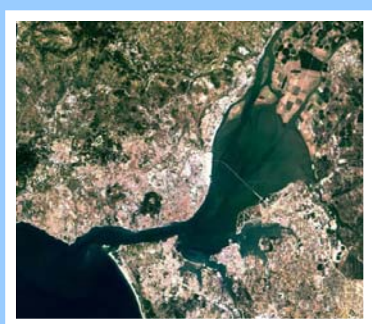
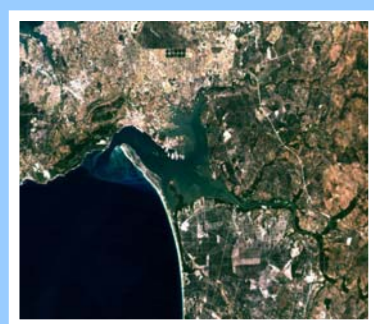
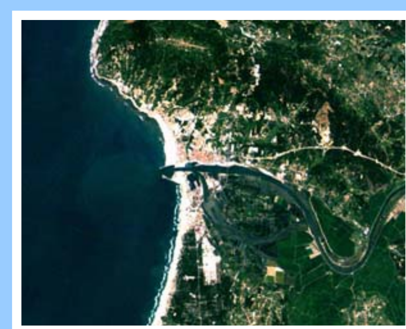
Qualidade da Água em Estuários Portugueses
Water Quality in Portuguese Estuaries







Tejo - Sado - Mondego

Directiva do Tratamento de Águas Residuais Urbanas

(91/271/CEE)

Directiva dos Nitratos de Origem Agrícola

(91/676/CEE)

Maretec
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Abstract

This report describes a numerical study of the trophic processes in the Tagus, Sado and Mondego Estuaries (Portugal), in order to evaluate their trophic levels and to identify the factors determining them. The study includes (i) a description of the hydrodynamics of each estuary and of the residence time of the water inside the estuary and inside each part of the estuary, (ii) a simulation of the estuary in the present conditions and (iii) simulations of several scenarios of reduction of nutrients, in order to evaluate the implications of different management scenarios.

The study puts into evidence the importance of the residence time for the ecological characteristics of the estuaries and shows that three ranges of residence time are important. If the residence time is smaller than the time required for developing a bloom, the nutrients discharged in the estuary will be exported without being consumed (this is the case of the Mondego estuary). The Sado estuary in on the other extreme, being the residence time long enough to allow the formation of a bloom and the regeneration of nutrients by mineralization of the organic matter generated. The Tagus Estuary is between this two ranges: the residence time is enough to generate a bloom, but their products are exported to the ocean as they are produced.

The study shows that in the Tagus estuary the trophic level is limited by light penetration due to the turbidity in the water column, which is associated to the resuspension of the fine sediments deposited in the intertidal areas by tidal currents and surface waves generated by the long fetch of local wind. As a consequence, a reduction of the nutrient loads discharged by the rivers or by the Urban Waste Water Treatment Plants has no consequences for the trophic activity in the estuary.

In the Sado estuary primary production is limited by nutrients and by the interaction between the phytoplankton and zooplankton and is modulated by the residence time inside the estuary and by the strong mixing between the different zones of the estuary. Although the residence time of the estuary is longer than one month, the residence time of the water inside each part of the estuary is of the order of one week, resulting into a strong mixing between zones of the estuary, with deposition and mineralization of the particulate organic matter in the shallow intertidal areas. The reduction of the nutrients load in the estuary does not modify the general behaviour of the estuary, maintaining the structure of a stronger bloom in spring followed by several smaller blooms. The

amplitude of the peaks following the first one are however smaller, especially for the zooplankton.

In the Mondego estuary, the limiting factor of phytoplankton production is the residence time, which is not long enough to allow the growing of a bloom. In this estuary the concentration of nutrients is higher in the northern channel; however eutrophication symptoms are detected in the southern channel (growth of macro-algae). It was shown that this is a consequence of the hydrodynamical properties of this channel. In fact this channel is a net importer of particulate organic matter from the northern channel, which enriches the sediments creating conditions for macro-algae growth, which is also stimulated by the small values of the transient and residual velocities. The settling characteristics of the southern channel have been stimulated by the artificial closing of the upper connection between the two channels. This study shows that the modification of the trophic characteristics of the southern channel requires the reopening of the communication between the channels and can not be achieved by a realistic reduction of nutrients discharged by the rivers.

1 Introduction

The European Commission has promoted a study to review the national classification of sensitive and vulnerable zones, according to the Urban Waste Water Treatment Directive and with the Nitrates Directive, respectively. According to the executive summary of the report concerned to Portugal, the Tagus, Mondego and Sado Estuaries should be classified as vulnerable/sensitive on the criterion of eutrophication, as described in the next table.

Vulnerable/Sensitive Estuaries, according to the Executive Summary of the study (report 5004) promoted by the European Commission about national classifications.			
Estuary	Criterion	Sensitive Zone	Vulnerable Zone
Tejo (Cala do Norte)	Eutrophication	Yes	Yes
Sado (Marateca e Canal de Alcácer)	Eutrophication	No	Yes
Mondego	Eutrophication	No	Yes

The aim of this numerical study was the understanding of the trophic processes in the Tagus, Sado and Mondego estuaries in order to assess the classification proposed by the Commission and to predict the consequences of an eventual reduction of the nutrient loads for the trophic levels of the estuaries.

The processes governing the trophic activity in the estuaries are the same, but their relative importance is much different. In all the estuaries the hydrodynamics is forced by the tide and by the river discharges, but the relative importance of the river flow and the differences between the dimensions and shapes of the estuaries generate very different flow patterns and residence times.

The study was carried out using an integrated hydro-ecological model, which simulates the hydrodynamics and the residence time, the sediment transport and the ecological processes. The model was used to simulate a reference situation using the actual loads and to simulate several scenarios of reduction of nutrients.

The Tagus estuary was used as the reference estuary since it is the most well known and is the estuary for which there are more data available to validate the results. The parameters of the model were calibrated in the Tagus estuary and used in the other estuaries. The data available for the Sado estuary show that those parameters are also adequate (as expected) to simulate the flow and ecological processes in that estuary.

The criterion for classification of the Tagus estuary by the Commission was the concentration of nutrients in the upper estuary and for the Sado was the residence time in Marateca, being stated that in none of the estuaries a problem of excessive trophic activity has been identified. In case of the Mondego, the argument for the classification was the symptom of eutrophication in the southern channel due to the macro-algae growth.

The study has concluded that the absence of eutrophication symptoms, despite the high concentration of nutrients in the upper Tagus estuary is a consequence of the growth limitation by light due to the high turbidity. High turbidity in the estuary is a consequence of the large extensions of the intertidal areas and of the long wind fetch that generates intensive resuspension of fine material reducing the transparency of the water. A reduction of the nutrients load by 50% was simulated and no modification of the phytoplankton concentration was obtained, showing that nowadays conditions are stable.

In the Sado estuary the production of phytoplankton is limited both by nutrients and by zooplankton predation. The maximum concentration is obtained during the spring bloom and remains low due to the limitation by the nutrients and predation by the zooplankton. The residence time in the estuary is long (over one month) due to the low value of the river discharge when compared with the volume of the estuary. However, the residence time of the water in each part of the estuary is smaller than one week due to the strong tidal and residual circulation. As a consequence gradients in the estuary are small, with quite low levels of production in most part of the estuary, except for the zones close to the Sado River and to the Marateca stream. A reduction of the nutrients load increases the limitation of phytoplankton growth by the nutrients, having as a consequence a reduction of the phytoplankton concentration and especially of the zooplankton.

In the Mondego estuary the residence time is very low (of the order of days) and do not allow for a bloom to develop before being exported seaward. Has a consequence, the concentration of phytoplankton remains low in the whole estuary and insensitive to a reduction of nutrient loads. The model could explain the specificity of the southern channel vis-à-vis of the northern channel. The southern channel use to be connect to the northern channel both in the upper and in the lower extremities, but some years ago the upper connection was closed aiming to enhance the ebb flow in the northern channel in order to minimize the costs of maintenance of the navigation channel. As a consequence of closing the upper communication between the channels, both tidal and residual velocities were reduced, creating conditions for deposition of particulate organic matter in the southern channel. The consequent enrichment of the sediments in organic matter and the small value of the maximum velocity created conditions for macro-algae growing.

Prediction of the behaviour of the estuary reopening the upper communication between the channels shows that the reopening of this communication is a requirement for the resolution of macro-algae growth in the southern channel of the Mondego estuary and should be object of a more detailed study.

2 Rationale of the study

The rationale followed by modelling activity of the project on evaluation of the eutrophication state of estuarine waters in Portugal was designed having in mind the "Criteria for the Definition of Eutrophication in Marine/Coastal Waters", proposed in the study carried out by ERM in 2000 on behalf of the European Commission. That study is divided into three main parts: (i) the scientific context of eutrophication, (ii) a tentative to review, assess and compare criteria used in some EU Member States and (iii) some suggestions of complementary criteria to define eutrophication in coastal areas.

In the scientific context part, some relevant statements for the purpose of this modelling study are:

- Eutrophication is not a "black and white" process (page 1);
- Eutrophication is a process not a state. Many upwelling areas have always been eutrophic and are not experiencing eutrophication (page 4);
- Eutrophication is a slow but universal phenomenon that started centuries ago (page 6);
- Quantification of the eutrophication rate requires the knowledge of baseline information and its current or predicted status, but baseline information is the exception rather then the rule (page 4);
- Short-term measurements of chlorophyll provide less certain evidence for eutrophication. The evaluation of eutrophication based on chlorophyll measurements requires information on grazers too.

In the conclusion of the scientific context, it is stated that:

- Much monitoring data has low statistical power to resolve the questions that were asked [about eutrophication], despite the sometimes enormous effort that was put into gathering it. Some aspects of marine eutrophication may be unanswerable, particularly with regard to baseline data.
- The elaboration of the precautionary principle in the late 80's was an attempt to resolve this question. The fact that marine eutrophication remains contentious implies that this attempt was not entirely successful.

- The relevant question is not whether eutrophication has occurred in marine waters, but whether unacceptable eutrophication has occurred.
- Expectation of a universal ecological index that provides a simple biometric approach for evaluating eutrophication may be unrealistic.
- When choosing criteria for assessing eutrophication, the relevant question is not "is the method perfect?", but "is the method good enough for the purpose". Techniques have to be judged in comparison with the strength and weakness of alternative methods rather then against a standard of perfection.

The considerations above are common to most systems. Identification and quantification of eutrophication rate in tidal systems is even more difficult due to the oscillating character of tidal flow. Models can be very useful tools in these systems.

Models aim to describe processes quantitatively and consequently they have the capability of putting into evidence the interaction between state variables in complex systems, as is the case of tidal estuaries.

In tidal estuaries, alternating flow enhances vertical and horizontal mixing and improves the interaction between nutrient load sources. Non-linear effects associated to the tidal flow can generate quite complex residual flows, which will be responsible for a wide range of residence times in the estuary. Residence time and mixing inside the estuary are major processes determining the fate of nutrients discharged in the estuary.

Circulation models are nowadays accept as powerful and economic tools to compute physical processes and are disseminate among coastal engineers and coastal system managers both for coastal works design and for management of navigation infrastructures. Validation of tidal circulation models is simple and economic since it can be based on historical data, which is available in major estuaries especially if commercial navigation is a relevant economic activity. In Portugal, this is the case in the Tagus and Sado estuaries and in a less extent in the Mondego.

Processes describing primary production and nutrient recycling are nowadays sufficiently well known to build models based on a set of parameters short enough to be manageable, but large enough to be common to many coastal systems. Coupling primary production models to physical models describing tidal transport allows for the development of sophisticated modelling tools to support coastal areas management.

In this study, models are used to describe circulation and residence times of the water inside the estuary and to simulate primary production, nutrient recycling and estuary-sea exchanges.

A detailed description of the model is object of a specific document, which includes a complete table with the parameters used in the simulations.

2.1 TEJO ESTUARY MODEL

2.1.1 Model Grid

Several model grids are used in this study, according to the purpose. To study the hydrodynamics (transient circulation, residual circulation and residence time) the model uses a grid with a step varying between 3500 m at the open sea boundary and 300 m in the estuary. This grid has 196 by 166 points and covers a surface of 90 km by 76 km. Figure 2-1 shows the whole model domain used for hydrodynamic simulations[1] and Figure 2-2 shows a zoom of the Tagus estuary. Vertical and horizontal lines in Figure 2-2 show the grid. To study the ecological processes, this bathymetry was integrated in space, merging 2x2 grid cells into one.

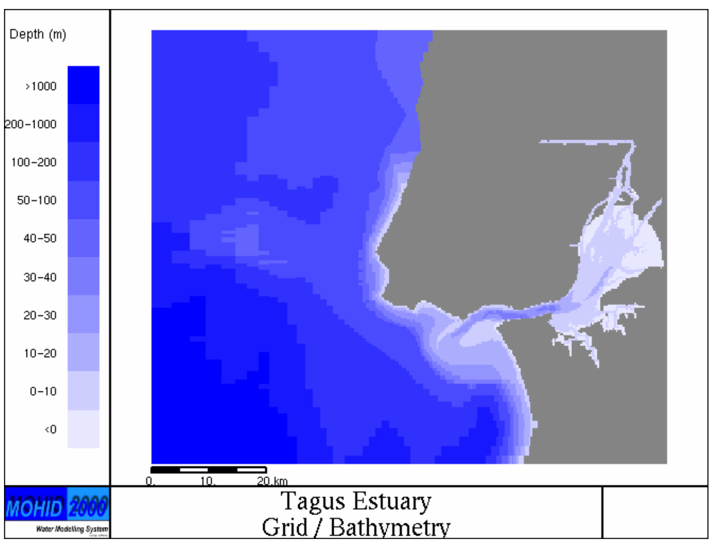


Figure 2-1: Bathymetry of the Tagus estuary. The location of the Tagus River is deflected due for computational efficiency when only a subset of this domain is considered in the simulations.

[1] IN this bathymetry, the river is "turned left" to allow simulations with a subset of the domain, still preserving the size of the fresh water zone in the estuary.

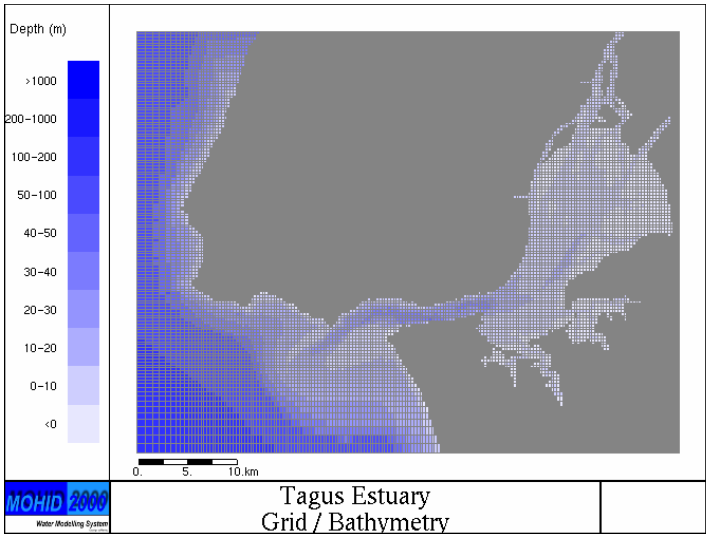


Figure 2-2: Grid of the Tagus estuary model

2.1.2 Hydrodynamics

The Tide and the river discharge are the main forces driving the Tagus estuary hydrodynamics. In the present study tidal forcing was imposed at the open sea boundary using tidal harmonics obtained from a global tidal mode and River discharges were obtained from records. In some simulations the wind forcing was also considered, although its contribution for the flow is of secondary importance.

2.1.2.1 Transient circulation

To describe the transient circulation of the Tagus estuary, the model was run using the grid presented in Figure 2-2 and forced with tide (all components) at the open boundary and with the average discharge of the Tagus River ($329.3 m^3 s^{-1}$). Simulations including both spring neap tidal conditions were accomplished and results are shown below for flood and ebb conditions. In all figures, colour represents the flow intensity and arrows the flow intensity and direction. Scales are indicated on the left side of the figures.

Figure 2-3 and Figure 2-4 represent the circulation during spring tide conditions. In these figures, it is possible to observe that inside the estuary, the water follows mainly the channels to reach the inter-tidal zones. Figure 2-5 shows a zoom of the estuary mouth during ebb. In this figure, it is possible to see that the maximum velocity, in the channel connecting the main estuary with the open sea, reaches 2 ms^{-1}. During neap tide periods,

Figure 2-6, the flow intensity is obviously lower, with maximum velocities of about 1 ms^{-1}.

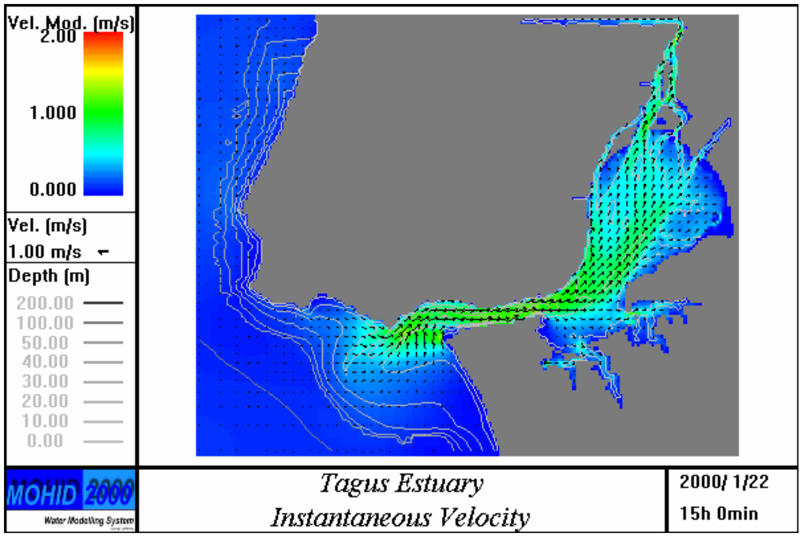


Figure 2-3: Velocity field during a spring tide (flood).

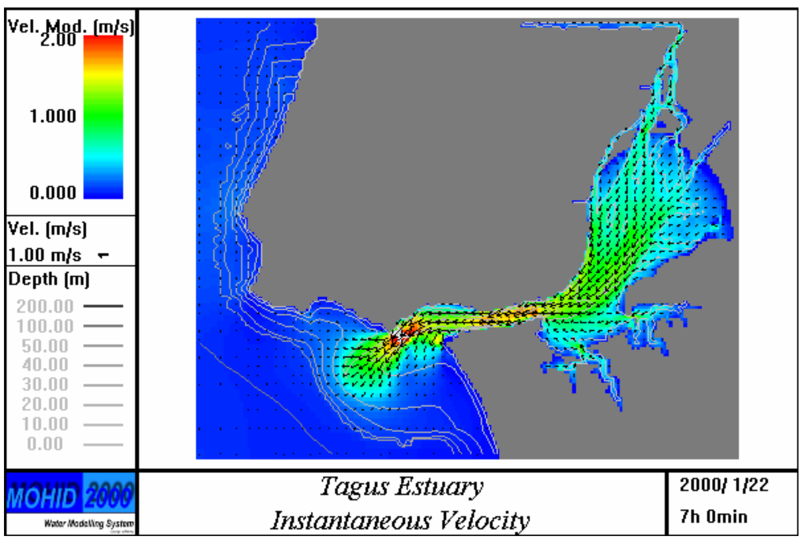


Figure 2-4: Velocity field during a spring tide (ebb).

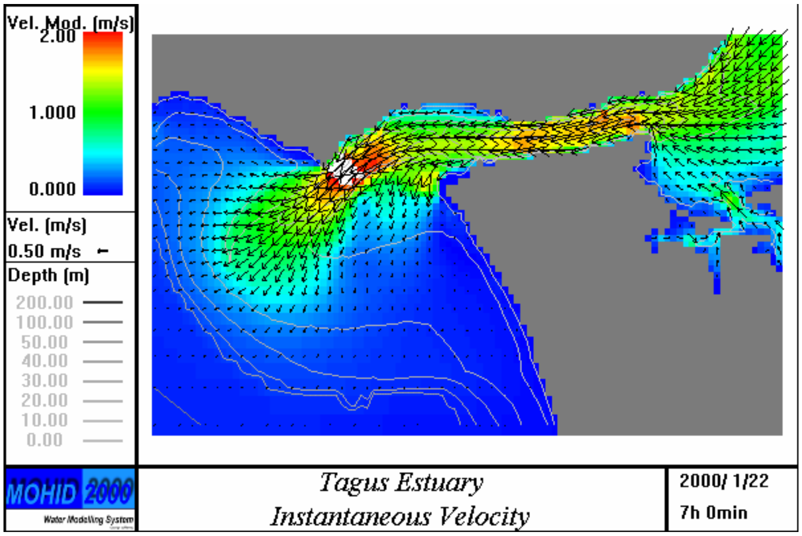


Figure 2-5: Velocity field at the estuary mouth during spring tide (ebb).

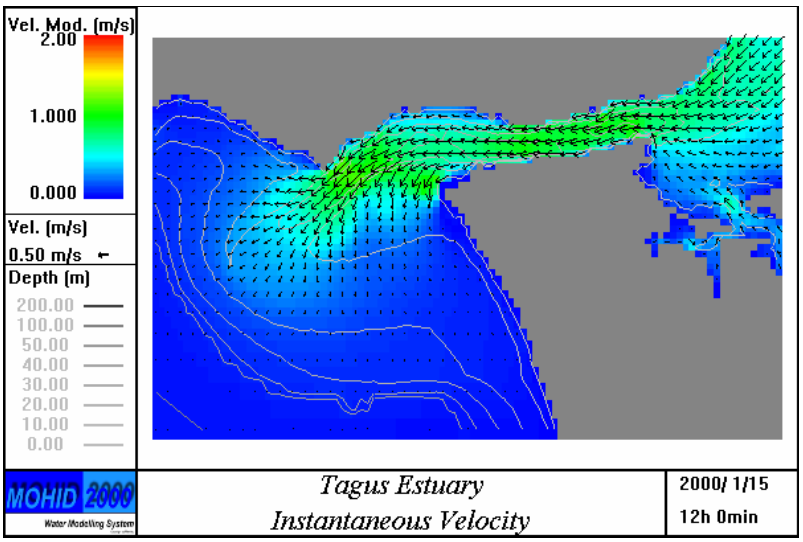


Figure 2-6: Velocity field at the estuary mouth during neap tide (ebb).

2.1.2.2 Residual circulation

The transient circulation gives information about the instantaneous flow. For a better understanding of the transport processes inside an estuary, the residual circulation is also presented. The residual circulation is the average flow and gives an idea of the preferential transport of any property discharged in the estuary. To obtain the residual velocity, the model must run over a period of time much longer than the time periods associated to the variability of the transient flow. The results presented in this report were obtained integrating the transient flow during 30 days..

The residual circulation can be defined in several ways: (i) as the average of the transient velocity field (m/s), (ii) as average of the transient water flux per unit of length – residual specific flux (m^2/s) - or (iii) as the residual specific flux divided by the average depth of the water column – which is also a velocity - (m/s). The residual flux gives a picture of the residual movement of the water volume, but it is difficult to visualise in figures including both deep and shallow areas, because the adequate scale is a function of the depth. Residual velocity computed directly integrating transient velocity and, residual velocity derived from the residual flux are identical in deep areas, but can be very much different in shallow areas. The former is convenient to infer on sediment transport above the bottom, while the latter is more adequate to infer on the residual transport by the water column. Only the residual flux has null divergence.

Figure 2-7 shows the residual velocity derived from residual flux at the mouth of the Tagus estuary. This figure shows two large eddies off the estuary mouth adjacent to the ebb jet, with residual velocities that can reach 20 cm/s. These eddies determine the distribution of the properties close to the mouth, and show that seawater enters in the estuary mainly along the land boundaries. Strong eddies occupy the lower part of the estuary channel, creating preferential paths for the water entering and leaving the estuary.

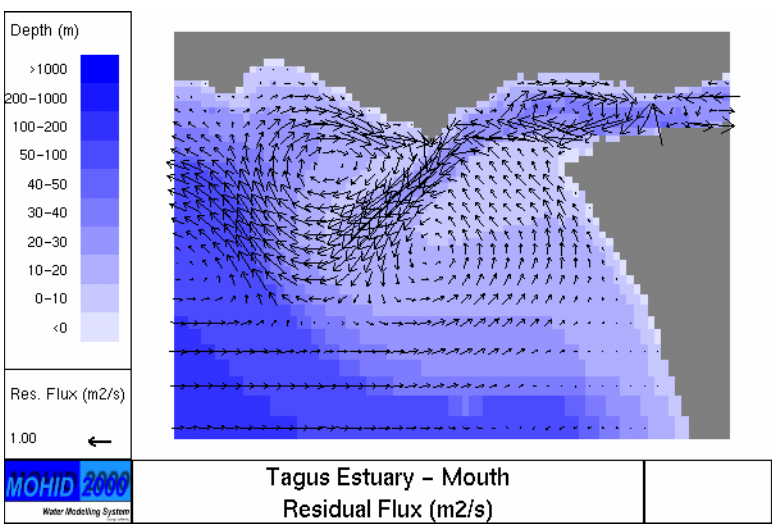


Figure 2-7: Residual specific flux in the lower part of the Tagus estuary.

Figure 2-8 represents the residuals in the interior of the Tagus estuary. Velocity is represented on the left and the specific flux on the right (only for the upper part of the estuary). In the upper part of the estuary the influence of the river discharge is very clear, showing the figure on the right side (specific residual flux) clearly the trajectory of the water. Most water flow along “Cala das Barcas” and a smaller part along “Cala do Norte”. In the Central estuary the flow is much more complex with small eddies, suggesting that this is an important mixing zone. In the lower part of the inner estuary there is a strong eddy which obliges material leaving the estuary to do it preferentially along the southern bank and water entering in the estuary to do it preferentially along the northern channel.

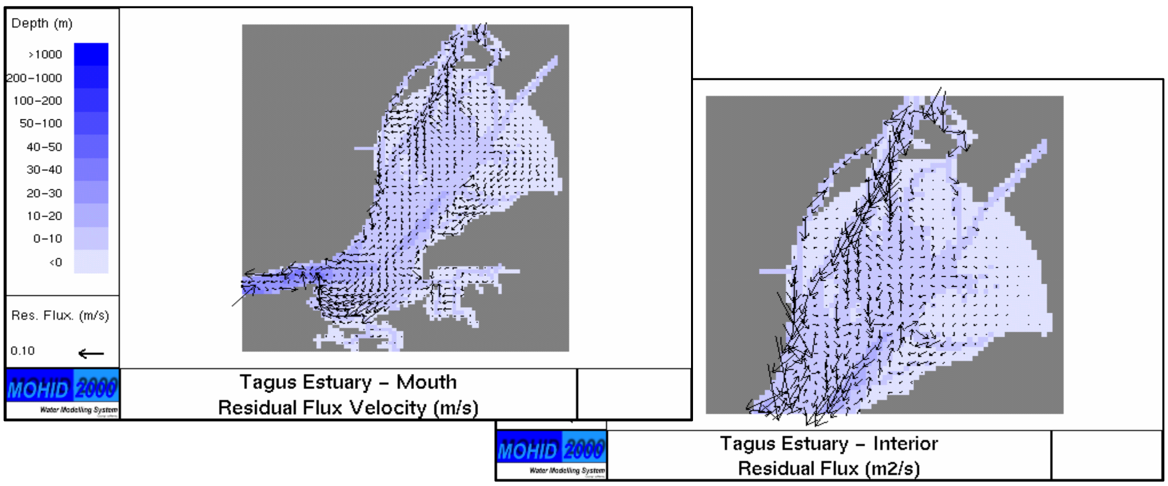


Figure 2-8: Residual velocity in the Tagus estuary. On the left figure it is represented the residual velocity and on the right the residual specific flux.

2.1.3 Residence time

Residence time is an important indicator for global understanding of an estuary. Estuaries with a short residence time will export nutrients from upstream sources more rapidly then estuaries with longer residence time. For the algae bloom this is particularly important as estuaries with very short residence time are expected to have much lower algae blooms, then estuaries with higher residence time. In addition, estuaries with residence times shorter than the doubling time of algae cells will inhibit formation of algae blooms (EPA, 2001).

There are several ways to define residence time, which depend a lot on the data available to compute it. A clear overview is given in the Technical Guidance Manual for Nutrient Criteria (EPA, 2001).The availability of a numerical model allows the most detailed calculation. In this study, the residence time is defined as the time required by water to leave the estuary and is computed using lagrangian tracers, which are used to label the water and to monitor its location. Different regions inside the estuary are identified by “boxes”, which are uniformly filled with tracers, representing each the same volume of water. The locations of the tracers are monitored in time and their residence time inside each part of the estuary and the time required to leave the estuary are computed.

Estuary residence time, in each estuary, was computed performing the following steps:

- Computation of hydrodynamics forced by tide, wind and mean annual river inflow (329.3 m^3s^{-1} in the Tagus).
- Division of the estuary into boxes that are filled with lagrangian tracers, which properties are the volume, the spatial coordinates and the number of the box where they were released. The total amount of tracers and their initial distribution in each box are calculated so that the total volume of the tracers inside of the box matches its water volume
- Calculation of the residence time as shown in the appendix describing the model detail.

Figure 2-9 shows the initial distribution of the lagrangian tracers in the Tagus estuary. The distribution fills the whole estuary, considering the lower limit of the estuary as defined in the study “Limites de Jusante dos Estuários Portugueses” (INAG, 2001).

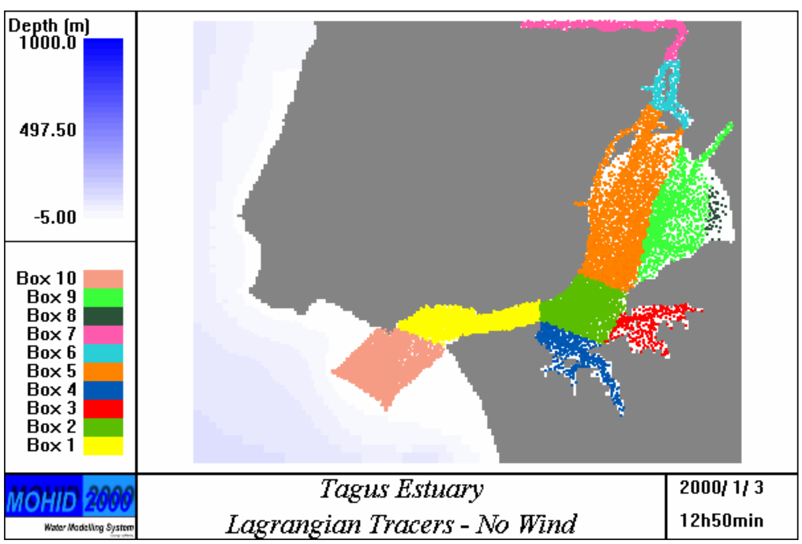


Figure 2-9: Initial distribution of the lagrangian tracers in the Tagus estuary

The total volume of the tracers in the estuary, at the beginning of the simulation, is equal to the total volume of the estuary. It is important to keep in mind that the total volume of the estuary varies with time, due to daily tidal oscillations and to the spring-neap tidal cycle. All simulations presented in this report start at high tide. Figure 2-10 shows the evolution of the volume of water inside the Tagus estuary, during the simulation period. The difference between high tide and low tide volumes - tidal prism - varies between $0.5x10^9m^3$ in neap tides and $1.0\ x10^9m^3$ in spring tides, corresponding respectively to 20 and 40% of the average volume of the estuary ($\approx 2.7\ x10^9m^3$). The freshwater inflow of the Tagus estuary ($1.5\ x\ 10^7m^3$ per tidal period, $2.85\ x\ 10^7m^3day^{-1}$) is much less important (about 1% of the tidal prism).

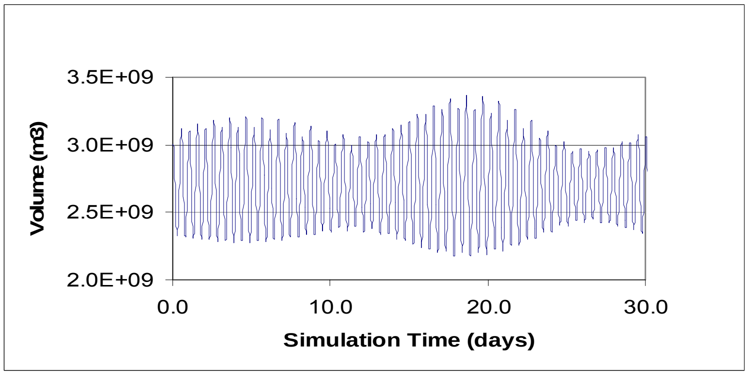


Figure 2-10: Variation of the water volume inside the Tagus estuary during the simulation period

To evaluate the residence time inside the Tagus estuary three forcing scenarios have been studied. In the first scenario, the model was forced only by the tide, in the second scenario a constant Northern wind of 3m/s was added to the tidal forcing and in the third scenario a Southern wind with the same speed was considered. For the scenario without wind forcing, besides the estuary, the exchange of water among boxes was analyzed together with the residence time.

Figure 2-11 and Figure 2-12 show the distribution of the lagrangian tracers respectively 10 and 20 days after tracer releasing for the scenario without wind forcing. In these two figures, it is possible to observe that the lagrangian tracers are gradually flushed out of the estuary. Most tracers leave the estuary northwards, as a consequence of the coriolis force.

In this scenario, n o coastal current was considered. In fact there is a coastal current which tend to remove the water discharged by the estuary off the mouth region. The pole ward density flow existing on the slope between 200 and 2000 meters deep gets very close to the coast in this region, enhancing the northward transport of the Tagus Plume. As a consequence of the circulation off the estuary, the realistic distribution of tracers outside the estuary is a much longer and narrower plume.

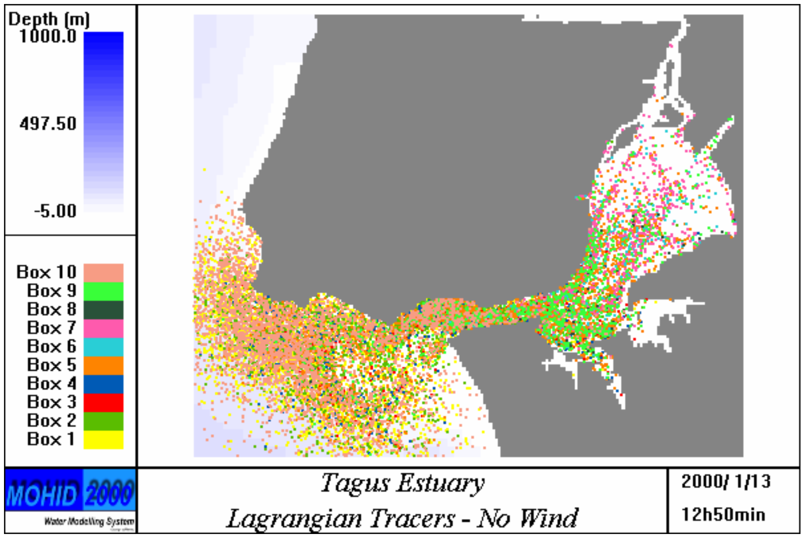


Figure 2-11: Distribution of the lagrangian tracers in the Tagus estuary after 10 days (No wind scenario)

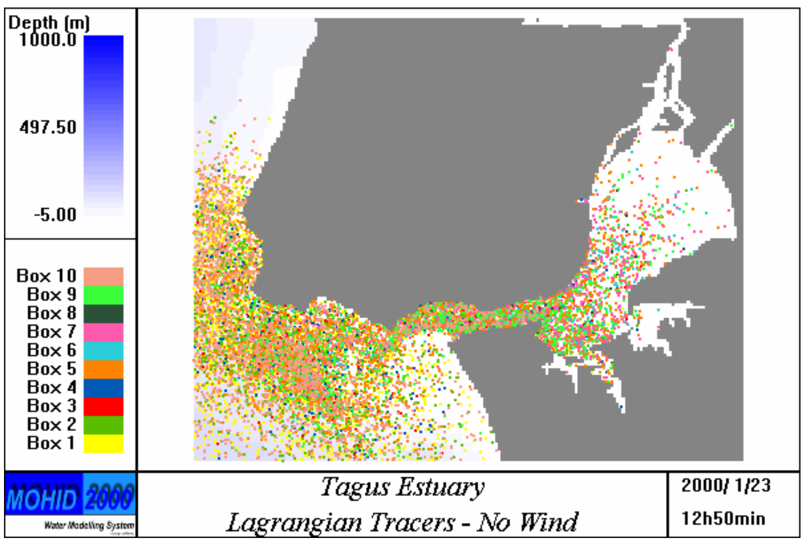


Figure 2-12: Distribution of the lagrangian tracers in the Tagus estuary after 20 days (scenario forced only by the tide and river discharge).

The evolution of the fraction of the tracers inside the estuary (volume of all tracers inside the estuary divided by the total volume of water in the estuary at the same instant) is shown in Figure 2-13. This figure shows that 10 days after releasing of the tracers about 50% of the initial volume remains inside the estuary and that after 20 days only about 25% remain there.

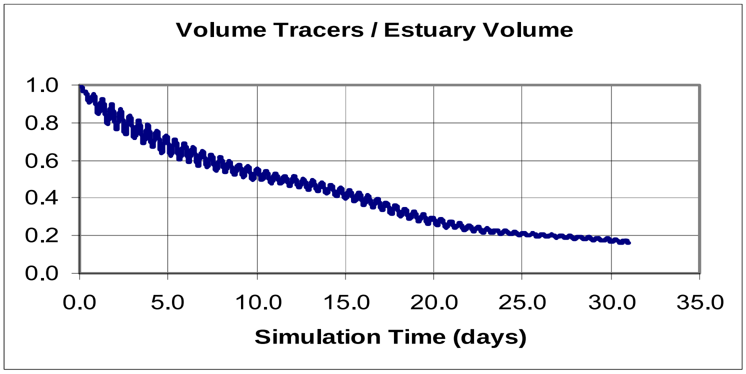


Figure 2-13: Evolution of the ratio between the volume of lagrangian tracers inside the estuary and the total estuary volume as a function of the time (No wind scenario).

The residence time is an objective parameter to compare estuaries, but its absolute value can be quite ambiguous for management purposes. In this text, two calculation methods are assessed to minimise this ambiguity. Defining residence time as the time required for a certain percentage of the water to leave the estuary, its value can be read in the "time axis" of Figure 2-13. In that figure, one can verify that after the 20^{th} day the slope of the curve is quite small. This is because in absence of the littoral current parallel to the coast, the tracers that left the estuary during ebb tend to reenter during flood. Defining the residence time as the time required for 80% of the water to leave the estuary, one would obtain 25 days.

This definition of the residence time accounts only for the time required for expelling a fraction of the estuarine water, but does not account for the history of the renewal process. A way to account for that history is to compute the residence time integrating the contribution of the lagrangian tracers for the instantaneous volume of the estuary. If the water inside the estuary was not renewed, a graphical representation of this quantity as a function of time would be a horizontal straight line, with unitary slope. In a situation when the initial water still remaining inside the estuary is 50%, the slope of the line would be 0,5 and for one unit of real time (x-axis) one would get 0.5 on the y-axis.

As the water is renewed in the estuary, the contribution of the initial water for the actual water inside the estuary tends to zero and the integral - represented on the y-axis - tends to a constant value. The ratio between the y-axis value and the x-axis value gives an idea of the contribution of initial water for the total water inside the estuary, at each moment.

This method can be interesting to simulate the residence time of the water in one region of the estuary providing simultaneous information on the contribution of that water for the composition of the water into another region of the estuary. For the particular case of the contribution of the water from one region for the composition of the water of the estuary as a whole, in the first part of the simulation one would get a graph that is a straight line, with a slope equal to the initial volume of the water being monitored, divided by the total volume of the estuary. The slope of that line would start decreasing when the water reached the sea boundary and started to be exported.

Using this approach for the whole estuary, the result is as shown in Figure 2-14. This figure represents the evolution of the residence time as a function of the simulated days (real time). For each instant, the figure represents the integration of the fraction of the estuary occupied by the initial tracers. As the initial tracer leave the estuary, the integral tends to a constant value. In case of the Tagus estuary 12 days is reached after 32 days of simulation. This value means that the initial water inside the estuary has influenced it as a whole on a fraction of 12/32, while the new water has influenced it on a proportion of 20/32.

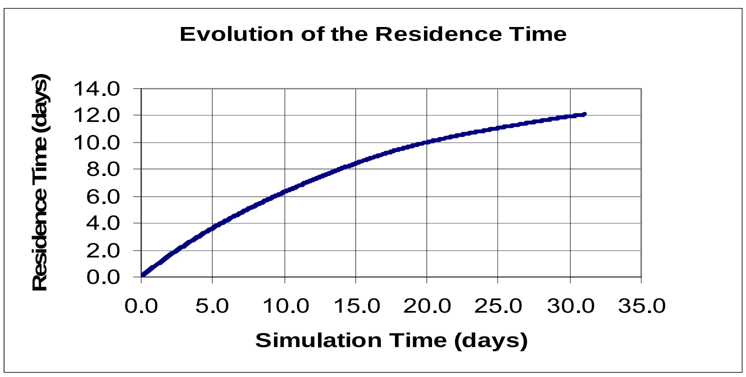


Figure 2-14: Alternative way for defining the residence time in the estuary, accounting for the role of the “old” water in the estuary.

Combining the information of Figure 2-13 and of Figure 2-14 one can say that during 25 days (value of the residence time defined on a traditional way), the water initially inside the estuary contributed for about 11/25 for the average properties of the estuary.

Figure 2-15 and Figure 2-16 correspond to Figure 2-13, but considering also north and south wind forcing, respectively. Figures show that the wind influences only marginally the residence time of the water inside the estuary. North wind tends to increase it, because it slows down the northward flow out of the estuary, contributing to trap the water discharged by the estuary in the neighbourhood of its mouth. In case of south wind the effect is a reduction of the residence time, for the same reason.

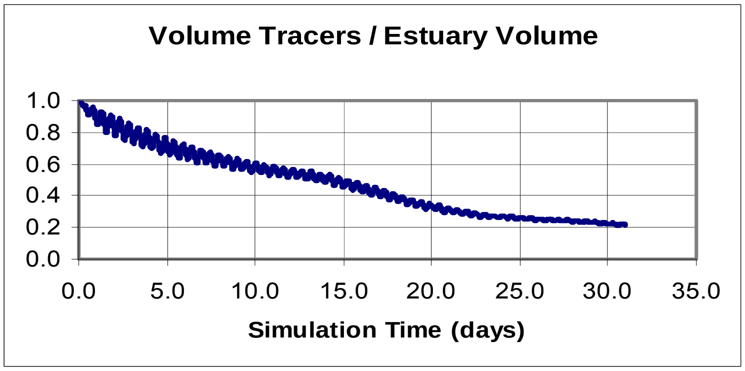


Figure 2-15: Evolution of the ratio between the volume of lagrangian tracers inside the estuary and the total estuary volume as a function of the simulated time (North wind).

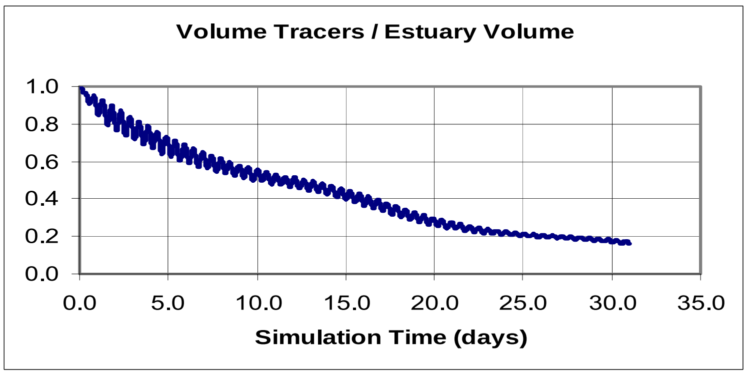


Figure 2-16: Evolution of the ratio between the volume of lagrangian tracers inside the estuary and the total estuary volume as a function of the simulated time (South wind).

Information identical to that shown in Figure 2-14 is presented in Figure 2-17 and in Figure 2-18 for North and South wind conditions respectively. From these figures, it is possible to conclude that North wind will increase the residence time in the estuary and South wind will shorten the residence time, for the reasons described above.

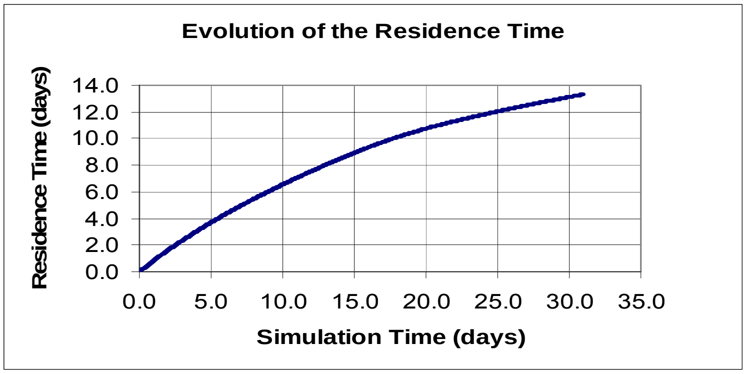


Figure 2-17: Alternative way for defining the residence time in the estuary, accounting for the role of the "old" water in the estuary (forcing also with north wind).

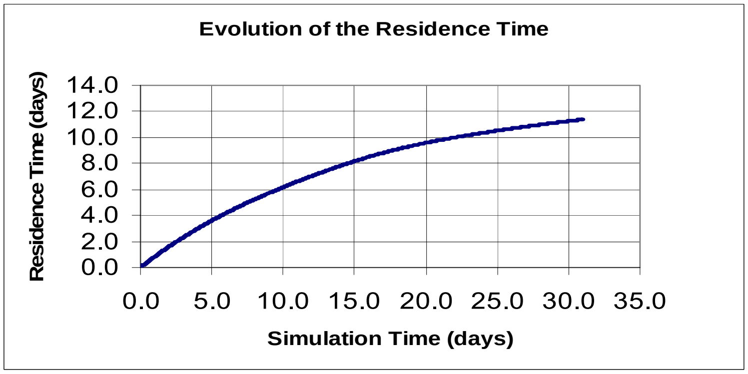


Figure 2-18: Alternative way for defining the residence time in the estuary, accounting for the role of the "old" water in the estuary (forcing also with north wind).

The knowledge of the exchange of water among boxes can be more important than the knowledge of the residence time of the water in the estuary as a whole. With the methodology used in this study, it is possible to track the path of water masses in time. This tracking allows calculating the residence time in each box and analyzes what is the origin of the water in a given box at each instant of time.

The exchanges among regions of the estuary are presented in Figure 2-19.The information is presented in the form of "pie charts" representing the integration of the contribution of the water generated in each part of the estuary for the composition of the water in a specific part of the estuary, as a percentage of the total water that was in the box during the integration period (5 days, in case of Figure 2-19). The white part of the pie chart represents the volume of new water[2] that wasn't inside the estuary in the

[2] New water is in fact fresh water flowing from the river and marine water flowing from the open sea.

beginning of the simulation. A map of colours to identify the boxes is provided on the left side of the figure.

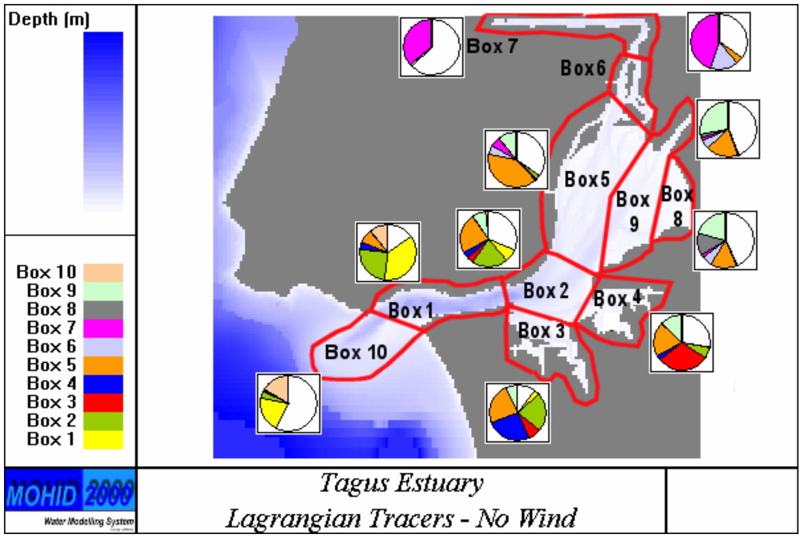


Figure 2-19: Water exchange among boxes (results integrated over 5 days).

Figure 2-19 permits to extract some interesting conclusions. Box 7 (river channel) contributes for the volume of all other boxes, but its contribution is dominant only for Box 6 (the box at the end of the channel) and significant for box 5. On other hand, other boxes do not contribute for the composition of the water in this box. This means that the new water inside this box is totally freshwater coming from the river. Other interesting conclusions are (i) Box 1 and 3 are those receiving less new water (ii) Typically, after 5 days more then ¾ of the water initially in the boxes has been replaced.

The explanation for the slower renovation of the water in Box 1 and 3 can be found in the residual circulation, especially in the two large eddies located off the mouth of the estuary. The water in Box 1 moves out of the estuary during ebb mainly along the ebb jet and moves in again mainly along the northern bank. Marine water enters in the estuary mainly along the southern margin and reaches the inner estuary in one tidal cycle. This mechanism can be visualized in Figure 2-20, representing distributions of tracers emitted continuously[3] in 4 points, 3 close at the mouth of the estuary (red, green, blue) and one at the river entrance (yellow).

[3] In former figures, tracers were emitted instantaneously in boxes. In the next figures tracers are emitted continuously in points and identify the water that has passed in the emission points.

In the figure are show the distribution of tracers in 4 instants of time, one just at the beginning of the emission, in a ebb situation, another after 1.5 days, another 5 days after the beginning of the emission, close to high water and the last in low water. One can see that the first marine water to reach the inner estuary is “green” water, entering close to the southern bank of the estuary mouth. One can also see that marine water progresses slowly in the inner estuary and that after 5 days it occupies most of the region with important residual eddies. The water discharged from the river reaches in low water, approximately the same zone of the estuary as the marine water at high water. The water discharged by the Tagus tends to flow along the northern bank, showing that the water new fresh water flowing into boxes 8 and 9 is water from the Sorraia River.

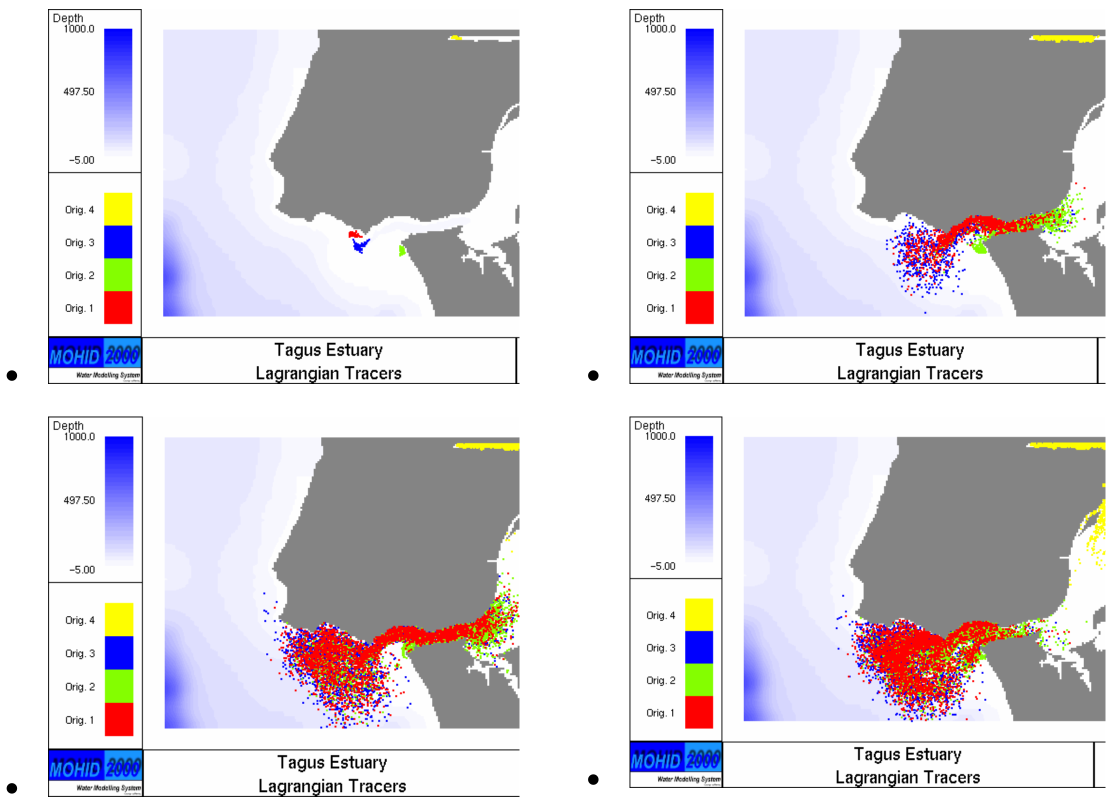


Figure 2-20: Distributions of tracers emitted in 4 sources, labelling marine and river water.

The red tracers tend to occupy the estuary channel (often designated as corridor) both in flooding and ebb period, because of the northern recirculation eddy off the mouth and of the eddy in the lower part of the inner estuary. This flow pattern explains why the water in this box is renewed slowly than the water in box 2, further inside the estuary.

This information complements the information about residence time and shows that the renovation of the water is not a linear process, with faster renovation close to the sea boundary. The non-linear processes accelerate the mixing in the estuary and make the solution complex.

Figure 2-21 represent the same type of information of Figure 2-19 but after 15 days of integration and Figure 2-22after 30 days of integration. These figures show the evolution of the results in time and provide some insight on the interpretation of this type of information.

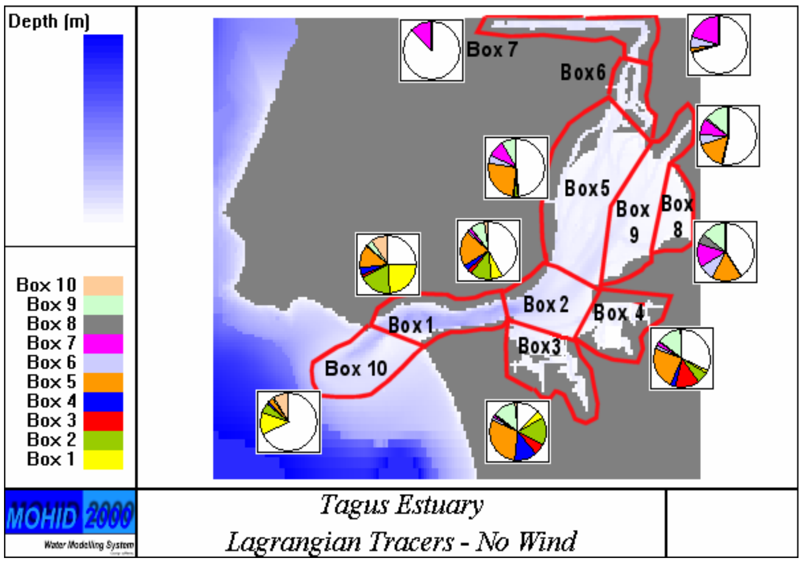


Figure 2-21: Water exchange among boxes (results after 15 days of integration).

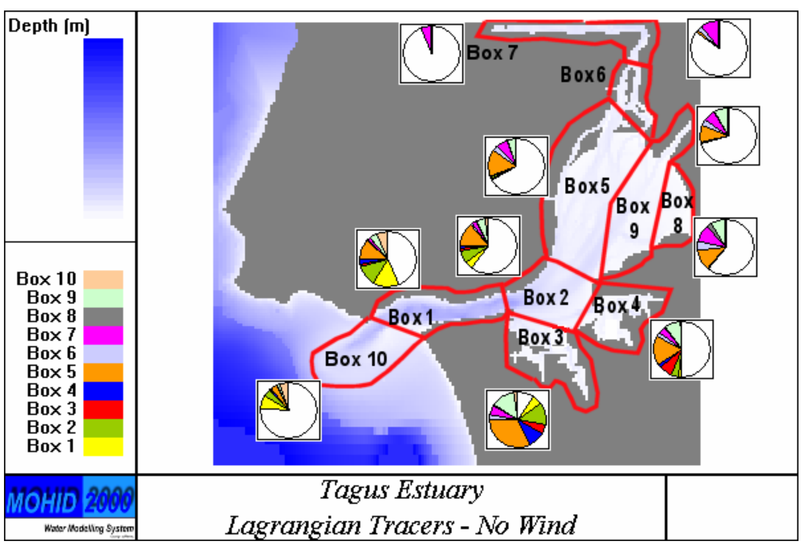


Figure 2-22: Water exchange among boxes (results after 30 days of integration).

Let us consider the water originated into Box 7. After five days of integration, this water had influenced mainly Box 6 and Box 5. During the next 10 days, that water was dispersed in the estuary and had been already in most boxes upstream of Box 1. 15 days later, the number of boxes visited by this water had increased, but the relative importance for boxes already visited after 15 days has decreases, showing that the water form box 7 had been already replaced by new water.

2.1.4 Ecological modelling

Ecological modelling was performed to understand and quantify the main processes responsible for the ecological functioning of the estuary. The simulations were carried out for nowadays conditions (reference situation) and for plausible scenarios of management. The model was validated using the reference situation results, which is in fact the scenario for which field data exists.

2.1.4.1 Reference Situation

The next paragraphs describe (i) field data used to impose boundary conditions and for model validation, (ii) the results of the model and their comparison with field data (model validation) and (iii) some integrated analysis of the results in order to give an overview of the ecological functioning of the estuary.

2.1.4.1.1 Estuary Loads

Loads are grouped into (i) river loads (Tagus, Sorraia and Trancão) and (ii) discharges from Urban Waste Water Treatment Plants (UWWTP). Diffuse loads due to lixiviation of agricultural land also exist, but they are negligible compared with the contribution of the agricultural load carried by the river.

Figure 2-23 shows the location of the relevant discharges in the Tagus estuary (rivers and UWWTP).Loads are characterized in terms of discharge and concentrations of Nitrate, Ammonia (NH_4^+), Organic Nitrogen and Nitrite.

2.1.4.1.1.1 Description of rivers discharging in the estuary

The main rivers discharging in the estuary are the Tagus, Sorraia and Trancão. Other streams discharging in the estuary have very small loads and have not been considered.

Figure 2-23: Location of more important discharges in the Tagus Estuary.

2.1.4.1.1.1.1 Tagus River

The Tagus River is the most important fluvial component in the estuary. Its discharge has a pronounced seasonal variability, with flow rates varying typically between 100 and 2000 m^3/s. Data to characterise the discharge was obtained from Ómnias-Santarém Field Station, which location is represented in Figure 2-24. Table 2.1-1 shows the properties measured in the Station and the methods used to estimate properties required by the model, but not measured.

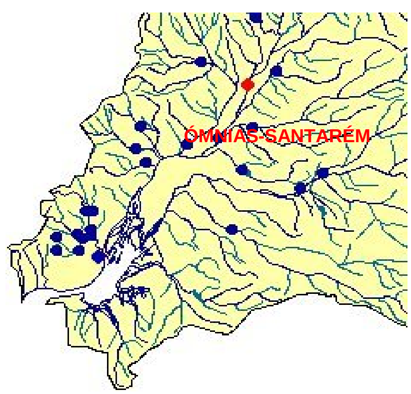


Figure 2-24: Location of Ómnias-Santarém Field Station.

Name	Units	Source
Flow	m^3 / s	Field Station Register
Nitrate	mg N / L	Field Station Register
Nitrite	mg N / L	Field Station Register
Dissolved Oxygen	mg O_2 / L	Field Station Register
Total Solids	mg / L	Field Station Register
Temperature	ºC	Field Station Register
Ammonia	mg N / L	Field Station Register
Dissolved Organic Nitrogen Refractory	mg N / L	15% Total Organic Nitrogen calculated using Total Nitrogen Kjeldahl, registered in the field station; Kjeldahl Method determine Ammonia and Organic Forms in the water
Dissolved Organic Nitrogen Non Refractory	mg N / L	35% Total Organic Nitrogen
Particulate Organic Nitrogen	mg N / L	50% Total Organic Nitrogen
Phytoplankton	mg C/L	Assumes chlorophyll-a registered is directly proportional to the concentration of phytoplanktonic biomass, considering 60 mgC/mg Chlorophyll–a as a conversion factor (Portela,1996)
Zooplankton	mg C / L	Considers zooplanktonic biomass about 0.0045

Table 2.1-1: Properties monitored in Ómnias-Santarém Field Station

Figure 2-25 shows all data available of ammonia and nitrate as functions of the river discharge. The figure shows that for large discharges, the concentrations become independent of the discharge. For small values of the discharge (below 600 m^3/s), the concentrations have high variability, but tend to be bounded by the value of the concentration for high discharges. Figure 2-26 shows for the year 1998 daily measurements of the river discharge - which arithmetic average value is 375 m^3/s – and monthly values for the concentrations of nitrate, ammonia and suspended solids. The values are within the range displayed by Figure 2-25.

For the year 1998, monthly values of properties measured in 7 points distributed along the estuary are also available. For that reason, the year 1998 was chosen to be the reference year in this study. The values of ammonia and Organic Matter measured in April seems to be anomalous, although the ammonia is in the range shown in Figure 2-25, and were not considered in the simulations. Anyway, even considering those values, the discharge of nitrogen in the form of ammonia remains quite below the discharge of nitrate and results of tests with the model showed that such a anomalous discharge would be identifiable only in the river channel.

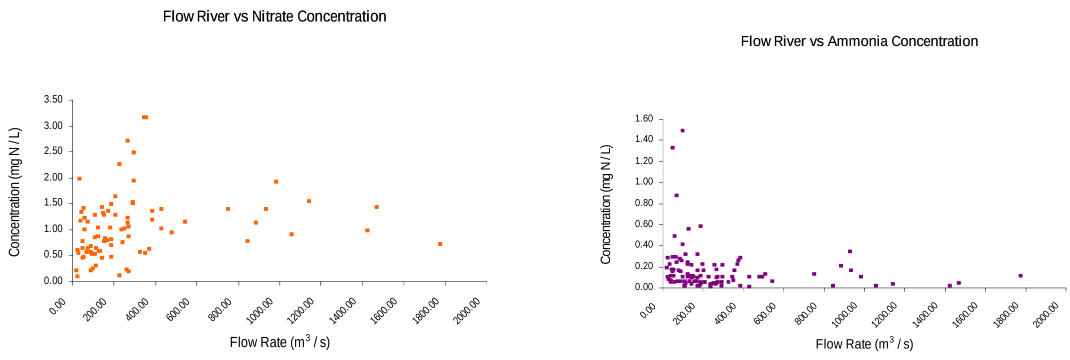


Figure 2-25: Tagus River Flow Rate vs Nutrients Concentrations

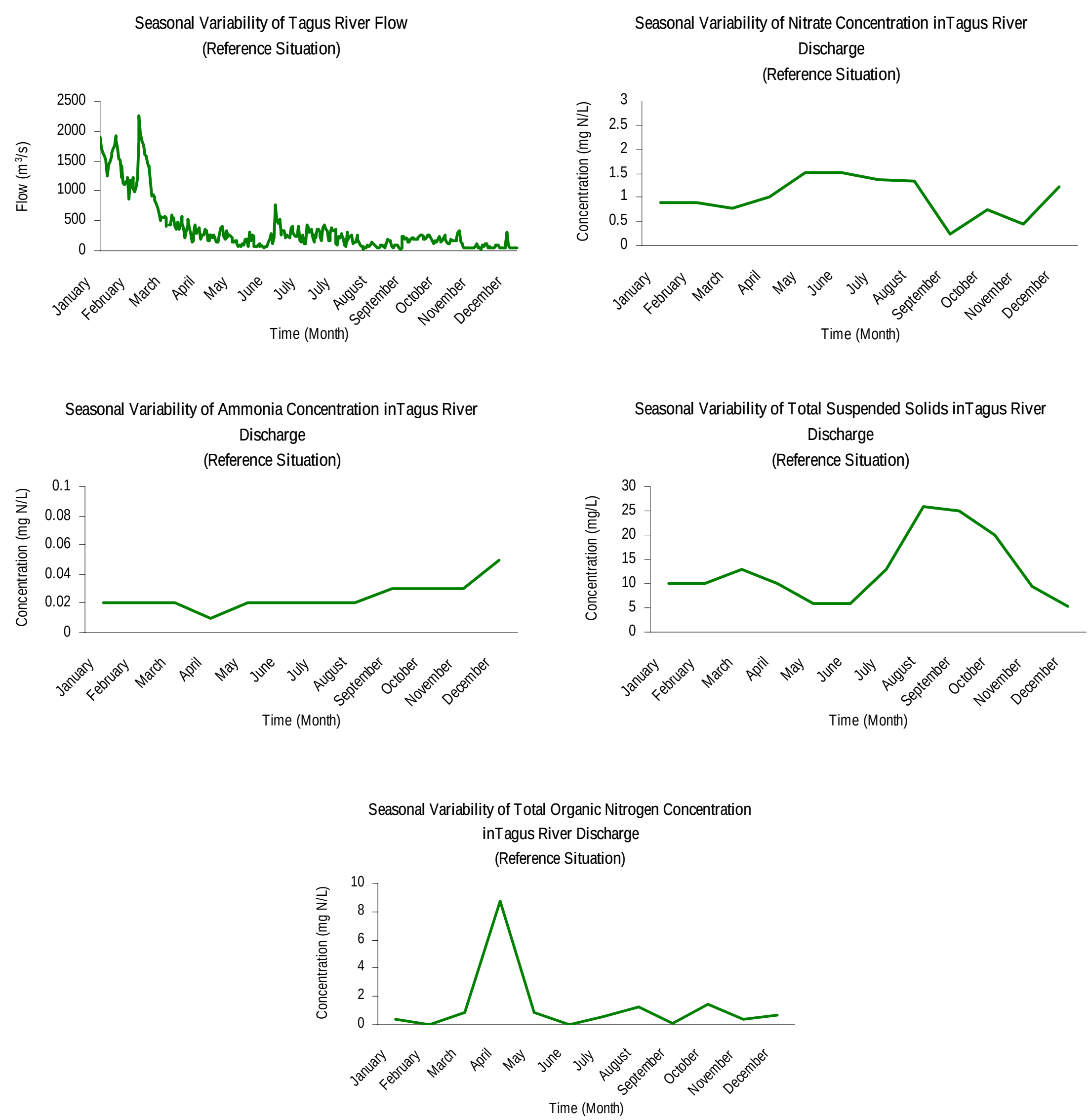


Figure 2-26: Monthly distribution of some properties in Tagus River during 1998. The two peaks of Organic Nitrogen and Ammonia do not seem realistic.

2.1.4.1.1.1.2 Sorraia River

The average discharge of Sorraia river is about 40 m^3/s, representing less 15% of the discharge of the Tagus river. It drains a plane with intense agricultural activity. Field data is measured in two field stations, Porto Alto and Coruche, represented in Figure 2-27. S. Estevão is a field station in one of the main tributaries of the Sorraia.

Figure 2-27: Field Stations used for Sorraia Discharge characterization

Property		Sorraia Discharge
Flow (m^3 / s)		39,5
Total Solids (mg / L)		196
Biochemical Oxygen Demand (mg O_2/ L)		8,30
Inorganic Nitrogen	Nitrite (mg N / L)	0.13
	Nitrate (mg N / L)	0.98
Ammonia (mg N / L)		0,567
Dissolved Organic Nitrogen	Dissolved Organic Nitrogen Refractory (mg N / L)	0,26
	Dissolved Organic Nitrogen Non Refractory (mg N / L)	0,613
Particulate Organic Nitrogen (mg N / L)		0,88
Phytoplankton (mg C/L)		0.05
Zooplankton(mg C/L)		0.0045

Table 2.1-2: Mean values of properties in Sorraia River.

Unlike in the Tagus River, in the Sorraia there isn't any single Station, where all the parameters have been sampled simultaneously. For that reason some approaches have to be done. The discharge was assumed to be the addition of the values measured in S.Estevão and Coruche (values measured between 1990 and 1993).

For water quality, the study uses known data records from Porto Alto station (between 1990 and 93). Organic nitrogen was not measured and was assumed to have the same concentration as in the Tagus River. Table 2.1-2 displays the average values obtained for the Sorraia. Comparison of the values in the table with values for the Tagus River show quite similar values.

2.1.4.1.1.1.3 Trancão River

The Trancão River has a small but highly densely urbanised basin. It has a very small natural flow (5 m^3/s) when compared with the Tagus and Sorraia, but the nitrogen load is important, although, WWTP were built recently in Beirolas, S. João da Talha and Frielas. Average values of the discharge and concentration measured in the Field Station of Ponte de Canas were used in this study. Again, like in the Sorraia records do not include Organic Nitrogen, but in this case it was assumed that the major contribution for Organic Nitrogen loads is from the WWTP effluents (see next paragraph).

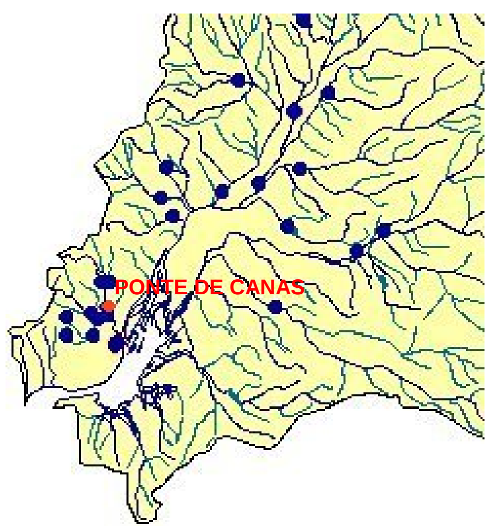


Figure 2-28: Ponte de Canas Field Station, in Trancão Basin.

2.1.4.1.1.2 Loads from Waste Water Treatment Plant

In the area surrounding Tagus Estuary, there is a large number of cities and consequently great disposal of wastewater into the Estuary. Presently there are 10 working WWTP and 6 are being built. The location of the treatment plants is indicated in Figure 2-23.

Table 2.1-4 lists the WWTP, giving the geographical coordinates and type of treatment. WWTP effluents are characterized through the same parameters used in the rivers: discharge and concentration values of Ammonia, Nitrate, Nitrite, Organic Nitrogen and Biochemical Oxygen Demand. The difference in temperature between wastewater and estuary water is not significant and was not considered.

Properties		Trancão Discharge
Flow (m^3 / s)		5
Total Solids (mg / L)		76.4
Inorganic Nitrogen	Nitrite (mg N / L)	0.2
	Nitrate (mg N / L)	4.7
Ammonial (mg N / L)		13.7
Dissolved Organic Nitrogen	Dissolved Organic Nitrogen Refractory (mg N / L)	3.4
	Dissolved Organic Nitrogen Non Refractory (mg N / L)	1.5
Particulate Organic Nitrogen (mg N / L)		11.1
Phytoplankton (mg C/L)		0.05
Zooplankton(mg C/L)		0.0045

Table 2.1-3: Trancão Discharge Characteristics

Some of the WWTP already working have monitoring studies of their efficiency and produce reports with information on affluent and effluent discharge and properties. In case WWTP being built, loads were estimated based on population number and typical values found in bibliography for per capita ratios. Values and considerations are reported

Table 2.1-5. Figure 2-29 describes the typical relation between different forms of nitrogen in domestic wastewater, used to estimate the values of the domestic loads, if not measured.

Table 2.1-6 lists the characteristics of the affluent of each WWTP and Table 2.1-7 lists the typical efficiency of treatment plants according to the type of treatment. Finally the total loads form WWTP in the estuary were computed and listed in

Table 2.1-4.

Name	Mesh Localization		Portuguese Militar Co-ordinates		Geographical Co-ordinates		Population Density	Situation	WasteWater Treatment
	I CELL	J CELL	X	Y	Latitude	Longitude			
Mutela	**19**	**52**	**111550**	**190000**	**38º 40' N**	**9º 9´ W**	**147900**	**Plan**	**-**
Portinho da Costa	**20**	**40**	**105450**	**190250**	**38º 41' N**	**9º 13´ W**	**140000**	**Plan**	**-**
Quinta da Bomba	**14**	**54**	**112750**	**187050**	**38º 39' N**	**9º 8´ W**	**277750**	**Working**	**Secundary**
Alcântara	**24**	**50**	**109400**	**192800**	**38º 42' N**	**9º 11´ W**	**623435**	**Working**	**Primary**
Chelas	**29**	**59**	**115150**	**195700**	**38º 44' N**	**9º 6´ W**	**210698**	**Working**	**Secundary with Nitrogen Removal**
Alhos Vedros	**19**	**66**	**120400**	**190250**	**38º 41' N**	**9º 3´ W**	**4000**	**Working**	**Secundary**
Moita	**17**	**74**	**124500**	**188850**	**38º 38' N**	**9º 1´ W**	**75780**	**Plan**	**-**
Palhais	**10**	**66**	**119350**	**185350**	**38º 38' N**	**9º 4´ W**	**342467**	**Working**	**Secundary**
Montijo	**24**	**74**	**123850**	**193200**	**38º 42' N**	**9º 1´ W**	**60000**	**Working**	**Primary**
Alcochete	**32**	**76**	**125900**	**197750**	**38º 45' N**	**8º 59´ W**	**10000**	**Working**	**Secundary**
Vila Franca de Xira	**70**	**75**	**126750**	**221500**	**38º 58' N**	**8º 58´ W**	**60100**	**Plan**	**-**
Alverca	**58**	**71**	**122650**	**213350**	**38º 53' N**	**9º 2´ W**	**213339**	**Plan**	**-**

Table 2.1-4 Location and characteristics of Waste Water Treatment Plants..

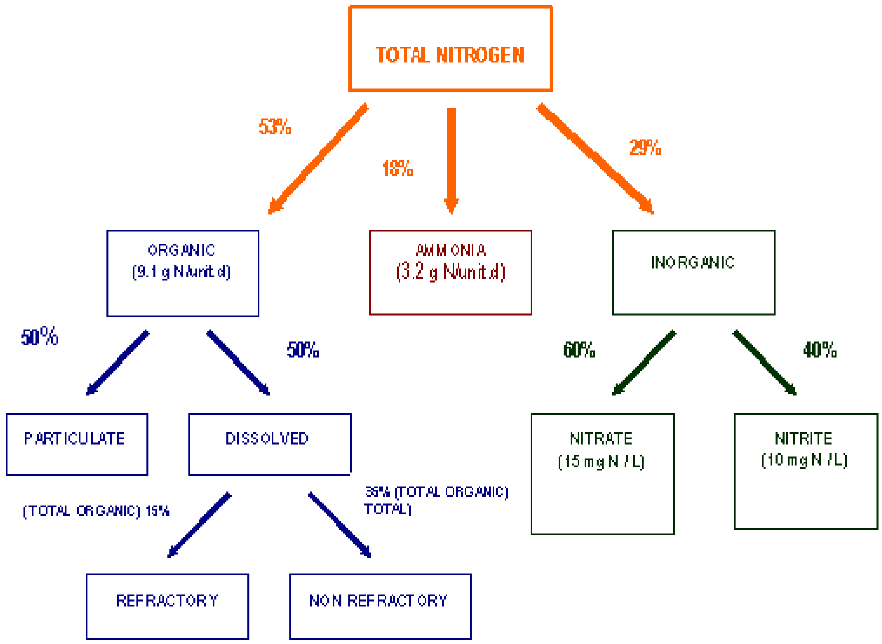


Figure 2-29: typical ratios between different forms of Nitrogen in domestic Waste Water Discharge.

Properties		Typical Value
Flow		**200 L / unit.d**
Total Solids		**90,7 g / unit.d**
Biochemical Oxygen Demand (CBO_5)		**60 g / unit.d**
Inorganic Nitrogen	Nitrite	**10 mg N / L**
	Nitrate	**15 mg N / L**
Ammonia		**3,2 g N / unit.d**
Organic Nitrogen		**9,1 g N / unit.d**
Dissolved	Dissolved Organic Nitrogen Non Refractory	**35% of Total Organic Organic**
	Dissolved Organic Nitrogen Refractory	**15% do Total Organic Organic**
Particulate		**50% do Total Organic Organic**

Table 2.1-5: Typical Values of the properties of the affluent to WWTP.

Name	Flow (m^3/ s)	Total Solids (mg / L)	Biochemical Oxygen Demand (mg O_2 / L)	Nitrate (mgN/L)	Nitrite (mgN/L)	Ammonia (mgN /L)	Dissolved Organic Nitrogen Refractory (mg N /L)	Dissolved Organic Nitrogen Non Refractory (mg N /L)	Particulate Organic Nitrogen (mg N /L)
Mutela	0,301	516	341	15,00	10,00	18,2	7,8	18,1	25,9
Portinho da Costa	0,259	567	375	15,00	10,00	20,0	8,5	19,9	28,4
Quinta da Bomba	0,707	413	246	15,00	10,00	14,6	6,2	14,5	20,7
Alcântara	1,985	280	280	7,65	0,05	8,1	3,6	8,6	11,7
Chelas	0,608	180	200	7,65	0,05	8,1	3,6	8,6	18,3
Alhos Vedros	0,009	120	180	11,63	0,08	12,3	5,5	13,0	17,8
Moita	0,175	454	300	15,00	10,00	16,0	6,8	15,9	22,8
Palhais	0,793	454	300	15,00	10,00	16,0	6,8	15,9	22,8
Montijo	0,139	454	300	15,00	10,00	16,0	6,8	15,9	22,8
Alcochete	0,023	160	210	15,00	10,00	16,0	6,8	15,9	22,8
Vila Franca de Xira	0,139	454	300	15,00	10,00	16,0	6,8	15,9	22,8
Alverca	0,494	454	300	15,00	10,00	16,0	6,8	15,9	22,8

Table 2.1-6: Characteristics of the affluent Waste Water to the WWTP, measured, or estimated from the equivalent- population.

Property		Primary Treatment	Secondary Treatment	Secondary Treatment with Denitrification
Total Solids		50%	85%	85%
Biochemical Oxygen Demand (CBO_5)		20%	90%	90%
Inorganic Nitrogen	Nitrite	0%	100%	100%
	Nitrate	0%	0%	85%
Ammonia		0%	10%	10%
Organic Nitrogen		10%	30%	30%
Dissolved	Dissolved Organic Nitrogen Refractory	3%	15%	15%
	Dissolved Organic Nitrogen Non Refractory	3%	100%	100%
Particulate		4%	15%	15%

Table 2.1-7: Removal Efficiency of WWTP considered when no measured data was available.

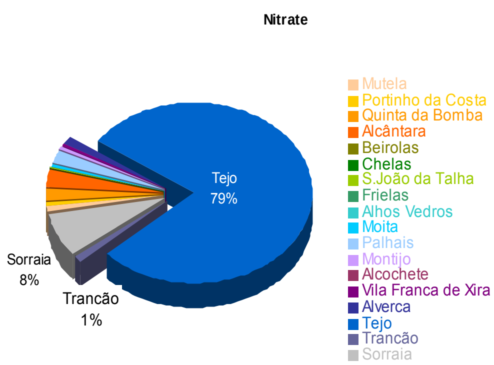
Name	Flow (m^3/ s)	Total Solids (mg / L)	Biochemical Oxygen Demand (mg O_2 / L)	Nitrate (mgN/L)	Nitrite (mgN/L)	Ammonia (mgN /L)	Dissolved Organic Nitrogen Refractory (mg N /L)	Dissolved Organic Nitrogen Non Refractory (mg N /L)	Dissolved Organic Nitrogen (mg N /L)
Mutela	0,301	516	341	15,00	10,00	18,2	7,8	18,1	25,9
Portinho da Costa	0,259	567	375	15,00	10,00	20,0	8,5	19,9	28,4
Quinta da Bomba	0,707	67	35	15,00	0	13.1	5,2	0	17,6
Alcântara	1,985	126	196	7,65	0,05	8,1	3,5	8,3	11,2
Chelas	0,608	35	25	1,15	0	7,3	3,1	0	15,5
Alhos Vedros	0,009	83	160	11,63	0	11,1	4,7	0	15,1
Moita	0,175	454	300	15,00	10,00	16,0	6,8	15,9	22,8
Palhais	0,793	68	30	15,00	0	14,4	5,8	0	19,3
Montijo	0,139	227	240	15,00	10,00	16,0	6,6	15,4	21,8
Alcochete	0,023	20	180	15,00	0	14,4	5,8	0	19,3
Vila Franca de Xira	0,139	454	300	15,00	10,00	16,0	6,8	15,9	22,8
Alverca	0,494	454	300	15,00	10,00	16,0	6,8	15,9	22,8

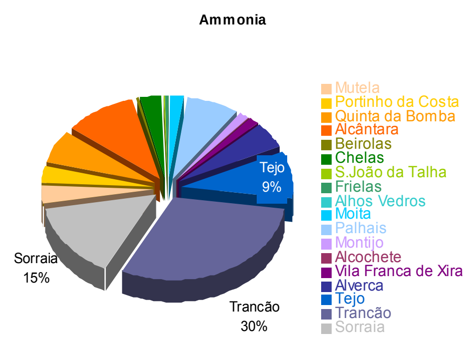
Table 2.1-8: Synthesis of WWTP Effluents used in the simulations.

2.1.4.1.1.3 Relative importance of Estuary Loads

Figure 2-30 shows the relative importance of the loads. The main source of nitrate and organic nitrogen is the Tagus river, and the main source of ammonia is Trancão river, although, together all WWTP account for about 50% of total ammonia.

Figure 2-31, presents the ratio nitrogen - phosphorus in the Tagus Estuary (all historical data) compared to the Redfield ratio (straight line). The figure shows that in the Tagus Estuary, nitrogen is the limiting nutrient since almost all point lay below the line.





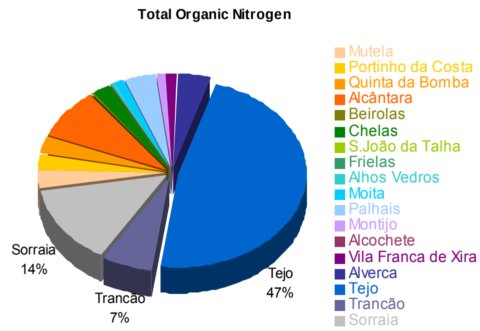


Figure 2-30: Relative importance of nutrient loads in Tagus Estuary.

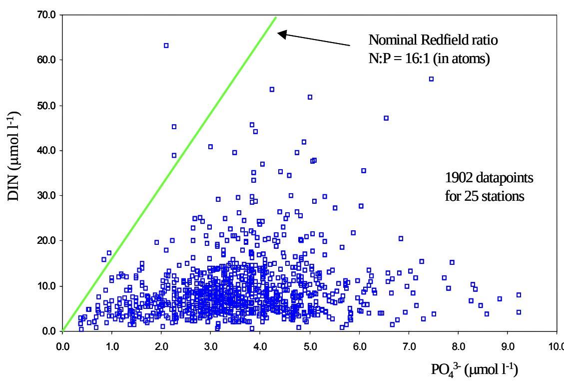


Figure 2-31: Nitrogen - phosphorus ratio for the Tagus estuary (data from the BarcaWin2000™ database) and Redfield ratio (straight line).

2.1.4.1.2 Time Series Analysis (Field Data and Model Results)

This section describes comparison of model results with field data records obtained in the 7 stations represented in Figure 2-32. The analysis of the figures gives information on the trophic conditions of the estuary and on the capacity of the model to describe the functioning of the estuary.

Figure 2-32: Location of sampling Stations used to evaluate the results of the model.

Five sampling stations are the most relevant for this project. “Station #1” is representative of the river water, and “Station #5”, of the ocean water. “Station #6” is the less interesting station because is measuring very close to the Trancão mouth, in a place where Trancão water is already diluted (and so does not represent its water), but in a place where concentration isn’t yet representative of the estuarine conditions in that region.

The set of figures below illustrate the field data records in 5 years, between 1994 and 1998. Records corresponding to the year of 1998 are represented by enlarged symbols since, as mentioned above, 1998 is the reference year in this project. This year was chosen to be the reference year because for this year there is a complete data set, including boundary conditions and monitoring data. The results of the model are represented by a discontinuous grey line representing instantaneous values. The range delimited by the discontinuous line shows tidal variability.

For each station there are four graphics corresponding to concentration of the four properties relevant for this study: Phytoplankton, Nitrate, Ammonia and Oxygen. Field data records are reported to high water and consequently they must be compared with the corresponding values of the model (lowest values of nitrate and phytoplankton and ammonia). The concentration of Oxygen depends on the tide, but also on the daily hour and no unique rule can be drawn for comparison.

From these figures one can extract information on: (i) absolute values, (ii), gradients (spatial variability), (iii) seasonal variability and (iv) model evaluation.

The figures show that inter-annual variability is of the same order of magnitude as seasonal variability. Horizontal variability is much more important that seasonal variability. At station #1 (close to the river entrance), nitrate varies between 1 and 2 mgN/L, between winter and summer. At the sea boundary (station #5), nitrate varies between 0.05 and 0.3 mgN/L. Comparing values at station #1 and #5, one can see that spatial variability is of about 1:20, bigger then seasonal variability. The same conclusion holds for the ammonia and for the phytoplankton.

Comparison between the model and field data has to be done in two steps In a first step one must analyse stations close to the open boundaries (station #1 and #5) to evaluate the boundary conditions and in a second step, the station in the estuary.

At station #1 and #5 the comparison is quite good, showing that concentrations imposed at both boundaries are good, but also that the Tagus discharge is also good. Station #3 is the inner station in better conditions to be compared with the results of the model. Having in mind that the data must be compared with model results at high water (lower part of the curves of phytoplankton, ammonia and nitrate) one can see that results of the model and data compare very well. Station #7 is in Seixal channel, in a shallow area. All values computed by the model compare well with data, except for to samples of phytoplankton. This seems to be a consequence of the sampling time and of the grid used by the model. At high water this channel is flooded with downstream water poor in phytoplankton. The model grid is too coarse (600 meters) to represent correctly the flow in such a narrow channel and consequently tends to generate concentrations of phytoplankton much higher than those measured in high water. September and November samples compare very well with the model for different reasons. In November phytoplankton concentration is very low everywhere and consequently the problem of transport is irrelevant. In September, for any reason (e.g. detail of sampling time or wind effect) the surface water in the channel was already water from the shallow areas boarding the channel which are well represented in the model.

Station #6 is very much influenced by the Trancão, and tends to be less representative of a region of the estuary, especially if sampling time is such that water discharged by that river is sample before mixing with estuarine water. That seems to be the case in August when very high values of ammonia and low values of oxygen were sampled. Another difficulty of this station to compare phytoplankton data with model results is the fact that the sampling point is located into a narrow channel with high transversal gradients during flooding, which are not well represented in the model. Anyway, the differences between phytoplankton measured in 1998 and model results are of the same order of magnitude as the inter-annual variability, showing that model results are representative of the estuary in that point.

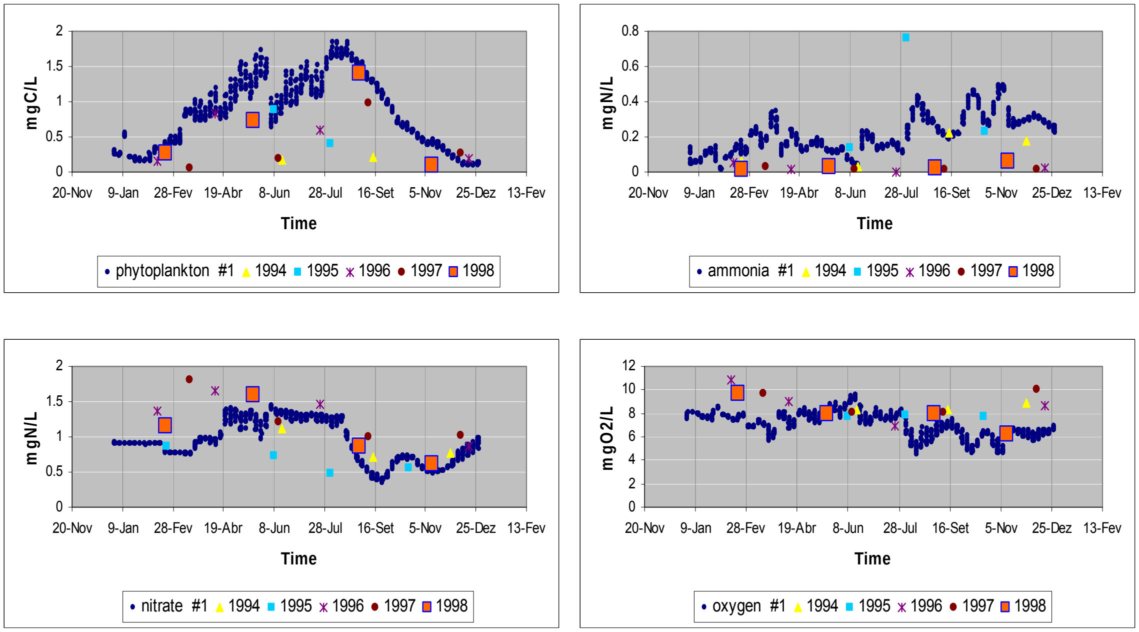


Figure 2-33: Comparison of field and model results at Station #1.

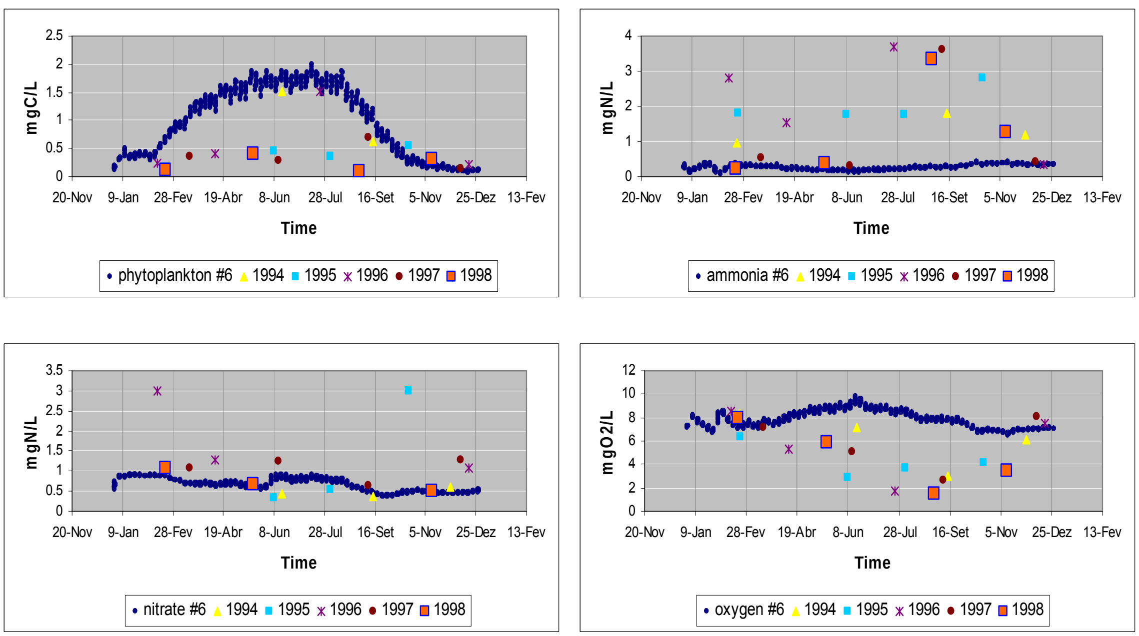


Figure 2-34: Comparison of field and model results at Station #6.

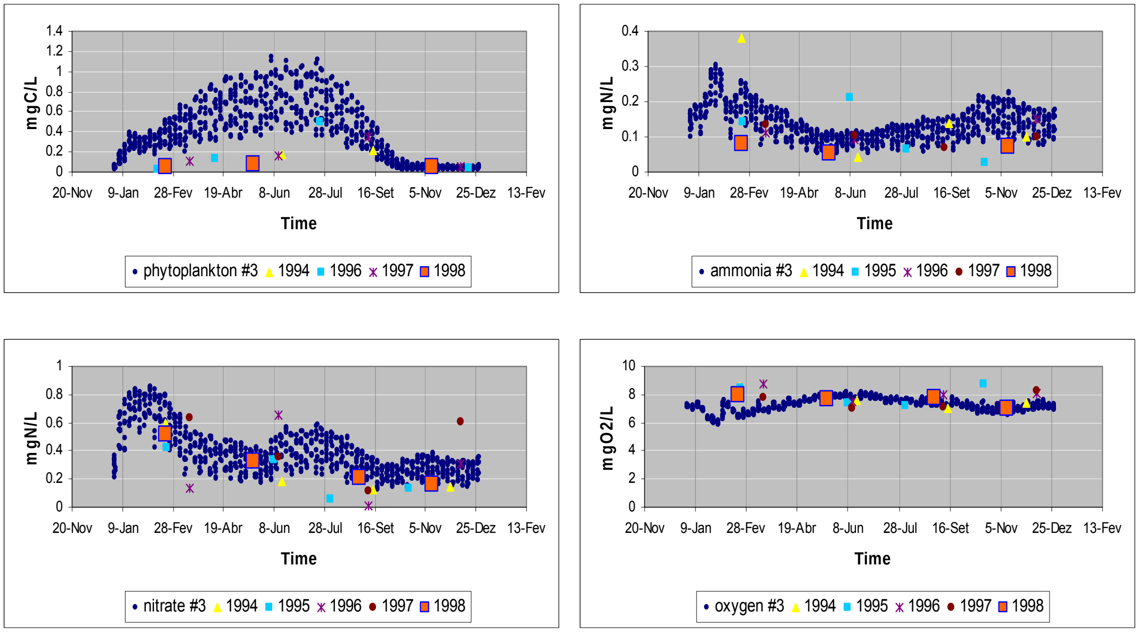


Figure 2-35: Comparison of field and model results at Station #3.

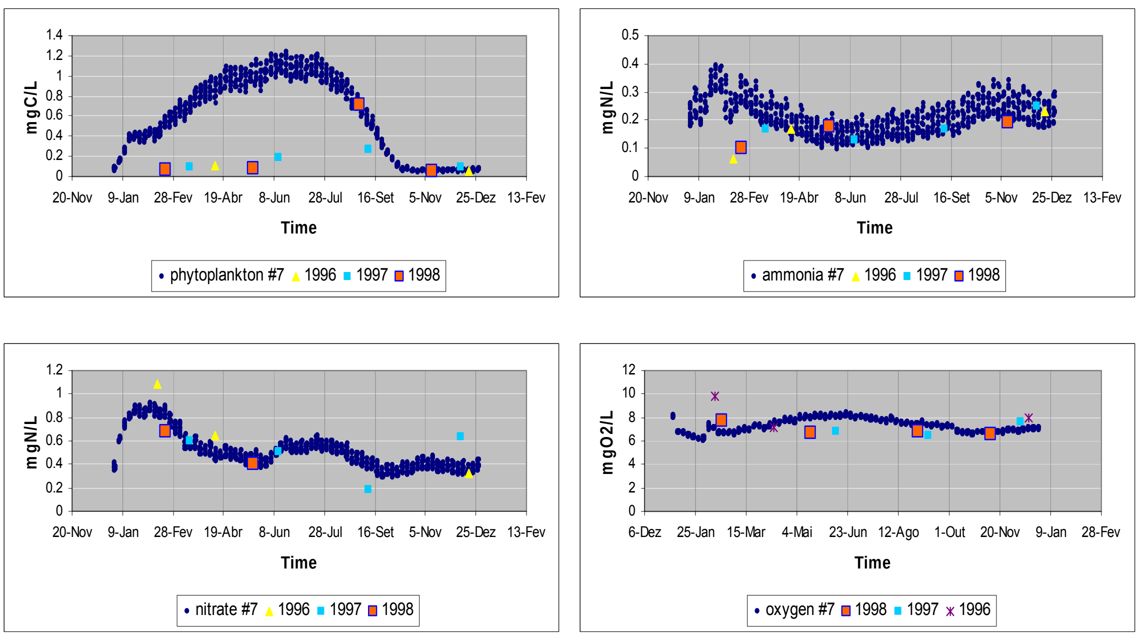


Figure 2-36: Comparison of field and model results at Station #7.

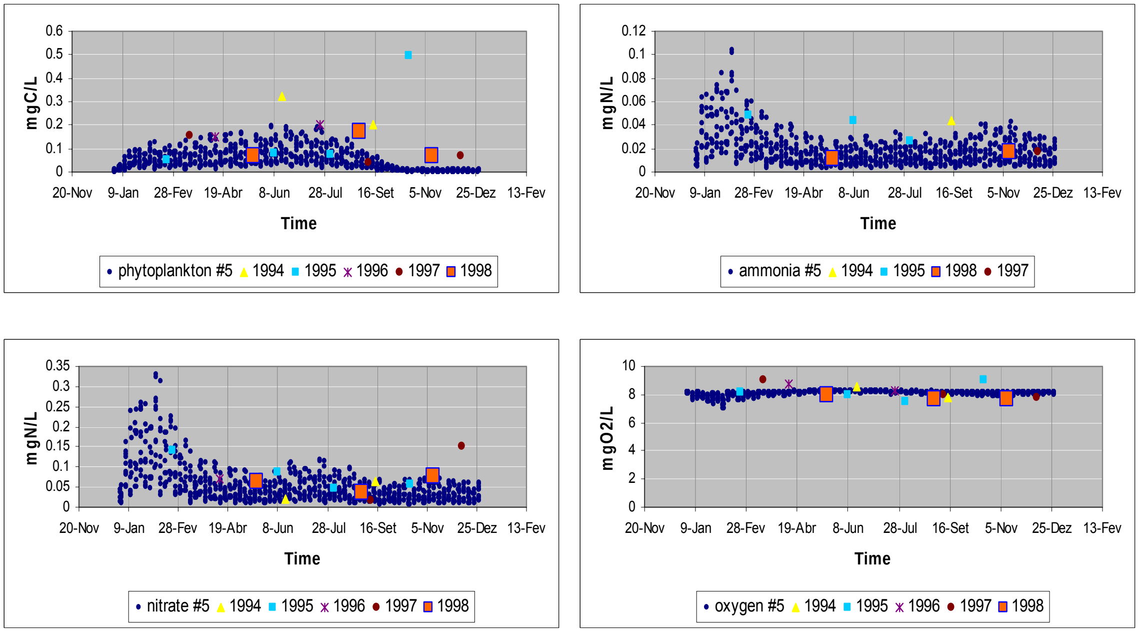


Figure 2-37: Comparison of field and model results at Station #5.

2.1.4.1.3 Spatial distributions of concentration

The next figures represent distributions of Phytoplankton, Nitrate, Ammonia and Oxygen computed by the model for the first of June 1998, in a flooding situation. The figures show the gradients between the upper part of the estuary and the sea, putting into evidence the most intense biological activity in the shallower areas of the estuary. The figures also show that river discharges are the most important sources of ammonia and nitrate. The discharges of ammonia from WWTP are also identifiable in Montijo and Barreiro sub-estuaries, which are quickly diluted into the main estuary, due to the small residence time inside those sub-basins.

The productivity in the estuary is linked mostly to the local depth because of its high turbidity due to the extensive surface of intertidal areas (≈100 km^2, equivalent to 1/3 of the estuary). The resuspension of fine sediments deposited in these areas is enhanced by the small waves induced by the long wind fetch (17km). In shallow areas, the light availability per unit of volume is higher and the productivity is higher too. However the total production is, bigger in the deeper areas, where the water volume is larger.

These figures are useful for a quick overview of the estuarine conditions, but are not enough to characterize the role of each area for the whole estuary. In the next paragraphs a description of the production/consumption in each box and of the exchanges between boxes will be presented. The comparison between scenarios will be based on the results integrated inside each box.

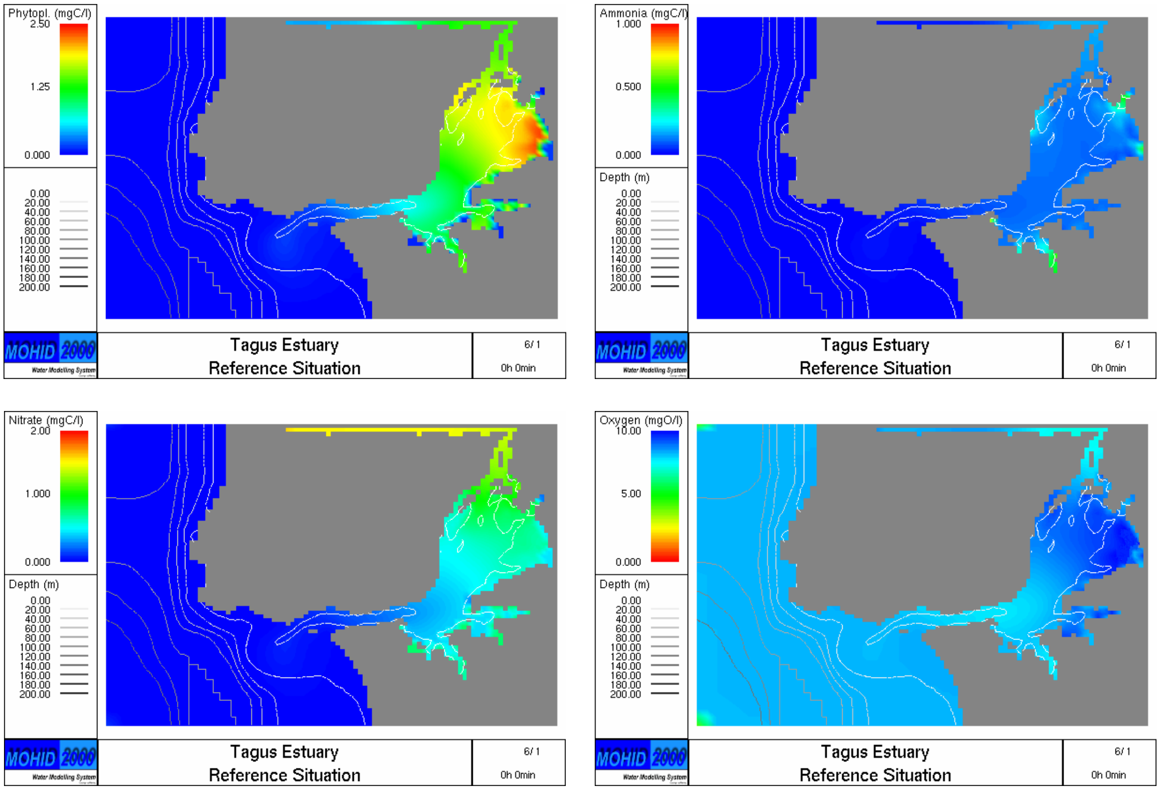


Figure 2-38: Tagus Estuary Concentration Maps in the Reference Situation (1st of June 1998).

2.1.4.1.4 Annual average distributions of properties per zone of the estuary

Figure 2-39 shows the boxes used to describe the processes and fluxes in the estuary. The boxes were drawn having transport and the biological processes in mind. The Tagus water flows along boxes 7 and 6 to enter in the main estuary. Then, it flows mainly along box 5, into box 2 and 1 to enter in the sea across box 10. In box 10 and 1, there is a strong dilution of estuarine water into sea water, having the water leaving box 10 properties very close to sea water. In box 2 there is a strong residual eddy, being this box a zone of intense mixing between estuarine internal water and the quasi sea water entering through box 1.

Boxes 3, 4, 8 and 9 are boxes receiving small local discharges and water from the main estuary, which is the result of the mixing between river and sea water. Boxes 8 and 9 are the most productive in the estuary. Boxes 3 and 4 have also high productions, but the residence time inside them is small and, has a consequence, the concentrations of phytoplankton are smaller than in boxes 8 and 9.

The average values of the properties and the exchanges between the boxes are represented in the next figures. Figure 2-40, represents the annual average distribution of phytoplankton, nitrate, ammonia and organic matter in each of the established integration boxes. The Organic Matter is defined as a sum of PON and DON existing in the water column, due to discharges into the estuary or produced by biological activity.

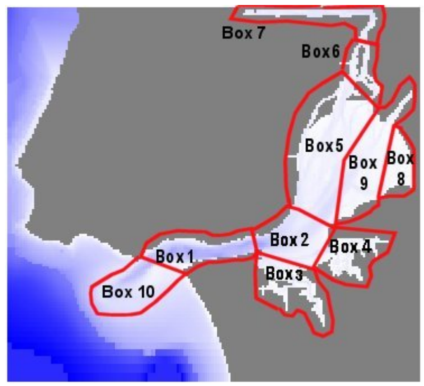


Figure 2-39: Integration Boxes in the Tagus Estuary.

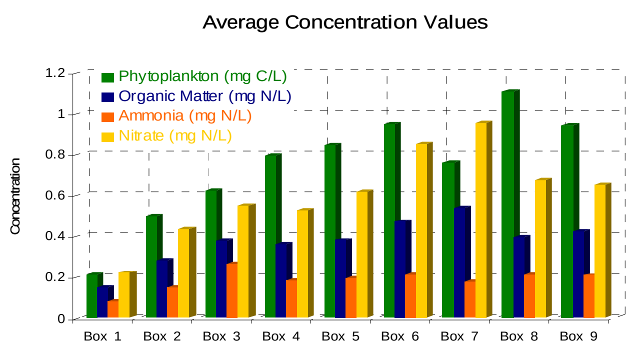


Figure 2-40: Annual Average values of Phytoplankton, OM, Ammonia and Nitrate per box of the Estuary in the Reference Situation.

The figure shows, clearly, that concentrations tend to diminish towards the ocean (mostly because of the dilution). Some exceptions occur due to local discharges or to physical processes, which is the case of organic matter in boxes 8 and 9. In these boxes with high phytoplankton growth, one should expect also high OM concentrations. The lower values can be explained by the fact that these boxes are also settling zones and part of the particulate forms of organic matter are deposited on the bottom, so they are not accounted for water column concentration. In boxes 6 and 7, the effect of Tagus River discharge is clear and results show that the discharge of the Tagus controls the distributions of nitrate in the estuary. Ammonia is higher in boxes 3 and 4 due to local WWTP discharges. Boxes 8 and 9 are very shallow and have very high light intensity per unit of volume and, as a consequence the most productive areas in the estuary in terms of planktonic biomass per unit of volume. Box 1 is close to sea boundary and all the considered properties have small concentrations, showing that the estuary is more productive than the coastal sea. The higher values of nitrate comparing to ammonia show that the agricultural contribution for the nutrient balance in the estuary is more important than the urban wastewater.

2.1.4.1.5 Annual Budgets per zone of the estuary

Figure 2-41 represents the annual exchanges between neighbouring boxes (ton/year) of Phytoplankton, Ammonia, Nitrate and Organic Matter. The same information is shown in Figure 2-42. Global budgets are represented in Figure 2-43 for the estuary, showing that the estuary is a net exporter of nitrate, of phytoplankton and an importer of ammonia and organic matter, which are discharged mainly by the WWTP's. Internal processes perform the conversion between those forms of nitrogen. Those processes will be described in the next paragraphs.

The upper part of the estuary (boxes 5, 8 and 9) receives a flux of 5000 ton/y of phytoplankton (from box 6) and exports 13000 tons/y (to box 2). Salt marsh areas in the low estuary (boxes 3 and 4) are exporting phytoplankton to box 2.

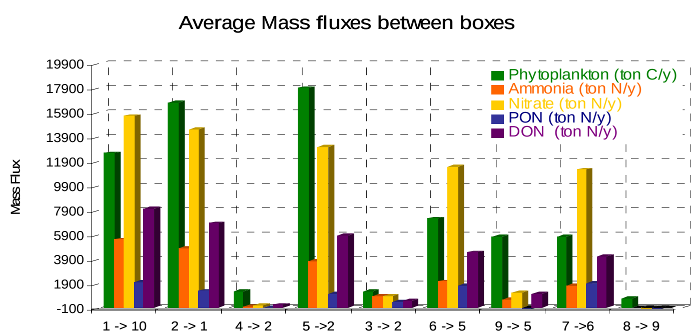


Figure 2-41: Annual Budgets between Zones of Estuary

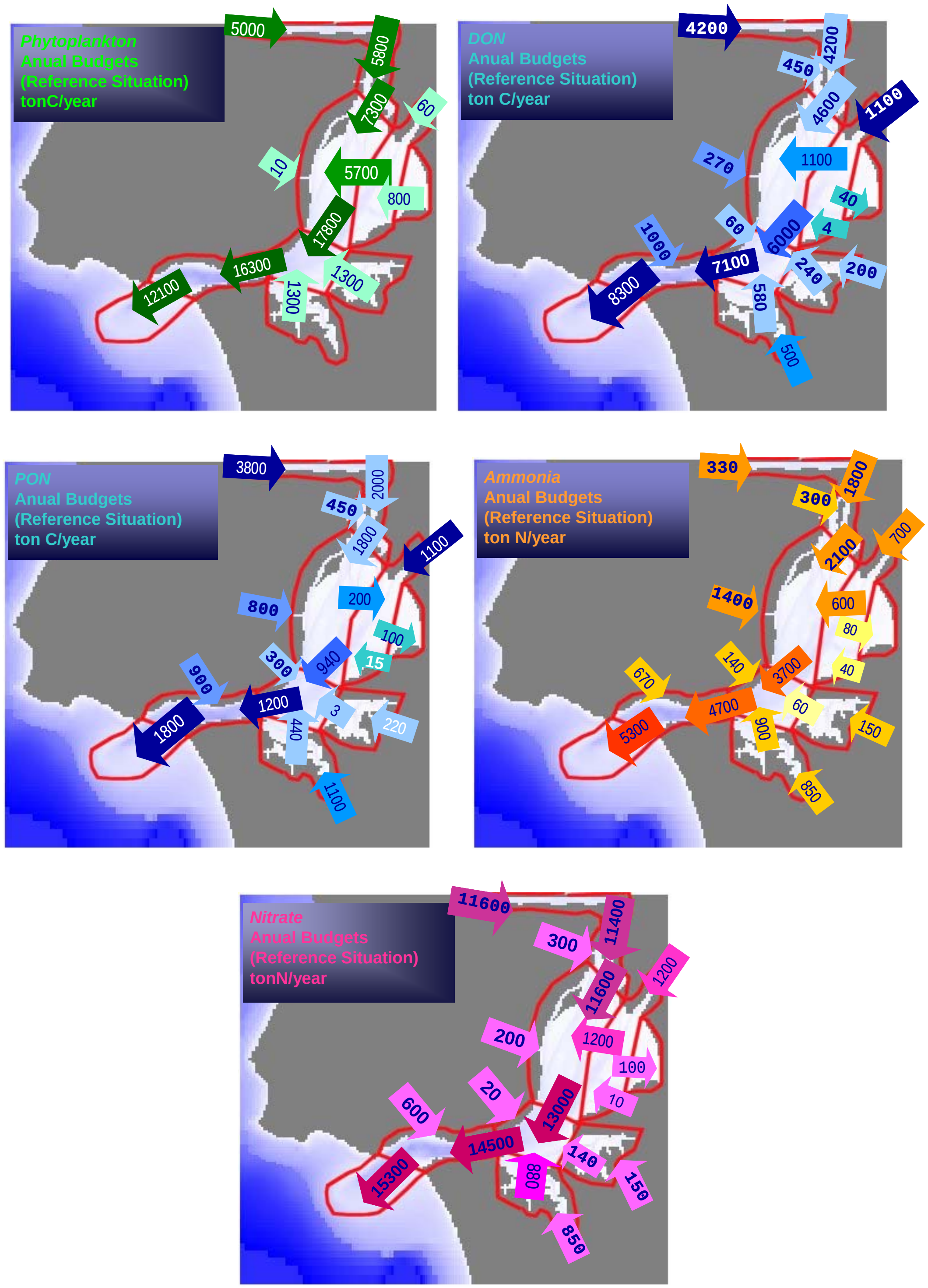


Figure 2-42: Annual Budgets between boxes in the Reference Situation

Boxes 2, 3, 8 and 9, have an important production of Organic Matter, exporting to the boxes leading to the sea. It should be noticed that most of this organic matter is in the dissolved form because the particulate form finds ideal hydrodynamical conditions to settle in the shallow areas, where it is remineralised. The analysis of the nutrient fluxes is more complex because we should account for local discharges and for consumption and regeneration of the variables[4].

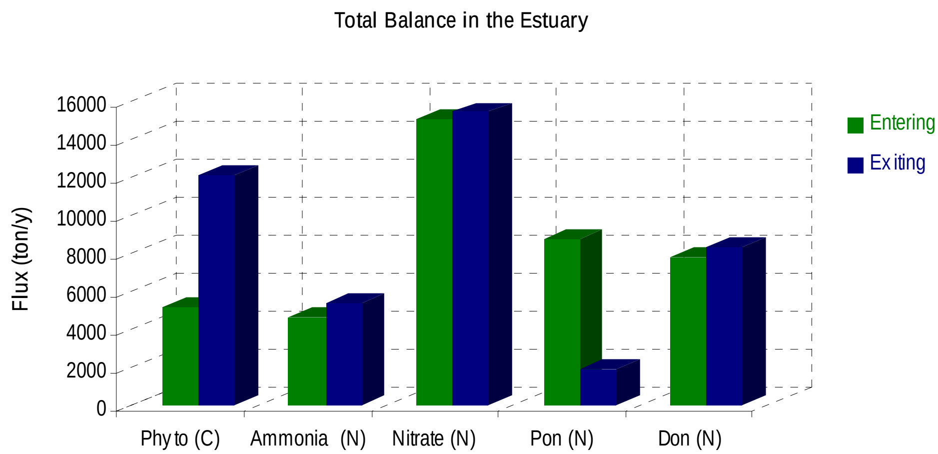


Figure 2-43: Total Balance in the Tagus Estuary for the Reference Situation.

It is interesting to notice that phytoplankton doesn't use all the nutrients available in the estuary. The main reason for that is light limitation due to high concentrations of suspended particulate matter (SPM) inhibiting phytoplankton to fully explore the nutrients available.

[4] To evaluate the interaction between deep and shallow areas, a test was done considering the river as the unique discharge of nutrients. In this test it was observed a net export of nutrients from the deeper areas into the shallower and a flux of phytoplankton on the opposite sense.

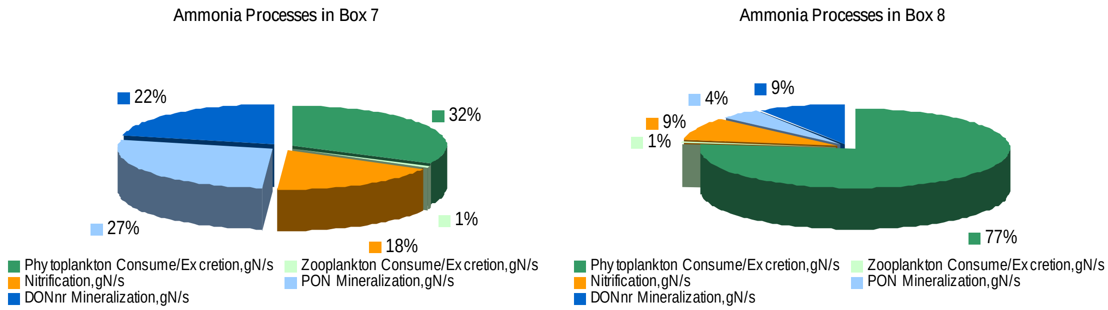


Figure 2-44: Ammonia Processes in Boxes 7 and 8 in the Reference Situation

The study of the processes involving ammonia can give an idea of what is happening inside the estuary. Figure 2-44 represents the relative contribution of each sink and source process in the ammonia ecological cycle, in Boxes 7 and 8.

Uptake of ammonia by phytoplankton in Box 8 (a sink term) is the most important process involving ammonia in that area, reducing its concentration, while in Box 7, mineralization of organic matter (a source term of ammonia) strongly contributes for increasing ammonia concentration.

2.1.4.1.6 Conclusions

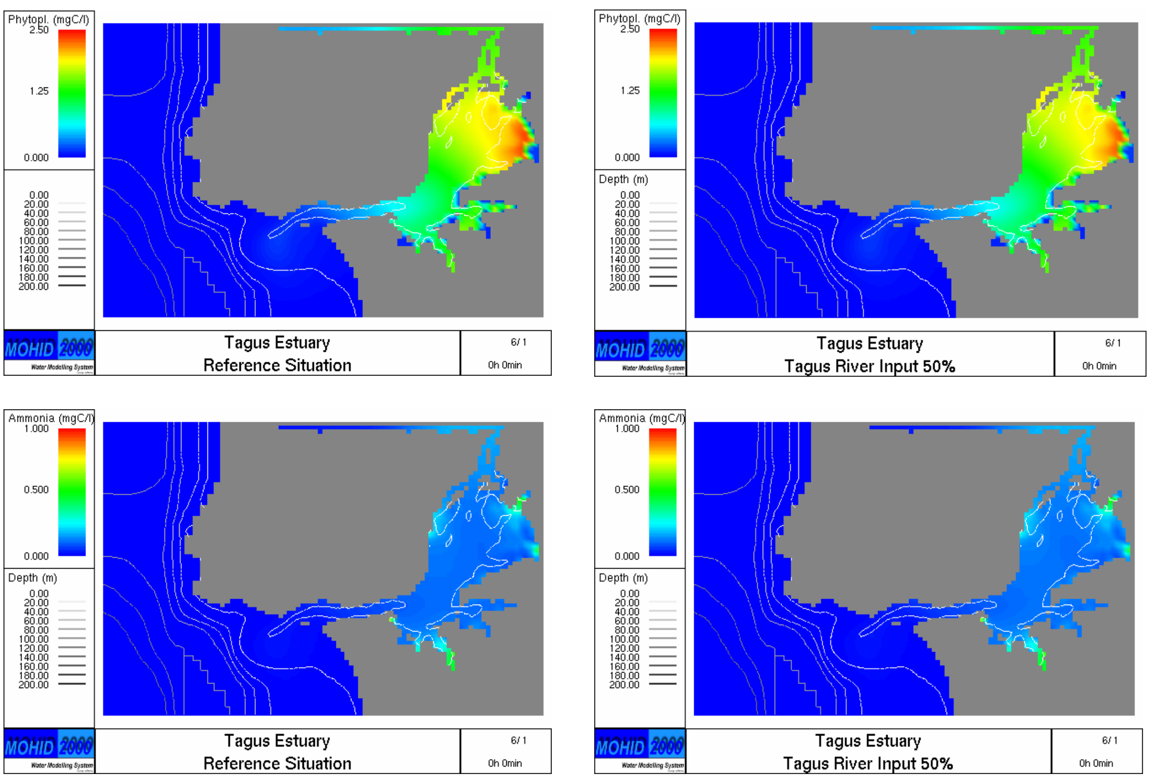
The main conclusion of the study of the ecological processes in the Tagus in the reference situation is that light availability is the most important factor limiting primary production in the estuary inhibiting the primary producers of using the nutrients available, which are exported to the sea after strong dilution. Temperature and nutrients are never limiting factors. The system is productive, produces and exports biomass (phytoplankton and zooplankton), consuming part of the nutrients entering the estuary. The concentration of dissolved oxygen is always above minimum values required by biological activity. The plumes of point discharges are dispersed in the estuary and only the river plumes are clearly identifiable on the spatial distributions of the properties.

2.1.4.2 Influence of the Nitrate Removal by Agriculture Systems

To evaluate the effects of reducing the discharge of nutrients from agriculture, the simulations performed for the reference situation were repeated, considering a reduction of 50% of the nitrate load and maintaining all other parameters. In fact, nitrate is the most important form of nitrogen used in agriculture and phosphorous is in excess in the estuary. Nitrate originated by agriculture reaches the estuary through the Tagus, Sorraia and Trancão and consequently no modification and WWTP were considered.

2.1.4.2.1 Distribution of properties assuming a reduction of 50% of agriculture nitrate

A comparison of the reference situation and of the scenario involving the reduction of nitrate form agriculture is presented in terms of spatial distributions, annual budgets and mean concentrations for the most representative boxes defined to describe the reference situation.



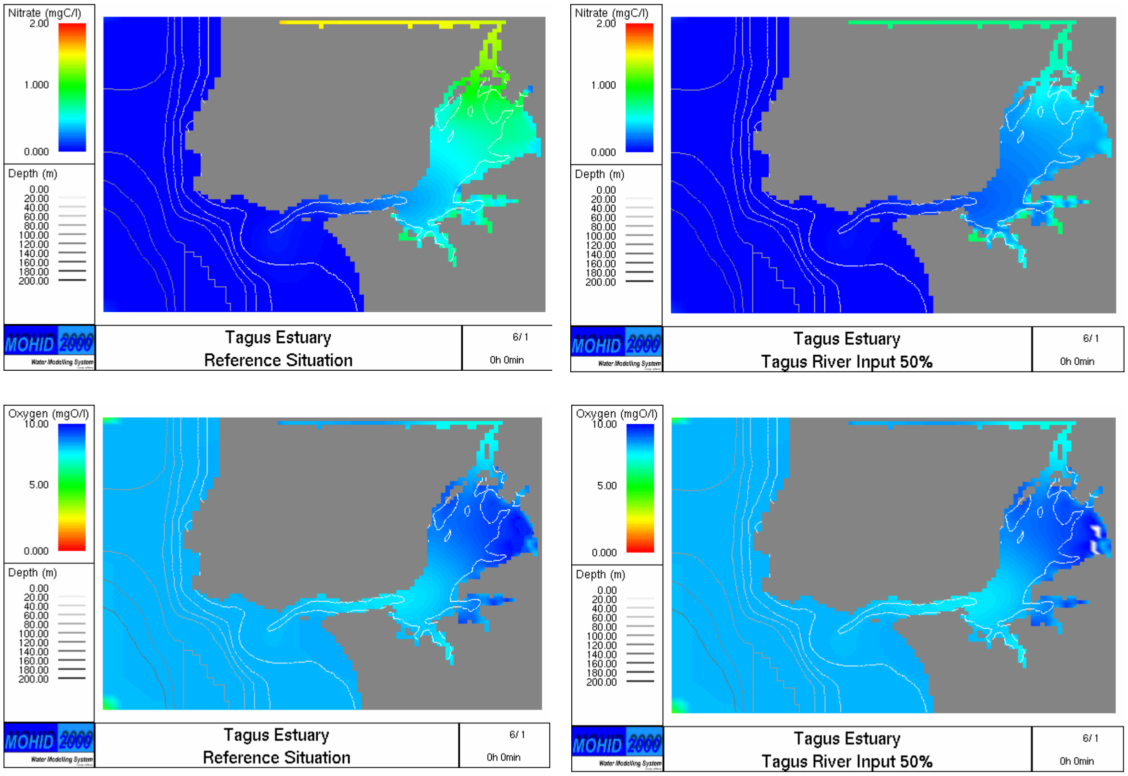


Figure 2-45: Comparison of spatial distributions in the reference situation (left column) and in the scenario of 50% reduction of nitrate form agriculture (right column), in June.

2.1.4.2.1.1 Spatial distributions of concentrations

Comparison of distributions for a spring condition (1st of June) is shown in Figure 2-45. On the left column are displayed figures for the reference situation and on the right column for the scenario with 50% reduction of the nitrate discharged by the Tejo and Sorraia. Both columns show very similar figures, being the differences not perceptible in this type of figure, except for nitrate, which shows higher concentration close to the entrance of the rivers.

2.1.4.2.1.2 Annual Distributions

The integrated values show differences following the strategy described in paragraph 2.1.4.1.5. The solution is integrated within the same boxes and results are compared per box and for the whole estuary.

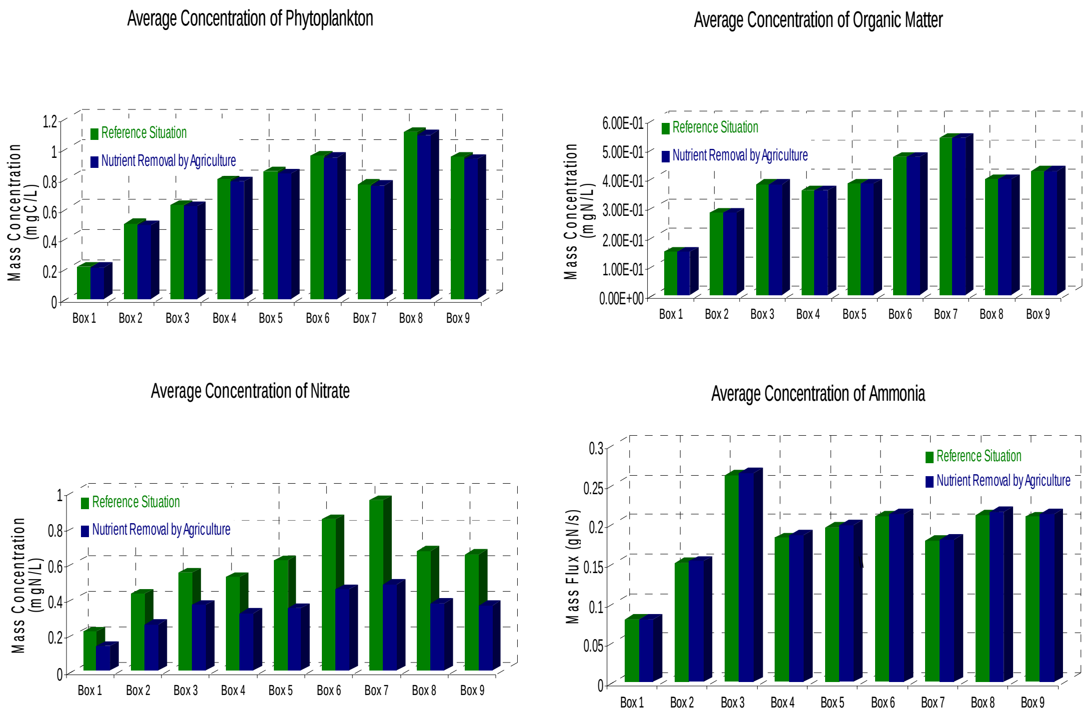


Figure 2-46: Comparison of annual average concentrations in the boxes for the reference situation and in the scenario of 50% reduction of the nutrients discharged by the rivers.

Figure 2-46 represents the differences between the reference scenario and the scenario with removal of 50% of nitrate. The figure shows that there are no visible differences between both simulations except for nitrate concentration. In all the boxes, the nitrate concentration is lower in the "discharge reduction scenario" as was expected, since the river discharges are the major sources of nitrate for the estuary. Despite the difference between the values of nitrate concentration, there is not a significant variation on the biomass production (similar values for Phytoplankton and Organic Matter concentrations).

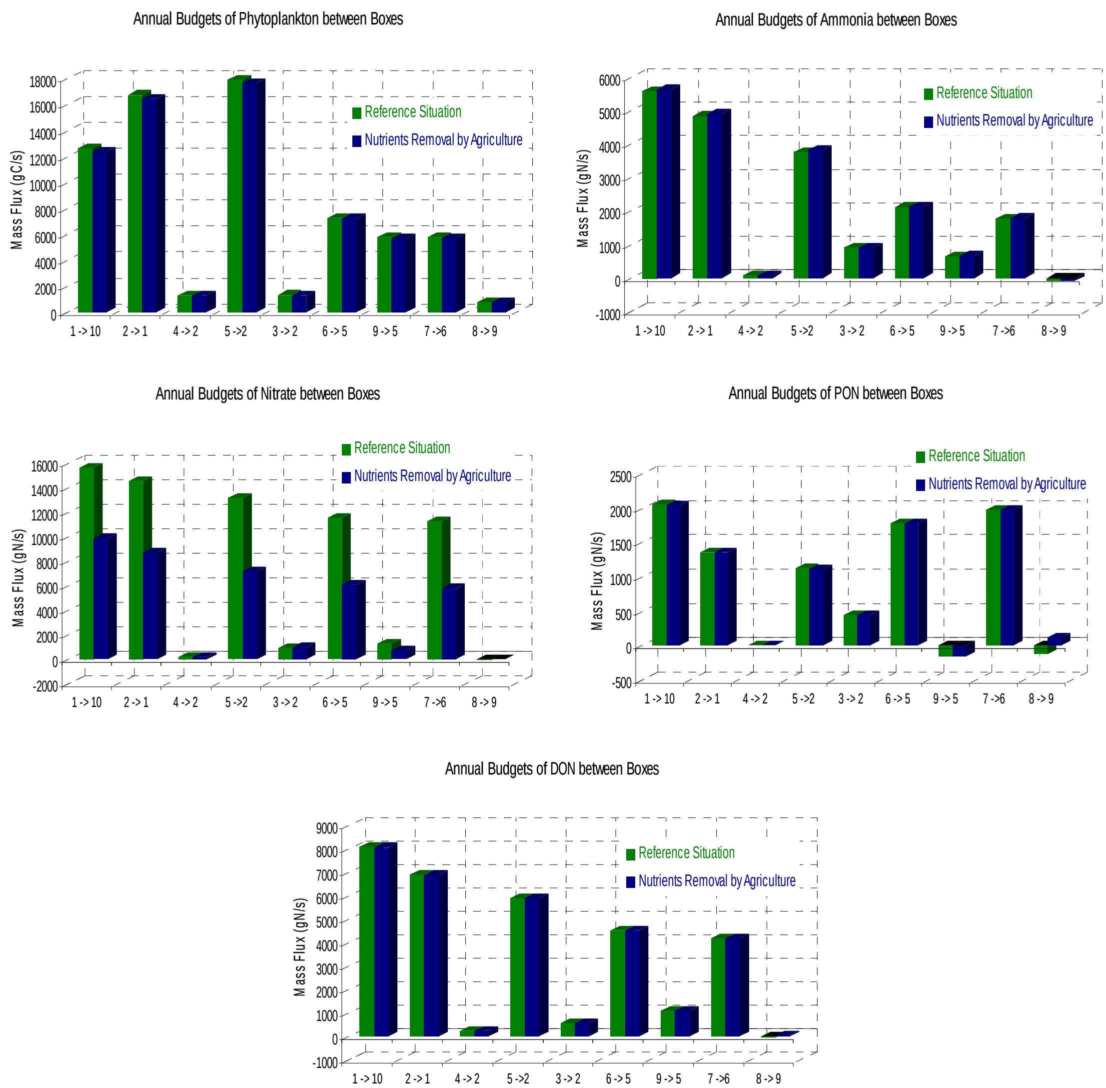


Figure 2-47: Comparison of budgets between boxes in the reference scenario and in the scenario of reduction of 50% of river load.

2.1.4.2.2 Annual Budgets per zone of the estuary

The annual budgets between the different boxes in the estuary for the two scenarios are compared in Figure 2-47. Only the nitrate fluxes show visible changes, suggesting that the nitrate in excess in the estuary crosses it as a passive tracer.

Figure 2-48 represents the dissolved oxygen consumed to oxidize the organic matter (PON and DON) and shows that the oxygen consumption in both scenarios is similar, as expected, since reactions involving nitrate do not consume oxygen and there is no difference in the other properties.

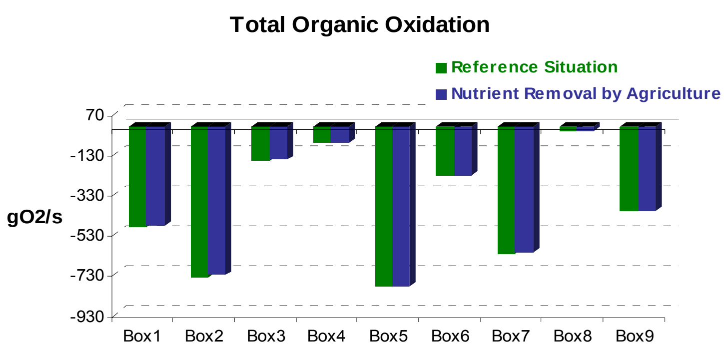


Figure 2-48: Comparison of oxygen consumption for organic matter oxidation in the reference scenario and in the scenario corresponding to 50% of reduction of nitrate discharged by the rivers..

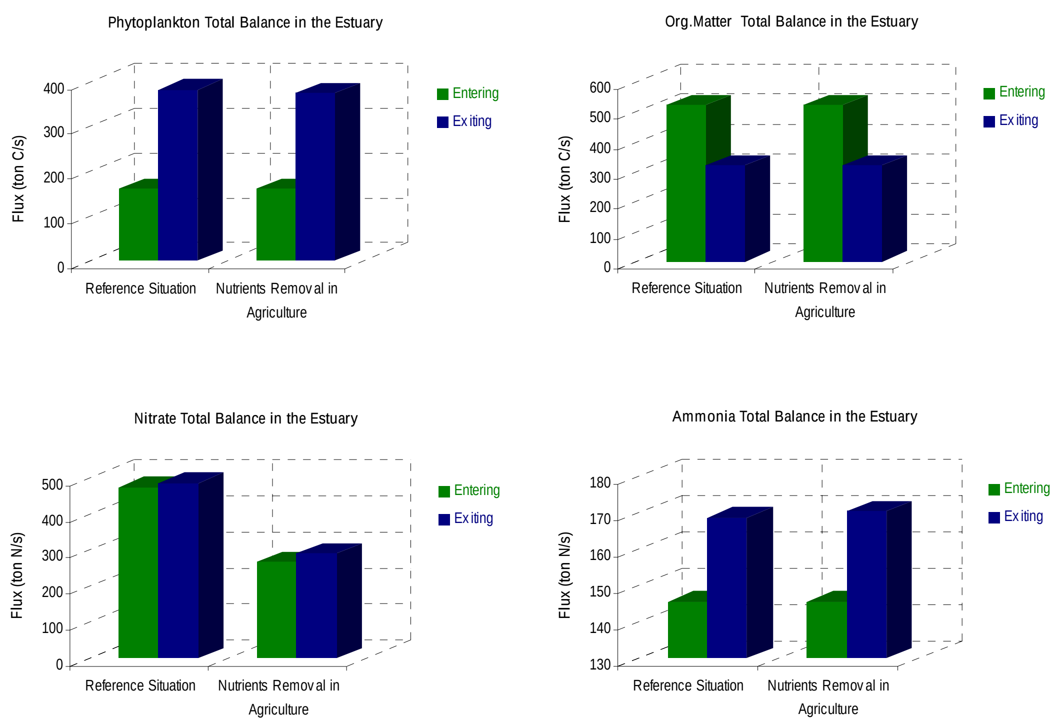


Figure 2-49: Influence of Nutrients Removal by Agriculture Systems in the Total Balance of Tagus Estuary

Figure 2-49 compares the scenarios in terms of global estuary budgets for phytoplankton, organic matter and nutrients. The biomass production in the estuary is similar in the two scenarios despite the difference on the nitrate flux discharged by the river in the estuary.

The insensitivity of the ecosystem to the nitrate excess is the consequence of two effects, light limitation and phytoplankton preference for ammonia. As described in the reference situation, although there are enough nutrients to support additional phytoplankton growth, the lack of light availability in the water column – due to suspended matter - inhibits it. The phytoplankton preference towards ammonia, which is explicitly included in the ecological model, explains the small consumption of nitrate.

2.1.4.2.3 Conclusions of the scenario of 50% reduction of nitrate discharged by the rivers

Reducing the nitrate discharged by the river in 50% does not have a significant influence on the primary production of biomass in the Tagus Estuary, because 50% of the actual discharge of nitrate plus the ammonia discharged in the estuary are enough to maintain the primary production allowed by the light availability. This means that even with such a drastic reduction of nutrients, the primary production in the estuary remains limited by light.

2.1.4.3 Effects of Nutrients Removal by WWTP

To study the effects of nutrient removal by WWTP, it was tested the extreme situation of removing completely the discharge of nutrients from urban origin. The test is performed following the same methodology described for removal of nitrate form agriculture. In this case the discharge of WWTP is assume to be clean water.

2.1.4.3.1 Properties Distribution

Again, maps with horizontal distributions were produced to give an overview of the distributions and figures with integrated values for boxes and for the whole estuary are presented.

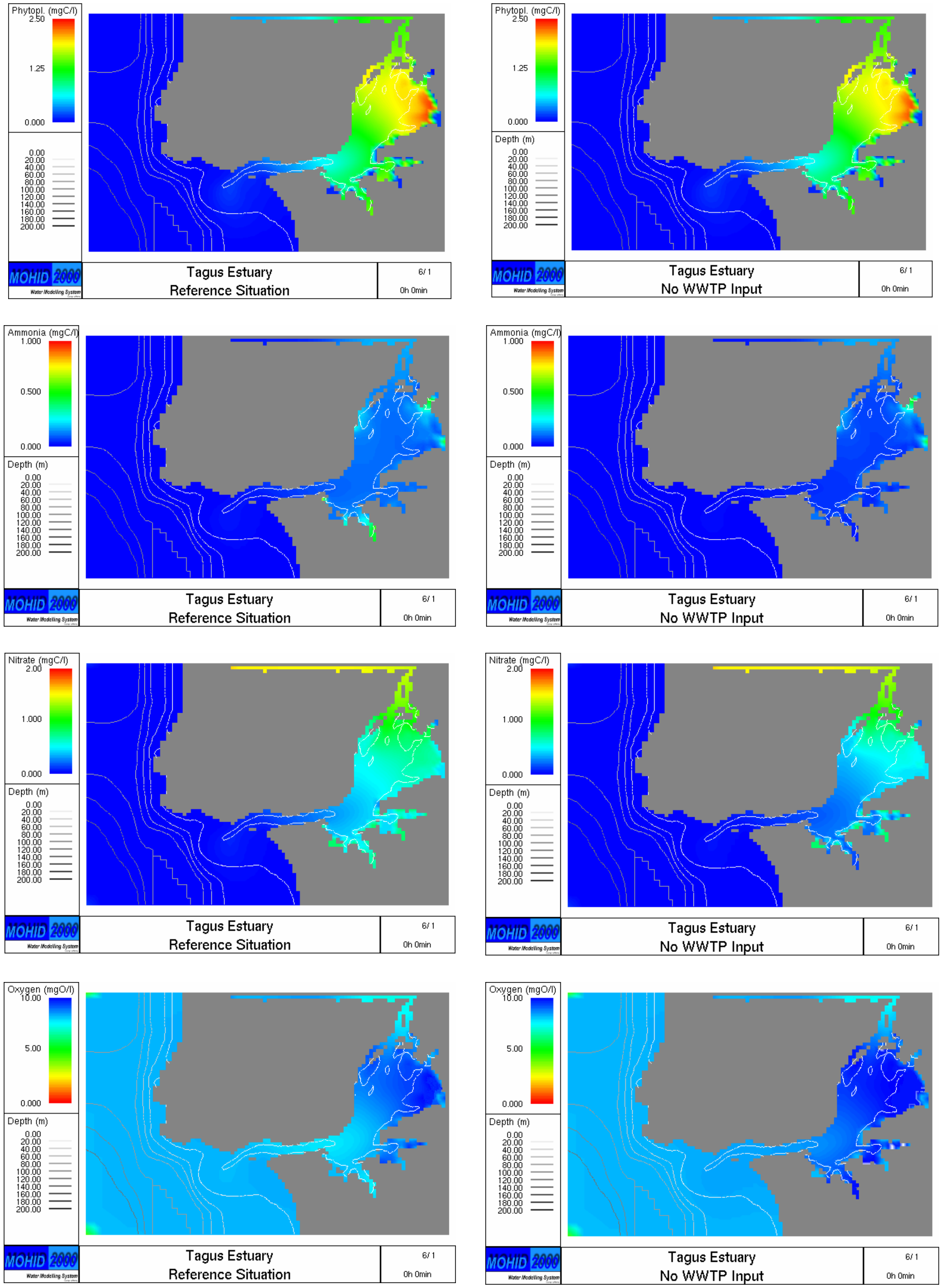


Figure 2-50: Comparison of spatial distributions in the reference situation (left column) and in the scenario of zero discharge from the WWTP (right column), in June.

2.1.4.3.1.1 *Spatial distributions of concentrations*

Figure 2-50 shows comparisons between distributions in the reference situation (left column) and in the scenario of zero discharge by the WWTP's (right column). The figure shows that only minor differences on ammonia in Montijo and Seixal sub-estuaries and even smaller differences on dissolved oxygen in the same places are detectable. In other parts of the estuary there is no detectable difference between the two scenarios. Comparisons of annual average concentrations confirm this conclusion.

2.1.4.3.1.2 *Annual Distribution*

Again, there is no significant difference between biomass computed in both scenarios, despite the variation of the nutrients concentration. In case of zero discharge of nutrients by WWTP there is decrease of ammonia concentration in the neighbourhoods of the WWTP, and a smaller reduction of nitrate concentrations, which is smaller in box 7 were the influence of the Tagus estuary is dominant. These reductions are clear in Boxes 3, 4, and much smaller in Box 8. The reduction of nitrate concentration is due to a reduction of nitrification near the WWPT discharges.

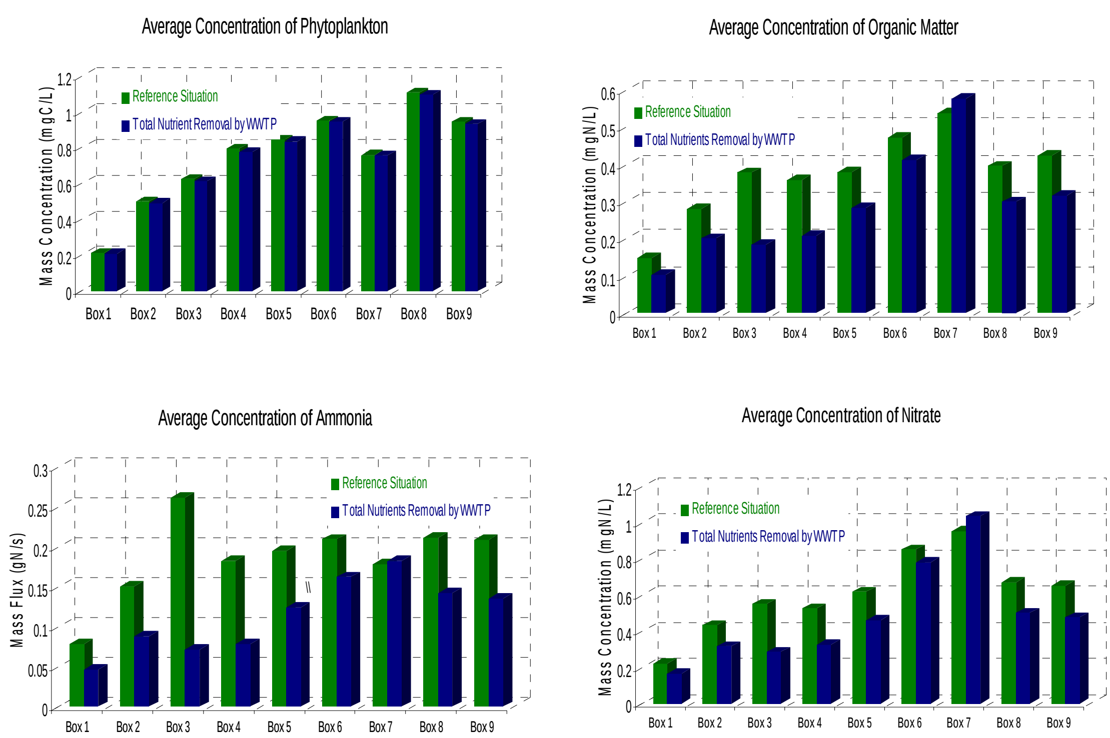


Figure 2-51: Influence of Total Nutrients Removal by WWTP in the boxes

As in case of the reduction of nitrate discharged by the rivers, there is a reduction of the concentration of nutrients in the estuary, but no clear variability of the trophic level.

2.1.4.3.2 <u>Annual Budgets per zone of the estuary</u>

The reduction of nutrients discharge from WWTP's has no significant consequences on biomass distribution and consequently very small differences are expected on the exchanges between boxes. Figure 2-52 presents those fluxes, and shows that variations would happen on ammonia and nitrate fluxes mostly from the boxes where WWTP are discharging.

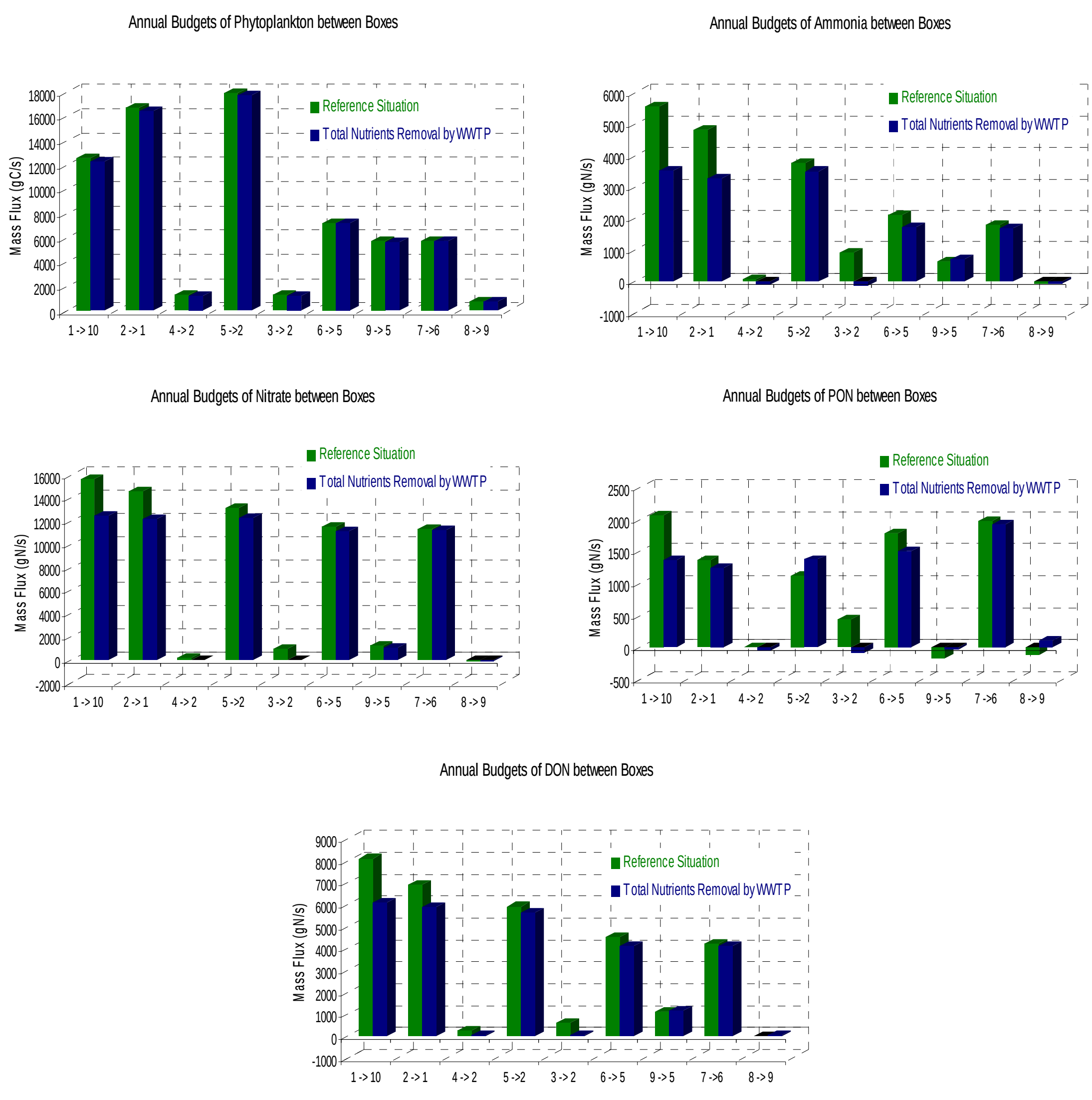


Figure 2-52: Comparison of Total Nutrients fluxes between boxes in the reference scenario and in the zero WWTP discharge scenario.

Figure 2-53 shows oxygen required for oxidation of organic matter in each box in both reference and in the zero discharge from WWTP scenario. As was expected, the figure shows some differences mostly in boxes 1 and 2. This is a consequence of the location of the treatment plants and of the transport processes, which transport the matter discharged to those boxes in a short period of time.

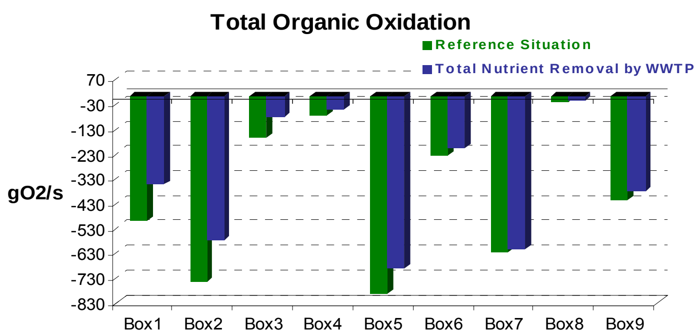
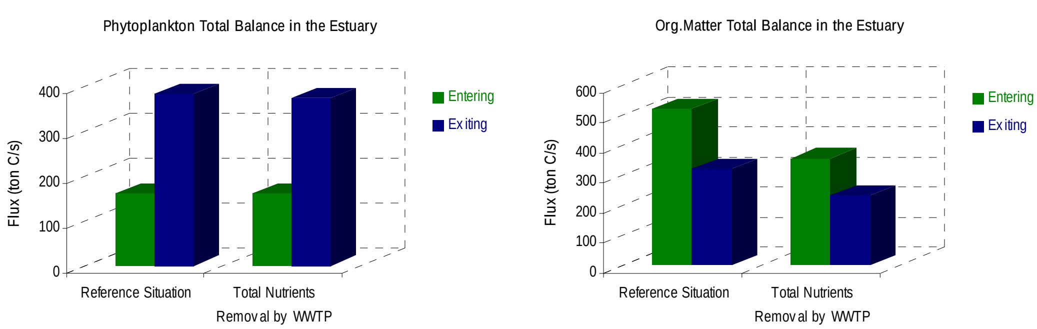


Figure 2-53: Comparison of oxygen consumption for oxidation of Organic Matter in case in the referenc scenario and in the zero WWTP discharge scenario.

Figure 2-54shows the comparison of the estuary balance of the most important properties for the whole estuary, for both scenarios. The figure shows that there is no significant difference in the biomass production in the estuary, despite the variations on the nutrients concentration. As in the test of 50% discharge of nitrate by the rivers, a reduction of nutrients load from WWTP leads only to a reduction of the nutrient export to the sea.



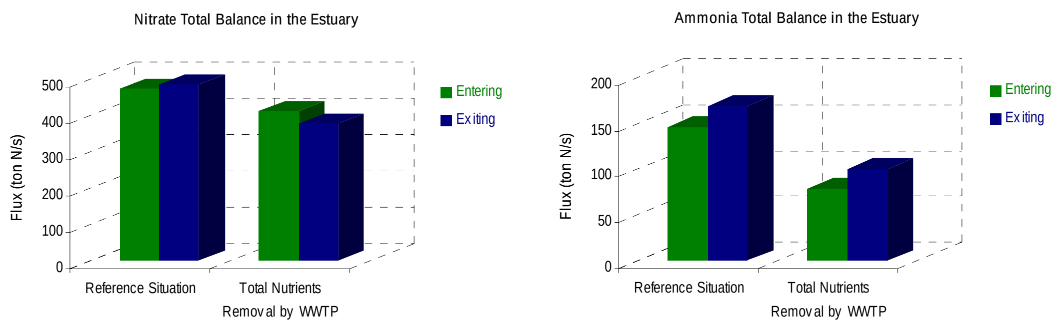


Figure 2-54: Comparison of the estuary balance of the most important properties for the whole estuary, for both the reference scenario and the zero WWTP discharge scenario.

2.1.4.3.3 Conclusions of the simulation of zero WWTP discharge scenario

The total removal of the discharge of nutrients and organic matter by WWTP would have negligible effects both on phytoplankton production and small consequences on oxygen consumption due to mineralization of organic matter. The main consequence would be a reduction of the export of nutrients from the estuary to the coastal sea.

2.1.4.4 Conclusions of the study of the ecological processes in the Tagus Estuary

The estuary is light limited so a large part of the nutrients flowing into the estuary is exported to the ocean without being consumed. For that reason a reduction of the nutrient load into the estuary does not have necessarily consequences for the biomass production in the estuary. The effects of a reduction of 50% of the nitrate discharged by the rivers and the effects of a complete removal of nutrients and organic matter discharged by WWPT's were tested. It was verified that the trophic activity in the estuary was not changed because the limiting factor of the trophic activity in the estuary is light penetration and not the nutrients availability.

The scenarios tested are not realistic in the sense that it is impossible a complete elimination of the discharges of nitrogen from WWTP's and a reduction of 50% of the nitrate discharged from the rivers is not plausible. However those numbers were selected to show that to turn nitrogen into the limiting factor of the trophic level of the estuary drastic cuts on nitrate are required.

Another important conclusion form the tests performed is that the excess of nutrients in the estuary is not a recent phenomenon and experience from last years shows that the estuary is not sensible to the present load.

As a final conclusion one can say that the estuary is not showing any eutrophication problem and consequently there is no need for including reduction of nutrients in the treatment performed by WWTP. Their discharges has however to be located in areas with strong hydrodynamics to avoid any local effects.

2.2 SADO ESTUARY MODEL

The Sado estuary is smaller than the Tagus estuary, but it is still a large estuary (about 150 km^2). It has also large intertidal areas (about 1/3 of its surface) and a more complex bathymetry, with two channels in the lower estuary separated by a set of sand banks and 3 main basin in the upper part (Marateca, Alcácer Channel and Comporta). The main fresh water discharge is the Sado River, entering through Alcácer Channel. A number of small streams also discharge in the estuary, Marateca Stream being the most important.

2.2.1 Hydrodynamics

The hydrodynamics of the Sado estuary is forced by the tide and by Sado River discharge. Tidal harmonics used to generate the open sea boundary condition were obtained from the same global tidal model, used in the case of the Tagus estuary. To describe the transient circulation and to compute the residence time, a spring-neap tide period has been simulated. For the long-term water quality simulations only the M2 tidal component was used, in order to obtain a cyclic hydrodynamics with a period of 12h25 min, representing the average tidal conditions. The mean flow of the Sado River was considered to be 10 m^3s^{-1}. This flow is a bit over estimated for summer period, inducing loads also overestimated. This corresponds to a pessimistic scenario, but in absence of more refined information, a pessimistic scenario should be considered.

This methodology allowed for the use of a fine grid and was possible due to the small contribution of the river discharge for estuarine hydrodynamics.

2.2.1.1 Model Grid

158 by 120 grid points, covering an area of 46km east-west by 24km north south, compose the grid of the Sado estuary. Figure 2-55 shows a map of the total area ploted from the information provided to the model and Figure 2-56 shows a zoom of lower estuary. This figure also shows the grid used by the model. The grid spacing varies between 200m (in almost all the estuary area) and 1600m (to simulate the Sado River Channel).

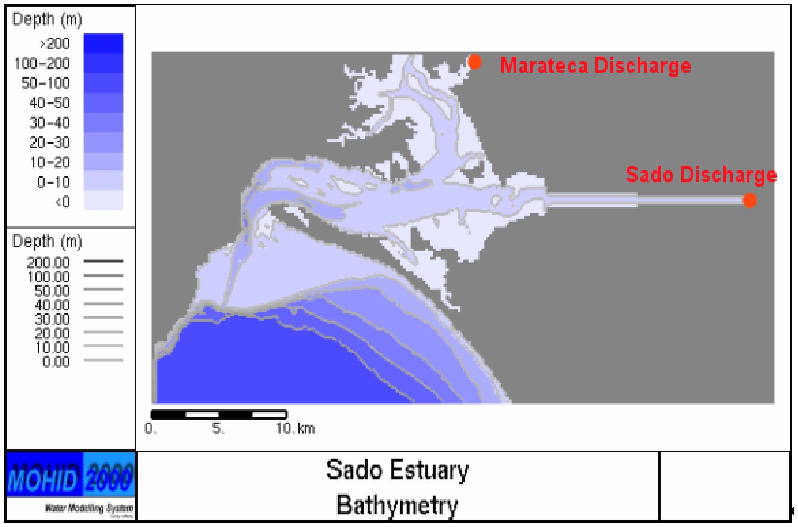


Figure 2-55: Bathymetry of the Sado estuary.

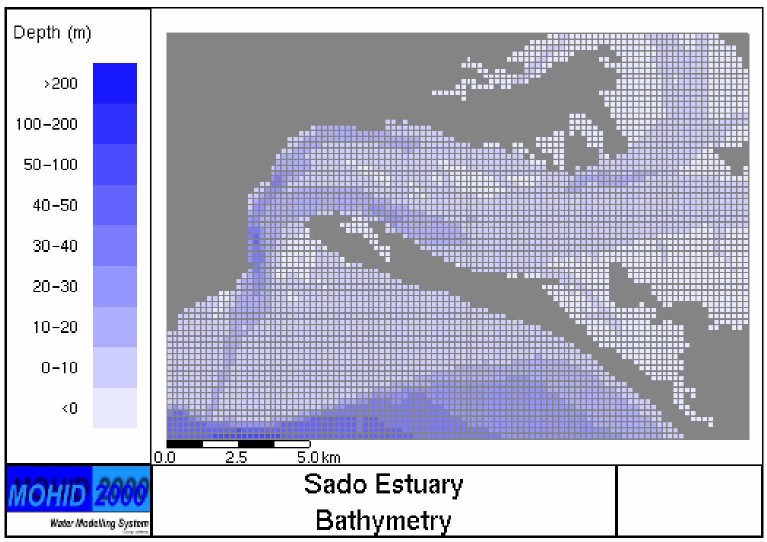


Figure 2-56: Grid of the Sado estuary model.

2.2.1.2 Transient Circulation

Maps showing the velocity fields in spring tide conditions are presented in Figure 2-57 and Figure 2-58 during flood and ebb tidal phases respectively. The velocity modulus, represented by the colour, exceeds slightly 1m/s at the mouth of the estuary. Inside the estuary the flow is conditioned by the local topography, showing strong curvature, which is responsible for the formation of the sand banks forming the system of two channels in the lower estuary. During ebb, the velocity is clearly higher in both in the southern channel and at the entrance of Marateca, creating conditions for the existence of a very intense residual flow.

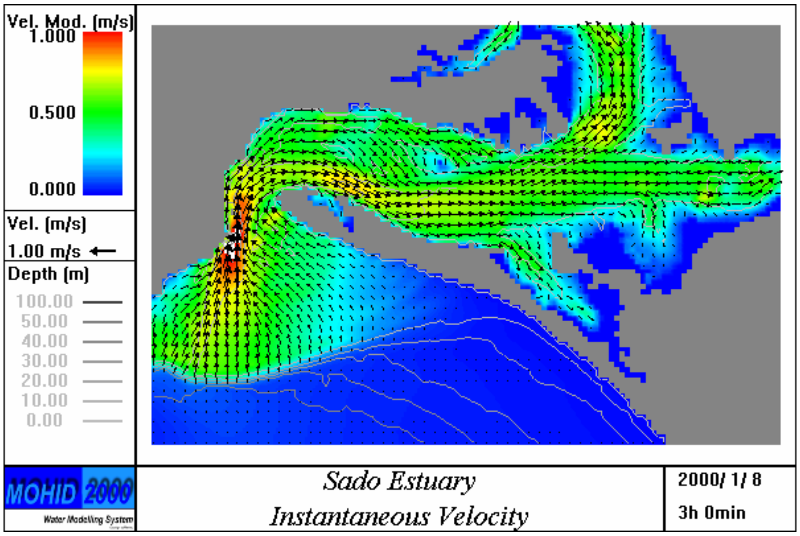


Figure 2-57: Instantaneous velocity during spring tide (flooding).

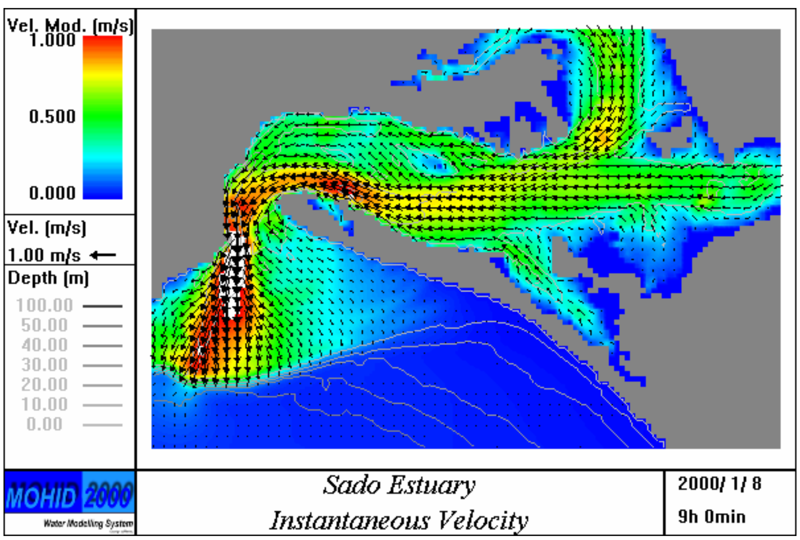


Figure 2-58: Instantaneous velocity during spring tide (ebb).

2.2.1.3 Residual Circulation

Like in case of the Tagus estuary, the residual velocity, Figure 2-59, is also analysed. The velocity represented in the figure is the residual specific flux divided by the residual depth of the water column. The figure shows an important recirculation inside the estuary, right in front of the town of Setúbal. This recirculation shows that in the northern channel there is more water flowing during flooding than during ebb and that in the southern channel it happens the way around. Integrating the flux all over across section, one would get the river discharge, and the corresponding residual velocity would be very small (of the order of 1 mm/s). This eddy shows residual velocities of the order of 10 cm/s, showing that the tidal mixing is the most efficient mechanism for estuary water renewal. In a more linear system, both flood and ebb velocities would be lower. This eddy is quite important for the residence time (see below), generating much shorter residence times in the lower estuary, through the generation of intense mixing. Similar eddies further inside the estuary also generate high mixing of water from different parts of the estuary. Through that mixing, those eddies also contribute to reduce the residence time of the water inside the estuary.

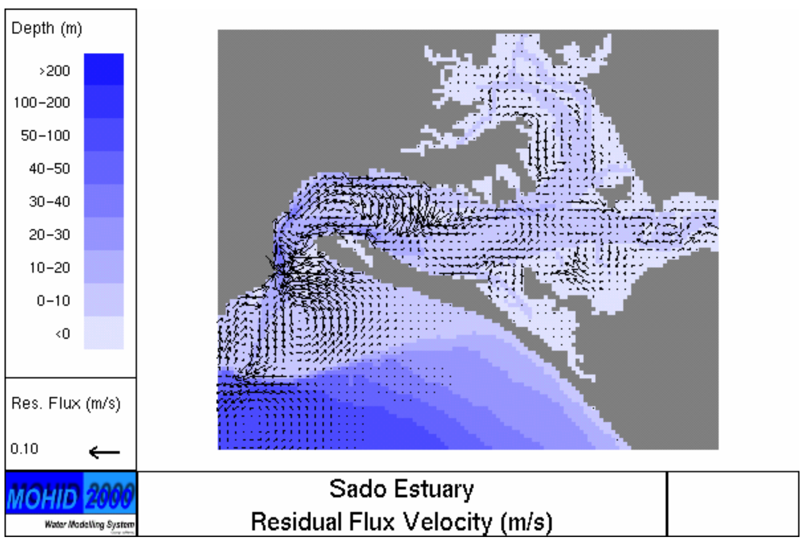


Figure 2-59: Residual velocity of the Sado estuary.

2.2.2 Residence Time

To calculate the estuary residence times inside the Sado estuary the same methodology used for the Tagus was followed, except that the residence was just analyzed for the no wind scenario because in this estuary the fetch is smaller and so the differences would be even smaller than in the Tagus. The hydrodynamic model was forced by tide and by the Sado River (10 m^3s^{-1}).

The initial distribution of the lagrangian tracers is shown in Figure 2-60. The whole estuary was filled with tracers, considering the limit of the estuary equal to the one defined in the study “Limites de Jusante dos Estuários Portugueses” (INAG, 2001).

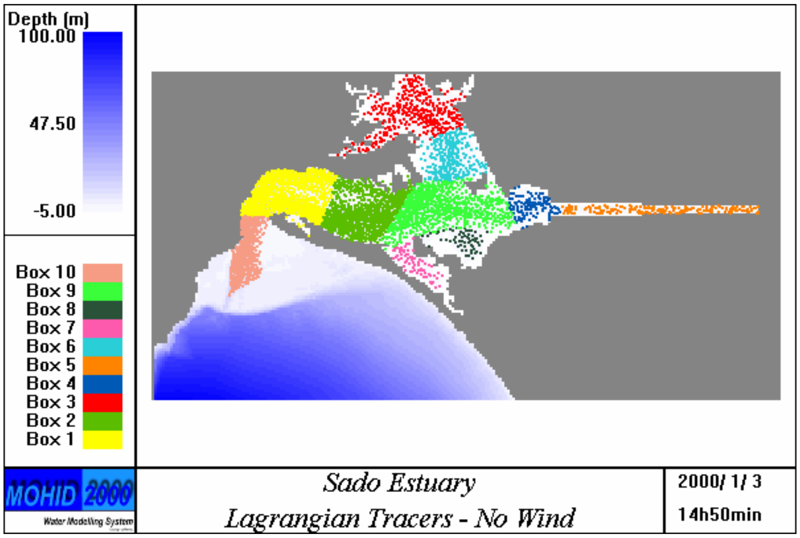


Figure 2-60: Initial distribution of the lagrangian tracers in the Sado estuary.

Like in the case of the Tagus estuary, the simulation starts at high tide. The evolution of the volume of water inside the Sado estuary, during the simulation period, is shown in Figure 2-61. The average volume of the Sado estuary is about $8x10^8m^3$ and average exchange with the open sea, in each tidal cycle, about $3x10^8m^3$. The daily discharge of the Sado River (≈8.6 $x10^5m^3$) is very small compared to the volume exchange with the open sea during one tidal cycle. These values show that residence time is controlled by diffusion and in a much less extent by the residual advection induced by the river discharge.

Figure 2-62 shows the location of the tracers 15 after emission and Figure 2-63 15 days latter. In both figures it is possible to observe that after 30 days many particles still reside inside the estuary, which let conclude that the residence time of the Sado estuary is longer that that in the Tagus estuary. The figure also shows that there is a complete mixing of the water from different parts of the estuary, putting into evidence that the residence time in a specific part of the estuary is small. Most particles moved already for the lower estuary, being trapped by the strong residual eddy located on that part of the estuary and will be slowly exported to the ocean. Out of the estuary, the tracers move along the northern bank due to coriollis effect.

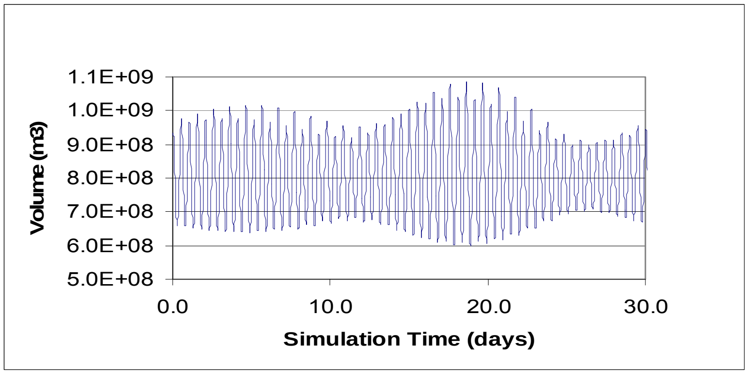


Figure 2-61: Evolution of the volume of water in the Sado estuary during the simulation period. The spring-neap cycle is clear.

Both Figure 2-8 and Figure 2-9 represent distributions in high water. Figure 2-64 represents the distribution in low water, only 7 days after the emission. Comparison of this figure with former figures puts into evidence the length of the tidal excursion, which is responsible for the strong tidal mixing. Figure 2-64 also shows that 7 days are enough for the water from Marateca to loose its identity.

As in case of the Tagus estuary, the regions where no tracers are represented are intertidal regions that are empty (intertidal areas at low water) or regions that have been occupied by new water (from the river or from the sea).

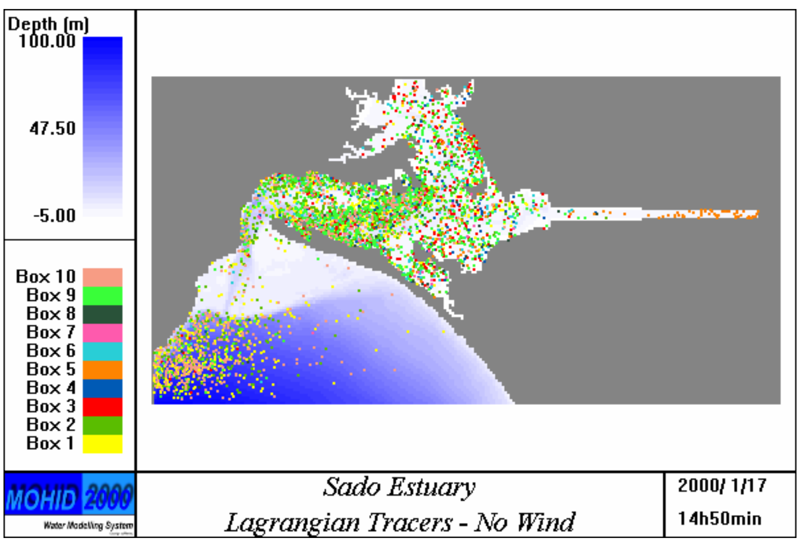


Figure 2-62: Localization of the tracers inside the estuary 15 days after emission (high water).

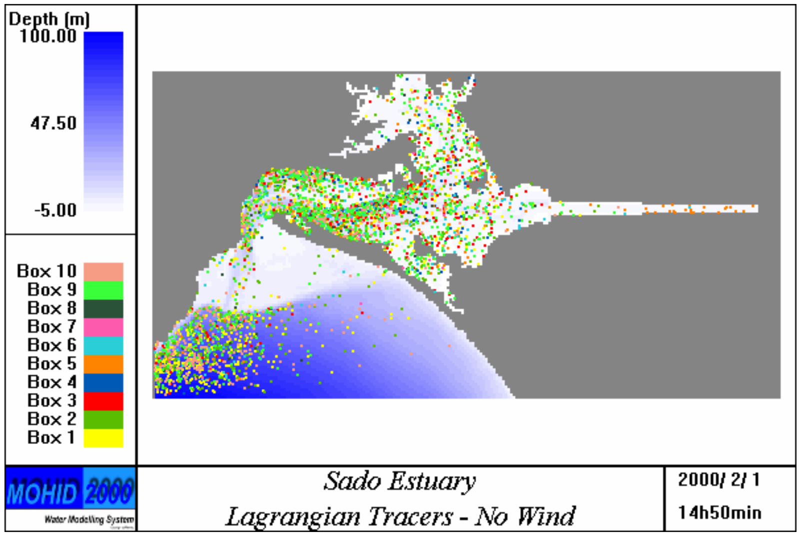


Figure 2-63: Localization of the tracers inside the estuary after 30 days (at high water).

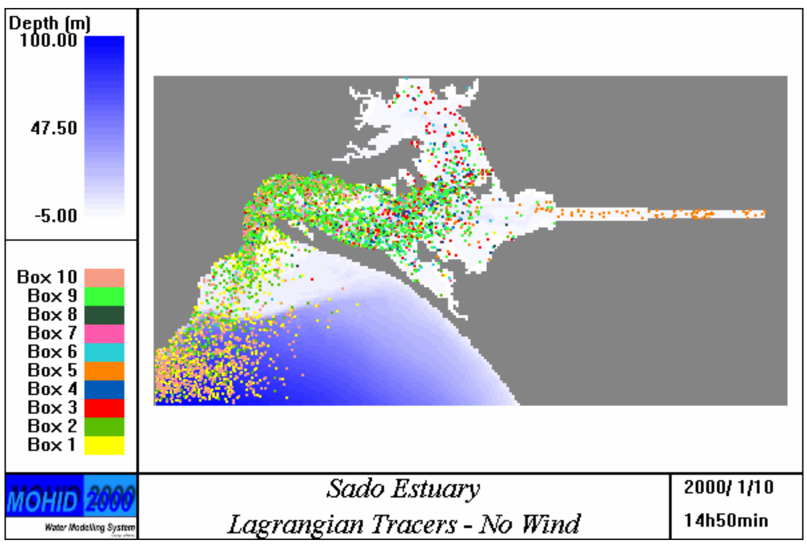


Figure 2-64: Location of the tracers 7 days after emission (at low water)

The evolution of the fraction of tracers still resident inside the estuary (total volume of the tracers inside the estuary divided by the instantaneous volume of the estuary) is shown in Figure 2-65. This figure shows that after 15 days more then 60% of the initial volume is still inside the estuary and that after 30 days still 40% of the tracers remain inside the estuary.

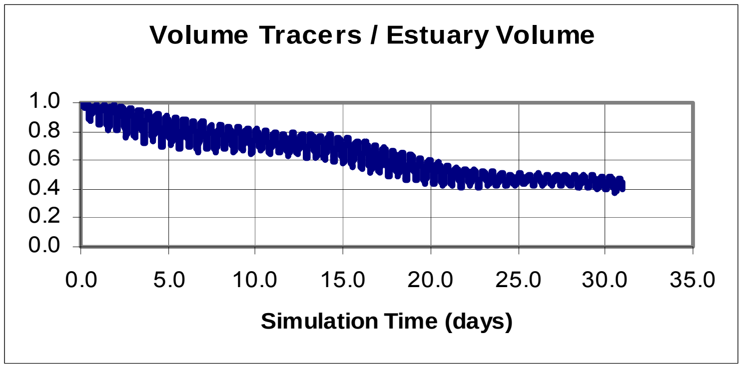


Figure 2-65: Evolution of the fraction between the volume of lagrangian tracers inside the estuary and the total estuary volume in function of the time

The figure also shows a curve with two steep slopes during two periods of a week separated by periods also of a week, with a slower slope. The steeper slopes correspond to spring tides and the slower slopes correspond to neap tides, putting into evidence the role of the tide on estuary flushing (this is not specific of this estuary)

Thus defining the residence time on the conventional way, one can say that the residence time of the water inside the estuary is longer then one month, although we can say that the residence time of the water in each part of the estuary is less then one week. The next figures give an overview of the flushing of the estuary, showing that it is not a linear process where the parts closer to the sea boundary are flushed quicker.

Figure 2-66 shows the evolution of the time multiplied by the fraction of the initial water still remaining in the estuary. The figure shows that after 30 days of simulation (real time), the estuary has been affected about 17/30 by the water initially in the estuary and 13/30 by new water (mainly from the sea, because the river discharge is very low).

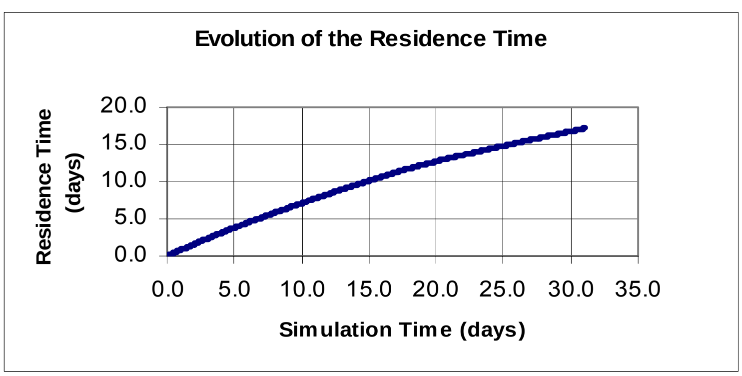


Figure 2-66: Alternative way for defining the residence time in the estuary, accounting for the role of the "old" water in the estuary.

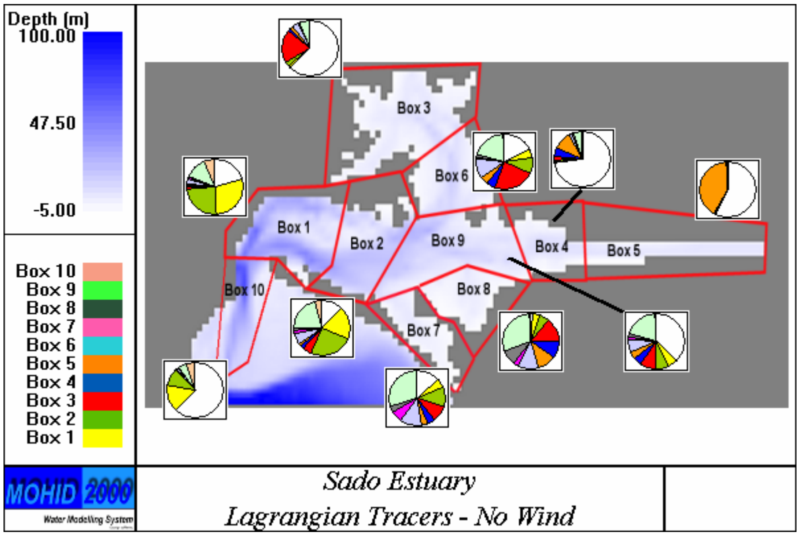


Figure 2-67: Water exchange among boxes (integrated results after 15 days)

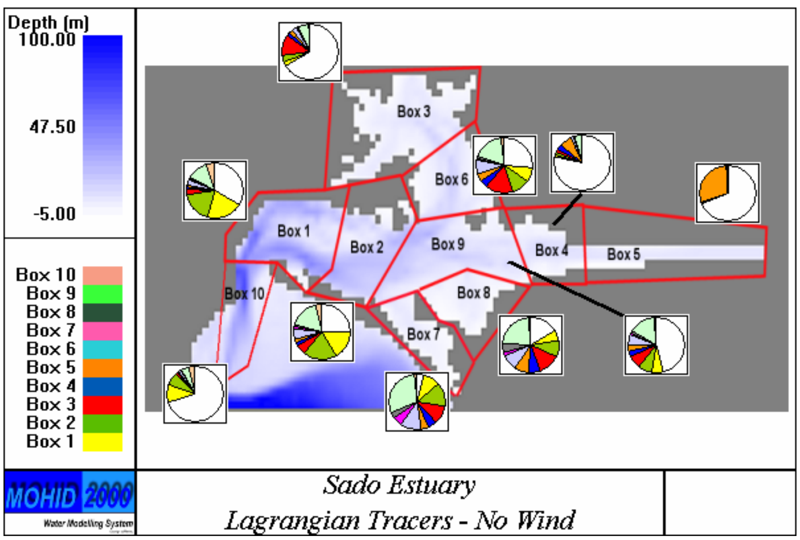


Figure 2-68: Water exchange among boxes (integrated results after 30 days)

The mixing of the new water inside the estuary is shown in Figure 2-67 and in Figure 2-68. The figures have to be read as in the case of the Tagus. The white part of the pies shows for each box the influence of the new water defined as for drawing Figure 2-66. These results show that the contribution of new water for the properties of Box 3, Box 4 and Box 10 is more important than for other boxes. This is a consequence of the residual circulation and of the topography. In case of Box 10 the location and the influence of seawater during flood and of estuarine water during ebb explains the distribution. In Box 3 and 4 the extensive shallow areas are responsible for the quick renovation. In the lower estuary (Box 1 and Box2) the residence time is long and a contribution from all other boxes can be observed. The same happens to the boxes in the southern part of the estuary (Box 7 and Box 8).

As a conclusion, one can say that the residence time in the Sado estuary as a whole is long when compared to the other estuaries presented in the current study. This integral result is a consequence of the low freshwater input from the River, compared with the average volume of the estuary, which implies that renovation of the water has to done mainly through mixing of the tidal sea water with estuarine water. From this integral conclusion, we can't infer on the residence time of the water inside each part of the estuary. In fact, the strong tidal flow generates strong mixing of the water inside the estuary and the residual flow pattern transports the new seawater very fast to the upper estuary. This means that the mixing is not a linear process. This result is also confirmed by the salinity distribution inside the estuary, which show small gradients in the main estuary and only in Alcácer channel show a typical estuarine salinity distribution. These results can be summarized stating that the estuary behaves as a coastal lagoon into which flows "Alcácer estuary".

2.2.3 Ecological modelling

The same ecological model and methodology used in the Tagus were used in the Sado. The unique difference was the consideration of a constant river discharge. The work is also described in the same way. The reference situation is used to validate the model and to describe loads and field data. Then management scenarios are presented.

2.2.3.1 Reference Situation

2.2.3.1.1 Loads

The Sado River carries into the estuary the most important nutrient load. The Sado river basin is represented in Figure 2-69, where the monitoring stations are also represented. The average discharge is 10 m^3/s. Average values for the concentrations are available, but no time series. However, from the Tagus data one can expect concentrations in the river water to be independent of the discharge, except for very small discharges, when smaller concentrations of nitrate and ammonia should be expected. As a consequence it was decided to run the model using the existing information to specify the boundary conditions and all the existing data to validate the model. The results obtained are very consistent with field data, showing that the methodology adopted is realistic. The

Marateca stream flowing to the estuary in the northern area was also considered. The flow used for its simulation was 1 m^3/s (10% of the Sado River) and the same concentrations were assumed.

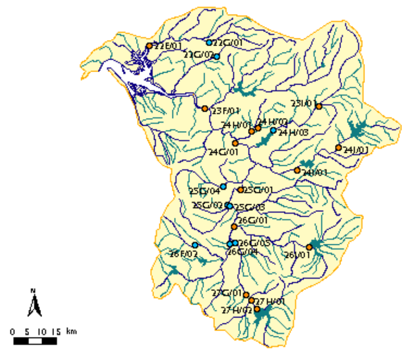


Figure 2-69: Localization of the monitoring stations in the Sado basin.

Property	Value		Reference
Sediments	200.0	mg/l	(Cabeçadas, 1993)
Temperature	18.0	ºC	-
Salinity	0.0	psu	-
Oxygen	8.0	mgO/l	(Duarte e Henriques, 1991)
Zooplankton	0.0	mgC/l	(Lobo et al., 2000)
Phytoplankton	0.9	mgC/l	(Cabeçadas, 1993)
Nitrite	0.04	mgN/l	(Duarte e Henriques, 1991)
Nitrate	3.6	mgN/l	(Duarte e Henriques, 1991)
Ammonia	0.24	mgN/l	(Duarte e Henriques, 1991)
DONnr	0.2	mgN/l	-
DONr	0.0	mgN/l	-
PON	0.2	mgN/l	-

Table 2.2-1: Average properties of the Sado river water entering in the estuary.

The Sado estuary has been object of many specific studies. However, those performed by IPIMAR (mainly by L. Cabeçadas) are the most systematic and relevant for the study of eutrophication. The loads of nitrate provided by Duarte & Henriques (see Table 2.2-1) are quite similar to the average values measured in most stations around the estuary.

A treatment plant for the population of Setúbal metropolitan area is concluded and will enter in functioning in May 2002. The effluent will be discharged in the northern channel after a Tertiary Treatment Process with Nitrogen and Phosphorus removal and disinfection with Ultraviolet Light will be performed.

Considering the characteristics of the treatment plant and that the discharge of the river is overestimated, it was decided to neglect this load in the simulations. The comparison of the results of the model with field data obtained before urban waste water treatment shows that neglecting this load do not correspond to an underestimation of the loads.

2.2.3.1.2 Time Series Analysis (Field Data and Model Results)

The field data available to validate the model results is scattered in time and space. The data used to validate the results of the model was mostly gathered by Graça Cabeçadas of the IPIMAR in field campaigns during 96, 97, 99 and 2000. Figure 2-70 shows the field stations in the Sado estuary and Table 2.2-2 the sampling dates. The table shows that in these stations, most data was collected in 2 campaigns, in September 97 and February 2000 and cannot describe the seasonal evolution.

Figure 2-72 shows the points selected to show time series computed by the model. These points characterize the seasonal evolution of the most important zones of the estuary. In the same location of Station #7, Cabeçadas, 1993, performed a time series that is also used to evaluate the results of the model.

The results of the model were also evaluated in terms of consistency. For that purpose, time series computed by the model and the annual averages of experimental values measured in the boxes were also compared (Figure 2-71)

Figure 2-70: Location of field Stations of IPIMAR's campaigns.

The figure shows field data (red dots) and average values of model results per box. The combination of model results and field data provides some interesting comments about the estuary properties. The figure shows that the nutrients concentration is always very low. The nitrate measured is always below 0.1 mgN/L and the concentration of ammonia is below 0.05 mgN/L. Therefore, one cannot expect a high trophic level, being in fact, the phytoplankton measured always below 0.5 mgC/L.

The concentrations computed by the model are quite similar to those measured, except for the nitrate in the boxes close to the river discharge (box 4 and 5), where the concentrations measured in the field are much below those computed by the model, suggesting that during this period, the load into the estuary was overestimated. In the main estuary, the concentrations given by the model tend to be higher, but remain in the same range and, show very low concentrations. This result suggests that the discharge from the river is overestimated. The comparison of time series of phytoplankton computed by the model and measured (Figure 2-77) shows that the maximum concentrations computed by the model are identical to those measured in the field, suggesting that the differences registered between the measured and simulated values are due to seasonal variability.

Another interesting result put into evidence by Figure 2-71 is that the boxes 4 and 5 are much different from all the others, where values of all the properties are quite similar. This result reinforces the hypotheses of coastal lagoon behaviour of the estuary, where the concentrations are mainly determined by estuary-sea exchange.

Station	Date
#9	18/09/97
#10	18/09/97
#18	20/09/97
#19	21/09/97
#20	21/09/97
#21	21/09/97
#23	22/09/97
#29	25/05/99
#34	14/02/00
#41	15/02/00
#42	16/02/00
#44	18/02/00
#45	18/02/00

Table 2.2-2: Sampling dates of IPIMAR campaigns in the Sado Estuary.

Figure 2-62 shows the location of the points corresponding to the time series of the model results presented in Figure 2-73 to Figure 2-77. These figures show evolutions of phytoplankton, nitrate, ammonia and oxygen in the stations represented in Figure 2-72 during one year. For Station #7 we can compare model results of phytoplankton with local measurements (Cabeçadas, 1993) during one year.

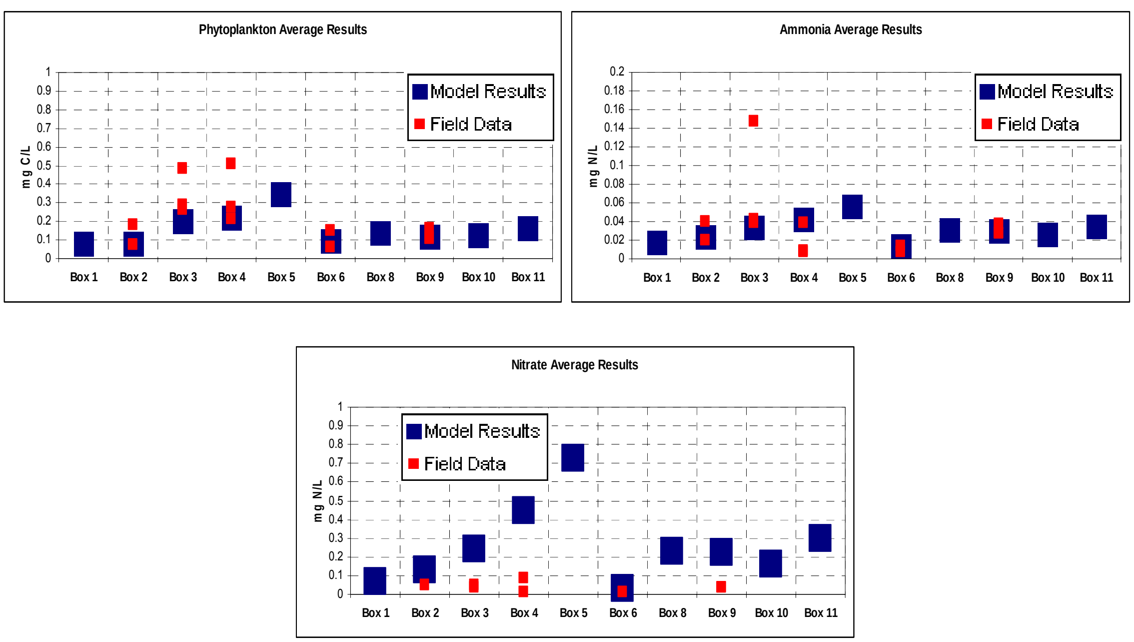


Figure 2-71: Annual average concentrations computed by the model and measured in boxes.

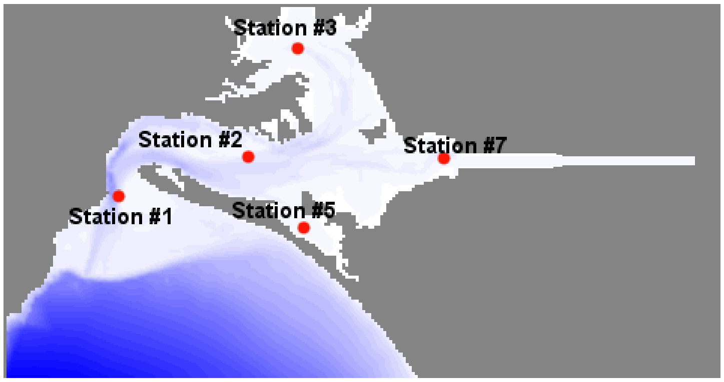


Figure 2-72: Location of model stations in the Sado estuary (points where time series were produced).

Figure 2-73 to Figure 2-77 show the seasonal evolution of the properties in the estuary as computed by the model. In the lower estuary there is no seasonal variability, being primary production limited by nutrients availability during the whole year. As one progresses towards the interior of the estuary, seasonal variability becomes clear, being maximal at station #7. Another interesting aspect of the estuary is the existence of several decreasing peaks over one year.

The analysis of the properties in the same point shows that there is a clear correlation between the phytoplankton and the nitrate, of the type “prey-predator”. When the phytoplankton increases, the nitrate decreases, and vice versa. This shows that there is a limitation of the primary production by the nutrients.

Another interesting aspect is the fact that the amplitude of the peaks decreases from spring to summer, while the frequency of the oscillation increases. This is a consequence of the intensification of the process by increasing light on one hand and of the increase of the rate of predation by the zooplankton on the other hand. All these processes have time enough to become evident because the residence time in the estuary is large enough to keep the blooms inside the estuary. In estuaries with shorter residence times this dynamics could be destroyed by estuary exports.

The effective interaction between the phytoplankton and the nutrients becomes more complex has one considers consumption of phytoplankton and production of ammonia by the zooplankton and mineralization of the organic matter, as is computed by the model. Particularly complex is the mineralization of organic matter, which is resuspended and redeposited while being mineralized.

As expected concentrations decrease towards the ocean, being phytoplankton concentration higher at Stations #3 and #7, respectively in Marateca and Alcácer Channel.

2.2.3.1.3 Spatial distributions of Concentration

Spatial distributions of the concentrations of phytoplankton, nitrate, ammonia and oxygen are presented in Figure 2-78. The maps show the reference situation at the end of February (20th), when phytoplankton is maximal.

The maps show that phytoplankton concentration is higher in areas under direct influence of river discharges (Marateca and Alcácer Channel), where nutrient concentrations are higher too. The low depth of these areas also creates favorable light conditions.

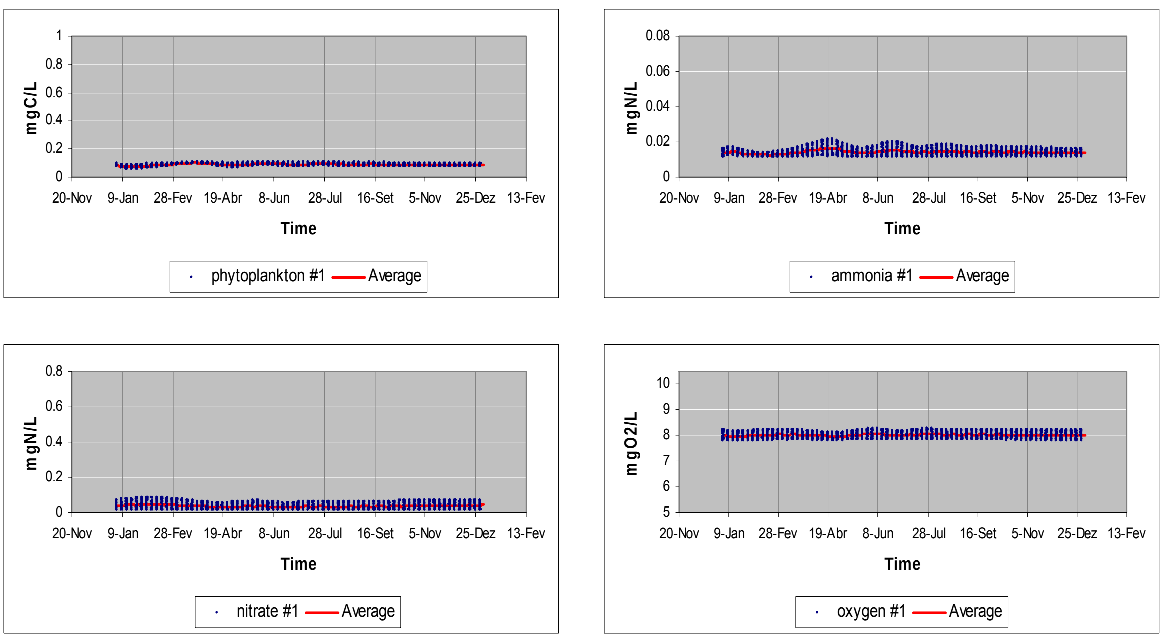


Figure 2-73: Time series of model results in Station #1 in the reference situation.

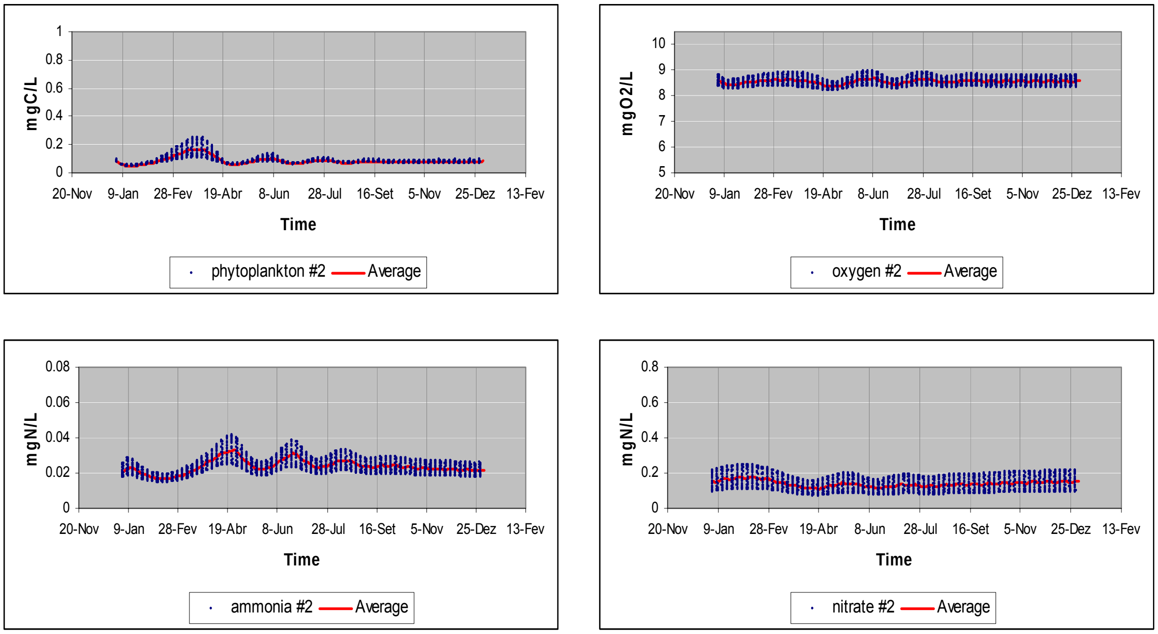


Figure 2-74: Time series of model results in Station #2 in the reference situation.

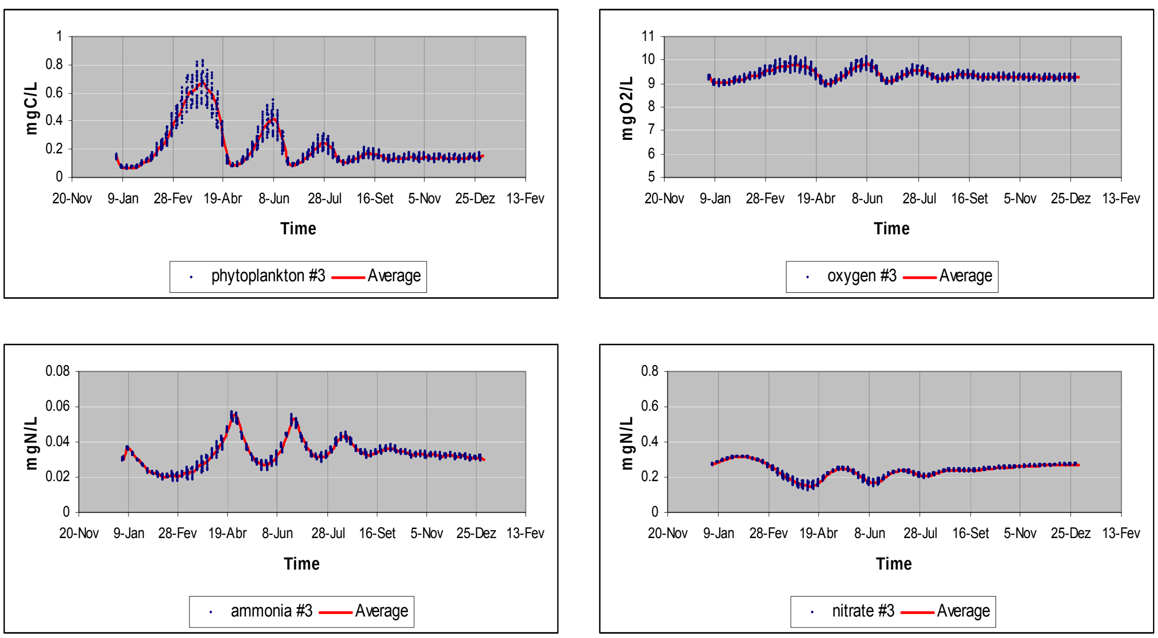


Figure 2-75: Time series of model results in Station #3 in the reference situation.

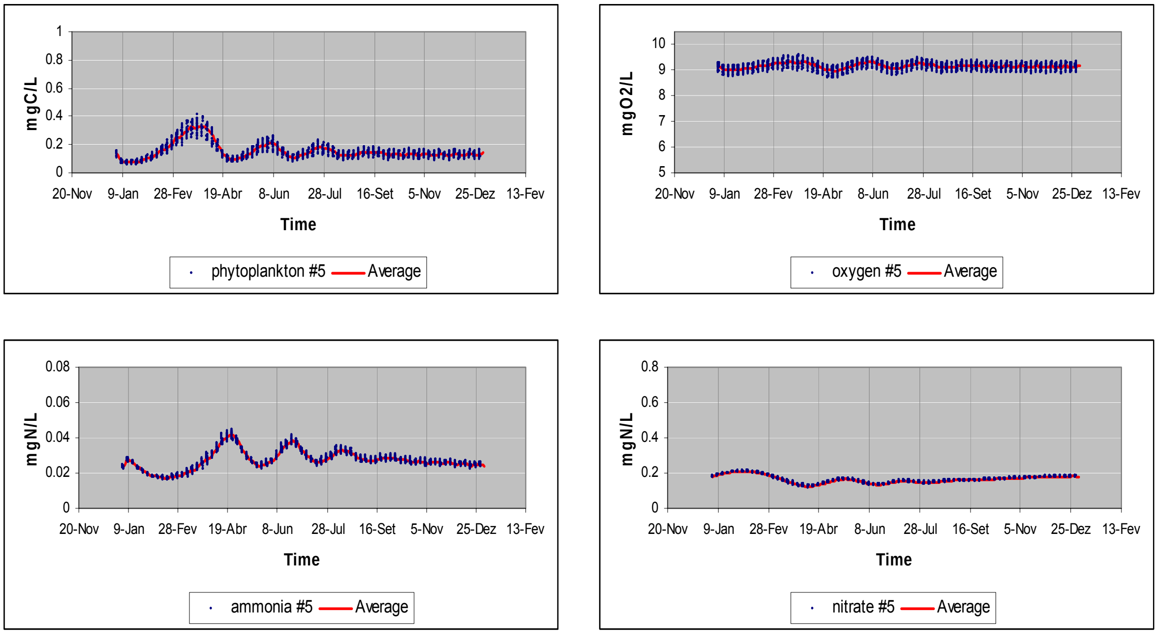


Figure 2-76: Time series of model results in Station #5 in the reference situation.

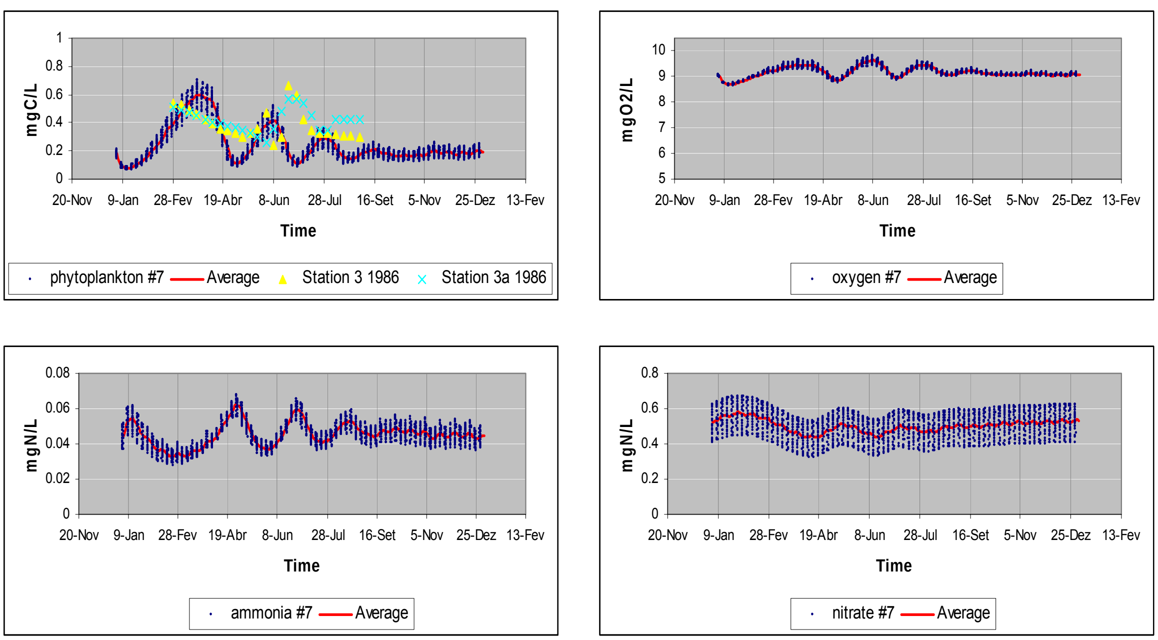


Figure 2-77: Time series of model results in Station #7 in the reference situation. and of phytoplankton field data for 1986 (Cabeçadas, 1993).

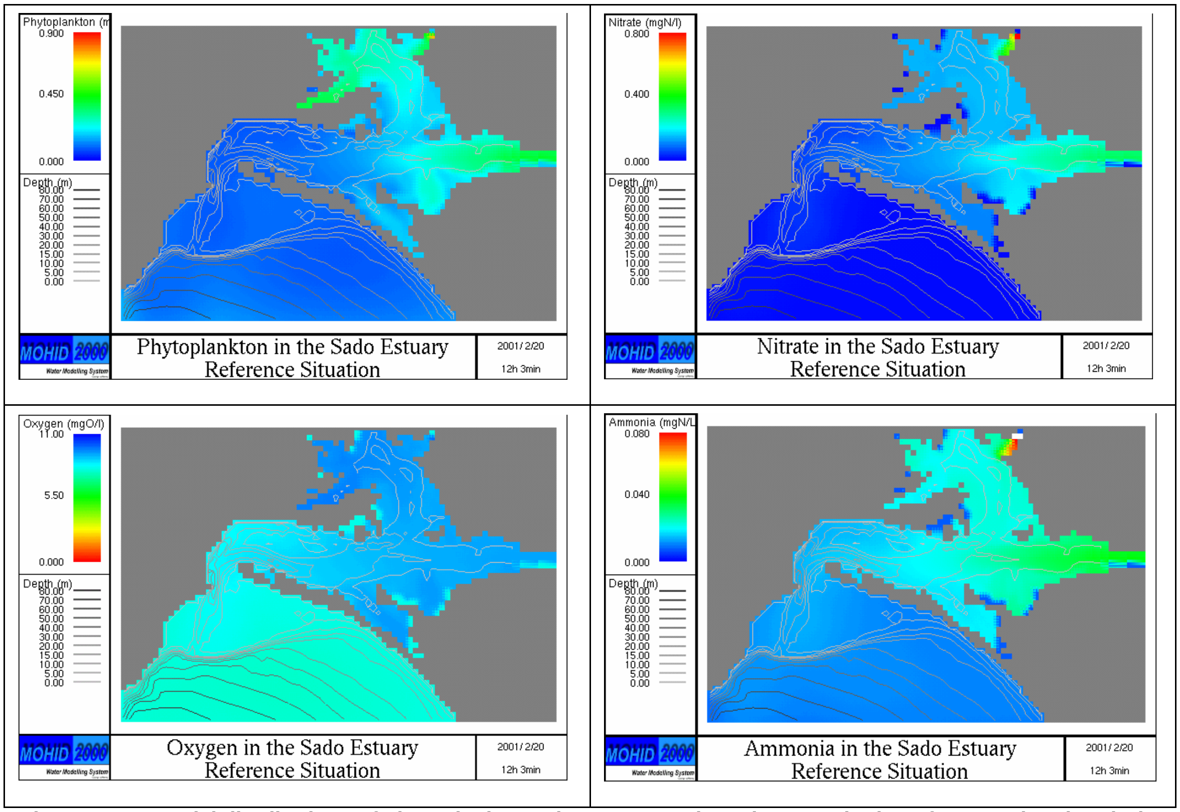


Figure 2-78: Spatial distributions of phytoplankton, nitrate, ammonia and oxygen in the reference situation during phytoplankton maximum (20th of February)

2.2.3.1.4 Annual average distributions per zone of the estuary

In order to visualize the annual fluxes across the estuary, average values of the properties were computed per zone of the estuary. The boxes, shown in Figure 2-79 and already used to integrate the information displayed in Figure 2-67 and in Figure 2-68 were used. Figure 2-80 shows the annual average concentrations of phytoplankton, organic matter (particulate plus dissolved), ammonia and nitrate in each box.

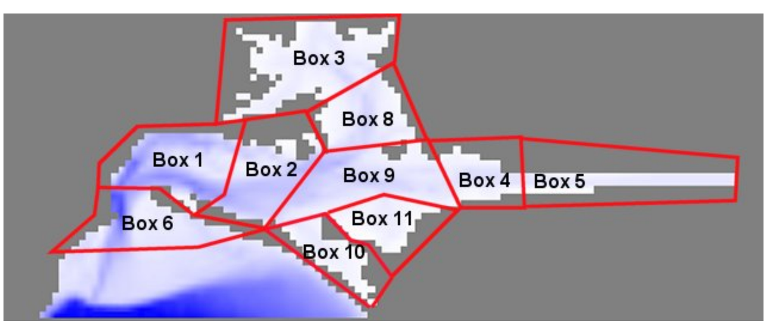


Figure 2-79: Integration Boxes in the Sado Estuary.

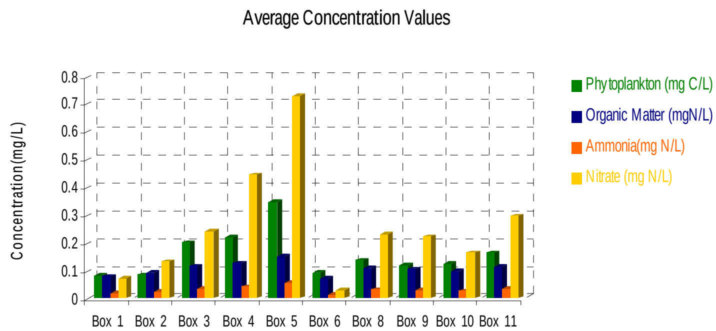


Figure 2-80: Annual average distribution per zone of the Sado estuary in the reference situation.

2.2.3.1.5 Annual Budgets per zone of the estuary

The values of the concentrations are quite low al over the estuary, being higher in the boxes 4 and 5 where more nitrate is available due to Sado's discharge. Figure 2-81 represents the annual fluxes exchanged between boxes. Nitrate, phytoplankton and dissolved organic have the higher fluxes. The same information is provide in a spatial representation in Figure 2-82.

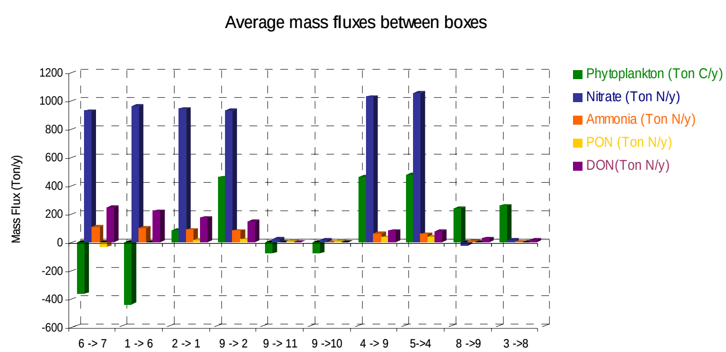


Figure 2-81: Annual fluxes exchanged between boxes in the Sado estuary.

These results show the expected behaviour inside an estuary with only a major point discharge (Sado River). The areas where the main channels are located drive the mass fluxes towards the ocean (boxes 5, 4, 9, 2, 1), the areas characterized by low depths, ecologically more active, (boxes 3, 8 10, 11) export phytoplankton and import nitrate and organic matter. Ammonia exported by these areas is produced by decomposition of organic matter n the bottom. At the sea boundary there is an interesting import of sea phytoplankton from box 6 to box 1.

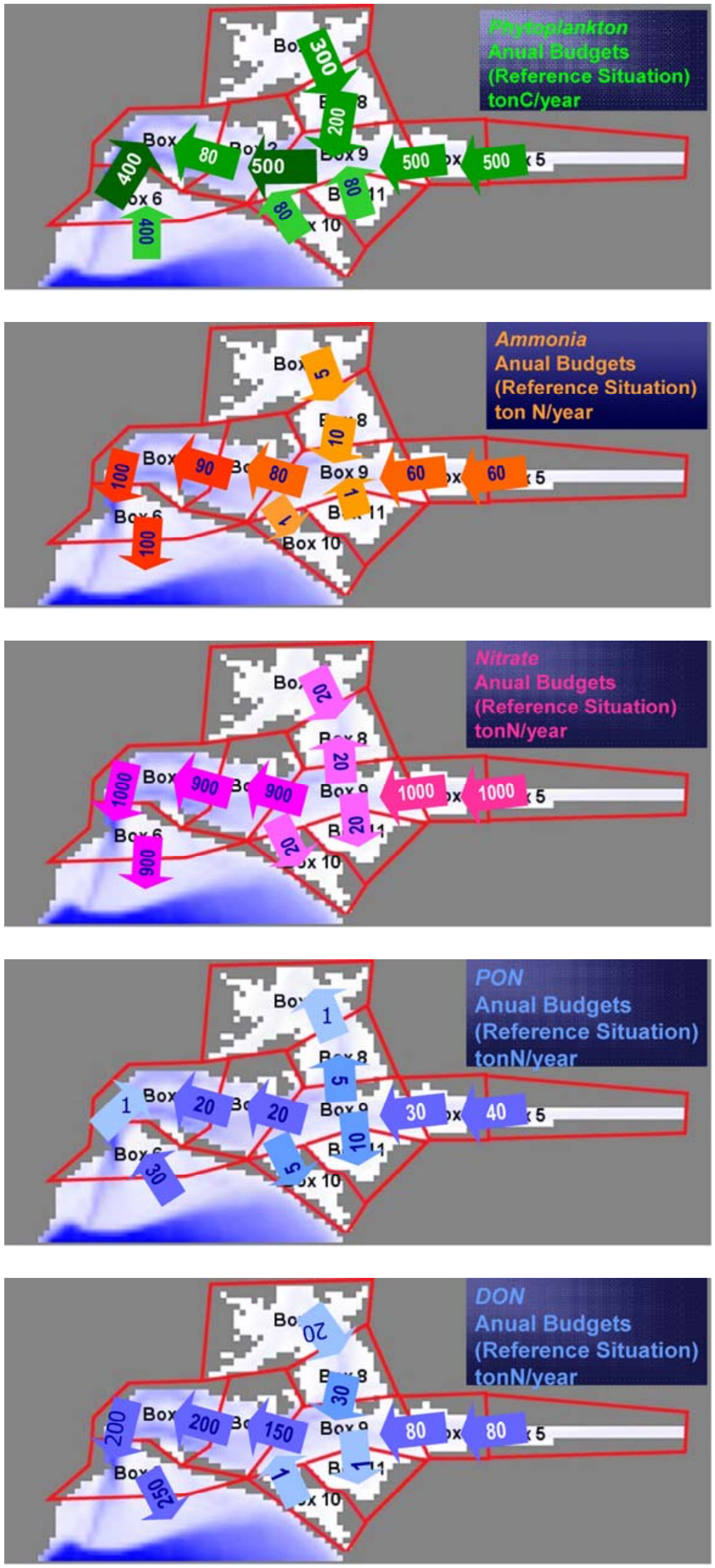


Figure 2-82: Annual Budgets between boxes in the Reference Situation.

This import is justified by the fact that the area near the mouth, in front of Tróia peninsula has significant production powered by nutrients from deep areas off the estuary plateaux and also by nutrients discharged by the estuary that enter in the estuary during flooding.

2.2.3.1.6 Conclusions

The Sado estuary has a very intense tidal circulation that associated to the curvature of the estuary is responsible for a strong residual circulation, with velocities that can exceed 10 cm/s, forming very intense residual eddies. These eddies determine transport, residence time and sedimentological processes in the estuary.

In fact the residual flux across any section of the estuary is equal to the fresh water flow, discharged upstream. In case of the Sado estuary, fresh water discharges would generate velocities two orders of magnitude smaller than those effectively registered in the estuary. As a consequence of the difference between actual residual velocity and that generated by the fresh water discharge, estuarine water is obliged to recirculate in the estuary intensively on its way to the ocean, reducing spatial gradients.

Tidal mixing inside the estuary enhances the role of diffusion for the effective residence time inside the estuary, reducing particularly the residence time of the water inside specific regions of the estuary[5].

The residence time of the water inside the estuary is longer than one month, but the water in none of the regions inside the estuary can maintain its identity for more that one week. The residence time in the estuary, associated to the low level of nutrients generates an interesting series of phytoplankton blooms of decreasing intensity, between the beginning of spring and the end of summer.

Nitrate concentration is always very low in the estuary, being the limitation factor of primary production. Because the residence time in the estuary is longer than one month, the shape of the bloom is modulated by nitrate availability and zooplankton predation. After a bloom, the conditions for another smaller bloom are created by additional

[5] Another important consequence of the strong residual eddies are the secondary flows with residual transport towards their centre, where they tend to build sand banks. This is the case for the sand banks separating the northern and southern channels.

nutrients discharged by the river and by remineralization of the organic matter inside the estuary.

Shallow areas are net producers of phytoplankton and deeper areas are net consumers. The shallow areas off the estuary are also net producers of phytoplankton that is consumed in the deeper areas of the lower estuary[6].

2.2.3.2 Influence of the Nitrate Removal by Agriculture Systems

Although it is known that production in the estuary is limited y nutrients availability, a scenario of extra nutrients limitation was tested. In this hypothetical scenario, the fluvial discharge was reduced of 50%, maintaining all the other forcing parameters.

2.2.3.2.1 Properties Distribution

In the next paragraphs modification of concentration distributions and annual budgets are presented.

2.2.3.2.1.1 Spatial distributions of Concentrations

Figure 2-83 shows concentrations in the reference situation (left column) and the scenario with a reduction by 50% of the nitrate input from the Sado and Marateca Rivers. The figure shows that the reduction of 50% of the input from the Marateca and Sado Rivers reduces the concentrations but the values remain in the same range and the distribution shape does not change.

2.2.3.2.1.2 Annual Distributions

Average concentrations in the boxes defined above are represented in Figure 2-84. This figure shows a general reduction of the average values in the estuary, which is much smaller than the reduction of the nitrate discharge. The figure shows that average nitrate concentrations are reduced to about 50%, but mean values of the other properties show much smaller reductions. In fact what is happening is a reduction of the turn-over of the estuary. The decrease of the phytoplankton induces a decreasing of zooplankton grazing and of its maximal concentration.

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[6] The production of phytoplankton in the shallow areas off the estuary is an interesting aspect of the interaction between deep and shallow oceanic areas in presence of strong tidal transport.

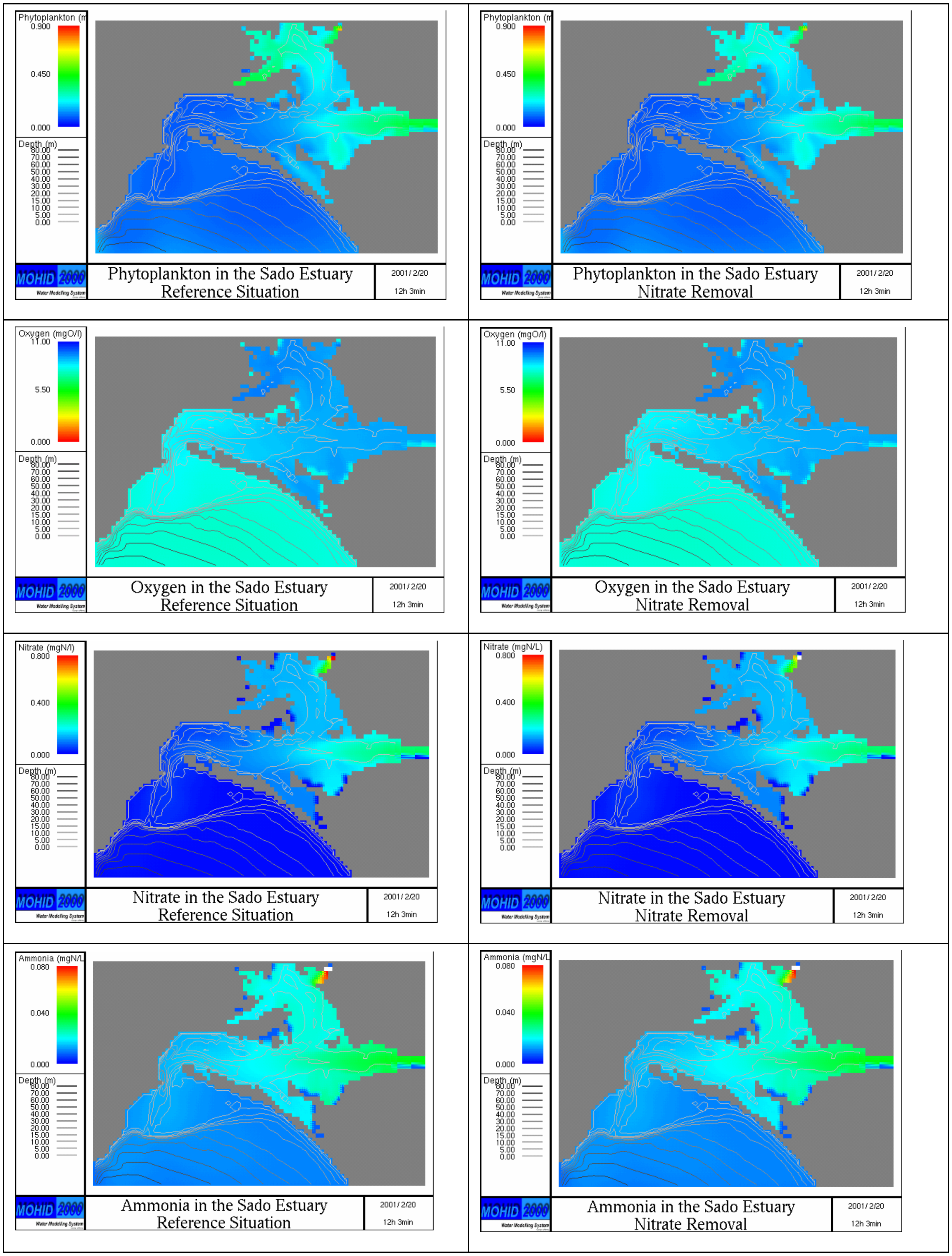


Figure 2-83: Concentrations in the reference situation (left column) and in a scenario of 50% reduction of nitrate discharged by the rivers (right column).

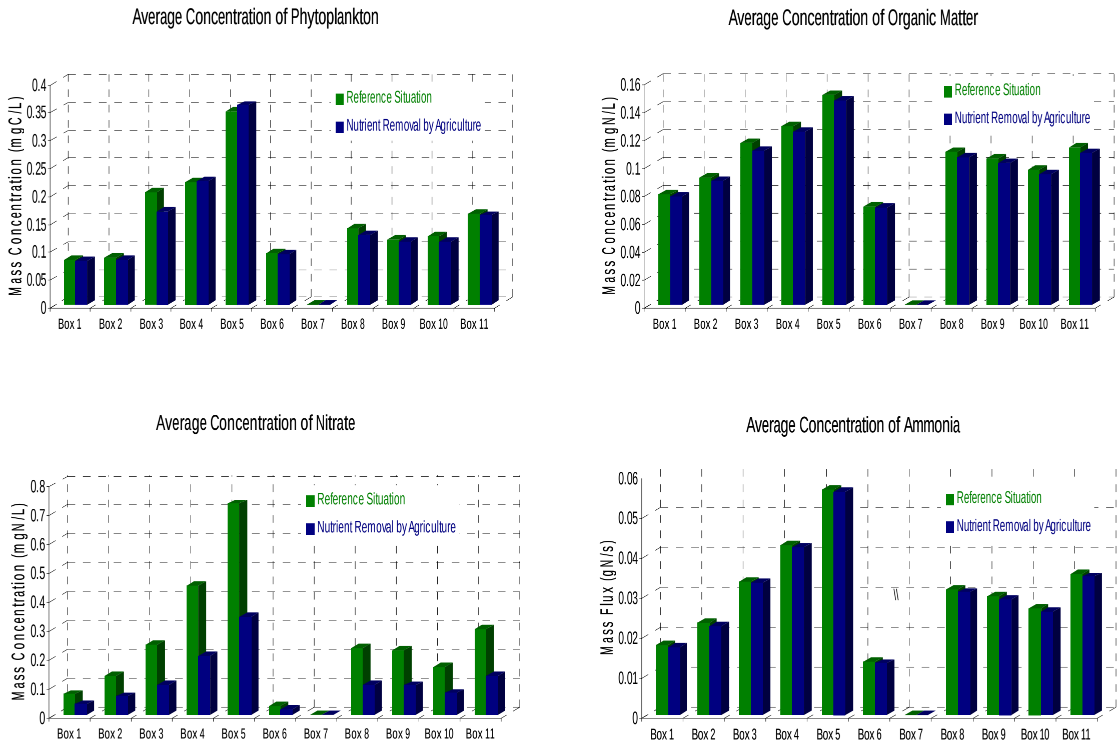


Figure 2-84:Average concentrations in the reference situation and in a scenario of 50% reduction of nitrate discharged by the rivers.

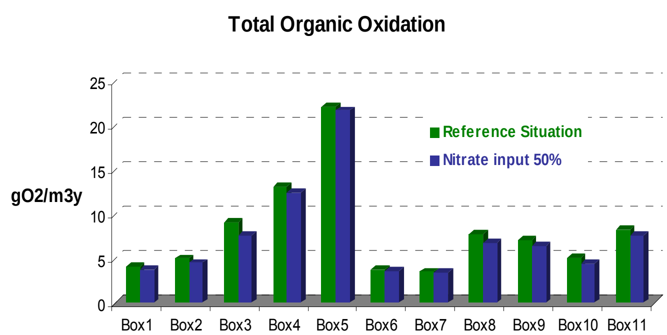


Figure 2-85: Average oxygen consumption for mineralization in the reference situation and the scenario of 50% reduction of river nitrate.

On other hand, the cyclic character of primary production and its low intensity during winter, allows for recharging of the estuary during that period and a still clear bloom in spring with smaller, but still comparable concentrations of phytoplankton.

2.2.3.2.2 Annual Budgets per zone of the estuary

Comparison of the budgets between different zones of the estuary in the reference situation and in a situation of reduction of 50% of the nitrate discharged by the river is presented in Figure 2-86. The figure shows that the exchange of nitrogen is clearly reduced all over the estuary. The other properties change much less, except between boxes 3 and 8 (inside Marateca). In the reference situation the upper part of Marateca was exporting phytoplankton to box 8 and reducing the discharge of nitrate from Marateca Stream, Box 3 becomes an importer of phytoplankton, ammonia and dissolved organic matter. The budget of nitrate becomes balanced.

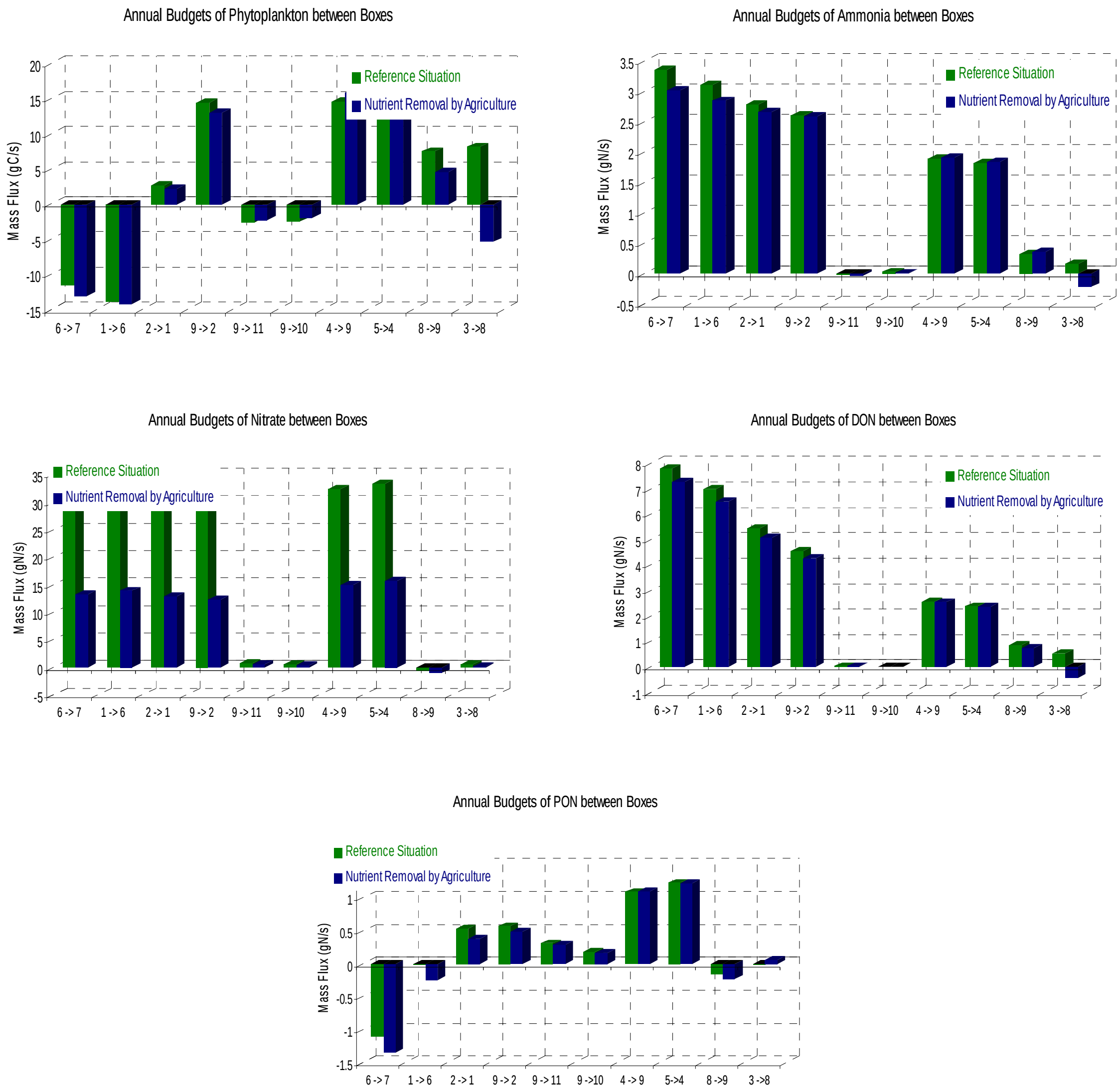


Figure 2-86: Budgets exchanged between regions of the estuary in the reference situation and in the scenario of 50% reduction of river nitrate discharge.

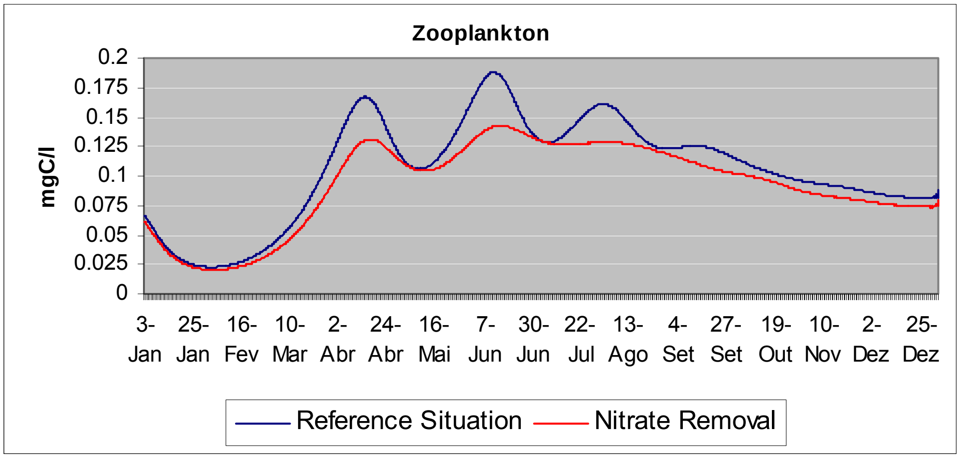
2.2.3.2.3 Conclusions

A reduction of 50% of the discharge of nitrate from the rivers Sado reduces the concentration of nitrate in the estuary of the same order of magnitude but the concentrations of phytoplankton, ammonia and organic matter are reduced only of the order of 5 to 10%. A reduction of the primary production was expected because nitrogen was identified as a limiting factor of the primary production.

The small value of the reduction of the primary production puts into evidence the non-linear character of the ecological systems. In fact primary producers are limited by nitrogen (limiting the production) and by grazing, controlling the mortality. In this case grazing activity is in fact reduced by the reduction of the phytoplankton, allowing its growing to levels close to those obtained in the reference conditions.

From these results one can say that a reduction of the nitrate discharged in the estuary does not reduce substantially the values of the primary producers, but it reduces levels of the second producers and the turnover of the phytoplankton. Figure 2-87 shows the evolutions of the mean concentrations of phytoplankton and zooplankton in the estuary in the reference conditions and in the scenario of reduction of nutrients discharged by the rivers. The figure shows that both concentrations are smaller, and that the peaks of zooplankton are very smooth. Figure 2-88 shows the evolution of limitation factor of phytoplankton by nitrate. The figure shows that nitrate is a permanent limitation factor of phytoplankton growth, even in the reference conditions. The figure also shows that a reduction of the nutrients load enhances its limitation. Having into consideration the exponential effect of the limiting factors, one can understand the importance of a 10% reduction.

The reduction of the nitrate discharged by Marateca stream reduces the production of phytoplankton in the upper part of the bay, which becomes an importer of phytoplankton, ammonia and dissolved matter from downstream.



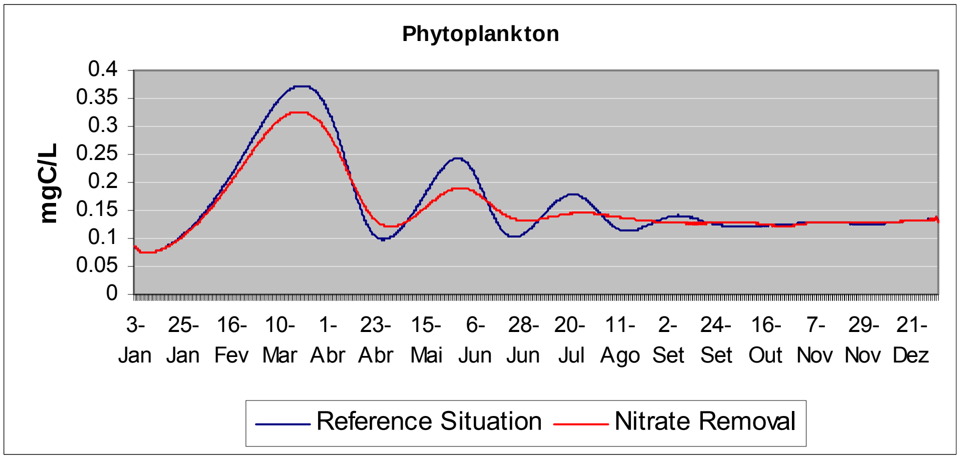


Figure 2-87: Evolution of the mean concentrations of phytoplankton and zooplankton in the estuary in the reference situation and in the scenario of reduction of 50% of the nutrients discharged by the Sado river and Marateca stream.

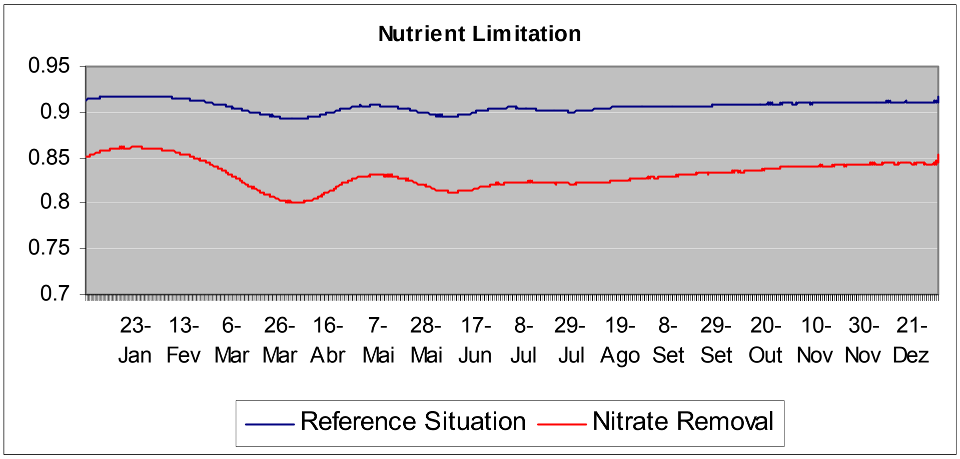


Figure 2-88: Evolution of the limitation of phytoplankton growth by nitrate in the reference situation and in the scenario of nutrients load reduction.

2.2.3.3 Conclusions

The results of the application of the model in the Sado estuary show that the properties of the estuary are determined basically by its extension and curvature and by the small discharge of fresh water and nutrients from the river.

The extension of the estuary generates a high tidal prism and strong tidal velocities, which associated to the curvature of the estuary generates very intense residual flow, with high velocities and strong residual eddies. The lower estuary is occupied by two very energetic eddies, one occupying the northern channel and most of the southern channel and the other occupying the central part of the estuary. These eddies determine mixing inside the estuary generating residence times much smaller than those obtained if the residual flow was due mostly to the river discharge. Another very important consequence of these eddies is the mixing of the water from different regions of the estuary, reducing gradients and the residence time of the water in a specific area of the estuary.

The ecology of the estuary is a consequence of its hydrodynamics and of the small discharge of nutrients by the river, which make nitrogen a limiting factor of primary production, being the actual stock of phytoplankton also a consequence of the grazing by the zooplankton. Grazing by zooplankton is in fact a critical aspect for the standing stock of phytoplankton in presence of growth limitation by the nutrients.

In the simulation of a reduction of 50% of the nutrients discharged by the rivers it was found out that the reduction of grazing was the major process determining the final standing stock of the phytoplankton. A reduction of phytoplankton of only 5 to 10 % was observed mainly due to a reduction of the grazing due to the reduction of the zooplankton concentration.

2.3 MONDEGO ESTUARY MODEL

The Mondego estuary (located about 200 km northern of Lisbon) is the smallest estuary, assessed in this study. It has a narrow inlet and two channels in the lower part separated by a large sediment island. The southern channel is very shallow, especially in the upper part, where communication with the northern channel is negligible due to engineering works. The communication between the channels has been artificially reduced to a minimum in order to increase the discharge through the northern channel to minimize the maintenance costs of the navigation channel.

The Pranto River is a small tributary of the southern channel, which importance for the ecological conditions of that channel has increased after the artificial closing of the upper communication between the channels. The average discharge of Pranto River is much, and episodic due to artificial control of the water in the basin but can generate episodic reductions of salinity in the upper part of the channel.

The level of nutrients in this channel is determined by the exchanges with the northern channel across the communication section between the channels located downstream. Nutrients discharged by the Mondego enter in the channel during flood after some dilution with seawater and as a consequence the level of nutrients is smaller in the southern channel than in the northern channel.

In the southern channel there are some indications of eutrophication due to growth of benthic macro-algae. The growth of these algae seems to be related more to the hydrodynamical conditions than to the level of nutrients, which concentrations are in fact higher concentrations in the northern channel. The artificial closing of the upper communication between the channels has reduced the velocity of the flow and the residual circulation around the island, enhancing the physical conditions required for the growth od macro-algae in the southern channel.

In this study we have studied 3 scenarios: (i) the reference situation, (ii) a situation of 50% reduction of Mondego nutrients and (iii) the maintenance of the loads and the reopening of the upper communication between the channels. These scenarios were preceded by a study of the hydrodynamics and residence time in the estuary, like in case of Tagus and Sado estuaries.

2.3.1 Hydrodynamics of the estuary

The hydrodynamics of the Mondego estuary is forced in the model by the tide and by the mean discharge of the Mondego and Pranto Rivers, respectively 60 and 8 m^3s^{-1}.

2.3.1.1 Model Grid

The grid of the Mondego estuary model has 173 by 128 points, covering an area of 15.9 km by 12.5 km. Figure 2-89 shows a map of the total area of the model and Figure 2-90 shows a zoom of the lower estuary, and the local computing grid. This figure also shows the grid cells used by the model, which size varies between 75m in the central zone of the bathymetry and 210m in peripheral zones.

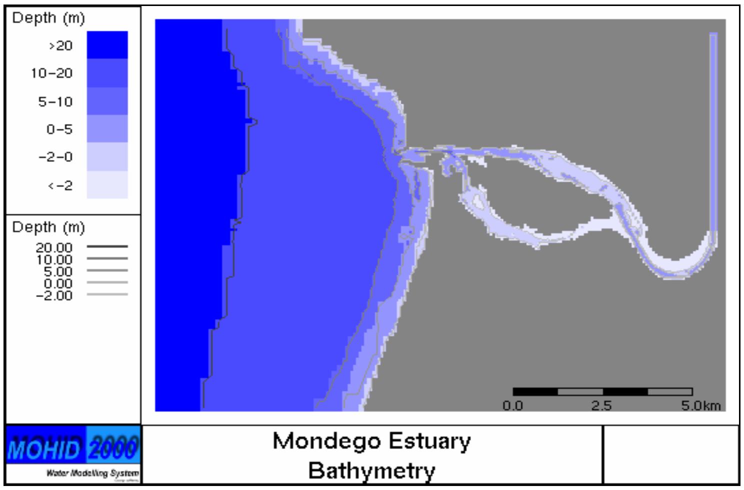


Figure 2-89: Bathymetry of the Mondego estuary model.

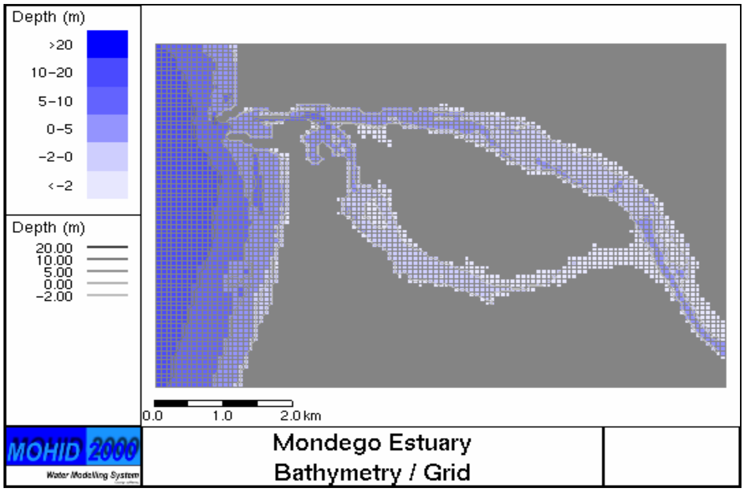


Figure 2-90: Grid of the lower Mondego estuary model.

2.3.1.2 Transient circulation

To describe the transient circulation in the Mondego estuary, results of a spring tide simulation are presented. Figure 2-91 and Figure 2-92 show the velocity field during flood and during ebb, respectively. These maps show that the velocity in the northern channel is much stronger than in the southern channel, where longitudinal gradient is clear. This is because the southern channel acts like a bay due to the artificial closure of the upper communication between the two channels. The flow is transversally quite uniform, with velocity parallel to the channel axis and a very clear influence of the river discharge. The maximum velocity reaches 1m/s at the mouth of the estuary.

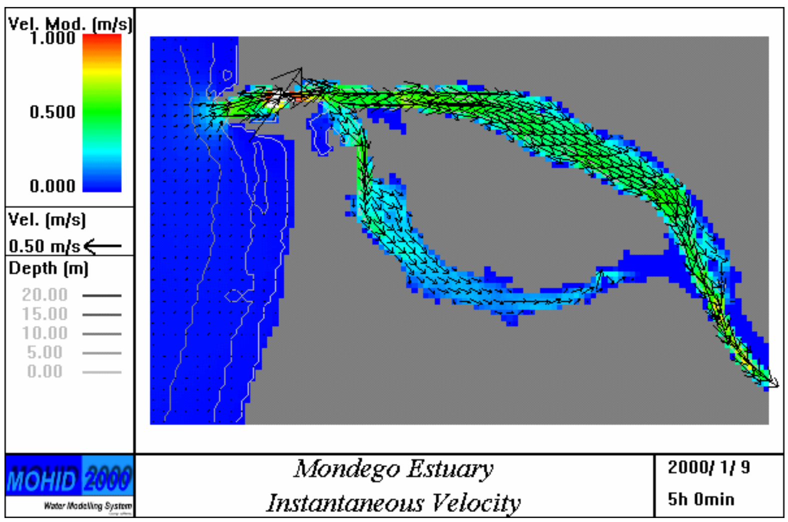


Figure 2-91: Instantaneous velocity during flood in spring tide and average river discharge conditions.

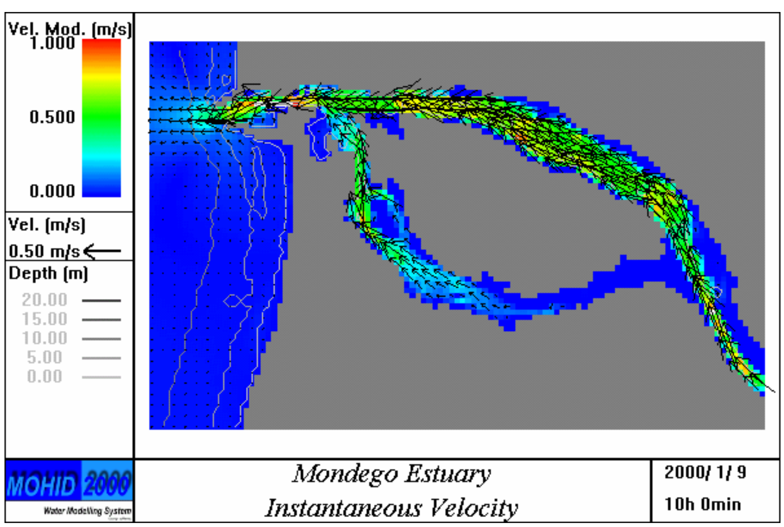


Figure 2-92: Instantaneous velocity during ebb in spring tide and average river discharge conditions.

2.3.1.3 Residual circulation

The residual velocity of the Mondego estuary is presented in Figure 2-93. This figure shows that the residual circulation is conditioned by the Mondego River discharge. In front of the estuary mouth there are two clear recirculation eddies. In this simulation no discharge from the Pranto river was considered because this discharge is episodic.

The velocity in the northern channel is above 10 cm/s. The high value of the velocity is due to the high value of the river discharge when compared with the average volume of the estuary. As a consequence of this ratio also the residence time is very low (or the order of days).

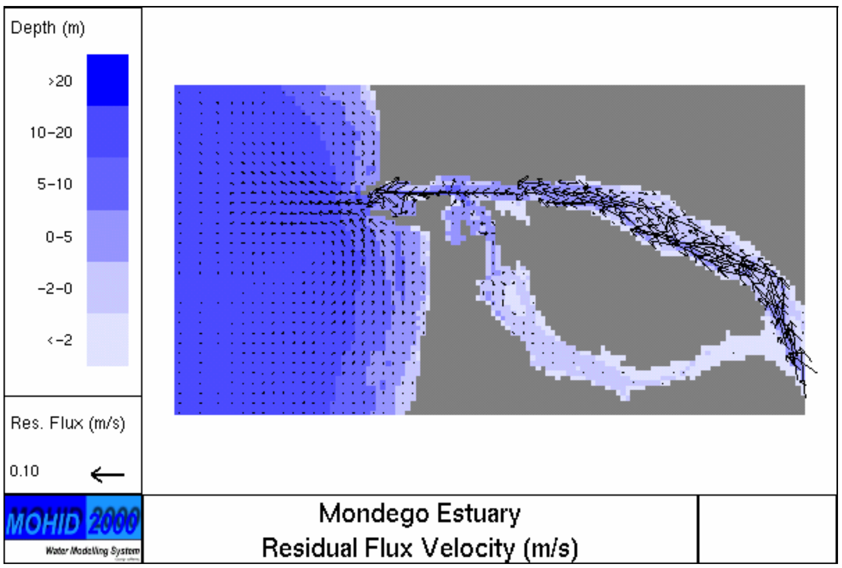


Figure 2-93: Residual velocity of the Mondego estuary, computed as the residual flux divided by residual water column depth.

2.3.2 Residence Time

To calculate the estuary residence time the hydrodynamic model was forced by the tide and by the Mondego River discharge ($60m^3s^{-1}$). The Pranto discharge was not considered because of its intermittent character. If the discharge of the Pranto river was considered, a shorter residence time would be obtained in the southern channel.

The initial distribution of the lagrangian tracers used to calculate the residence time is shown in Figure 2-94. The whole estuary is filled with tracers, considering the limit of the estuary equal to the one defined in the study “Limites de Jusante dos Estuários Portugueses” (INAG, 2001). The simulation starts at high tide.

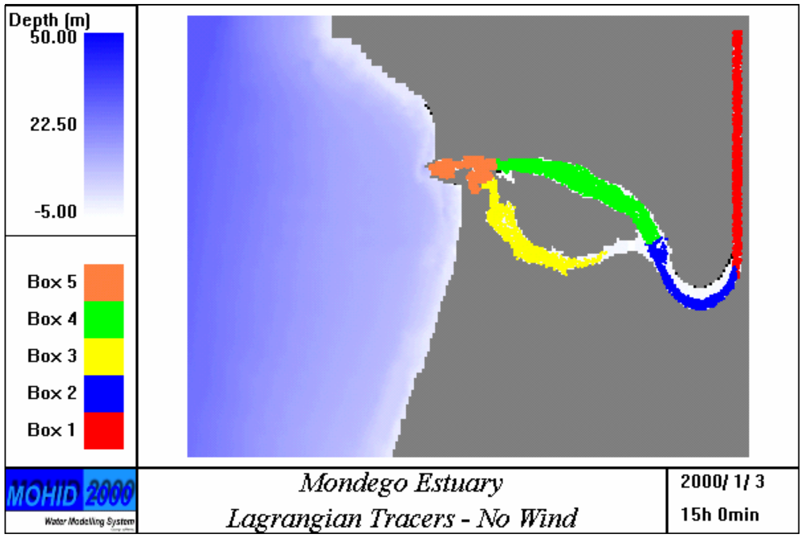


Figure 2-94: Initial distribution of the lagrangian tracers used to calculate the residence time in the Mondego estuary.

The variation of the volume inside the estuary during the simulation period is presented in Figure 2-95. The figure shows that in every tidal cycle the quantity of water entering in the estuary (tidal prism ≈ $1.1 \times 10^7 m^3$) is identical to the average volume of the estuary (≈ $1.6 \times 10^7 m^3$). The daily contribution of the river discharge (≈$5.2 \times 10^6 m^3$) is about one half of the tidal prism, suggesting a short residence time in the estuary.

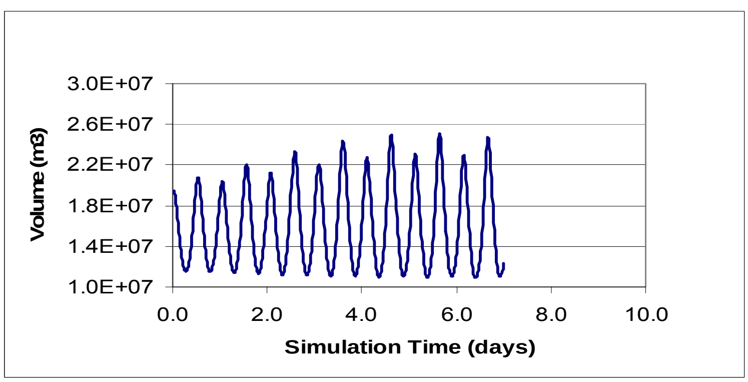


Figure 2-95: Variation of the water volume inside the Mondego estuary during a neap-spring tide period.

The location of the lagrangian tracers, 12h and 24h after the emission, is shown in Figure 2-96 and Figure 2-97, respectively.

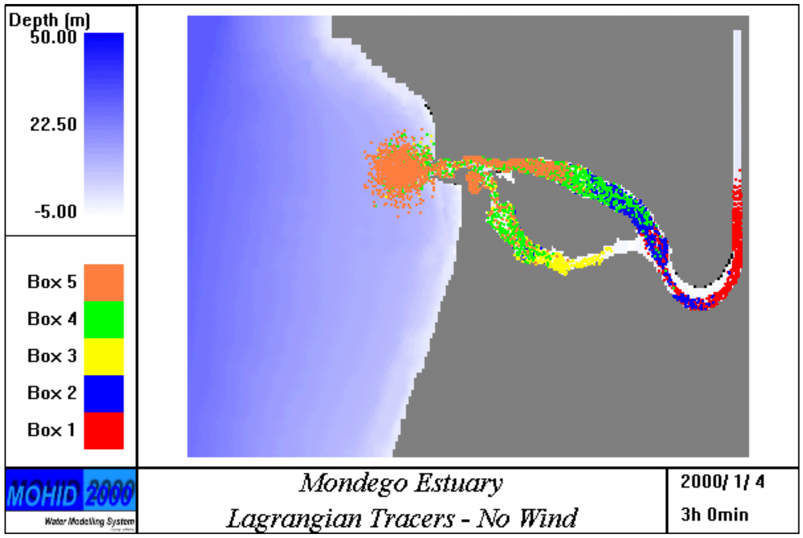


Figure 2-96: Distribution of the lagrangian tracers in the Mondego estuary 12 hours after the emission.

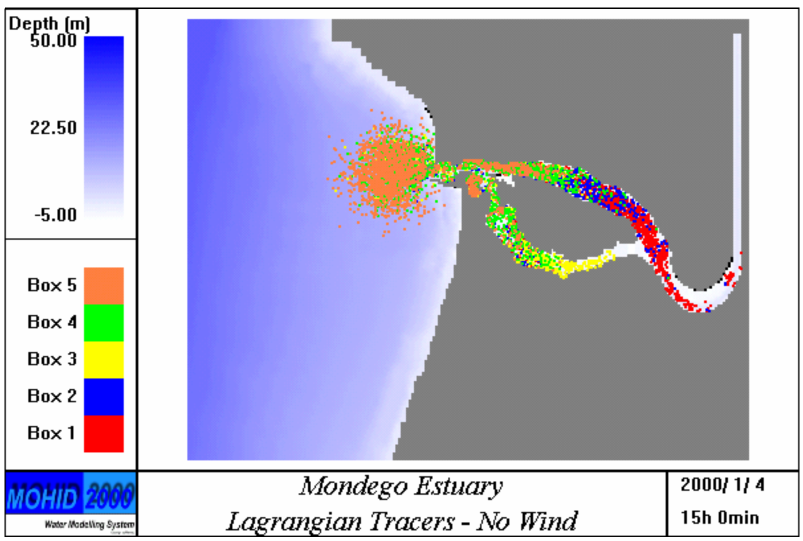


Figure 2-97: Distribution of the lagrangian tracers in the Mondego estuary 24 hours after the emission.

The evolution of the fraction of the tracers inside the estuary (volume of tracers inside the estuary divided by the volume of the estuary) is shown in Figure 2-98. This figure shows that 2 days after the emission only 30% of the initial volume remains inside the estuary and after 4 days only less then 10% of the tracers still remain there.

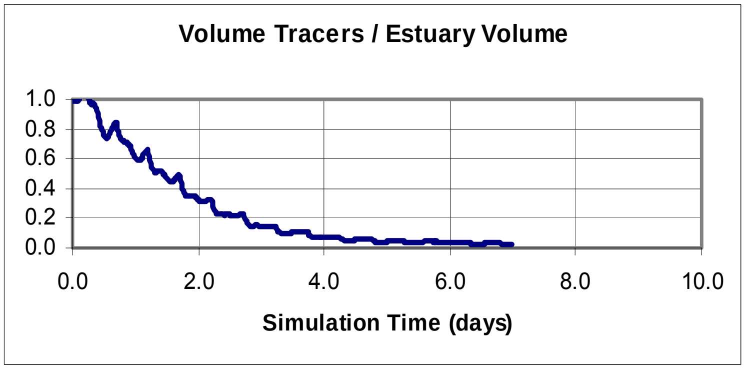


Figure 2-98: Evolution of the fraction of lagrangian tracers remaining inside the estuary, as a function of the time.

Figure 2-99 represents the time integral of the fraction of the tracers inside the estuary, as a function of the time[7]. The figure shows that this quantity reaches a value almost constant (0.7) after 4 days, showing this is the time required for flushing the whole estuary. At each point, the slope of the curve gives the ration between the fraction of the water initially inside the estuary and still remaining there and the total volume of the water actually inside the estuary. The information of this figure is similar to that of Figure 2-98, but its slope is always positive, while in that figure it can be positive or negative.

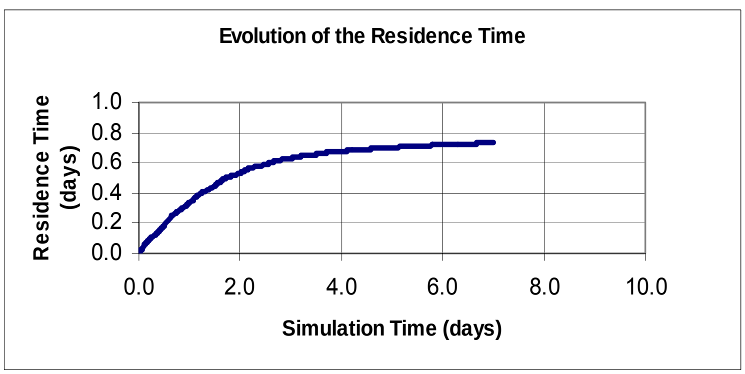


Figure 2-99: Equivalent full time permanence of the tracers inside the estuary.

The type of information represented in Figure 2-99 can be represented for each box using pie graphics. Figure 2-100 and Figure 2-101 represent the information for each

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[7] The time integral of the fraction of the tracers inside the estuary represents the "full time" equivalent to a full occupation of the estuary by the tracers. In this computation, having 50% of the tracers during 2 days in the estuary is equivalent to have 100% of the tracers during 1 day in the estuary. When all tracers have been exported, this value becomes constant.

box after 12 and 24 hours, respectively. The figures show that Box 3 (southern channel) and Box 1 (river channel) are flushed with "new water" faster than any other box in the estuary. The southern channel is flushed with seawater (or river water mixed with sea water) during flood and the river channel is flushed with river water. As a consequence the percentage of new water is higher in the southern channel.

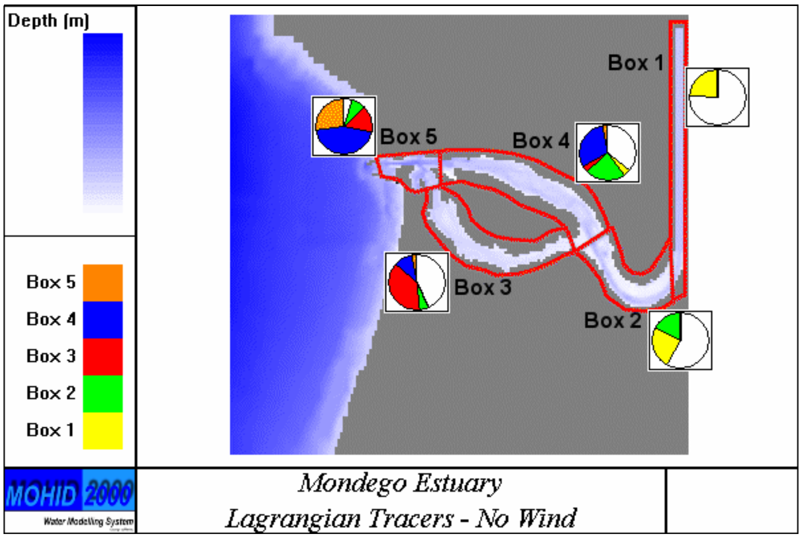

Figure 2-100: Water exchange between boxes (integrated over 12 hours)

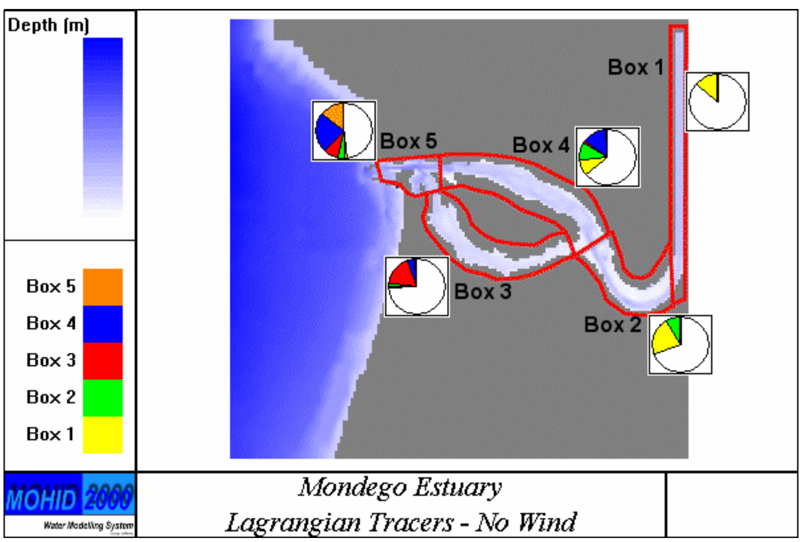

Figure 2-101: Water exchange between boxes (integrated over 1 day)

The figures show that the contribution of new water for the properties of the water inside every box is already important after one day. Box 1 is in fact the river channel and does not receive water from any other box.

Box 2 receives water from Box 1, and new river water from upstream (which has to cross Box 1 to reach it). The boxes in the lower estuary are affected by all the others and by new water mainly from the river but also from the sea. Box 4 and Box 5 are the most affected by other boxes, having contributions from all other boxes. If a flow parallel to the coast off the estuary was considered, the amount of tracers that would re-enter in the estuary during flood tide (see Figure 2-96 and Figure 2-97) would be smaller, reducing the computed residence time and increasing the role of new water in boxes 4 and 5.

The estimated residence time of days leads to preview that the phytoplankton inside the estuary will have no time to produce a bloom.

2.3.3 Hydrodynamics in a reopening scenario of the upper communication between the channels

In this paragraph the hydrodynamics of the estuary is analysed in a scenario of reopening of the upper communication between the two channels. In that area the natural bathymetry is shallow and it was closed artificially some years ago, in order to increase the flow in the northern channel for “self-cleaning” purposes of the navigation channel.

Figure 2-102 compares the hydrodynamics in present conditions and in the reopening scenario. The figure shows that in the reopening scenario, the velocity inside of the southern channel is higher and consequently, dredging of this section should be considered as part of the solution for the rehabilitation of the trophic conditions in the southern channel. The effectiveness and the details of the dredging to modify the trophic conditions of the estuary and of its implications on sediment transport and navigability in the port areas of the estuary require a more detailed work.

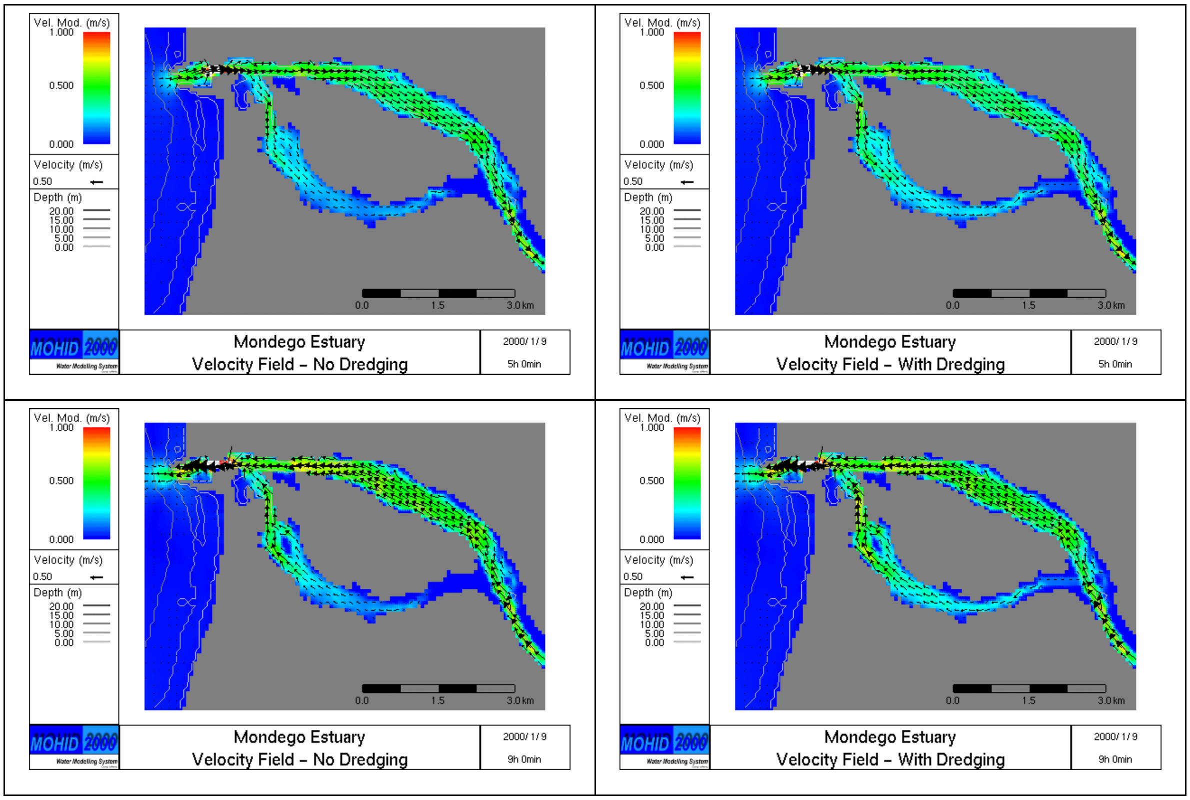

Figure 2-102: Comparison of transient velocity between the actual bathymetry scenario (left) and a bathymetry dredged in the region of confluence of the two channels (right).

2.3.4 Ecological modelling

Ecological modelling was performed in the reference situation and in a nutrient reduction scenario, in order to evaluate its potential benefits. The results show that the residence time determines the ecological functioning of the estuary since the phytoplankton has no time to generate blooms.

2.3.4.1 Reference Situation

2.3.4.1.1 Nutrient Loads

The Mondego and the Pranto Rivers loads are the important loads for the estuary. The data required to specify the boundary conditions in the estuary is published in the public database (web based) of the “Serviço Nacional de Informação dos Recursos Hídricos”.

The flow of the Mondego River was calculated from the stations Ponte de Stª Clara (Ref. 12G/04) and Açude de Coimbra (Ref. PVR25). The biological variables were obtained from the station Ponte Formoselha (Ref. 12F/04). Figure 2-103 shows the localization of these stations.

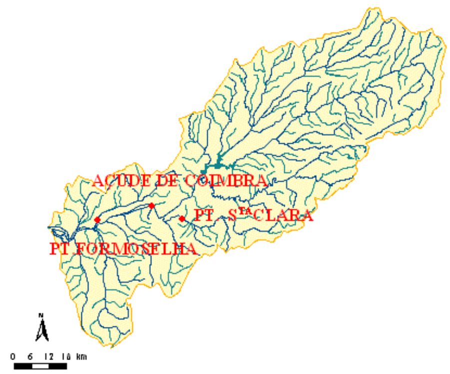

Figure 2-103: Localization of the stations near the Mondego estuary

The Mondego River is the most important fluvial discharge in the estuary and it has a pronounced seasonal variability, with winter peaks up to 1600m^3/s. The most frequent flow of the Mondego River is 60 m^3/s. Annual evolutions of ammonia, nitrate and total suspended solids are given in Figure 2-104. For the Pranto River only the water discharge is available (average value 2.3m^3/s) and concentrations were considered identical to those of Mondego River.

Figure 2-104: Annual evolutions of ammonia, nitrate and TSS in the Mondego River.

2.3.4.1.2 Time Series Analysis

The parameterization of the water quality module used in the Mondego River is the same used in the Sado and in the Tagus estuaries. Figure 2-105 shows the locations of the points where time series of model results were produced.

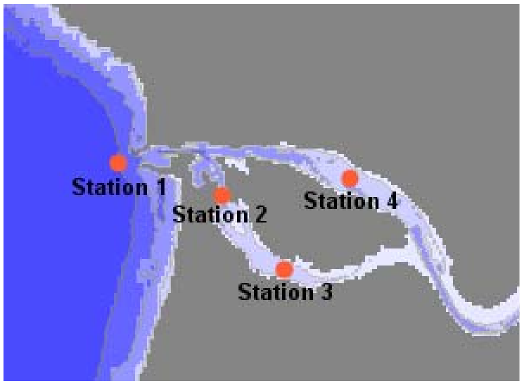

Figure 2-105: Localization of the time series results in the Mondego estuary.

Figure 2-106 to Figure 2-109 show annual evolutions of phytoplankton, nitrate, ammonia and oxygen at Station 1 for the reference situation. Due to the small residence time of the water in the estuary the results are strongly influenced by the boundary conditions. The stations inside the estuary are particularly influenced by the river discharge and those close to the sea, by both the river and the sea concentrations.

Station #1 shows low variability, both daily and seasonal, being the values registered there influenced mainly by the ocean conditions. Station #4 is the most influenced by the river discharge, following closely the evolution in the river. Stations #2 and #3 also follow the river discharge but are also influenced by the dilution of estuarine and ocean waters prior to re-entering in the estuary during flooding tide.

2.3.4.1.3 Spatial distributions of concentration

Spatial distributions of phytoplankton, nitrate, ammonia and oxygen are presented in Figure 2-110. The maps show that there is a clear difference between the values inside and outside the estuary and that northern channel has higher concentrations of nutrients than the southern channel. Although the residence time in the southern channel is longer, there is not yet enough time to allow a phytoplankton bloom. The tide promotes an important mixing between the water of both channels.

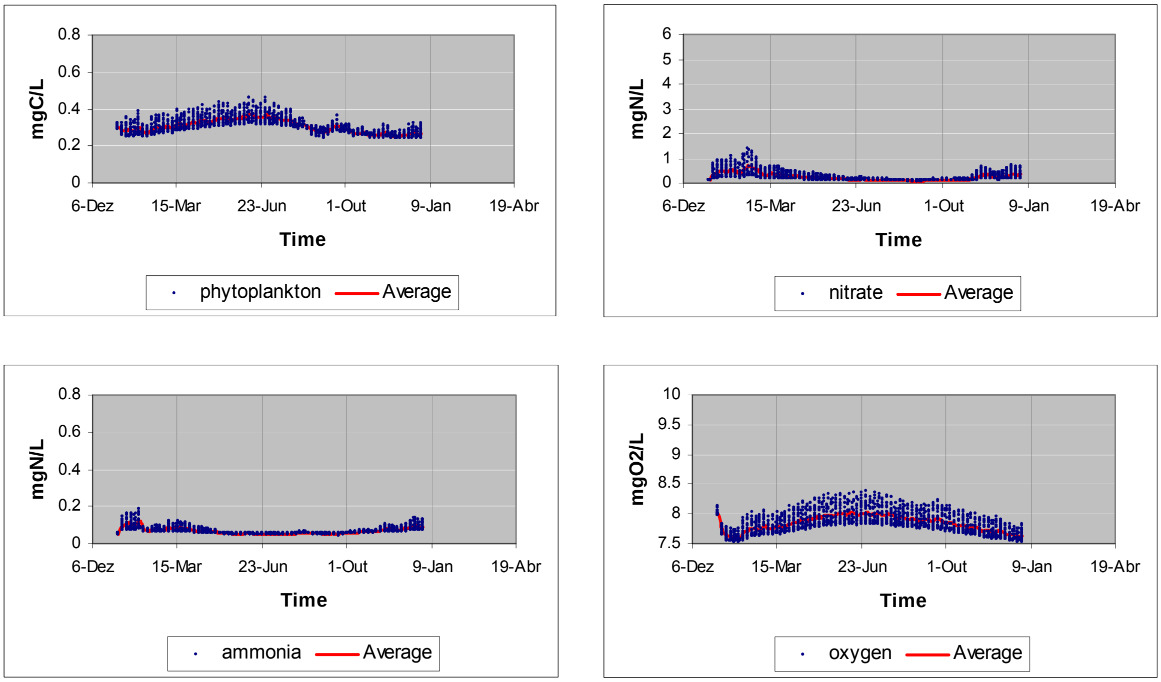

Figure 2-106: Model results for reference situation at Station #1.

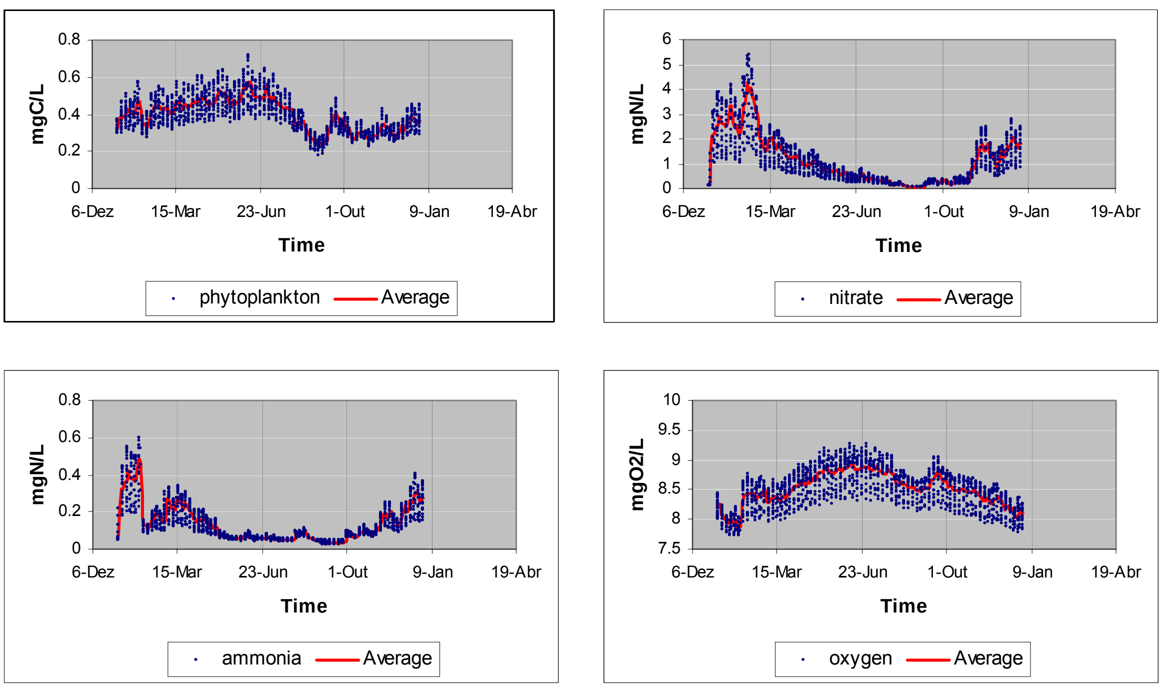

Figure 2-107: Model results for reference situation at Station #2.

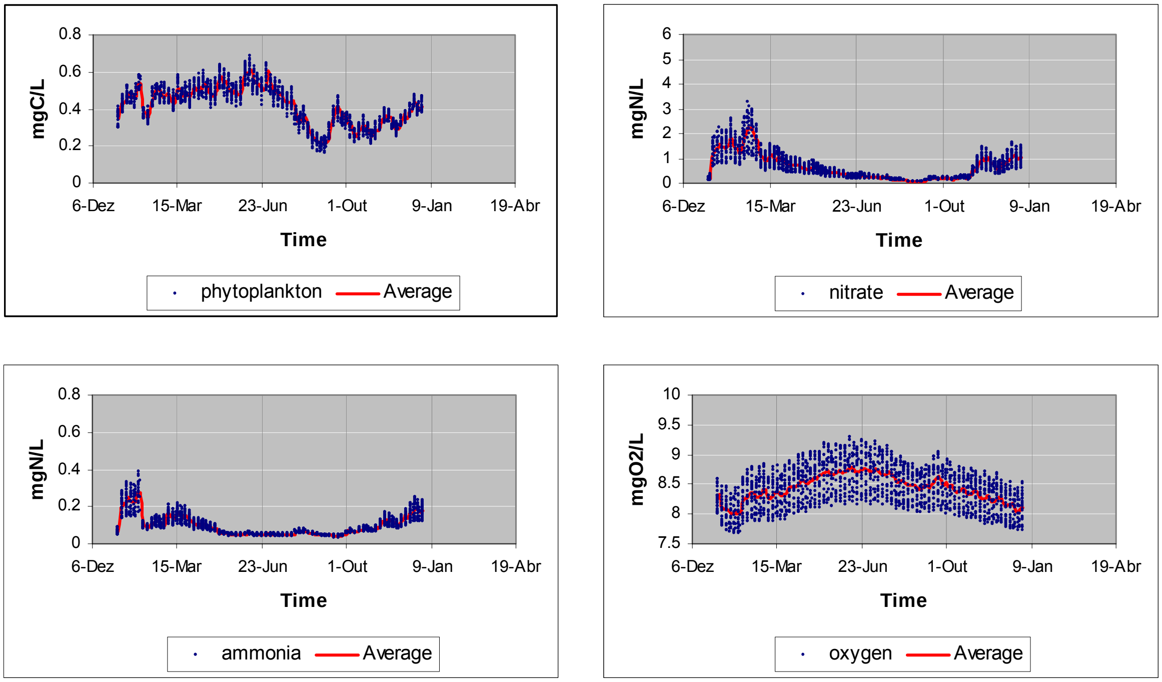

Figure 2-108: Model results for reference situation at Station #3

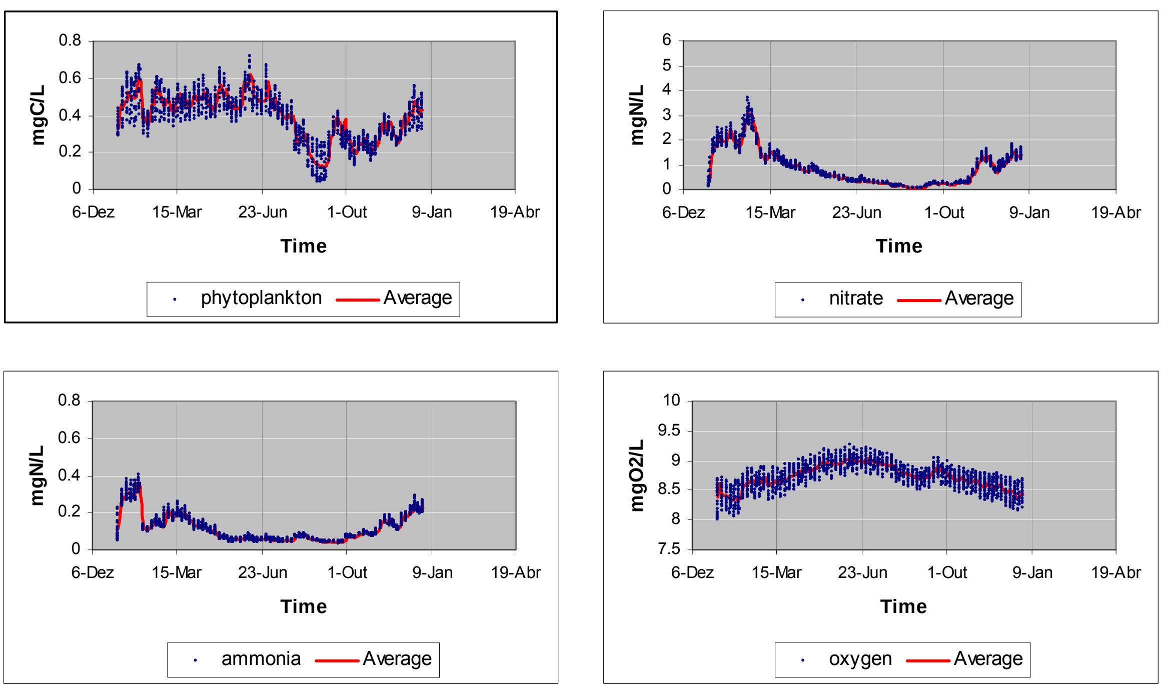

Figure 2-109: Model results for reference situation at Station #4.

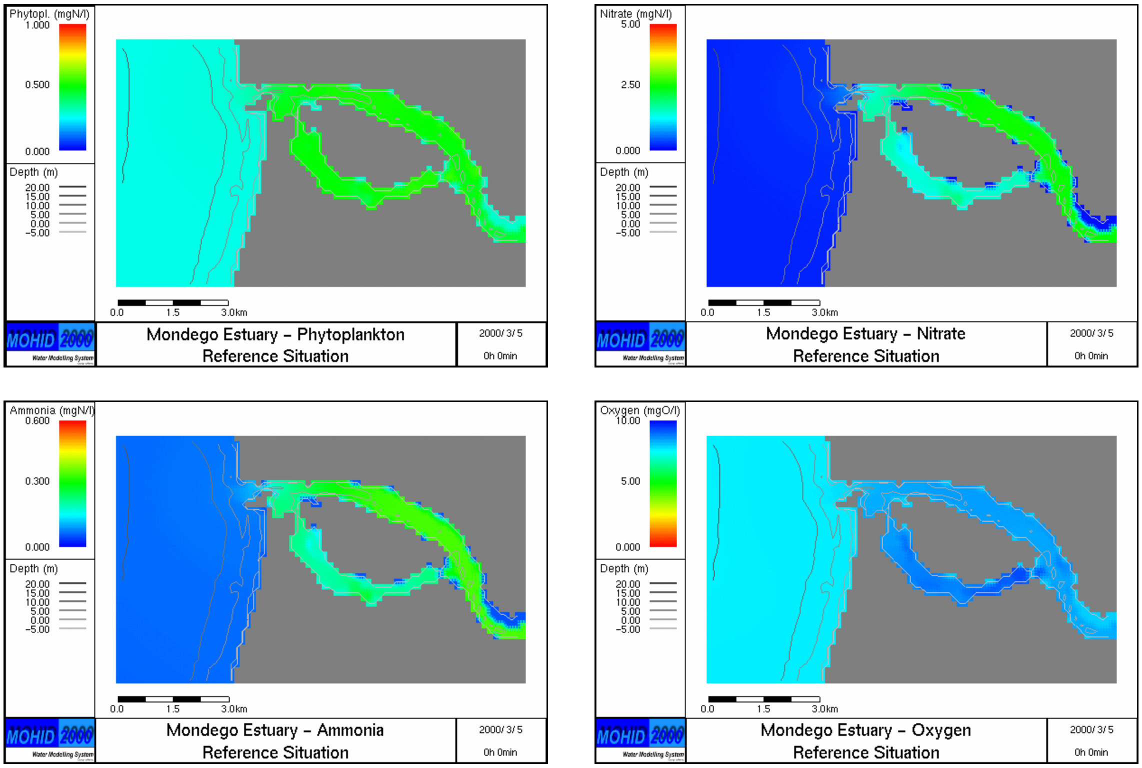

Figure 2-110: Spatial distribution of phytoplankton, nitrate, ammonia and oxygen in the reference situation (early spring time)

During ebb, the water that moving out of the estuary, is mixed with seawater and with water from the southern channel. During flood this mixed water is distributed between both channels. Has a result, the phytoplankton produced in the southern channel is in part exported to the northern channel and the nutrients discharged from the Mondego enter in the southern channel after some dilution with sea-water.

2.3.4.1.4 Annual average distributions of properties per zone of the estuary

Figure 2-112 represents the annual average distribution in each integration boxes (the same boxes that were established in the study of the residence time, Figure 2-111). The properties presented are phytoplankton, organic matter (defined as sum of particulate organic matter and dissolved organic matter), ammonia and nitrate.

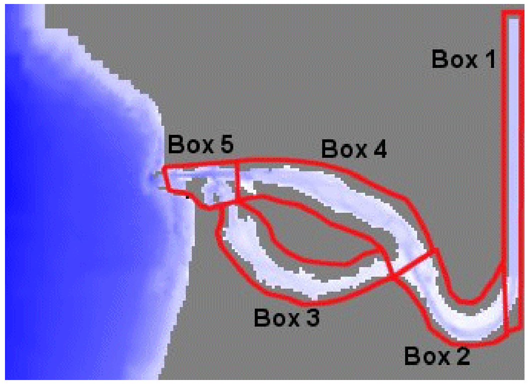

Figure 2-111: Integration Boxes in the Mondego Estuary.

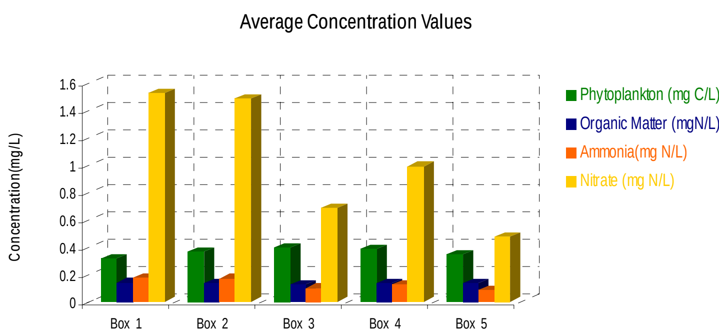

Figure 2-112: Annual average concentrations per zone of the Mondego estuary in the reference situation.

Figure 2-112 shows that nitrate has elevated concentrations in all boxes, especially in Box 1 and in Box 2 due to the influence of the Mondego River. The average concentration of phytoplankton is much lower then in the Tagus estuary, but higher than in the Sado estuary. Box 5 has lower concentrations then the other boxes, once it is the most influenced by seawater.

In Mondego estuary, phytoplankton has no time for growing due to the small residence time. In case of the Tagus, the limiting factor was the light, and in the Sado were the nutrients. In the southern channel of the Mondego estuary, macro-algae development is promoted by the reduced shear stress due to reduced velocities consequence of the artificial closing of the upper communication between the channels.

2.3.4.1.5 Annual Budgets per zone of the estuary

Figure 2-113 represents the annual budgets exchanged between boxes. This information allows tracking the net transport of the properties inside the estuary. The figure shows that nitrate is determined mainly by the Mondego River discharge.

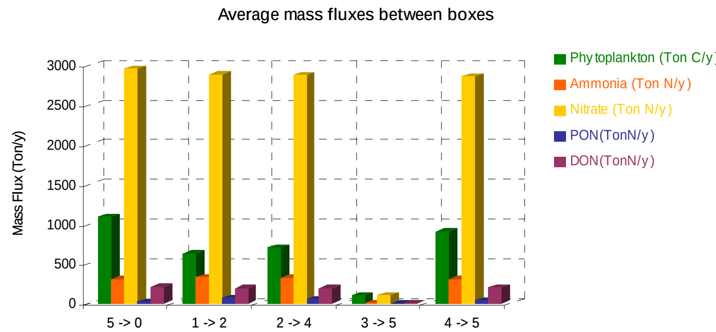

Figure 2-113: Annual fluxes between boxes in the Mondego estuary.

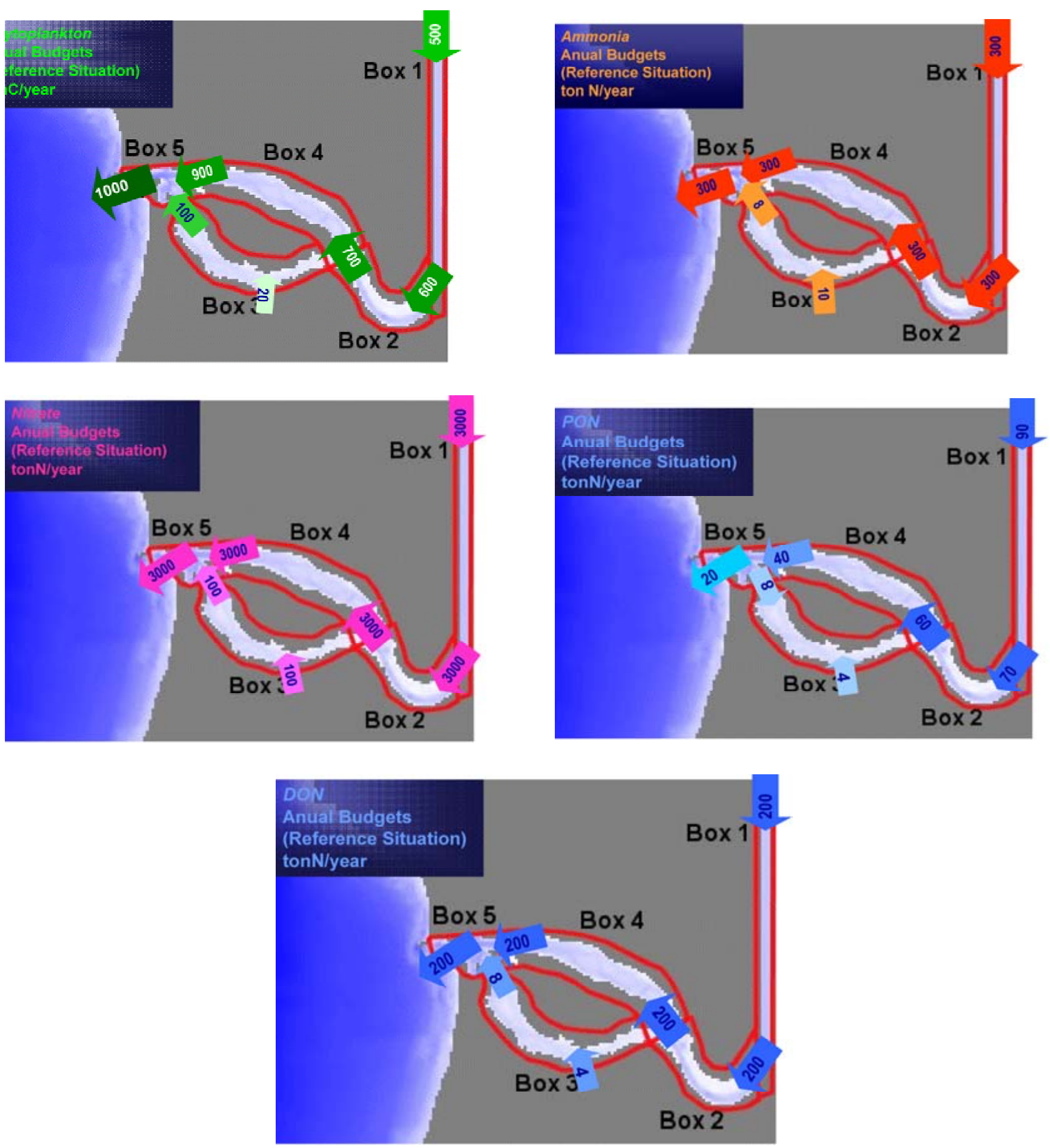

Figure 2-114: Annual Budgets between boxes in the Reference Situation

From Figure 2-113 and Figure 2-114 it is easy to conclude that the most important process in the Mondego estuary is the transport. Most nitrate, which is transported from Box 1 to Box 2, is afterwards transported to Box 4, then to Box 5 and finally exported to the open sea (Box 0). These figures also show that there is production of phytoplankton inside the whole estuary, which is transported downstream, until being finally exported to the sea. There is a net export of phytoplankton, ammonia and nitrate from box 3 to 5 (from southern channel to northern channel) and an import of Particulate Organic Matter. The export of this box corresponds basically to the discharge of the Pranto river. This results has however to be analysed carefully. In fact, the level of nutrients in the southern channel is determined by its level in the northern channel and by tidal mixing. The residence time in the southern channel, although higher then in the northern channel, is not long enough to permit a total consumption of the nutrients coming from the river and from the northern channel, which leads to an exportation of non-consumed nutrients to box 5.

Another interesting result is the import of PON by the southern channel, which is associated to the small value of the velocity, creating the conditions for the deposition of particulate matter. This aspect shows that also the PON discharged by the Pranto River and that corresponding to the local production are deposited in that channel increasing the organic matter in the sediments and the consumption of oxygen.

Re-opening the upper communication between the two channels would increase the velocity and reduce the hydrodynamic conditions for deposition of organic matter. On the other hand it would reduce the habitat physically acceptable for the macro-algae, through a generalised increase of the velocity and reduction of the residence time.

2.3.4.1.6 Conclusions

The dynamics of the Mondego estuary was studied in terms of circulation, residence time and primary production. The average value of the volume of the estuary is of the same order of amplitude as the tidal prism and of the average daily river discharge. As a result, the velocity is quite high in the river channel, with a strong residual flow towards the sea and a short residence time.

The southern channel behaves as a bay since the upper communication with the northern channel was closed, aiming to enhance the sediment transport in the northern channel. For that reason, velocities are much smaller than in the northern channel and residence time in higher, creating conditions for the deposition of fine particulate matter (especially organic matter) and the enrichment of the sediments.

It was shown that the limiting factor for phytoplankton is the residence time, which is of the order of days. In the southern channel velocity is smaller and residence time is higher, allowing for the growth of macro-algae, which is enhanced by sediment enrichment of organic mater, which deposition is facilitated by the “bay behaviour” of the channel.

The concentration of nutrients is higher in the northern channel that in the southern channel, because the discharge of the Mondego river is much more important than the discharge of the Pranto in the southern channel. The background concentration in the southern channel is imposed by the northern channel, being the actual level increased due to the Pranto discharge. The consumption of the nutrients is limited by the residence time, which does not permit the growth of the phytoplankton, being in fact the Pranto discharge enough to fulfil the needs of phytoplankton production.

In order to understand the role of the Pranto and of the Mondego discharges for the functioning of the estuary, two scenarios were studied. In the first scenario the discharge of the Pranto River was reduced to 50% and in the second scenario, both the Pranto and the Mondego were reduced to 50% each.

2.3.4.2 Influence of the nitrate removal in the Pranto River discharge

In this chapter, the results of a reduction of 50% of the load of the Pranto River are described. Results show that there is no modification of the functioning of the estuary except that the amount of nitrate exported to the northern channel is smaller. The maintenance of the trophic activity is a consequence of its limitation by the residence time and of the fact that the level of nutrients is imposed by the concentration in the northern channel.

2.3.4.2.1 Spatial distributions of properties

Figure 2-115 shows distributions in the reference situation (left side) and in the scenario with a reduction by 50% of the nitrate input from the Pranto River.

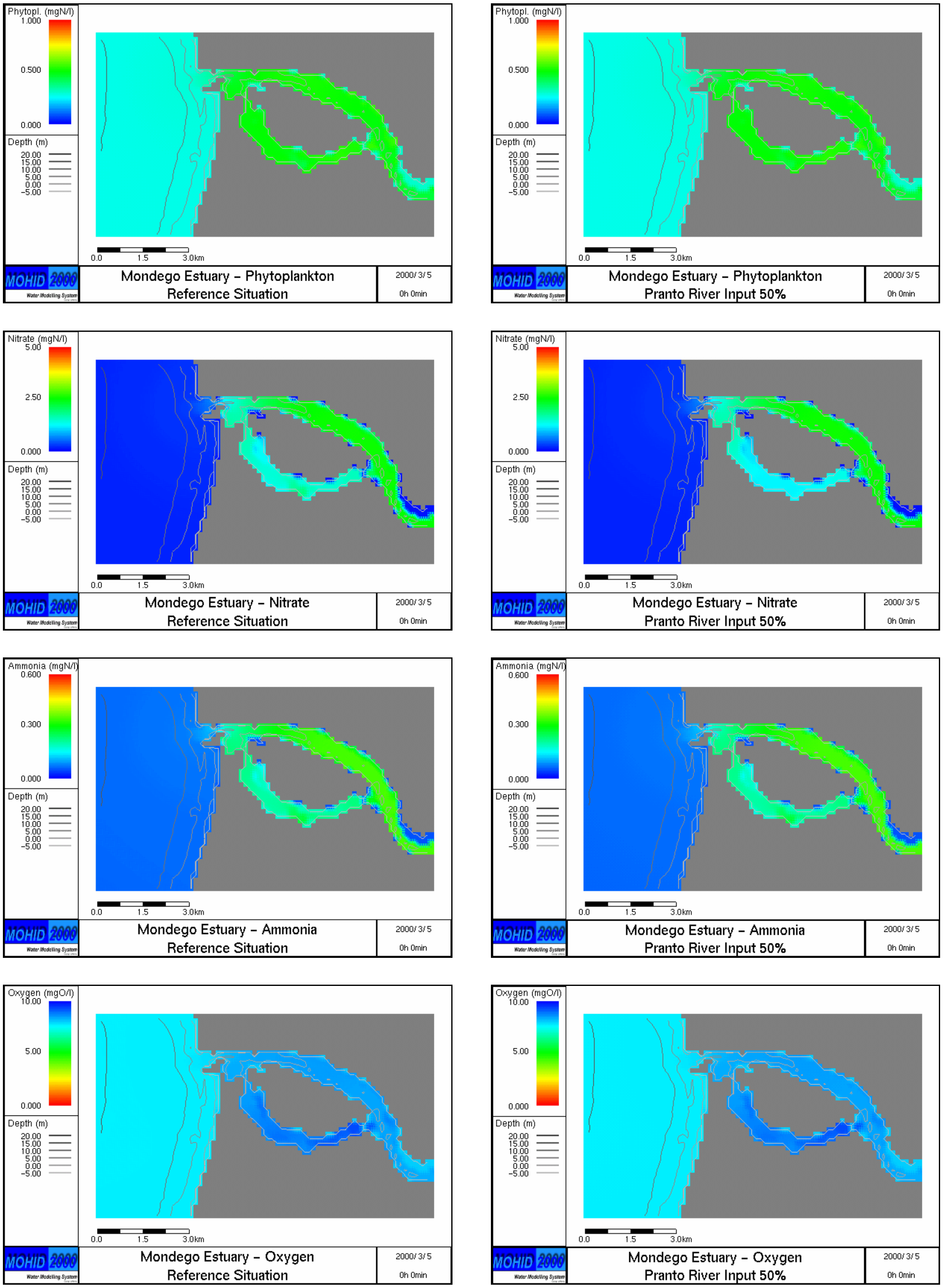

Figure 2-115: Distributions of concentrations in the reference situation (left) and in the scenario of reduction of 50% of Pranto River discharge (right) during spring.

The figure shows that the reduction of 50% of the input from the Pranto River does not affect significantly the overall distribution of the variables. In the southern branch, a small reduction of the nitrate concentration is however visible.

Figure 2-116 shows the comparison of annual average concentrations in both scenarios. The figure shows for the whole year what Figure 2-115 shows for a specific situation. Only Box 3 (which receives the discharge from the Pranto River) shows a small reduction of the average concentration of nitrate. Also the annual budgets (Figure 2-117) show identical values.

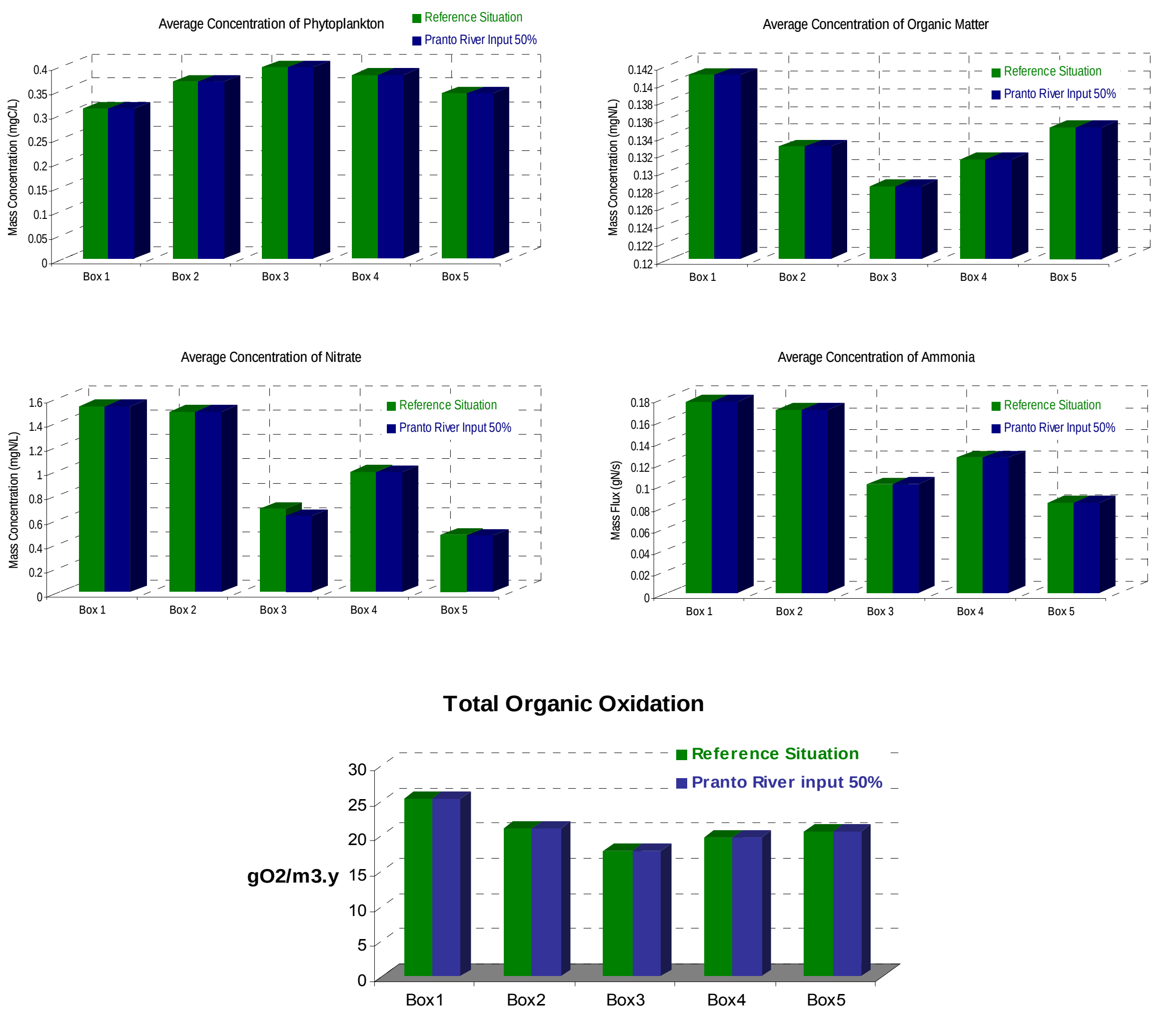

Figure 2-116: Average annual concentration in the reference situation and in a scenario of 50% reduction of nitrate discharged by the Pranto River.

As a conclusion, one can say that the reduction of the discharge of the Pranto of 50% do not change the trophic conditions of the estuary, since the background values of the concentrations depend on the Mondego discharge and the production of the estuary is limited by the residence time.

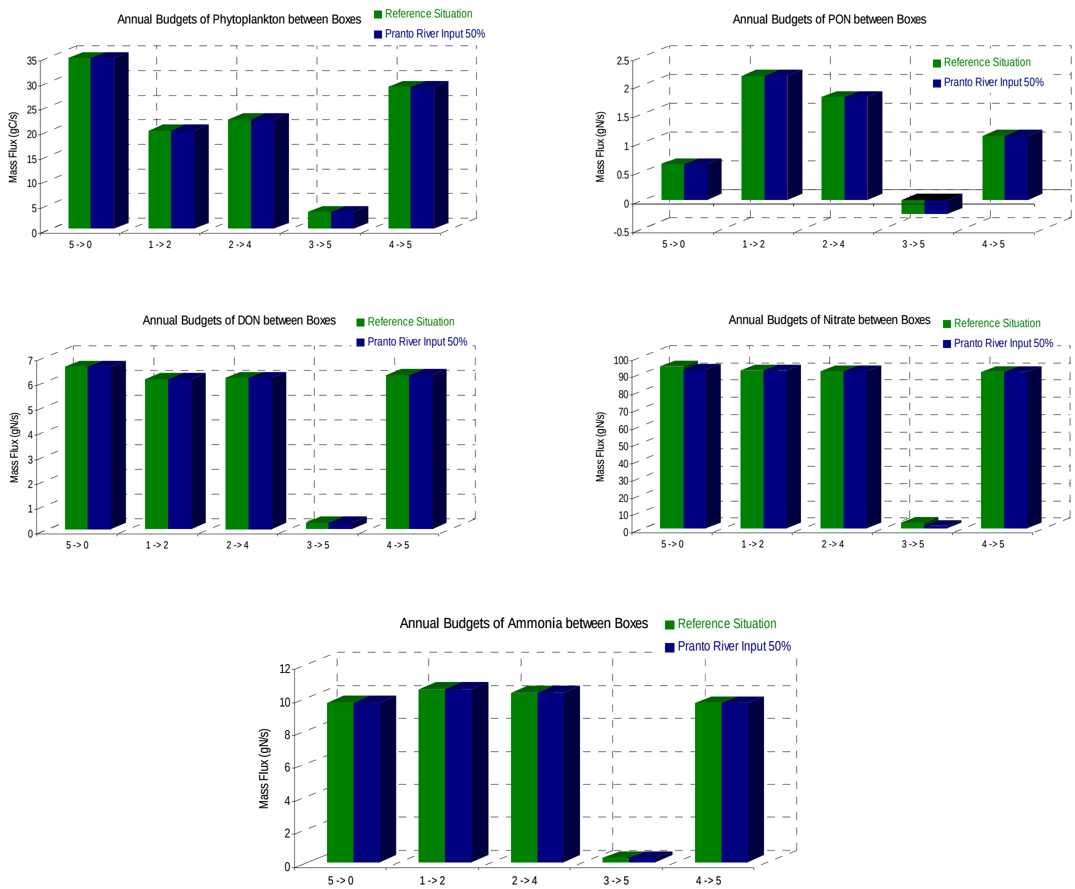

Figure 2-117: Budgets in the reference situation and in a scenario of 50% reduction of nitrate discharged by the Pranto River.

2.3.4.3 Influence of the nitrate removal in Mondego River discharge

The second scenario analyses the reduction by 50% of the nitrate input of the Mondego River. Like in the case of the Pranto River reduction scenario, all other parameters are kept equal to the reference situation.

Figure 2-120 shows, like expected, that the unique budget which changes, is that of nitrate. The other fluxes among boxes remain the same as in the reference situation, which again confirms that the residence time is the factor limiting the production in the estuary.

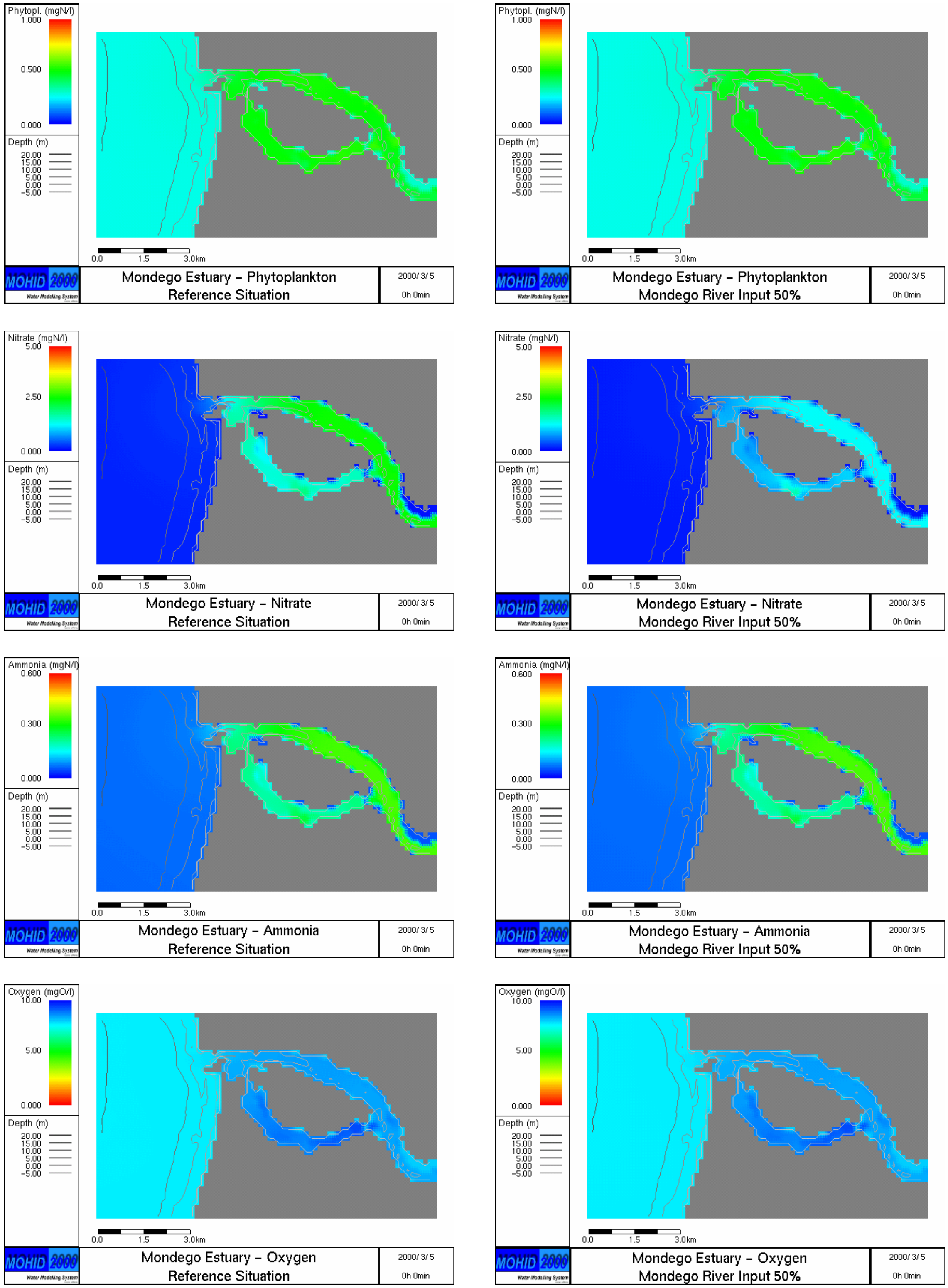

Figure 2-118: Distributions in the reference situation (left) and the scenario corresponding to a reduction of 50% of the Mondego River load.

Observing Figure 2-118 it is possible to conclude that the reduction of 50% of the input from the Mondego River affects the concentration of nitrate inside the estuary, but does not affect the concentration of the other variables. Also in the southern branch, there is a reduction of the nitrate concentration.

Figure 2-119 shows that the concentration of nitrate is reduced in all boxes, by about 50%. The other variables are not affected, meaning that even this reduction (50% of the main source) will not change the biological processes in the estuary.

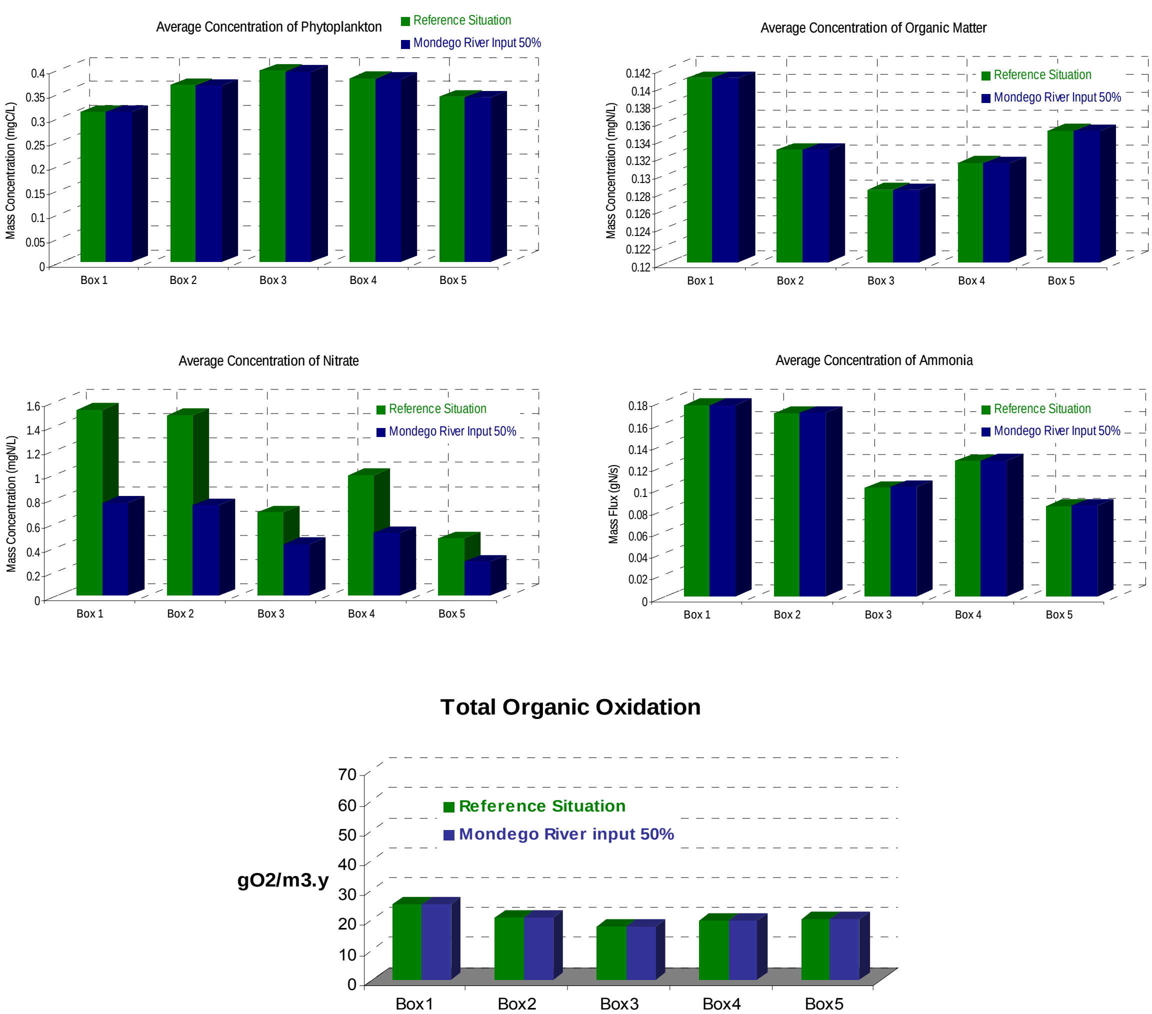

Figure 2-119: Annual average concentrations in the reference situation and in the scenario corresponding to a reduction of 50% of the Mondego River load.

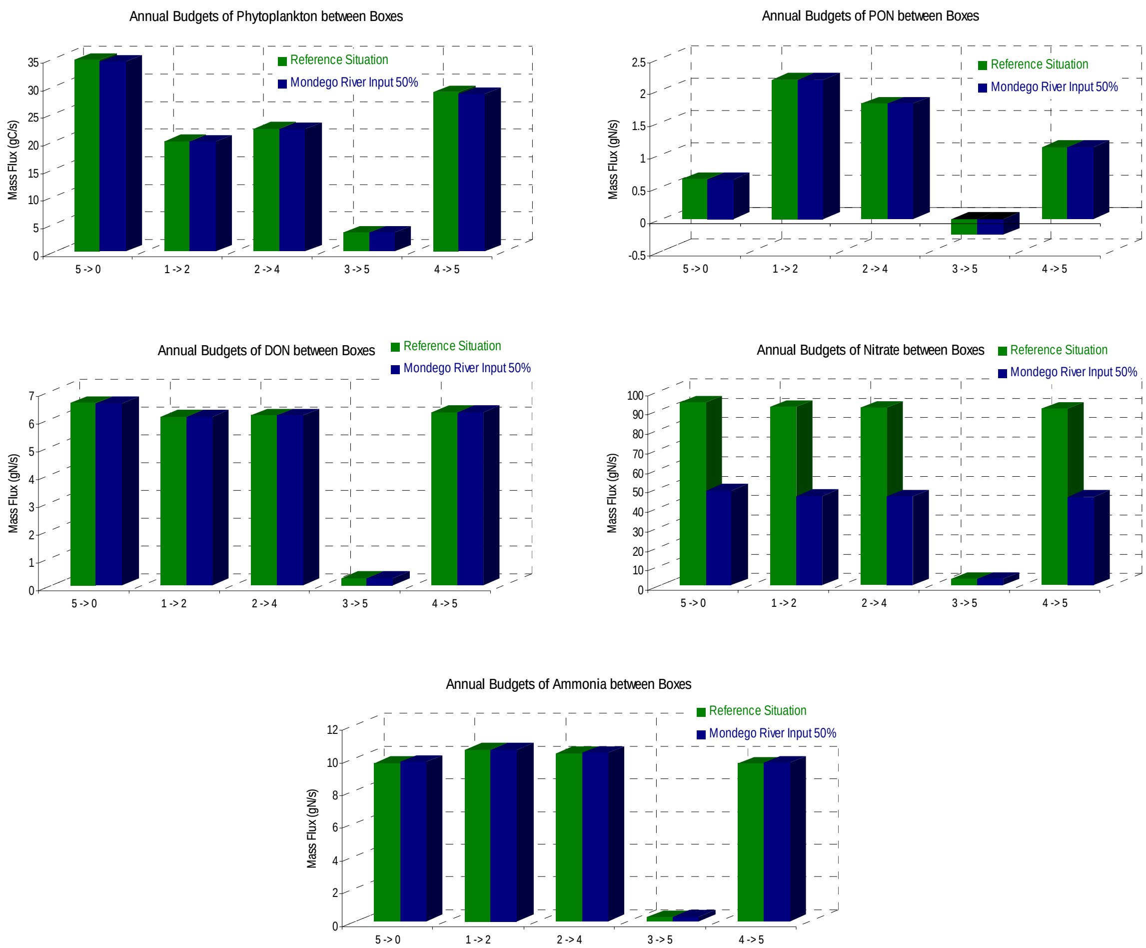

Figure 2-120: Annual budgets in the reference situation and in the scenario corresponding to a reduction of 50% of the Mondego River load.

2.3.4.4 Influence of the nitrate removal in both river discharges

The third scenario analyses the reduction of 50% of the nitrate concentration in both Mondego and Pranto Rivers. Like in the other cases, all other parameters are equal to those used in the reference situation.

Figure 2-121 is very similar to the figure showing the results of 50% reduction just in the Mondego River. Small differences of nitrate concentration can be seen in the southern branch, which are due to the reduction of the Pranto River load. Comparing the current scenario with the reference situation, the same conclusions as for a reduction of just 50% in the Mondego River are valid. Figure 2-122 shows that a reduction of 50% of the nitrate input into the estuary reduces the overall nitrate concentration, but have no influence on other variables.

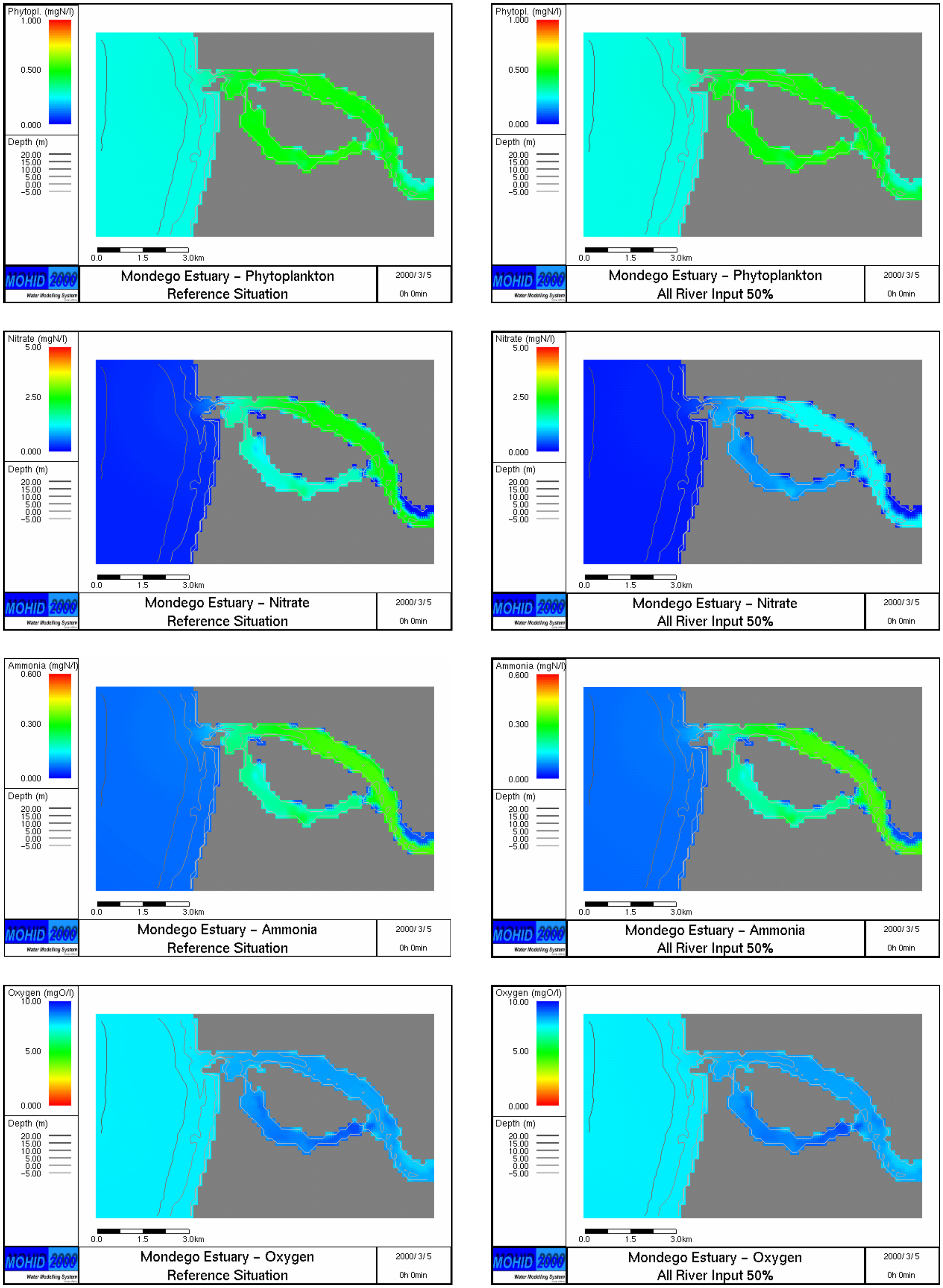

Figure 2-121: Distributions in the reference situation (left) and in a scenario of 50% reduction of the nitrate discharged from both Monego and Pranto Rivers (right)in a spring situation.

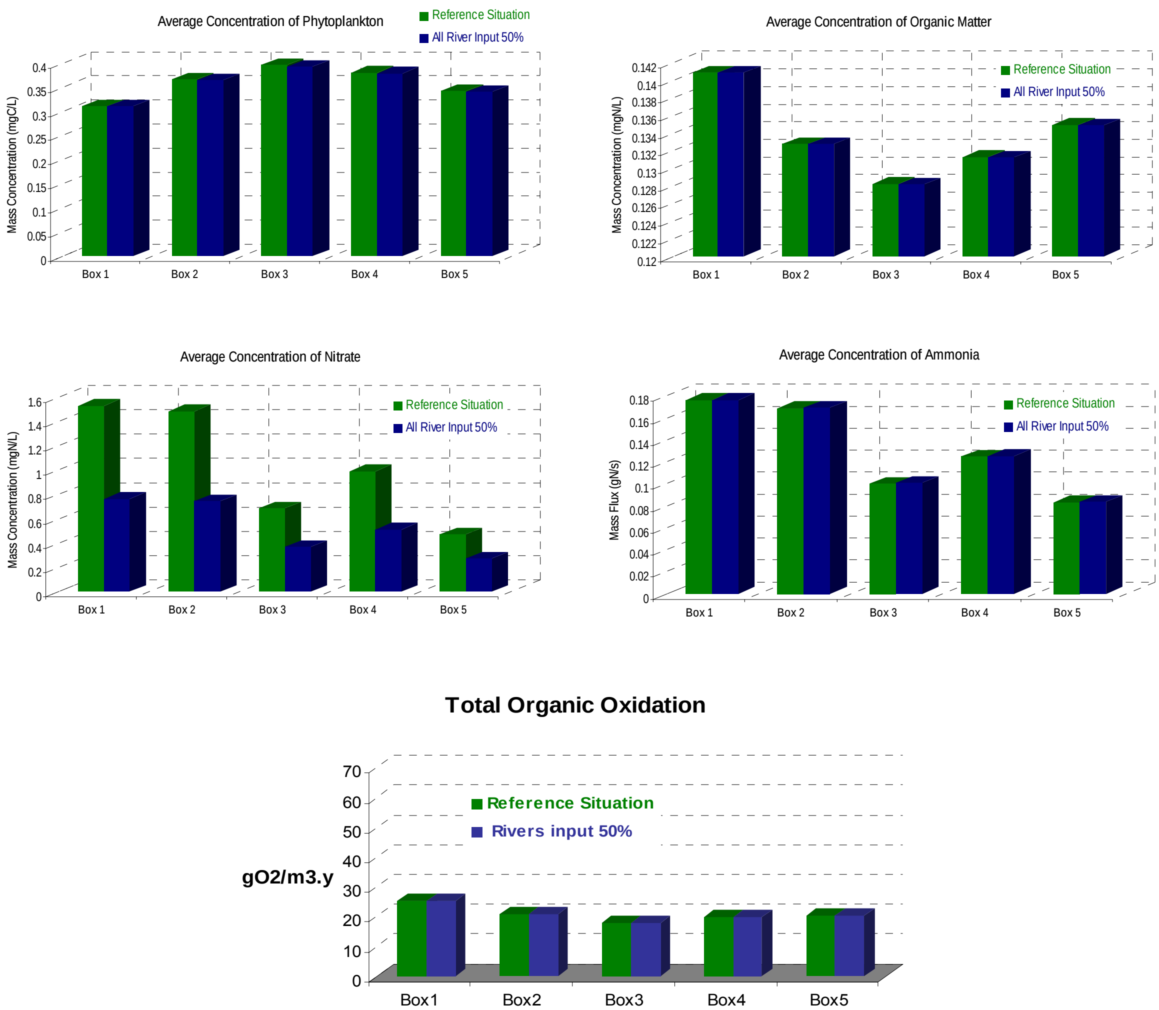

Figure 2-122: Average concentration in the reference situation and in a scenario of 50% reduction of the nitrate discharged from both Monego and Pranto Rivers.

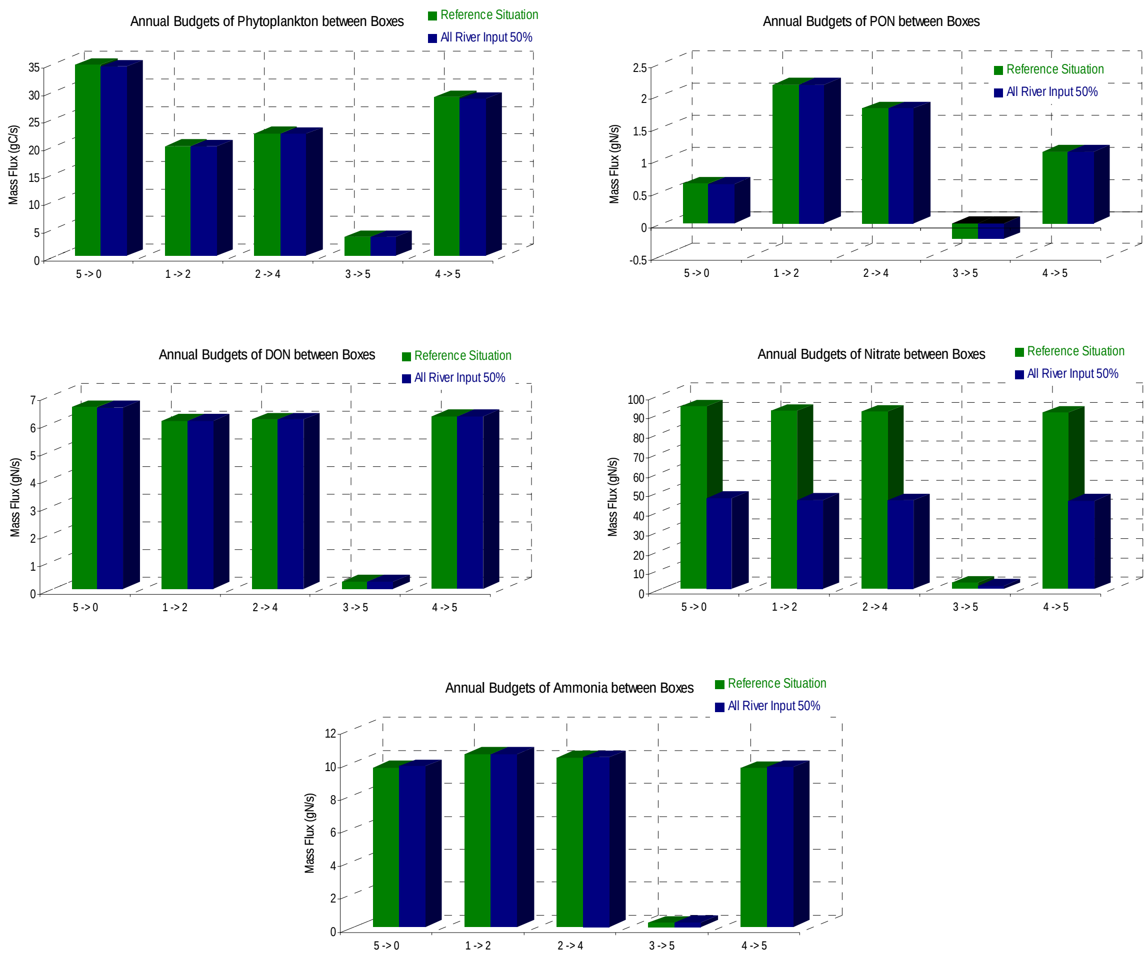

Figure 2-123: Budgets between boxes in the reference situation and in a scenario of 50% reduction of the nitrate discharged from both Monego and Pranto Rivers.

2.3.4.5 Conclusions

The dynamics of the Mondego estuary was studied in terms of circulation, residence time and primary production. The average value of the volume of the estuary is of the same order of the tidal prism and the average river discharge is also of the same order of magnitude as the tidal prism. As a result, the velocity is quite high in the river channel, with a strong residual flow towards the sea and a short residence time.

The southern channel behaves as a bay since the upper communication with the northern channel was artificially closed, aiming to enhance the sediment transport in the northern channel. For that reason, velocities are much smaller in that channel than in the northern channel and residence time in higher, creating conditions for the deposition of fine particulate matter (especially organic matter) and the enrichment of the sediments.

It was shown that the limiting factor for phytoplankton growth is the residence time, which is of the order of days. In the southern channel the smaller values of the velocity and the higher values of the residence time allow the growth of macro-algae that is enhanced by the enrichment of organic mater, which deposition is facilitated by the “bay behaviour” of the channel.

The concentration of nutrients in the northern channel is higher than in the southern channel, because the discharge of the Mondego River is much more important than the discharge of the Pranto, in the southern channel. The background concentration in the southern channel is imposed by the northern channel, being the actual value increased by the Pranto’s discharge. The consumption of the nutrients is limited by the residence time, which does not permit the growth of the phytoplankton, being in fact the Pranto’s discharge enough to assure the production of the phytoplankton.

In order to understand the role of the Pranto and of the Mondego discharges for the functioning of the estuary, three scenarios were studied. In the first scenario the discharge of the Pranto River was reduced to 50%, in the second scenario, the Mondego discharge was reduced of 50% and finally, in the third scenario both the Pranto and the Mondego discharges was reduced to 50% each.

The results of these scenarios have shown that the reduction of the nitrate discharged in the estuary has no consequences in terms of trophic activity, reducing the concentrations of nitrate in the estuary, but not the production of phytoplankton. This is a consequence of the limitation growth by the residence time.

The results have shown also that the “bay behaviour” of the southern channel induces the deposition of particulate organic matter in the channel and the consequent enrichment of the sediments, enhancing the conditions for the development of macro-algae. The growth of these algae is also facilitated by the low values of the velocity. A sensitivity study of the hydrodynamics of that channel to the re-opening of the communication between the channels was performed and it was verified that it clearly modifies the flow.

All together, the scenarios tested with the model show that the reduction of the macro-algae growth in the southern channel can not be achieved through a reduction of the discharge of nutrients by the rivers, but has to be achieved by the reopening of the communication between the channels and consequent modification of the depositional characteristics of the southern channel.

The details of that work have to be object of a specific study, which has to consider the objectives of its closure (sediment transport in the estuary and the maintenance of the navigation channels) and must include a clear comparison between the trophic conditions in both estuaries and a complete model for macro-algae growth and its explicit dependence on the hydrodynamic conditions.

2.4 CONCLUDING REMARKS

This report describes a numerical study of the trophic dynamics of the Sado, Tagus and Mondego estuaries and of the most important features of hydrodynamics and of its implications on their ecology. For each estuary the transient circulation, as well as the residual circulation and the residence time are described. It is shown that the three estuaries have very different hydrodynamical features and that the differences are due mainly to the ratio between the river discharge and the mean volume of the estuary and to the shape of the estuary.

Mondego estuary is a narrow estuary where the tidal prism, the daily river discharge and the mean volume are numbers of the same order of magnitude. Has a consequence the residence time in the estuary is very short (2 to 4 days) and there is no time for blooms of phytoplankton to develop. The residual flow is quite uniform, from the river to the sea. On the other extreme is the Sado estuary, where the river discharge is several orders of magnitude smaller that the flow associated to the tidal prism and where the residence time is longer then 1 month. The estuary has strong tidal velocities that associated to the curvature of the estuary generating strong residual eddies with important secondary flows associated. This circulation is responsible for the formation of large sand banks inside the estuary and for strong mixing between different zones of the estuary. Although the residence time inside the estuary is long, the residence time of the water in each part of the estuary is short.

The Tagus estuary is the largest estuary studied in the project and the rivers have the largest discharges. In terms of ratios between river discharge, residual volume and tidal prism, the estuary fits between the Sado and Mondego estuaries. The transient velocities are stronger than in the other estuaries and residual flow patter is also complex, especially in the lower estuary where the geometry is more complex and transient velocities have higher magnitude. The residence time is of the order of three weeks and the fetch of the wind is long enough to generate surface waves with amplitudes of the order of some tens of centimetres, which have a critical role on fine sediment dynamics in the estuary.

The study has addressed the ecological functioning of the estuaries in nowadays conditions and in scenarios of reduction of nutrient loads from river discharges and/or from urban discharges. The Tagus estuary has been used as the reference study, because it is the most well known and has been object of a regular monitoring programme for several years. The model was calibrated in the Tagus using that field data and the same set of parameters have been used in the other estuaries. In the Sado estuary some data is also available and was used to verify the model. In the Mondego estuary the data available was not enough to validate the model. However the model agrees with the existing knowledge about the functioning of estuary and the scenarios tested show that the model is capturing the most relevant processes in the estuary.

The results of the model in the Tagus estuary show that light limitation by suspended matter is the factor limiting phytoplankton growth. As a consequence only a part of the nutrients that are discharged in the estuary is used in the trophic processes. The high turbidity in the estuary is a consequence of the intense tidal flow, of the large extension of the intertidal areas (1/3 of the total surface) and of the large wind fetch (width of the estuary is about 17km), which allow the generation of surface waves able to enhance sediment resuspension. For that reason, a reduction of nutrient discharge (both from the river and from the UWWTP) has no consequences on the trophic level in the estuary.

In the Mondego the results of the model show that the phytoplankton growth is limited by the residence time. The phytoplankton produced in the estuary is exported before having the time to generate a bloom. This happens both in the northern and southern channels, although in the southern channel residence time is longer due to the artificial closure of the upper connection with the northern channel that gives it "a bay like" behaviour. The southern channel is a net importer of particulate organic matter from the northern channel, which is deposited and mineralised on the bottom, enriching the sediments. This behaviour of the southern channel is a consequence of the smaller transient and residual velocities and is at the origin of the eutrophication by macro-algae development. Several scenarios of reduction of nutrients discharge were tested and it was verified that no modification of the estuary behaviour must be expected. A test of the consequences of opening the upper communication between the channels was performed and it was verified that in this case the velocities increase and that a seaward residual flow is produced. From the tests it was concluded that the resolution of the eutrophication symptoms in southern channel by macro-algae development must pass by re-opening the communication between the channels that was closed artificially with the purpose of enhancing the self cleaning of the sediments in the navigation channel in the northern branch of the estuary.

The Sado estuary is a very interesting estuary in terms of trophic activity. The discharge of nutrients in the estuary is small and the residence time is much longer than the time required for developing a bloom. As a consequence, the estuary has the behaviour of a closed basin, where the primary production is limited by nutrients supply, and predation by zooplankton. The results show the formation of typical spring blooms of phytoplankton which amplitude are limited by nutrients and by grazing. After the shooting of the phytoplankton bloom, the zooplankton also decreases and nutrients increase again in the estuary due to the river discharge and regeneration from mineralization of organic matter especially in the shallow intertidal areas. Then a new and shorter bloom develops by the end of spring, followed by another much smaller in summer. The scenario of reduction of nutrients does not change this evolution pattern, but reduces the amplitude of the blooms, especially the zooplankton bloom.

As a global conclusion one can say that the study explains the trophic mechanisms on the three estuaries and relates them to the physical properties of the estuaries (circulation and residence time). A reduction of the nutrients load in the Tagus would have no consequences for the trophic processes in the estuary, while in the Sado it would imply a reduction of the trophic activity, especially in terms of secondary production. In the Mondego estuary a reduction of 50% of the nutrients load would have no consequences for the trophic level in the estuary and would not modify the trophic conditions in the southern channel. The modification of the conditions of macro-algae development in this channel can only be achieved modifying its hydrodynamical properties, increasing the velocity of the flow and reducing the conditions for deposition of organic matter, imported from the northern channel and discharged from land sources.

3 References

The goal of this report is to describe the results of the numerical study of the trophic activity in the Tagus, Sado and Mondego estuaries. In order to simplify its reading references were added only when they were considered stricktly necessary. That for the case of a few institutional reports and specific publications about the Sado estuary, which is less described in the literature. The documents indicated below are cited in the text.

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