Spatial residence time description for water discharges in harbours

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Keywords

Residence Time, Environmental Management, Lagrangian Model, Barcelona harbour

Introduction

The harbours, as a pole of commercial and economic activities, are of vital importance for a wide influence zone (hinterland). These commercial activities produce anthropogenic pressure in the physical medium. Besides, for historical reasons, the harbours used to be associated at urban zone cities with the impact in the water that this produce. Nowadays, there is a tendency to reclaim the harbour platforms for recreational, touristical and nautical purposes. In this sense, poor water quality can influence negatively in these economical activities. So, the study of the water quality response at discharges impact is of importance under economic, social and environmental point of view. According to the environmental management point of view, four methods are presented in this work to determine the residence time understood as a characteristic time for potential discharge dropped in any point of the harbour leaves the inner water domain. Theses methods are applied in Barcelona harbour where the hydrodynamic behaviour is characterized through data analysis and numerical modelling.

Hydrodynamics in Barcelona harbour

The inner circulation in a harbour determines the flushing action. This circulation is related with tides, baroclinic effect, waves, wind and fresh water discharge inside the harbour. Moreover, Barcelona harbour hydrodynamics is influenced by the opening of a second mouth on June 2002.

With the purpose of determining the harbour hydrodynamics, a field campaign data was carried out (figure 1) between the 18th of November and the 30th of December of 2003. The measurements from the Doppler Acoustic Profiler current meter deployed in the inner harbour, CTD profiles, sea level gauge and meteorological stations were analyzed [1]. The hydrodynamic result from the field campaign data gives a north-south circulation pattern, so the water tends to enter inside the harbour through the north mouth and exits through the south mouth. Figure 2 shows the time-averaged vertical velocity profiles where this circulation pattern is verified. The directions of the profiles are rotated according to a study direction given by the direction of the central channel of the harbour (DOP-2) and the perpendicular of the North and South mouth entrance (DOP-1 and DOP-3 respectively).

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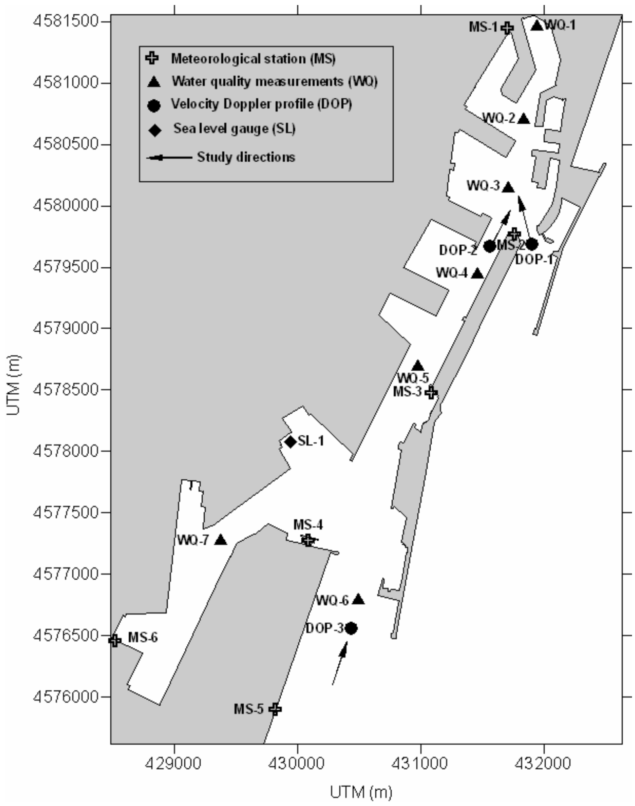

Figure 1. Measurements in Barcelona harbour during the field campaign. The arrows correspond the directions studies considered for the data analysis.

Once the hydrodynamic behaviour has been determined, a numerical model is applied in order to simulate the currents in the whole harbour domain. In our case, a 3D-non hydrostatic model is applied [2]. The spatial discretization is solved using finite elements considered more suitable for cases of complex geometry such as harbour lay-out. The scenario simulated has been done according to a representative wind description measured (NW direction and 6 m/s of intensity) and the flow profile measured in the north mouth. The model has been validated (figure 2) with the velocities recorded in the central zone (DOP-2) and the south mouth (DOP-3).

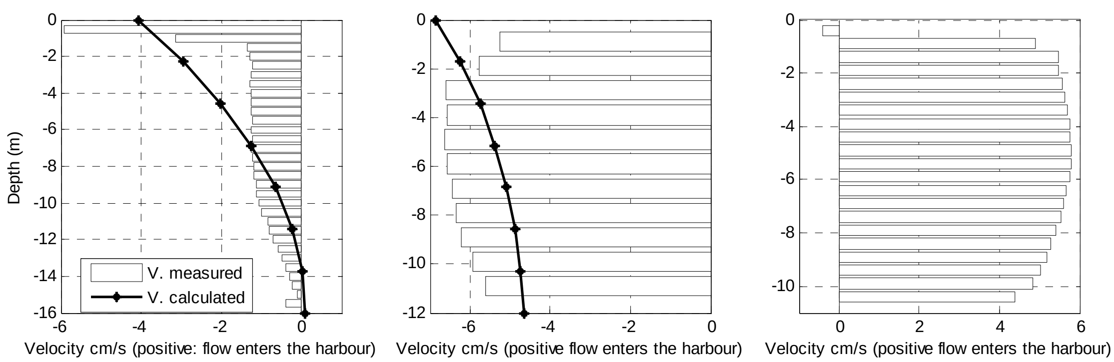

Figure 2. Velocities measured (by Dopplers profilers) and computed (by numerical modelling) according the to direction studies in the south entrance (on the left), central zone (centre) and north entrance (on the right).

Method I

The first selected method is based on the determination of a local residence by applying a conservation law in the different subdomains. The LRT (Local Residence Time), introduced by [3], is evaluated as the ratio between the volume of water within the inner domain (V_{total}) and the renovation flow (Q_R) at the exchange section (with the outer domain). Therfeore:

$$Tr = \frac{V_{TOTAL}}{Q_R} \qquad (1)$$

The renovation flow is defined as the flow that enters the inner water body. However, some authors have defined this renovation flow as the flow of water that leaves the water body [4]. Such as it was suggested in the previous chapter, the renovation flows can be evaluated in different ways. There exist equations that allow the evaluation of the entrance flow as a function of the geometric characteristics of the inner domain and the tidal parameters [5]. However, these equations are restricted to areas where the predominant hydrodynamic forcing is tidal. Another form of evaluating the flows is through observations. It is advisable to obtain an approximation of the exchange flow in the whole section or, at least in the water column if we suspect negligible horizontal gradients. Lastly, we can use of numerical modelling with the purpose of solving the hydrodynamic problem and thus obtaining the currents in the whole domain.

This method discretizes the spatial domain in areas or “boxes” where similar behaviour is expected. The integral residence time obtained is then applied for each of the areas. The segmentation of the water body is done according to a hypothetical circulation pattern. The suitability of the assumed pattern will affect the quality of the spatial description of residence times. The circulation pattern therefore allows obtaining a connectivity scheme for each subdomain. The matrix connectivity represents the areas that a hypothetical discharge would cross according to the hydrodynamic pattern considered. Consequently, in each area of study k, the partial residence time is obtained by the following equation:

$$Tr'(k) = \frac{\sum^{M} V_m}{Q_R} \qquad (2)$$

Where M is the matrix connectivity dimension for each of the area k. This time parameter is partial because it only considers the cumulative domain area. In this sense, an underestimation of the residence time in the obtained values should be suspected. The residence time variation is computed in each subdomain of the water body from:

$$\Delta Tr'(k) = Tr'(k) - \overline{Tr'} \qquad (3)$$

Where:

$$\overline{Tr'} = \frac{\sum_{k=1}^{N} Tr'(k)}{N} \qquad (4)$$

Being N the number of boxes or areas considered. From these computed variations, the integral residence is obtained (eq. 1). In this way, a characteristic value of the residence time, that is interpreted as the LRT is calculated for each area as:

$$Tr(k) = Tr + \Delta Tr'(k) \quad (5)$$

In the figure 3, the LRT distribution according this method is shown. Such as suggested by [6], this "boxes" method can be perceived like a redistribution in space of the mean value of the residence time. Following this idea, this redistribution is calculated from the geometry and circulation pattern. For this reason, the results can differ significantly from the real values of the LRT or from the results calculated by other more sophisticated methods. However, the main advantage of the method lies in the possibility of obtaining an approximate of the LRT using only the flows in the exchange section. Consequently, due to its simplicity, it can be a useful methodology to obtain a first evaluation of the spatial distribution of residence times.

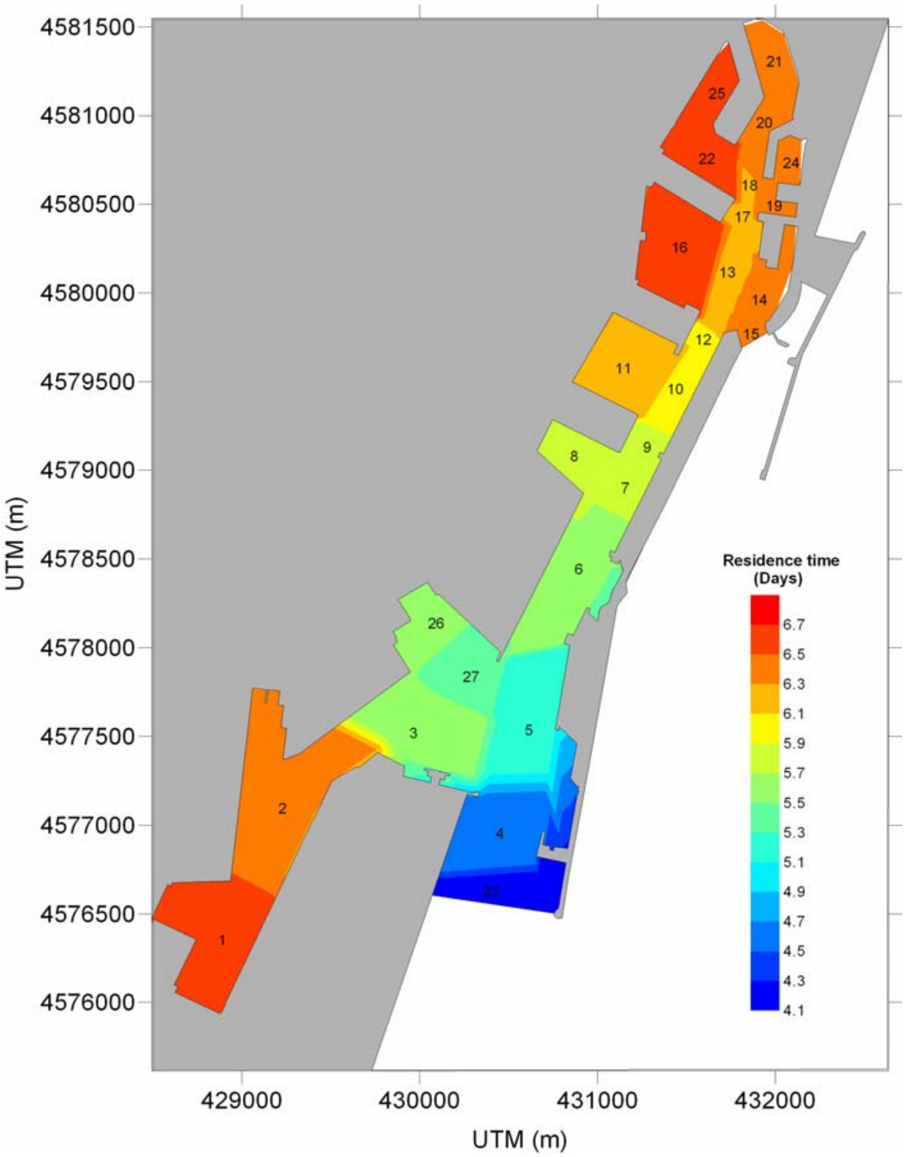

Figure 3. Local residence time (in days) according to method I.
The numbers indicate the box for the discretized harbour domain

Method II

The second method discretizes again the domain in areas or "boxes." In these subdomains an expression of the integral residence time is evaluated as if they were independent areas (eq. 1). Consequently, it is necessary to determine the exchange flow among each considered area. The exchange flows can be obtained from numerical modelling or from field data. However, if the number of boxes considered is large, the acquisition of field data becomes is not very feasible. Once the exchange flows are defined, the TRL is calculated from the accumulation of residence times within each area, according to the controlling circulation pattern (figure 4).

This methodology is considered more accurate than the previous one since it incorporates the hydrodynamics within each area. However, for the application of this method, it is necessary to solve numerically hydrodynamics domain.

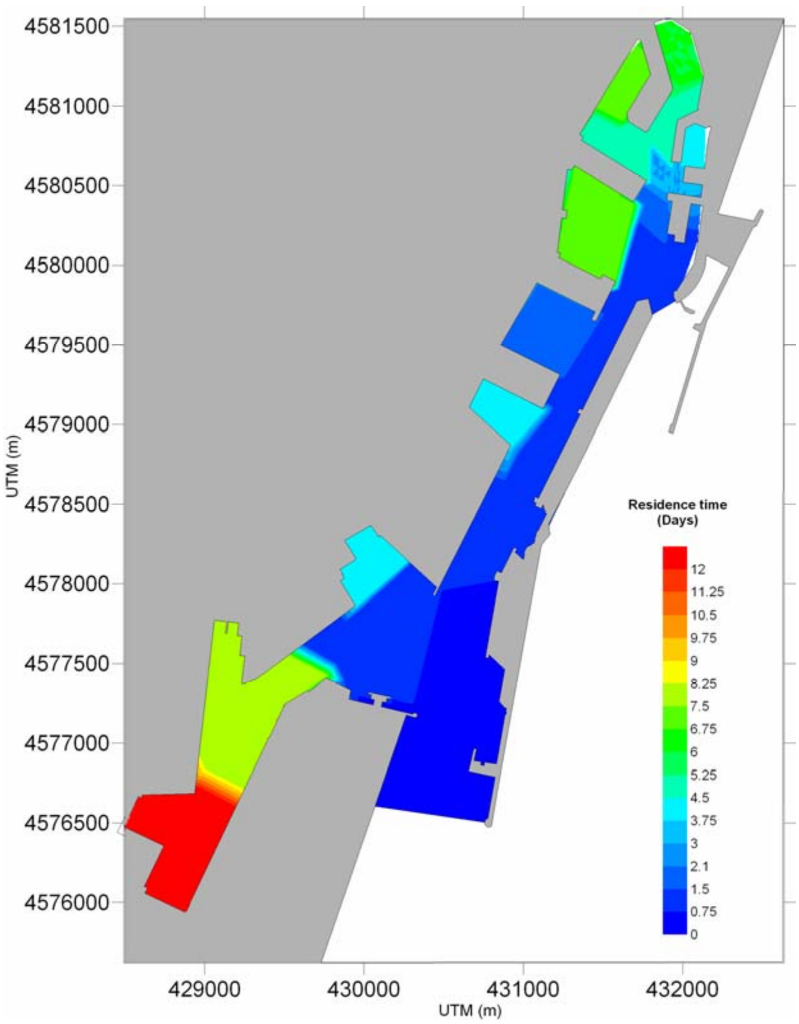

Figure 4. Local residence times (in days) in each of the boxes considered according method II.

Method III

The third method is based on solving partially the transport equation. The method solves only the advection part of the equation, which can be expressed as:

$$\frac{\partial C}{\partial t} + u_i \frac{\partial C}{\partial x_i} = 0 \qquad (6)$$

Where C is the concentration of a generic substance in the water and u_i are the flow velocities. Numerically this equation is solved under a lagrangian approach. A discrete number of particles in different positions within the harbour are released calculating in each time step the new positions. These positions represent water parcels. The equation of motion for the discrete particles is determined by the following differential equation (equation of trajectories):

$$\frac{dx_i}{dt} = u_i\left(x_i, t\right) \qquad (7)$$

being x_i the positions of the particles. This equation is solved numerically by a Runge-Kutta fourth order method [7] that allows to minimize the numerical error in the trajectories for cases of particulary complex flows such as it happens in coastal zones [8]. This operation is repeated in time until the considered particle leaves the harbour. In that instance the total trajectory of the particle is known and the total time of residence inside the harbour can be obtained. This time is the LRT associated to that parcel of water where the particle had been introduced in the initial instant. One can observe how this method solves the transport equation in a discreet form as a function of the velocity field. Consequently, this methodology requires that the hydrodynamic field inside the domain had been solved previously using suitable numerical code. The LRT computed according this method is shown in the figure 5.

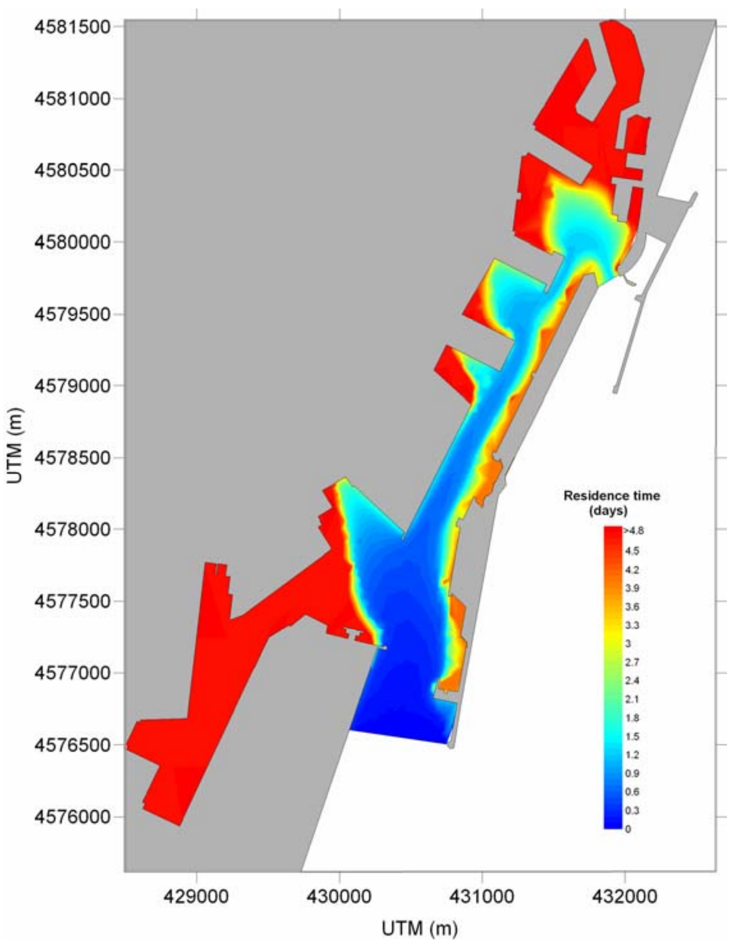

Figure 5. Local residence time (in days) according to Method III.

Method IV

The fourth method can be understood as an extension of the third method but considering turbulence diffusion. This method solves the full transport equation:

$$\frac{\partial C}{\partial t}+u_i\frac{\partial C}{\partial x_i}=\frac{\partial^2 C}{\partial x_j^2}\left(K_j C\right) \tag{8}$$

Where C is the concentration, u_i the velocities and K_j are the turbulent diffusivity components. The advective part of the equation is solved as presented for method III. The diffusive part is solved through a “random walk” algorithm [9]. This algorithm is based on considering that the particles trajectories are characterized by a Brownian process where the displacement of a particle at a time t is independent to the previous time step t '. One of the characteristics of this algorithm is that it solves the diffusive part of the equation from a stochastic perspective. This means that the position of the particle is subject to a movement with a random component. In accordance with the random-walk algorithm, the velocity of a particle due to diffusion can be written as:

$$u^i_{dif_j}=2\left(0.5-\left[Rnd\right]_0^1\right)\cdot\sqrt{\frac{6\cdot K_j}{\Delta t}} \tag{9}$$

Where Rnd is a random number between 0,1 with a statistically uniform distribution and K_j represents turbulent diffusivity (j=1,3). One of the characteristics of this method is its capacity to reproduce the randomness of the particle movement. The reliability of the method depends on the use of libraries that really reproduce random numbers to model properly diffusion [10]. However, the fact of considering a stochastic component in the trajectories implies that to characterize the residence time of a water parcel it is necessary to use a certain number of particles per parcel. Consequently, the problem solution becomes the calculation of the propagation of a trace inside the domain. As discussed previously; it is considered that the trace has abandoned the domain when the concentration within the inner domain is less than e^{-1} the original one. Using more particles to solve the residence time for each water parcel will influence the computational time required. This aspect should be kept in mind when assessing the functionality of the method as tool for environmental management.

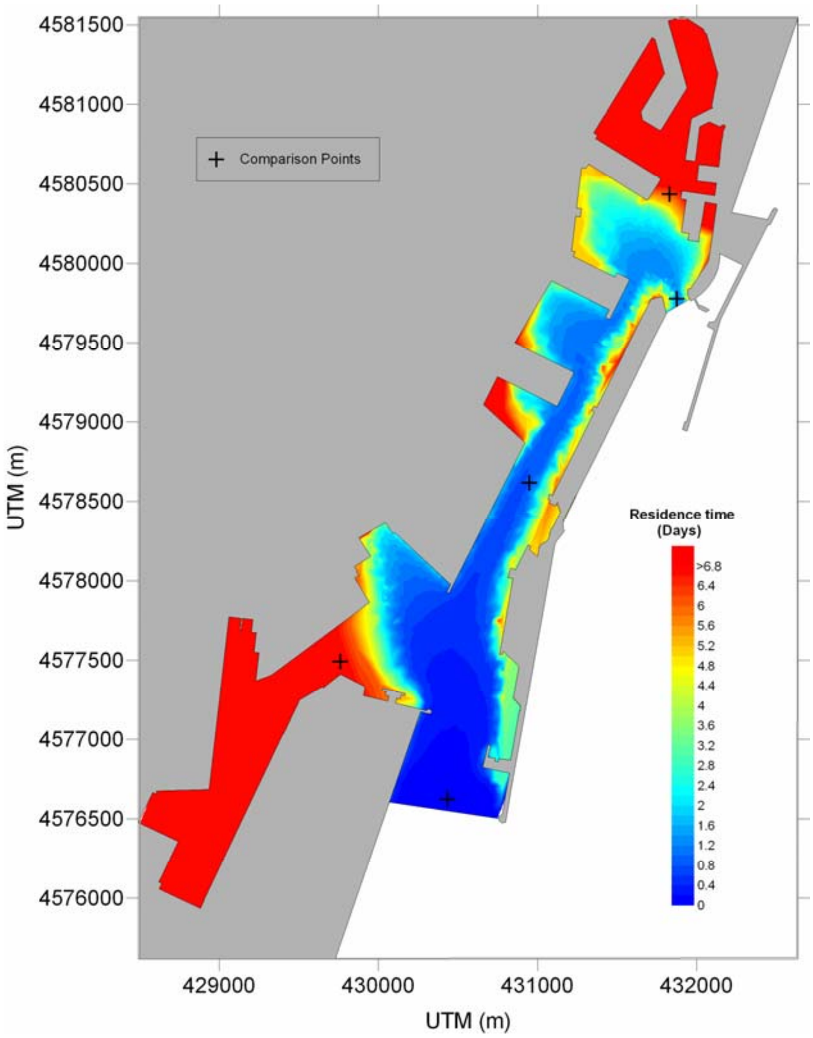

Figure 6. Local residence time (in days) according to Method IV.
The cross symbols represent the comparison points' location used in the discussion.

Discussion and Future works

Four different methods have been presented to obtain the spatial descriptions of residence times. These methods have been developed under different assumptions and using various techniques (table 1). Therefore, the resulting LRT descriptions for Barcelona harbour are different. These differences basically depend on the grade of realism of the hypothesis assumed and on the computational time needed. Moreover, the input and data requested are different. In this section the four methods are compared according to the realism of the solution obtained and the computer time requirements.

Table 1. Summary of the characteristics of the four methods presented.

	Type of discretization		Use of numerical model for the hydrodynamic input.	Transport phenomena considered in the lagrangian model	
	Boxes	Parcels		Convection	Diffusion
Method I	X				
Method II	X		X		
Method III		X	X	X	
Method IV		X	X	X	X

Table 2. Values of the residence time (days) for comparison points located inside the harbour (see figure 12).

	Point 1 (North entrance)	Point 2 (Central channel)	Point 3 (South entrance)	Point 4 (North basin)	Point 5 (South basin)
Method I	6,4	5,9	4,1	6,4	6,4
Method II	1,6	1,3	0,5	6,3	12,1
Method III	1,8	1,5	0,3	> 4,8	> 4,8
Method IV	1,7	1,2	0,2	> 6,8	> 6,8
Integral approach	6,6				

To evaluate the realism of the different methods, the definition of residence time proposed by [11] as the time needed by a parcel of water in a concrete situation to leave the domain, is adopted. In accordance with this definition, Method III is considered the most realistic among the simplified approaches since it solves the streamlines equation. However, from an environmental management point of view, this method neglects the diffusive transport which may be important in an eventual discharge of substances.

In the table 2, the LRT values obtained using the four methods in five points located inside the harbour (figure 6) are shown. The firsts three points of comparison are located in a transect section of the harbour. The fourth and fifth points are in the inners basins of the north and south mouths respectively. In this table the integral value computed through the integral method based on mass conservation is also compared. A significant difference among methods is verified. Regarding results (table 2 and corresponding figures), method III gives a larger TRL in comparison with method IV due to the absence of turbulent diffusion. However, this fact leaves us in the safe side for the residence time of a spill discharge. Method I is less realistic since the LRT obtained in areas close to the south mouth are slightly higher than in other methods. In this sense, Method II improves the results obtained in the south mouth and in the central area of the channel. Also in the inner basins, the results in Method I are under predicted in comparison with method II. This last approach considered more realistic because it takes into account local hydrodynamics. However, the methods based on a box discretization are subject to the suitability of the sub domains considered. This represents a disadvantage in front of methods based on water parcels. However, the first two methods are valid to obtain a first idea of the spatial distribution of times of residence.

Once the realism of the result is assessed, the computational time required should be considered.

Method IV is the most expensive, due basically to the stochastic modelling of diffusion, which requires more than one particle to define the LRT of each water parcel. Method III reduces significantly the computational time as a function of the particles considered to model diffusion. In our case, the computational time required for modelling diffusion is in the order of days (PC environment: 1,8 GHz) and the advection is in the order of minutes. On the opposite side, for Methods I and II, the result is almost instantaneous because they do not model directly the transport phenomena. However, it should be kept in mind that methods II, III and IV require numerical modelling to obtain the current field and therefore additional time is needed for their implementation. In this sense, only Method I requires the flow in the exchange section as the sole "input" for its implementation.

Methods III and IV, provided only a lower limit of the LRT in the inner regions (in method IV this feature is attenuated due to the diffusive behaviour). The reason is because flow convergence zones are appeared in inner basins. To avoid this, transition scenarios should be solved in order to obtain a hydrodynamic "driver" varying in time. In this case an operational environment should be set up in order to obtain residence time distributions "on line". In this case, the time for obtaining the residence time distributions will be a major limitation for the forecasting system. Summarizing, from an operational implementation point of view, Method III is more suitable than Method IV for harbour management. However, methods I and II are suitable to obtain an approximation to residence times.

To conclude, some ideas about future work are presented. The first one is to advance towards an operationally system providing residence time descriptions in real time. Another item that should be improved is related with the hydrodynamic and transport modelling, sinc the baroclinic component in the hydrodynamics expect to be relevant in inner basins for micro-tidal environments [12]. The dispersion coefficients should be also improved considering the implementation of a baroclinic turbulent closure. Finally, methodologies based on eulerian schemes to solve the transport phenomena should be also considered and compared with the proposed lagrangian method.

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