A methodology to estimate renewal time scales in estuaries: the Tagus Estuary case

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Abstract – High resolution hydrodynamic models are a common tool to simulate water dynamics in estuaries. Results from these models are however difficult to interpret without the aid of additional parameters to integrate the information. In this paper a methodology to understand the transport patterns in Tagus Estuary is proposed. It is based on the computation of two renewal time scales: residence time and integrated water fraction. This last parameter is used to build a dependency matrix that gives the integrated influence of each region of the estuary on a selected point. The parameters are computed using a lagrangian transport model coupled to the hydrodynamic model. Results show that Tagus Estuary has two different types of regions: The central part of the estuary, with low renewal efficiency, and three regions with higher renewal efficiency. Renewal mechanisms are however different for each region as shown by the dependency matrix. Comparison of renewal time scales with results from a water quality model revealed that residence time is not a limiting parameter for primary production in Tagus Estuary.

Keywords: Residence times, Renewal time scales, Estuary modeling, Tagus Estuary, Mohid model, Hydrodynamic model, Lagrangian model

1 Introduction

Transit times, residence times and other renewal time scales have long been used as classification parameters for estuaries and other semi-enclosed water bodies (Dyer, 1973), (Bolin & Rodhe, 1973), (Zimmerman, 1976), (Takeoka, 1984). The common objective of these parameters is to quantify the time that water remains inside an estuary. These time scales can be used as indicators to assess the transport of substances inside an estuary. In this way, general conclusions can be drawn regarding pollution dispersal, sediment transport or ecological processes in an estuary. From the ecological point of view, for example, estuaries with a short transit time will export nutrients from upstream sources more rapidly then estuaries with longer transit times. On the other hand, the domain average residence time -average residence time of water parcels inside the estuary- determines if micro-algae can stay long enough to generate a bloom. In fact, estuaries with residence times shorter than the doubling time of algae cells will inhibit formation of algae blooms (Kierstead & Slobodkin, 1953), (Lucas et al. 1999), (EPA, 2001). As a consequence, estuaries with short residence time are expected to have much lower algae blooms then estuaries with longer residence times. Renewal time scales also characterize the exchanges between the water column and the sediment: deposition of particulate matter and associated adsorbed species depends on the particle's settling velocity, water depth and particle residence time. This is particularly important for the fine fractions with lower sinking velocities.

The different renewal time scales can thus be used to generally characterize an estuary, to compare different estuaries in respect to the transport processes, or to aggregate field data in easy to use parameters. Numerical models produce large amounts of information that must be processed and classified to become amenable to interpretation. Renewal time scales with a high spatial and temporal resolution can be used to aggregate and summarize information produced by numerical models. The main questions are: which are the best renewal time scales to characterize each process and how to compute them? A large number of different methods have been proposed, ranging from simple integral estuary-wide formulas to more complex methodologies (Geyer, 1997), (Miller & McPherson, 1991), (Hagy *et al*, 2000). These methods attempt to account for advection and mixing inside the estuary using indirect measurements such as fresh water flows and/or tracer concentrations. They are usually applied to the whole estuary or to a few areas of it. These methods are useful to classify an estuary in a general way or to compile field data, giving a picture of the estuary's transport. Since they possess a very low spatial and temporal resolution and they lack to describe accurately the dynamics of the water masses, they cannot be used for detailed considerations.

In another type of approach, several methods were proposed, using high-resolution hydrodynamic models, to simulate explicitly the transport processes. The concept of water age is one of these methods (Delhez et. al., 1999), (Hirst, 2000), (Beckers et al., 2001). Deleersnijder et. al. (2001) show that this concept can be generally applied to a constituent with any age characteristic (like radioactive tracers for example). In case of the water itself, the tracer age concentration is unitary. The water age calculation reduces in that case to a standard advection diffusion equation that can be solved with a eulerian or lagrangian formulation. The eulerian formulation can produce a high-resolution picture of the water age distribution over the entire domain. From these results, global and local renewal time scales can be computed. One advantage of the eulerian approach is that the same equations and numerical methods are used both to the hydrodynamic model and to transport water constituents. With this approach it is however difficult to label water masses and relate their positions in any instant of time with their release points. That task is easily accomplished in lagrangian models because particles can carry information about their origin. Several authors have used lagrangian implementations of the age concept (Tartinville et al., 1997), (Oliveira & Baptista, 1997) but usually the memory characteristic of the lagrangian tracers is not explored. One problem of the lagrangian approach is that the renewal time scales are difficult to define in an unequivocal way. Residence time of a region, for example, is usually calculated as the time elapsed until all the water of that region (corresponding to all the tracers released in instant zero) is replaced by new water. This criterion can lead to very high residence times. For practical applications the residence is considered complete when a small amount of residual water is still in the region. The residual water is usually defined in a subjective way as a certain fraction of the original water mass. Tartinville et al. (1997) show that this problem can be overcome considering that the water mass evolution in the region follows the exponential law

$$m(t) = m(0)\exp(-t/\tau) \qquad 1$$

The residence time can thus be determined adjusting an exponential regression to the model results and defining τ as the residence time. It must be noted that this assumption is only valid if the region is of a diffusive type, in the sense defined by Deleersnijder et. al. (1998). If the flux of tracer entering the region is constant over time, the tracer mass will behave as equation 1 when the outgoing flux is proportional to the mass of tracer in the region. If the advective processes are important the outgoing flux is related to the ingoing flux by a delay time. For the regions considered here the input flux is not constant in time since the output from one region is the input to the adjacent ones. All regions have also some advective nature in the sense described above. Inspecting the tracer evolution in time it can however be seen that it decreases following approximately an exponential law, allowing the use of equation 1.

In this paper the characteristic time τ is used to quantify residence times in Tagus Estuary. An integrated renewal time scale, the integrated water fraction, is also used to understand the history of renewal in each region. Results were obtained using the MOHID primitive equation hydrodynamic model (Martins et. al., 2001), coupled to its lagrangian transport module. Since the lagrangian tracers can carry explicitly the information of its origin, this property is used to build a dependency matrix that helps to understand the fate of water masses inside the estuary. Residence times and water history are then interpreted together. As stated above, renewal time scales can be an important indicator of water quality and largely affect biologic processes. The renewal parameters are compared with these ecological results to assess the importance of transport in the biologic processes of Tagus Estuary.

2 Renewal time scales

In this study two different physical parameters are defined: The Residence Time and the Integrated Water Fraction. These parameters are applied separately to different regions of the estuary. For that purpose the estuary was divided into ten boxes where the high resolution model results are integrated. It must be noted that these boxes are used only for monitoring purposes and no box model was applied. Each box covers a given area and is composed by several cells of the underlying grid. The boxes are used in two functionalities: (i) release lagrangian tracers and (ii) examine the lagrangian tracers which pass trough them. A different set of boxes can be used for each of these functions but, in order to simplify the result analysis in this paper, the same set of boxes was used for the two purposes. The boxes were placed in a way to fulfill the whole estuary. Figure 1 shows their configuration. The number and location of the boxes was based on prior knowledge of physical and biologic characteristics of the estuary. Boxes 3, 4 and 8 are placed over tidal flats, boxes 1, 2, 5, 6 and 7 are located in the main channel, box 9 cover the Sorraia channel and box 10 is located in the coastal region, near the mouth, in the region of influence of the estuary plume.

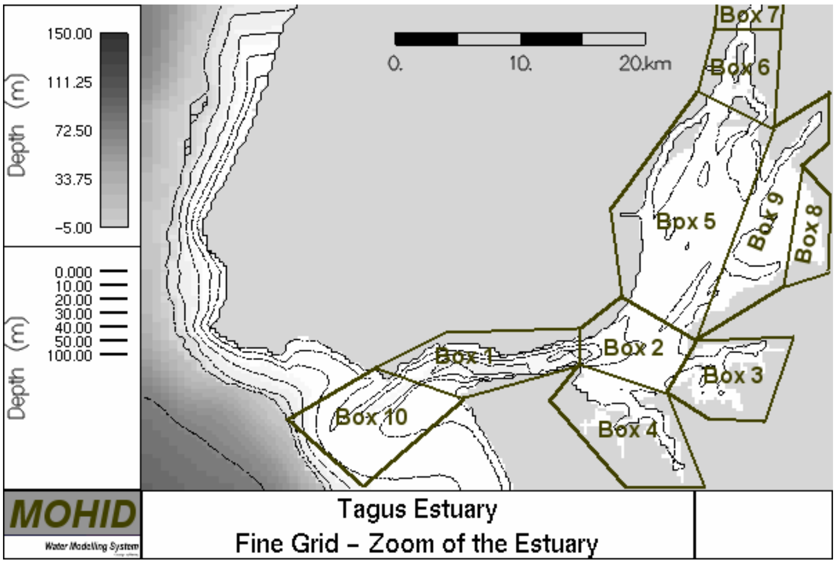

Figure 1: Division of the Estuary into boxes

Using the monitoring boxes, together with the memory property of the lagrangian tracers, it is possible to answer several important questions related to the water renewal process inside the estuary: (i) In which areas are the water masses initially released in box *i* located? (ii) From which areas came the water masses that occupy box *i* at a certain instant? (iii) What are the mass fluxes between areas? In the next sections the water renewal parameters applied to these boxes are presented.

2.1 Residence Time

The first renewal time scale analyzed is the box's average residence time. This parameter is defined as the time needed until the water volume initially in a given region is replaced by new water. This can be applied to the estuary as a whole or to a single box.

Using the lagrangian approach this parameter can be computed releasing an amount of tracers with a volume equal to the entire water body. The water fraction inside box i in each instant of time, with origin from box j ($f_{i,j}$) is calculated as:

$$f_{i,j}(t) = \frac{V_{i,j}(t)}{V_{i,i}(0)} \qquad 2$$

Where $V_{i,j}(t)$ is the volume of tracers emitted in box j, present inside box i at time t and $V_{i,i}(0)$ represents the water volume in box i at the beginning of the simulation. For the especial case $i=j$ the average residence time for a given box can be computed. When $V_{ii}(t)$ reaches zero all box's water is renewed and the box's average residence time is found. In some regions a residual fraction of particles tend to stay inside the box for a long time. Consequently $V_{ii}(t)$ approach zero very slowly. This definition of residence time would then lead to excessively high values. An expedite way of solving this problem is to use a limiting residual fraction below which the box is considered completely renewed. This however brings some subjectivity in the choice of the residual fraction. In this article an alternative approach was chosen using the method proposed by Tartinville et al. (1997). In this method results are adjusted to equation 1 using an exponential regression. The residence time is obtained as the value of τ in that equation, without the need of any subjective parameter.

The application of the residence time parameter to different boxes instead of using it for the whole estuary, increases the spatial resolution of the analysis, but does not account for the interaction between boxes over time. The next parameter, Integrated Water Fractions, can give that information.

2.2 Integrated Water Fraction

The Integrated Water Fraction, F, is obtained integrating the water fraction defined by (2) and normalizing it by time:

$$F_{i,j}(T) = \frac{1}{T}\int_{0}^{T}\frac{V_{i,j}(t)}{V_{i,i}(0)}dt \qquad 3$$

The parameter $F_{i,j}$ measures the integrated influence from box j over box i during the time T. For the special case $i = j$ this parameter is related to the residence time. In that case if the water inside the estuary were not renewed at all, F would be equal to one. As the water is renewed inside a box, the contribution of the initial water for the total volume of the box decreases and F tends to zero. The time required until F = 0 is thus another unequivocal way of computing the box's residence time. The basic difference between these two methods of computing residence times is that F keeps track of the renewal history of the box. The first method described in this section was however preferred since it produces a value with an easier physical interpretation. On the other hand, considering $i \neq j$, F is a good parameter for relative comparisons between boxes. In this case the value of F gives the integrated influence of box j over box i. Comparing the relative contribution of all boxes over i a clear picture of water dynamics over time can be obtained. In this article the Integrated Water Fractions F were used to build a matrix of dependencies between boxes.

3 Numerical Model

3.1 General Considerations

The numerical model used in the present study is the MOHID water modeling system. It uses a full 3D formulation with hydrostatic and the Boussinesq approximations (Miranda, et al. 2000), (Martins *et al.*, 2001). For the turbulent closure, the general ocean turbulence model – GOTM is used (Buchard et al., 1999). In this work the model is used with only one layer, behaving as a 2D depth integrated model. This is justified by the estuary shallowness. Previous runs have shown that 3D effects are only present close to the mouth and during high flow periods. Two transport models are coupled to this hydrodynamic module using eulerian and lagrangian formulations, respectively. A zero dimensional water quality model is coupled to the two transport models. Interactions between the surface and the water column (ex. Heat fluxes, wind stress) are handled by the surface module and the interaction between the bottom and the water column (ex. Oxygen sinks, bottom friction) by the bottom module. River discharges are imposed explicitly.

3.2 Model Implementation

For the present study a horizontal grid of the Arakawa C type, with variable spacing between 1500 m and 300 m was used. The grid covers an area of 90 km by 76 km. Figure 2 shows a zoom of the refined grid for the estuary zone.

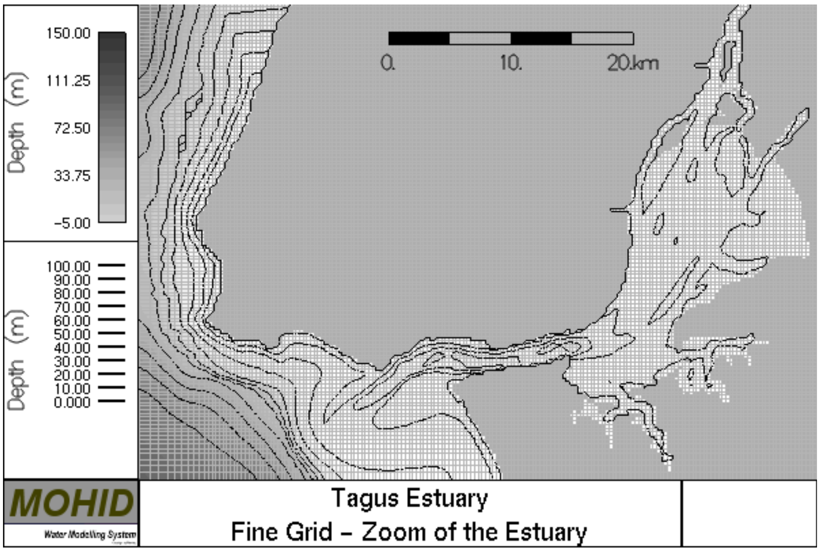

Figure 2: Tagus Estuary bathymetry and grid. Grid lines for the refined grid are shown.

Tagus estuary is a meso-tidal estuary, with spring and neap tide amplitudes of 1.5 m and 0.6 m respectively. The Tagus River modal average monthly flow is rather constant from March to December with an average value of 330 m^3/s. From January to March higher values are recorded. The wind blows predominantly from South and Southwest during Winter, rotating progressively to Northwest and North during Spring and maintaining this direction during Summer.

The hydrodynamic model was forced imposing tide gauge elevations at the open boundary and using the mean river discharges of the Tagus River (330 m^3/s). The influence of wind over the renewal process was also studied. Two scenarios were used, one with no wind forcing and other with a constant South wind of 10 m/s. The differences between the results were however small as shown in figure 5. For that reason only the results with no wind are analyzed. In the vertical direction, only one layer was used to reduce computational effort. Thus 2D depth integrated results are obtained.

4 Results

4.1 General Considerations

For the Tagus Estuary 30 days runs were used to compute the renewal time scales. The evolution of the water volume inside the estuary during this period can be observed in Figure 3. An important fact is that the tidal prism, during neap tide, is about 25% of the mean water volume and, during spring tide, about 40%.

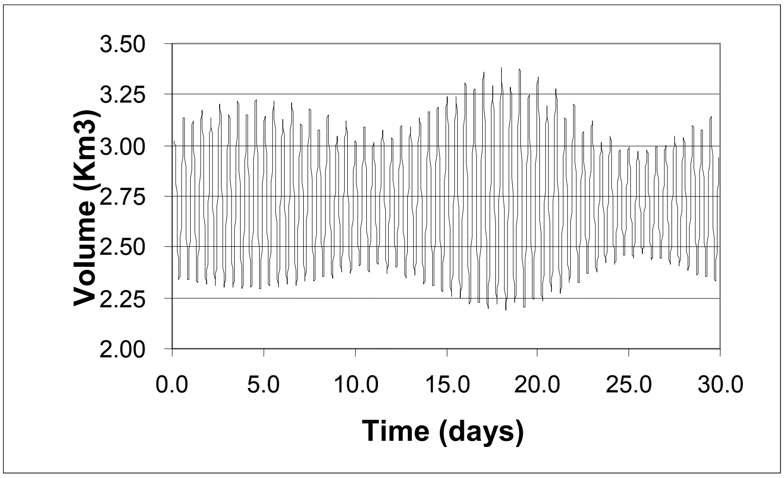

Figure 3: Volume variation inside the Tagus Estuary during the simulated period

Taking into consideration the tidal prism, one can expect a quick renewal of the water inside the estuary (considering the water from the open sea as fresh water), but some of the water which is flushed out of the estuary during ebb is “flushed in” again during flood increasing the residence time. The residual circulation at the Tagus Estuary mouth helps to understand the water dynamics of that region. Figure 4 shows the residual water flux (residual velocity multiplied by depth) at the mouth. Eddies observed in Figure 4 show clearly that water flushed out trough the main channel is transported back to the estuary, along the shores.

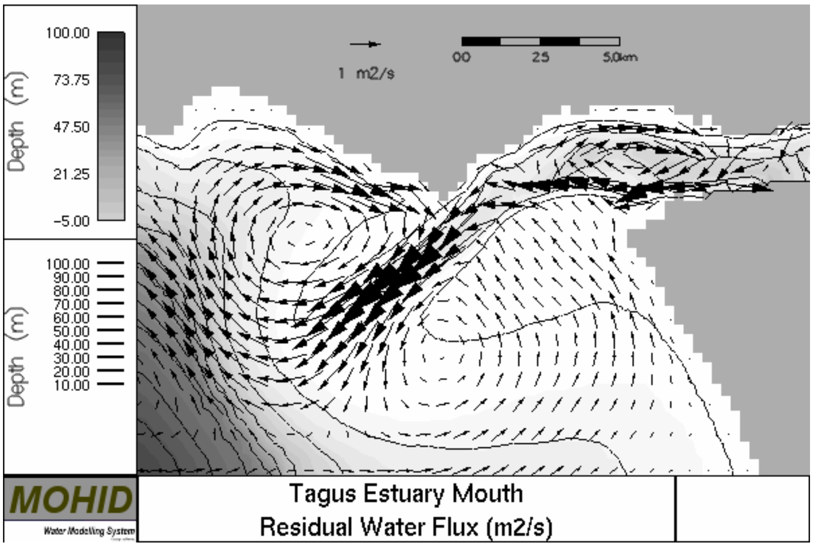

Figure 4: Residual water flux of the Tagus Estuary mouth

4.2 Residence Times

In the present study all simulations started at high tide and in a transient period from neap tide to spring tide. The water fraction is first used to calculate the residence time of the estuary as a whole. Figure 5 shows the evolution of the water fraction for the whole Tagus Estuary for two scenarios: (i) no wind imposed and (ii) a constant South wind with 10m/s. This figure shows a slight difference between the two scenarios. The global residence times are however very similar: around 25 days. From the analysis of the boxes it was concluded that the tracers initial located near to the estuary mouth are removed more quickly from the estuary in scenario (ii) but tracers initially located in the upper part of the estuary stay inside the estuary for longer times. Since the differences are only slight only the no wind scenario is used thereafter.

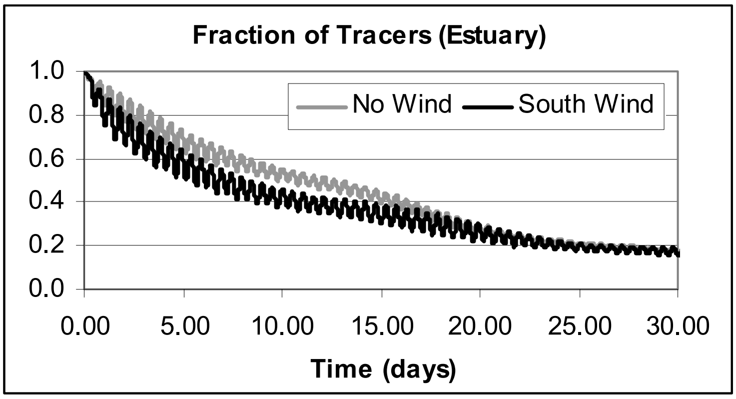

Figure 5: Evolution of the water fraction in the whole estuary during one month for no wind and south wind conditions

The residence times were then computed for each box represented in figure 1. In the present paper two different boxes (6 and 8) are used to explain the methodology. These two boxes have distinct natures: box 6 is located in the upper part of the estuary, characterized by relatively deep channels, where the fresh water influence in the renewal process is high. Box 8 is located in a shallow area away from the main channel. The renewal parameters must be able to identify these differences. Figure 6 shows the evolution of the water fraction *f(t)* for boxes 6 and 8. In box 6 the water fraction decreases to almost zero in a few days. In Box 8 the greater part of the water is flushed away in the first days but a residual volume of tracers, with about 5% of the box volume, remain inside the box for a long time. This is due to the location of box 8 in a shallow area, away from the fresh water influence of Tagus River. In this case the choice of a subjective residual fraction slightly above or below 5% would lead to dramatically different results. Adjusting Equation 1 to the results of those two boxes residence times of 7.3 days and 12.8 days for boxes 6 and 8 respectively are obtained.

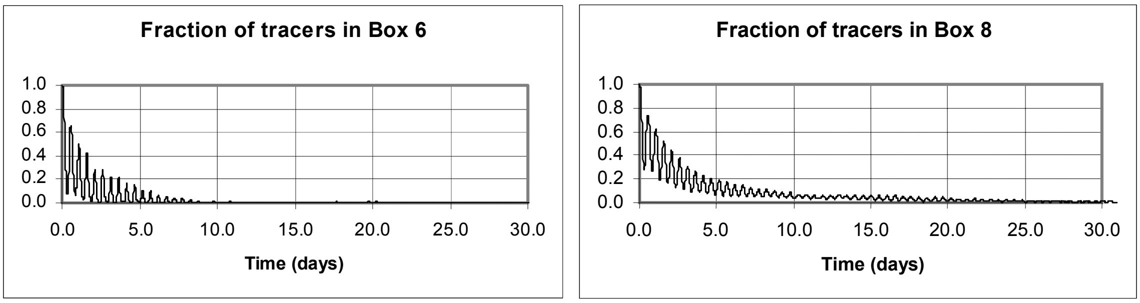

Figure 6: Fraction of tracers in Box 6 and in Box 8

Using the same methodology for the other boxes, the results shown in Figure 7 are obtained.

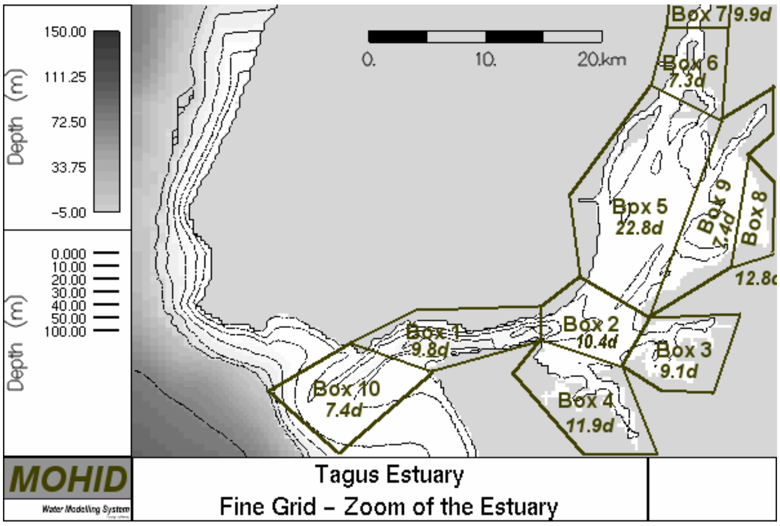

Figure 7: Values of the residence time (in days) for each box using Equation 1

It can be seen that the estuary has a central region, composed mainly by boxes 2 and 5 with large residence times and several regions with lower residence times. This result is somewhat different from what would be expected at first sight. The residence time parameter alone can not explain this fact since it only quantifies renewal, it doesn't describe the water dynamics.

In the next section the integrated water fractions are used to understand the processes leading to these results.

4.3 Integrated Water Fractions

As pointed out before, the integrated water fractions are used to build a dependency matrix for the water exchange among boxes inside the whole estuary. Table 4-1 shows the dependency matrix for the Tagus Estuary, considering a value of T = 30 days. The values in one row i of this matrix give the integrated contribution of water masses from all the boxes j over box i. The difference between the sum of all the values and 1 indicates the water fraction that has been renewed during time T.

The values in one column j of this matrix give the integrated contribution along time of the water mass initially in box j over all the boxes i.

F (30 d)	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6	Box 7	Box 8	Box 9	Box 10
Box 1	0.15	0.12	0.01	0.03	0.12	0.01	0.02	0.00	0.04	0.15
Box 2	0.05	0.08	0.02	0.02	0.15	0.02	0.03	0.00	0.06	0.05
Box 3	0.02	0.06	0.10	0.03	0.24	0.03	0.06	0.01	0.12	0.02
Box 4	0.07	0.16	0.06	0.12	0.39	0.04	0.07	0.01	0.17	0.07
Box 5	0.01	0.02	0.00	0.00	0.18	0.04	0.07	0.00	0.06	0.01
Box 6	0.00	0.00	0.00	0.00	0.01	0.03	0.12	0.00	0.00	0.00
Box 7	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00
Box 8	0.00	0.00	0.00	0.00	0.20	0.09	0.17	0.05	0.14	0.00
Box 9	0.00	0.00	0.00	0.00	0.13	0.04	0.08	0.01	0.10	0.00
Box 10	0.08	0.04	0.00	0.01	0.04	0.00	0.00	0.00	0.01	0.08

Table 4-1: Dependency matrix for the Tagus Estuary after 30 days

With this matrix it is easy to understand why the central part of the estuary has large residence times. Following the row for box 5 for example, it can be seen that this box receives water mainly from itself (18%). This means that 18% of the water originated in box 5 travels up and down the estuary staying most of the time in box 5. The integrated influence in box 5 is therefore high. Boxes 6 and 7 have low residence times. Following the corresponding rows in the matrix it can be seen that water staying in box 6 comes mainly from box 7. This is expected since box 7 is located upstream from box 6. Thus the river flow is the principal mechanism contributing to the renewal of these boxes. Boxes 3, 4, and 8 have also small residence times but with different reason. Following the matrix rows for that boxes it can be seen that they all receive water from the central boxes 2 and 5 and also from the Sorraia Channel (box 9). The low residence times are thus due to exchange with the central part of the estuary. Finally box 1 has also a low residence time but due to strong advection over box 10 located outside the estuary and over boxes 2 and 5 located inside. This can also be seen by inspection of the first row of the matrix.

4.4 Comparison with ecological results

As mentioned in the introduction, the residence time of water inside an estuary can influence algae growth and primary production. The primary production in estuaries depends on four major conditions: (i) nutrient availability, (ii) temperature, (iii) light and (iv) residence time. In general, if one of the four mentioned conditions is not fulfilled major algae blooms will not occur. The last condition (residence time) is governed by transport phenomena, and is present in the simulations due to the coupling of the ecological model with the hydrodynamic module. The first three conditions are solved explicitly by the MOHID water quality module. This module solves the nitrogen, phosphorus and oxygen cycles. Primary production is modeled in terms of phytoplankton and as secondary producer zooplankton is included. The module was initially developed using the Environmental Protection Agency model (EPA, 1985). The model was successively improved during applications in estuaries (Portela, 1996), (Pina, 2001).

In order to reduce computational effort the results presented in this paper are obtained using a coarser grid with variable resolution between 3000 m and 600 m. Three years simulations are carried out. The first year is used to stabilize the ecological model; the second and third years must replicate the same results to ensure that the solution is periodic. The results are integrated in the same boxes as in Figure 1. The average annual gross primary production is used as a water quality parameter, since it can be related to eutrophication conditions. In these simulations a value of 2.2 days for algae duplication is used, which was obtained during the calibration of the ecological model (Pina, 2001). In Figure 8 the average production for each box is presented (values correspond to the second and third year).

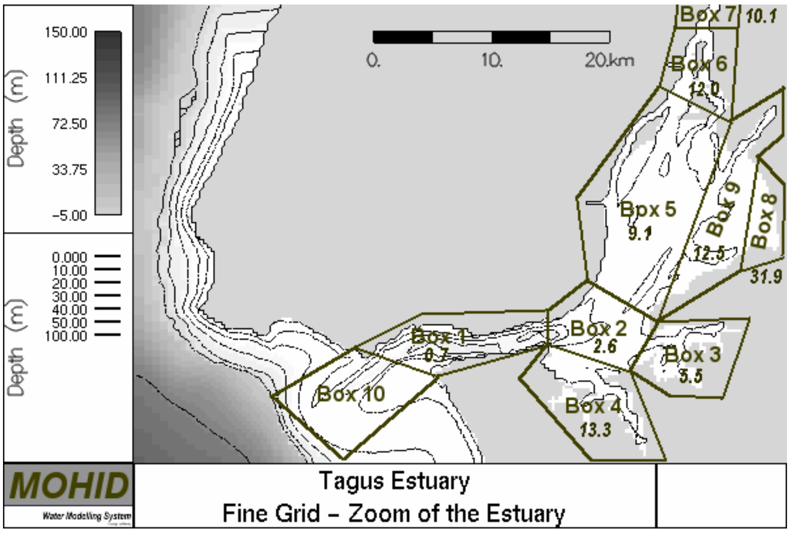

Figure 8: Annual gross primary production in each box (g/m^3/year). Results obtained with the MOHID water quality module

These results can be compared with the values from Figure 7. A distinct behavior is observed between the main channel boxes 1, 2, 5 and 6 and the other boxes. These main channel boxes have low productivity though the box average residence times are higher than the other boxes.

The higher depth of these boxes easily explains the low average productivity per m^3. In the Tagus Estuary light is, in fact, the limiting factor. Nutrients and temperature are usually not the limiting factors (Pina, 2001). As shown in Figure 7, the residence time in every box is greater then 2.2 days, the duplication time for algae used in the simulations. This leads to the conclusion that in the case of Tagus Estuary the residence time is not a limiting factor.

5 Conclusions and future work

In this paper a methodology to understand the transport patterns in Tagus Estuary is proposed. The method is based on the use of renewal time scales, computed using a high resolution hydrodynamic model, coupled to a lagrangian transport model. The analysis makes use of two parameters: the box average residence time, applied to each region of the estuary and the integrated water fraction. This last parameter is used to build a dependency matrix that quantifies the integrated influence of the water from each region over the other regions. The central part of the estuary has large residence times because water initially in that regions travels up and down the estuary, remaining several days over their origin region. The residence times of that region are usually larger than 20 days. The upstream region has residence times lower than 10 days. The renewal efficiency in this region is due to the fresh water flow. The tidal flats in the South and Southeast of the estuary have also residence times lower than 10 days. The renewal efficiency now is due to exchange of water with the central part of the estuary. The narrow channel close to the moth has also low residence time but the mechanism responsible for that is advection. The renewal time scales are also compared with water quality results. The comparison show that in Tagus Estuary the residence times in all the regions are several times larger than the doubling time for phytoplankton cells. Thus it can be concluded that water renewal is not a limiting factor for primary production in Tagus Estuary.

In order to reduce computational effort, the work presented in this paper was run in a 2D depth integrated configuration. This simplification affects the residual transport (which affects the renewal time scales) in front of the estuary's mouth where density driven currents are important. The wind driven currents are also averaged over depth in this 2D approach. In future work this problem should be overcome using a 3D model. The influence of varying river discharges and instant of tracer release will also be studied.

In order to obtain a more correct relation between physical and biological parameters, other relations (like light limitation, average depth) should also be taken into account.

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