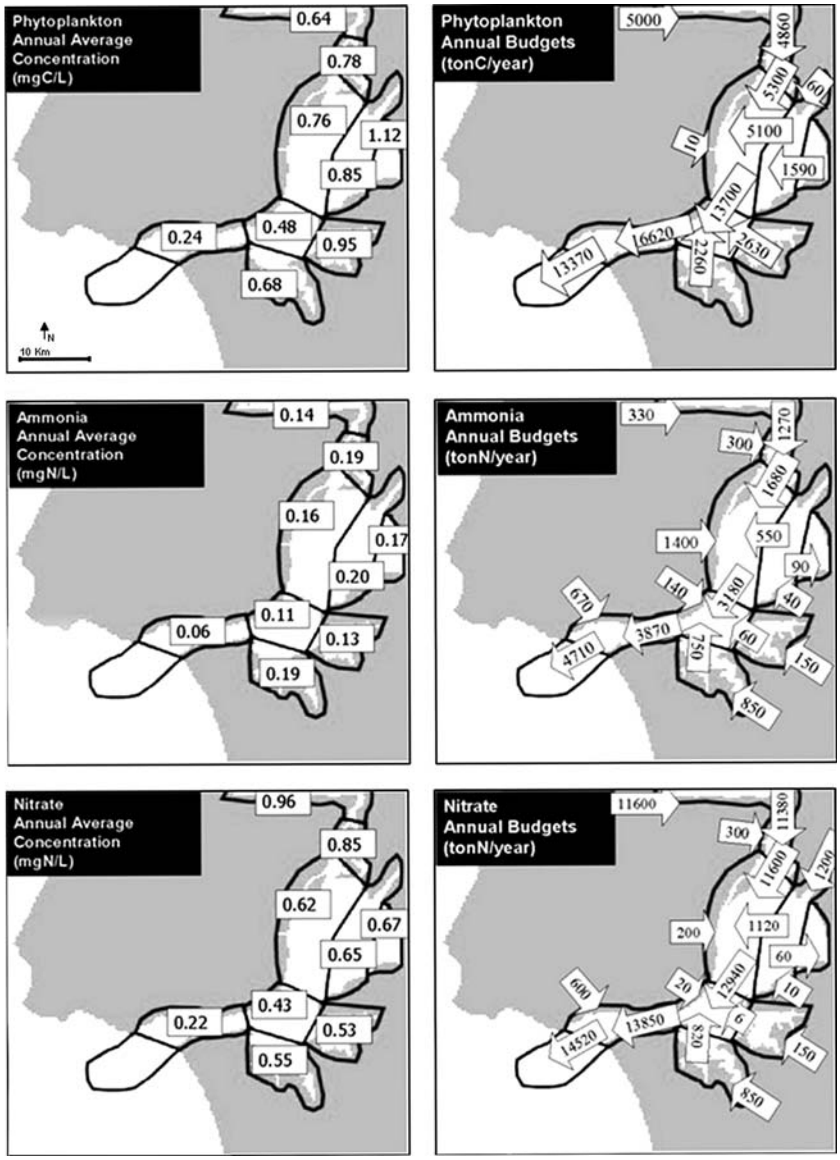


Fig. 8 Tagus estuary: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

Influence of nitrate removal by agriculture

To evaluate the effects of reducing nutrient loads from agriculture, the simulations performed for the reference situation were repeated, considering now a reduction of 50% in nitrate load while maintaining all other conditions. Table 2 represents, for each system, the difference found in annual budgets of phytoplankton, expressed in terms of percentage of reference situation values. Due to the inexistence of a regular river discharge in Ria Formosa, this scenario was not performed in this system.

The results show that nitrate removal has a negative influence on phytoplankton total balance in all systems, except Sado estuary, which means that a reduction in nitrate input will cause a decrease in phytoplankton production. In Sado estuary, the percentage of influence has a positive value related with the fact that the estuary imports phytoplankton. The reduction of nitrate loads reduces the production of phytoplankton

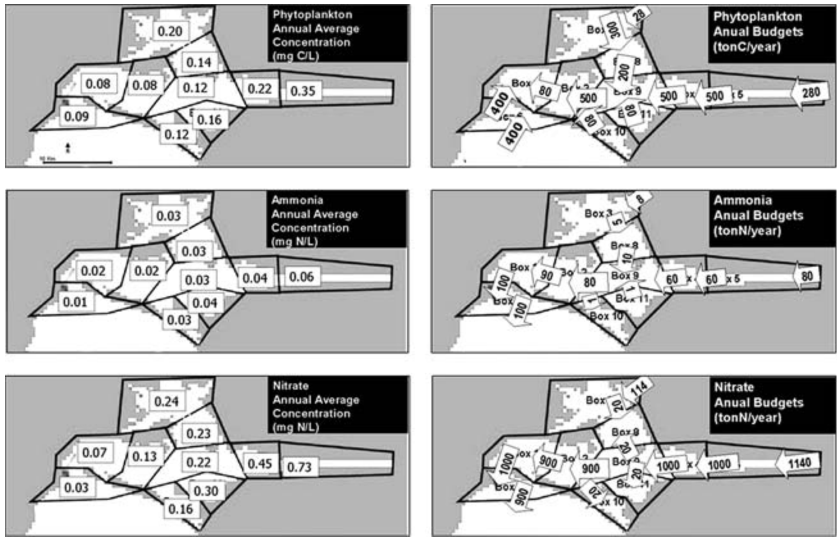


Fig. 9 Sado estuary: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

inside the estuary, which strengthens the already existing gradients between inside and outside of the estuary. The effects of 50% nitrate removal by agriculture in the total balance of phytoplankton vary from estuary to estuary, depending on the particular characteristics of the system, such as residence time and hydrodynamic conditions. In general, results show that systems with long residence time are more susceptible to nitrate removal by agriculture influence, but the influence of nitrate reduction also depends on geomorphology, mean depth and turbidity. The interaction between different factors controlling primary production is very strong in Tagus estuary, where the results show that, despite the long residence time (25 days), the effects are not very significant. This can be explained by the fact that primary production in the Tagus estuary is mainly light-limited, due to high turbidity induced by large amounts of suspended sediments.

Influence of the nutrients removal by WWTP

To study the effects of nutrient removal by WWTP, an extreme situation of completely removing the discharge of nutrients from urban origin was simulated. In this scenario the WWTP discharge is assumed to be clean water. For some of the studied areas it was not possible to perform this scenario because there were no WWTP discharges or their influence is negligible. Table 3 presents the influence of nutrients reduction in WWTP in phytoplankton total balance (as the difference between model results obtained in this scenario and in the reference situation, expressed in percentage of the reference situation results). The table also shows the reduction of nutrient input to the systems in this scenario. Similarly to the previous comparison, the influence of nutrient removal by WWTP in phytoplankton total balance has a negative sign for all systems, which means that there is a small decrease in phytoplankton production when the nutrient input is reduced, but it has no significant effect on the net phytoplankton production.

Conclusion

With this work it was shown that the effect of nutrient reduction can be very different in each system. Phytoplankton production limitation has different natures for each system: for estuaries with long residence times such as Ria de Aveiro, Sado, Tagus, Lima and, to some extent, Guadiana, the residence time is long enough to enable ecological processes to take place inside the estuary and the main limitation is the lack of nutrients or shortage of light (temperature is usually not a problem in these latitudes). On the other hand, in estuaries with short residence times such as Douro, Minho, Mondego and Ria

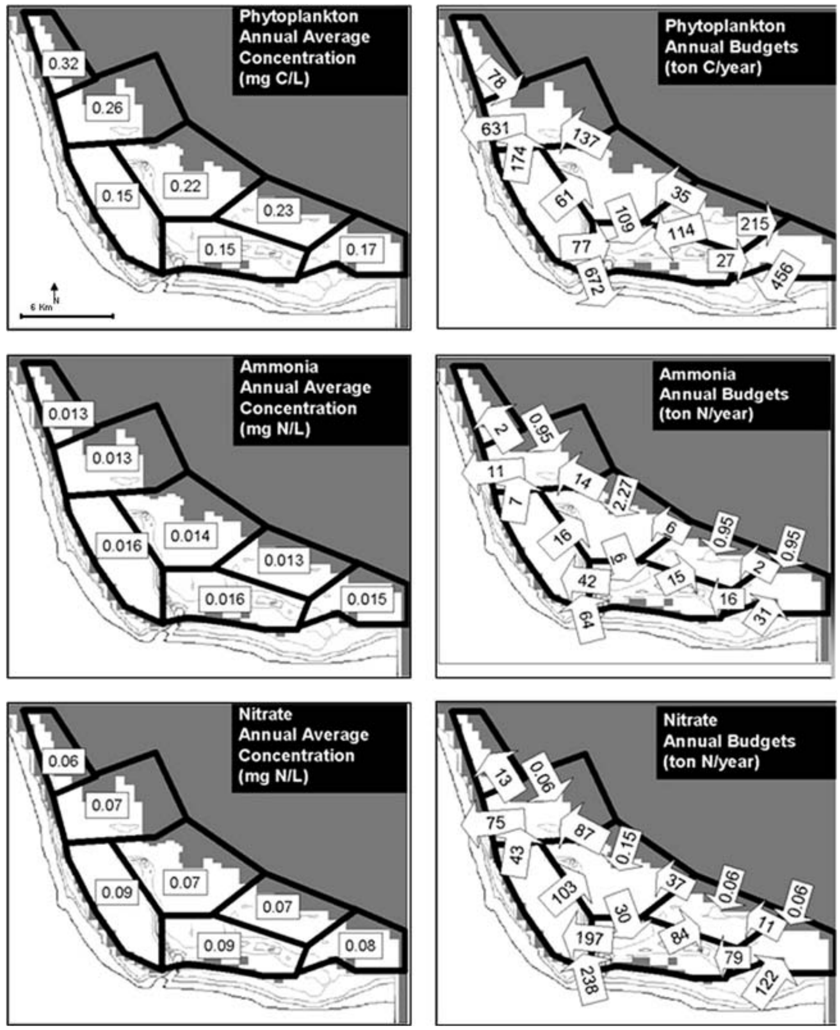


Fig. 10 Ria Formosa: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

Formosa, ecological processes do not have enough time to develop inside the estuary because phytoplankton cells and nutrients are flushed out of the system, and the uptake and recycling of nutrients occurs in the coastal zone. Thus, systems with different environmental conditions will respond in a different way to the application of nutrient loads reduction and consequently to the implementation of nitrate and wastewater directives.

According to model results, in systems with short residence time the reduction of nutrient input will only produce a decrease in nutrient transit, having a negligible effect on primary production and consequently on the system's global status. In systems with long residence time the effects will depend on the main factor that limits primary production: if nutrient concentration is the most important factor controlling primary production, reducing nutrient loads will produce significant effects on phytoplankton total balance in the system (e.g. Ria de Aveiro) but if the system is light-limited, primary production will not be significantly affected and the ecological status of the system will display no changes (e.g. Tagus estuary).

This study used a modelling approach as an integration tool to assess the interactions between several processes and conditions controlling eutrophication phenomena. Thus, the precision of results will depend on formulations and assumptions considered by the model as well as

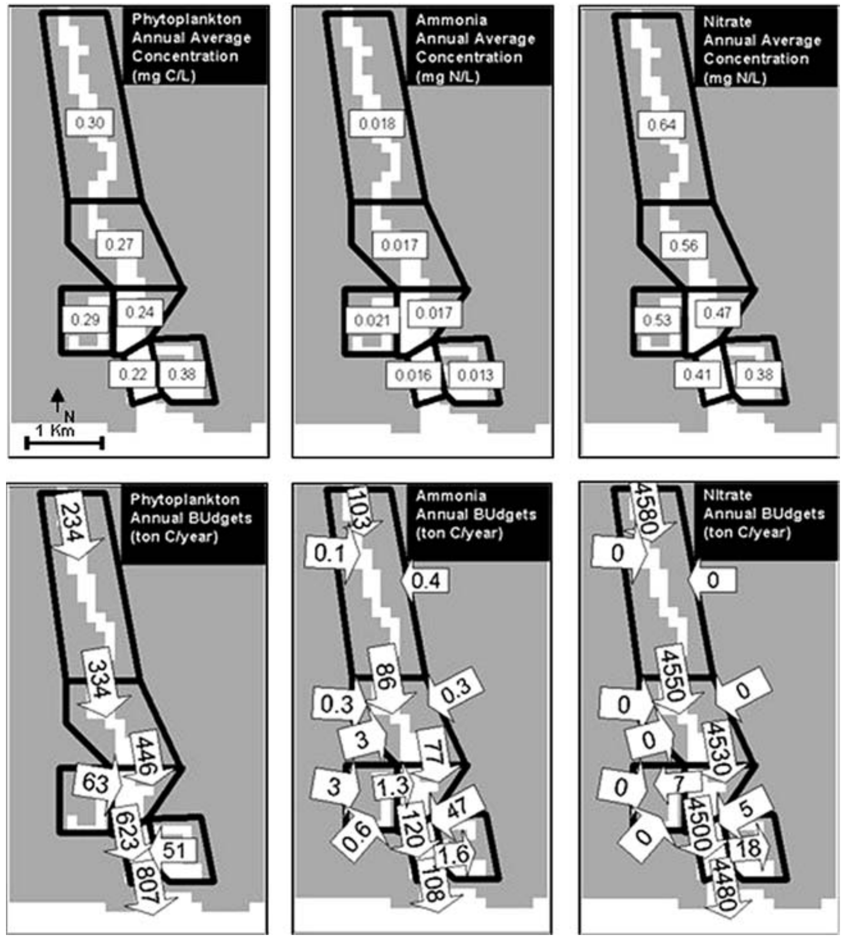


Fig. 11 Guadiana estuary: phytoplankton, ammonia and nitrate average annual concentration and annual fluxes between boxes

the quantity and quality of field data available to validate model results. Most systems have been subject of other research projects and studies, and thus the amount of available field data and the knowledge of historical system behavior are considered enough to promote model simulations. However, this type of assessment is not a closed process: as we learn more about estuarine and

Table 1 Total annual balance of phytoplankton, ammonia and nitrate, in the reference situation. The total balance represents the difference between input and output fluxes computed by the model. For Ria Formosa, the total balance corresponds to the difference between fluxes from land and fluxes across the inlet

Estuarine system	Residence time (days)	Phytoplankton (ton C y^{-1})	Ammonia (ton N y^{-1})	Nitrate (ton N y^{-1})
Minho	1	+1446	–20	–462
Lima	7	+1048	+68	–120
Douro	1	+474	+157	–175
Ria de Aveiro	20	+5810	–253	–1400
Mondego	3	+480	–10	–100
Tagus	25	+8300	+170	–410
Sado	30	–708	+12	–354
Ria Formosa	1.5	+1759	–89	–285
Guadiana	4	+573	–50	–105

Table 2 Influence of nitrate removal by agriculture on the total balance of phytoplankton in the systems (difference between total budgets in nitrate removal scenario and the reference situation, expressed in % of reference situation value)

Estuarine system	Influence in phytoplankton total balance (%)
Minho	–3
Lima	–12
Douro	–4
Ria de Aveiro	–15
Mondego	–2
Tagus	–4
Sado	7
Guadiana	–5

Table 3 Influence of nutrient removal by WWTP on the total balance of phytoplankton in the systems (difference between total annual balance in a scenario with 100% nutrients removal by WWTP and the reference situation, expressed in % of reference situation value)

Estuarine system	Ammonia input reduction (%)	Nitrate input reduction (%)	Influence in phytoplankton total balance (%)
Minho	–3	–0.02	0
Douro	–34	–1.3	–8
Tagus	–46	–16	–4
Ria Formosa	–100	–100	–0.1
Guadiana	–36	–0.1	–7

coastal systems, the estimates presented in this study must be recalculated in order to include any occurring environmental changes from natural or anthropogenic origin.

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