A two-dimensional particle tracking model for pollution dispersion in A Coruña and Vigo Rias (NW Spain)

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Abstract – A two-dimensional hydrodynamic model coupled to a particle tracking model is applied to study the dispersion processes and residence time in two Galician rias (A Coruña and Vigo, NW Spain) under summer conditions. In A Coruña a long residence time was found in the harbour area due to the existence of a dock, and a short one in the river area. On the contrary, in Vigo, the residence time is smaller in the harbour area, due to the Rande Strait, beyond which the river effect is negligible. © Elsevier, Paris / Ifremer / Cnrs / Ird

two-dimensional model / passive tracers / residual currents / pollution / Galician rias

Résumé – Modèle bidimensionnel de suivi des particules et dispersion de la pollution dans les rias de La Corogne et de Vigo (Espagne). Un modèle hydrodynamique bidimensionel couplé à un modèle de suivi des particules a été appliqué à deux rias de Galice (La Corogne et Vigo) pour étudier la dispersion et les temps de résidence dans les deux estuaires en été. Dans la ria de La Corogne, le temps de résidence des eaux est important dans la zone portuaire et court à l'embouchure du fleuve. L'inverse est observé dans la ria de Vigo, où le détroit de Rande limite l'effet du fleuve. © Elsevier, Paris / Ifremer / Cnrs / Ird

modèle bidimensionnel / traceur passif / circulation résiduelle / pollution / rias de Galice

1. INTRODUCTION

According to the classic definition of F. von Richtofen [31], a ria is a transverse coast, resulting from a marine transgression, which interferes with a preexistent relief of fluvial origin [37]. Along the northwestern shoreline of the Iberian Peninsula [26], a great number of bays correspond to this general description.

The vertically integrated two-dimensional (2D) models have been widely used over the last two decades [1, 11, 16, 24, 33]. In spite of the improvement of three-dimensional (3D) models during the past decade, 2D models still remain valid to describe situations with a weak vertical stratification. They are very useful for wave phenomena such as tides and tidal currents, or transport of solutes for which effective dispersion coefficients can be determined empirically. Thus, a 2D model can be used to describe the above-mentioned rias, during seasons with low river discharge or when the area under study is far enough from the river mouth, and stratification is weak. Finally, one of the main advantages of 2D models is their low computational cost. Some of the Galician rias have been studied by different authors using these kinds of models. Pascual [28, 29] modelled the circulation driven by tide and wind in the Ria de Arousa. Using a finite-element method, Bermúdez et al. [5, 6], carried out different numerical studies in the rias of Pontevedra and Vigo.

Montero et al. [20] analyzed the dispersion of pollutants near Vigo harbour using a finite-differences Eulerian method.

Our aim throughout this paper is to describe how hydrodynamics can control the water quality in the A Coruña and Vigo Rias. The analysis will be based on the dispersion of passive traces (particle tracking model), which simulate the transport of a generic contaminant dumped into the estuary. Results will be related to the residual velocity field — defined as the velocity averaged in each point during a period much longer than the period of the main tidal harmonics. A lagrangian model constitutes a powerful tool for studying dispersion in estuaries. It allows analysis of dispersion and estimation of residence times at a low computational cost compared to eulerian models. This gives the conclusions of this study an applicability only found in some preliminary results [15, 22]. In particular, we will consider the least favourable conditions in terms of residence time: summer conditions with small river discharge and negligible wind stress.

2. STUDY AREAS

The Ria of A Coruña (*figure 1a*) belongs to the so-called Galician Rias Altas. Its main axis is 6 km long and its mouth is about 3 km wide. The inner zone of the Ria — which includes the harbour area — has estuarine features while the outer zone is under oceanic influence. The River Mero mean annual discharge is 6 m^3s^{-1}. Due to these features, some authors [36] have claimed that, from a hydrological point of view, A Coruña is not a ria but a bay. Their argument is corroborated by the mean estuarine Richardson number: $R \cong 0.03$, smaller than the upper limit for well-mixed estuaries ($R = 0.08$) and one order of magnitude above that for stratified estuaries ($R = 0.8$). The mean estuarine Richardson number [13, 14] is defined as $Ri_E = g\frac{\Delta\rho}{\rho}\frac{Q_f}{bU_t^3}$, where Q_f is the river discharge, b the mean width of the estuary, $\Delta\rho$ is the density difference between river water entering at the head of the estuary and sea water at the mouth and ρ is the mean density; g is the acceleration due to gravity and U_t is the *rms* of the tidal velocity.

The ria of Vigo (*figure 1b*) is the southernmost of the so-called Galician Rias Baixas. Its main axis is 33 km long and the whole estuary can be divided into three different areas. The innermost area corresponds to the San Simon inlet. It has estuarine features due to the tidal effect and the River Oitaben outflow (about 13 m^3s^{-1}). The middle part stretches from the Strait of Rande to the Cape of Mar. The outermost zone, downstream of Cape of Mar to the Cies Islands, is under oceanic influence.

In the ria of Vigo, the mean estuarine Richardson number is $R \cong 0.08$. Actually, during the wet season, the estuary behaves as partially mixed displaying a two-layered residual current pattern due to the high river discharge. On the other hand, during the dry season, the river flow is low and, in absence of upwelling and intense heat radiation, the ria of Vigo behaves as a weakly stratified estuary [23, 30].

Despite both estuaries being quite different from a hydrological point of view (see *table I*), they share common management needs. The biggest human settlements in Galicia are the cities of A Coruña and Vigo (250 000 inhabitants each) and the two most important Galician harbours are located in these estuaries — the oil refinery located in A Coruña has provoked several accidents with considerable oil spills over recent decades. The control of water quality alone justifies the estimation of the renovation rate of the whole estuary — or of particular areas.

Table I. Physical and computational characteristics of A Coruña and Vigo Rias.

	A Coruna	Vigo
Volume	251 hm^3	3275 hm^3
Mean Width	3.1 km	4.8 km
Mean Depth	16 m	21 m
Main Axis Length	5 km	32.5 km
Mean River Flow	6 $m^3 s^{-1}$	13 $m^3 s^{-1}$
Computational Time Step	25 s	25 s
Computational Grid Mesh	50 m	200 m
Grid Size	103 × 114	162 × 116
Turbulent Diffusion Coefficient	50 $m^2 s^{-1}$	50 $m^2 s^{-1}$
Drag Coefficient	0.022 $m^{1/3} s^{-1}$	0.022 $m^{1/3} s^{-1}$
Imposed River Flow	3 $m^3 s^{-1}$	3 $m^3 s^{-1}$

3. MODEL

In order to investigate the transport processes under summer conditions (i.e. low river flow and negligible wind stress) a 2D model was considered. This barotropic model is coupled to a particle tracking model [7–9, 12, 19]. The hydrodynamics model, MOHID (MOdelo HIDrodinâmico) [24] solves the continuity and momentum conservation equations:

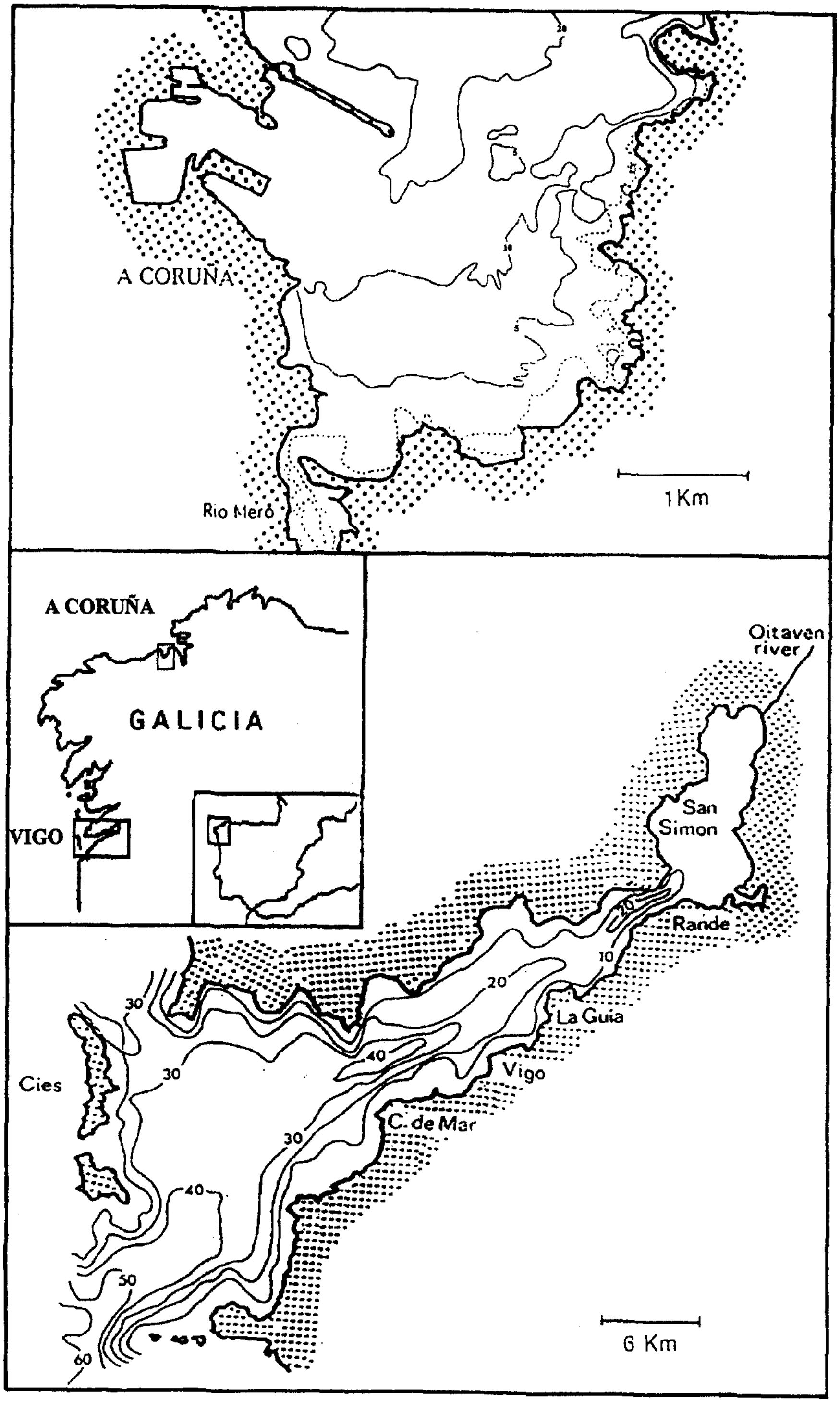

Figure 1. (a) Bay of A Coruña. (b) Ria of Vigo.

$$\frac{\partial\zeta}{\partial t}+\frac{\partial(Hu)}{\partial x}+\frac{\partial(Hv)}{\partial y}=0 \qquad (1)$$

$$\frac{\partial(Hu)}{\partial t}+\frac{\partial(Huu)}{\partial x}+\frac{\partial(Huv)}{\partial y}-Hfv \qquad (2)$$

$$=-Hg\frac{\partial\zeta}{\partial x}-(\tau_{hx}-\tau_{sx})+H\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial(Hv)}{\partial t}+\frac{\partial(Huv)}{\partial x}+\frac{\partial(Hvv)}{\partial y}+Hfu \qquad (3)$$

$$=-Hg\frac{\partial\zeta}{\partial y}-(\tau_{hy}-\tau_{sy})+H\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)$$

where (u, v) are the vertically integrated velocity components, (x, y) the Cartesian coordinates, ς the elevation over a reference level, t the time, H the water column height, f the Coriolis parameter (twice the vertical component of the Earth's rotation vector), g the gravity acceleration, (the turbulent horizontal viscosity, and τ_{bi} and τ_{si} the bottom and wind shear stresses in the i direction.

In this set of equations the hydrostatic hypothesis and the Boussinesq approximation have been assumed. Besides, the Coriolis parameter has been considered to be constant, since the size of the area under study is small.

To solve this set of equations numerically, MOHID uses an Arakawa- C grid [3] with a semi-implicit alternating direction scheme. A 1D model was coupled to the 2D model to simulate the river flow. Experimentally measured river discharges [30, 36] were imposed at the most inland grid point of the 1D model. The turbulent viscosity is considered to be constant in time and space (see *table I* for values). At open ocean boundaries the elevation over the reference level was imposed by means of the tidal harmonics provided by the *Instituto Hidrográfico de la Marina* (the amplitude of the main tidal harmonic M2 is 1.09). Along the solid boundaries, a null normal velocity was imposed and a free slip condition was assumed, since the grid is not fine enough to simulate the horizontal boundary layers.

The bottom stress was calculated using a quadratic law and a constant Manning rugosity (0.022 $m^{1/3}s^{-1}$). No wind stress was considered because in estuaries like A Coruña and Vigo, the wind has little effect on the residual current pattern. The initial conditions were a horizontal level and null velocity. The hydrodynamic model was run during an initialization period of one day to adjust the solution to the periodic circulation regime. During this period, the time step and the turbulent diffusion coefficient were progressively adapted to their stationary value. The eulerian residual current is calculated integrating the solution calculated at every time step by the hydrodynamic model (u_M): $u_R = \frac{1}{T}\int_0^T u_M dt$, where T is the integration period, much longer than the tidal period.

As mentioned above, a particle tracking model (PARTIC) [25] was coupled to the hydrodynamic model to describe the movement of passive tracers. The main advantage of a fully lagrangian formulation over eulerian transport models [2, 9] is its higher accuracy in describing localized emission spots avoiding artificial numerical diffusion in presence of sharp gradients. Besides, the method provides considerable time saving, because it only follows the track of the locally dumped particles, in contrast with eulerian transport models, which calculate the concentration of any property anywhere in the simulation domain.

The particle tracking model assumes that the velocity of each particle (u_P) can be split into a large-scale organized flow, characterized by a mean velocity (u_M), provided by the hydrodynamic model, and a smaller scale random fluctuation (u_F) such that $u_P = u_M + u_F$.

Following [8] it is possible to prove that the lagrangian method is equivalent to solving the transport equation for a certain property.

$$\frac{\partial q}{\partial t}+u_{M_i}\frac{\partial q}{\partial x_i}=A_{ij}\frac{\partial^2 q}{\partial x_i \partial x_j} \qquad (4)$$

where A_{ij} is the dispersion coefficient matrix. Normally in 2D dispersion study cases, shear effect dispersion is not considered leading to $A_{11} = A_{22} = A$ and $A_{12} = A_{21} = 0$, which avoids a lot of numerical problems in the eulerian approach. Considering the random velocity with a top hat distribution, then $u_F \in [-p,p]$, where p can be related to the dispersion coefficient as:

$$A=\frac{p^2\Delta t}{6}\Leftrightarrow p=\sqrt{\frac{6A}{\Delta t}} \qquad (5)$$

where Δt is the time step. Usually, (4) and (5) are solved after an analysis of the relevant scales in the phenomenon under study following Ozmidov [27].

Leitao [18] made a sensibility analysis to test the relative importance of the three main dispersion processes in a well-mixed estuary: advection, horizontal turbulent diffusion and shear effect dispersion. The last effect was simulated imposing a velocity profile on a 2D hydrodynamic model. One of the main conclusions of this work was that advection is the main process and the other phenomena play minor roles. Thus, when studying big areas (the whole estuary) over several tidal cycles it is possible to neglect shear effect and to consider a main advective term and a small random fluctuation (horizontal turbulent diffusion). In summary, in the estuaries under study and considering a grid mesh of about 100 m and a time step of 25 s, it is formally correct to consider a random fluctuation in tracer velocities, since it only affects slightly the transportative properties.

The used particle-tracking model computes the equation

$$\frac{dX}{dt} = U(X, t) \tag{6}$$

at each time step. $X = X(x, y)$ is the tracer position at t and $U(X, t)$ the tracer velocity. The previous equation is solved by a simple explicit method. $U(X, t)$ has a mean component (u_M, advective transport) that is calculated at each X position by linear interpolation of the velocity field provided by the hydrodynamic model, and a random component (u_F, turbulent transport).

Following [34] and [2], the tracer random velocities are simulated using a mixing length (L) and the root mean square of turbulent velocity (u_σ). This is an excellent methodology to simulate the shear effect dispersion in well-mixed flows where an analytical profile velocity can be imposed [2], and also in 3D cases, whenever the 3D model is coupled with a 1D turbulence model [18]. The objective of Allen's methodology is to model the physics of the dispersion process in a more realistic way than the standard diffusion equation. In our case, this methodology was extended to calculate horizontal turbulent diffusion.

The mixing length in this methodology represents the tracer displacement from which a new random velocity is computed. Formally, we can affirm that it represents the distance to which correlation between turbulent velocity and tracer displacement tends to zero ($u_F X) \to 0$), [35]. A turbulent velocity with a top hat distribution was considered in this work, while Allen [2] used a simple discrete distribution $u_F = \pm u_\sigma$.

To extend Allen's methodology to our case, it is necessary to define a characteristic dimension L, which can be assumed to be the dimension of the biggest eddies not resolved by the hydrodynamic model, in other words, the horizontal mixing length. Theoretically, this dimension is equal to twice the grid mesh [4]. Allen's methodology also needs values of turbulent diffusion standard deviation. These values can be determined using in situ measurements, although they were not available in the present study. Nevertheless, the following relation was admitted,

$$\frac{u_{\sigma_1}}{\sqrt{u_{M_1}^2 + u_{M_2}^2}} = \frac{u_{\sigma_2}}{\sqrt{u_{M_1}^2 + u_{M_2}^2}} = 0.2 \tag{7}$$

which is consistent with averaged field data in other estuaries with similar characteristics [10]. The turbulent velocity of each tracer (u_F) was computed using the equation,

$$\begin{aligned} u_F &= \text{Rand} \times \sqrt{3} \times u_\sigma \\ &= \text{Rand} \times \sqrt{3} \times 0.2 \times \sqrt{u_{M_1}^2 + u_{M_2}^2} \end{aligned} \tag{8}$$

where Rand is a random function with a top hat distribution between –1 and 1.

The velocity u_F is recalculated after a time (Δt_L), which does not necessarily coincide with the hydrodynamic model time step.

$$\Delta t_L = \frac{L}{u_\sigma} = \frac{2 \times \Delta x}{0.2 \times \sqrt{u_{M_1}^2 + u_{M_2}^2}} \tag{9}$$

where Δx is the grid mesh. Formally, u_F should be used in (9) instead of u_σ, but the probability of u_F having very low values in relation to L is very high and, consequently, there is also a great probability of having high Δt_L values. In the limit, if u_F is small enough, a tracer can maintain the same turbulent velocity during several tidal cycles. In summary, Δt_L does not represent the time a tracer needs to perform a random step, but the average time the tracer needs to perform the random step.

Special attention should be paid to describing tracer movement near the boundaries. Particles can move from the 2D to the 1D domain and vice-versa. When they move from the 1D into the 2D, they are placed randomly along the interface. The particles that move out of the computational domain through the open boundary are assumed to loose their identity and do not return. Finally, those particles crossing the solid boundary are relocated at their previous position.

In both estuaries particles were emitted from two boxes. The first box was placed near the river mouth and the second one close to the harbour area. This particular choice is due to the fact that those areas are the most polluted ones in both estuaries.

4. RESULTS AND DISCUSSION

Figure 2 shows the residual flow field in the ria of A Coruña. The flow pattern is due both to the interaction between tidal forcing and bathimetry features (mainly the dock), and to the river discharge [32]. It is possible to observe the existence of three small eddies close to the river mouth (counter clockwise, clockwise and counter clockwise respectively from west to east). In the northern area, near the dock, there are two bigger eddies, which are situated to the north and south of the dock and rotate counter clockwise and clockwise respectively.

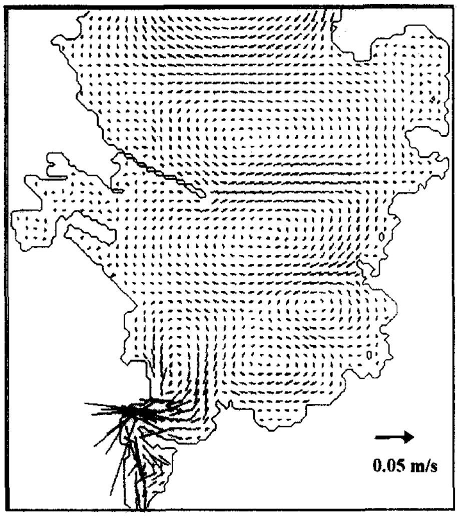

Figure 2. Residual current calculated in A Coruña over 28 days.

Other features can be observed in this general circulation pattern. Inside the harbour the residual current is negligible while in the southernmost area higher values, due to the shallowness of the channel more than to the high river flow, are observed.

The displacement of the particles emitted from the boxes (*figure 3*) confirms some of the features glimpsed through the residual current analysis. Most of the particles emitted in the harbour (darker colour particles in *figure 3a*) remain there throughout the calculation. Only some of them, initially placed in the outermost area of the harbour, are able to move out under the influence of the eastward jet generated by the northernmost eddies (*figure 3b*). Once these particles arrive at the eastern coast, they spread northwards and southwards due to both eddies (*figure 3c*). Finally, only a small percentage of the particles initially placed inside the harbour were able to leave it. Among these particles, only some of them drift out of the estuary, and the remainder drift to the inner part of the estuary (*figure 3d*).

On the other hand, the particles initially placed near the river mouth (lighter colour in *figure 3a*), leave that area rapidly (*figure 3b*). Nevertheless, there is no jet transporting the particles outward, they spread along the southernmost part of the estuary (*figures 3c, 3d*) due to the existence of the three eddies mentioned above. Besides, once the particles attain the main eddy (located southern of the dock) they follow a pathway similar to that followed by the particles situated in the outermost part of the harbour. Experimental measurements [36] display low salinity values near the dock, which seems to confirm our predictions of the river water pathway.

The probability of the dumped particles leaving their initial boxes after 14 days is shown in *figure 4*. For a particle initially placed in the harbour area the probability is 0.3. Only the particles initially placed at the outermost part of the harbour will have left the zone during the first week (as shown in *figure 3*). The particles leave the river area much faster. The probability is 0.8 after five days and almost 1 after 14 days.

In the ria of Vigo the situation is quite different. The residual flow pattern is much more complex (*figure 5*), which is mainly due to the complexity of the bathimetry. In the outermost part of the ria (near the Cies Islands), there is a large eddy rotating counter clockwise. All along the ria, there are plenty of small eddies produced by the shoreline (they appear even in absence of river forcing), which consists of irregular shaped shallow basins. The area beyond the Rande Strait (San Simon Bay) presents a very complex circulation pattern with high residual velocities due to the shallowness of the area. Nevertheless, the direction of the current (inwards or outwards) through the strait cannot be directly deduced from the residual current.

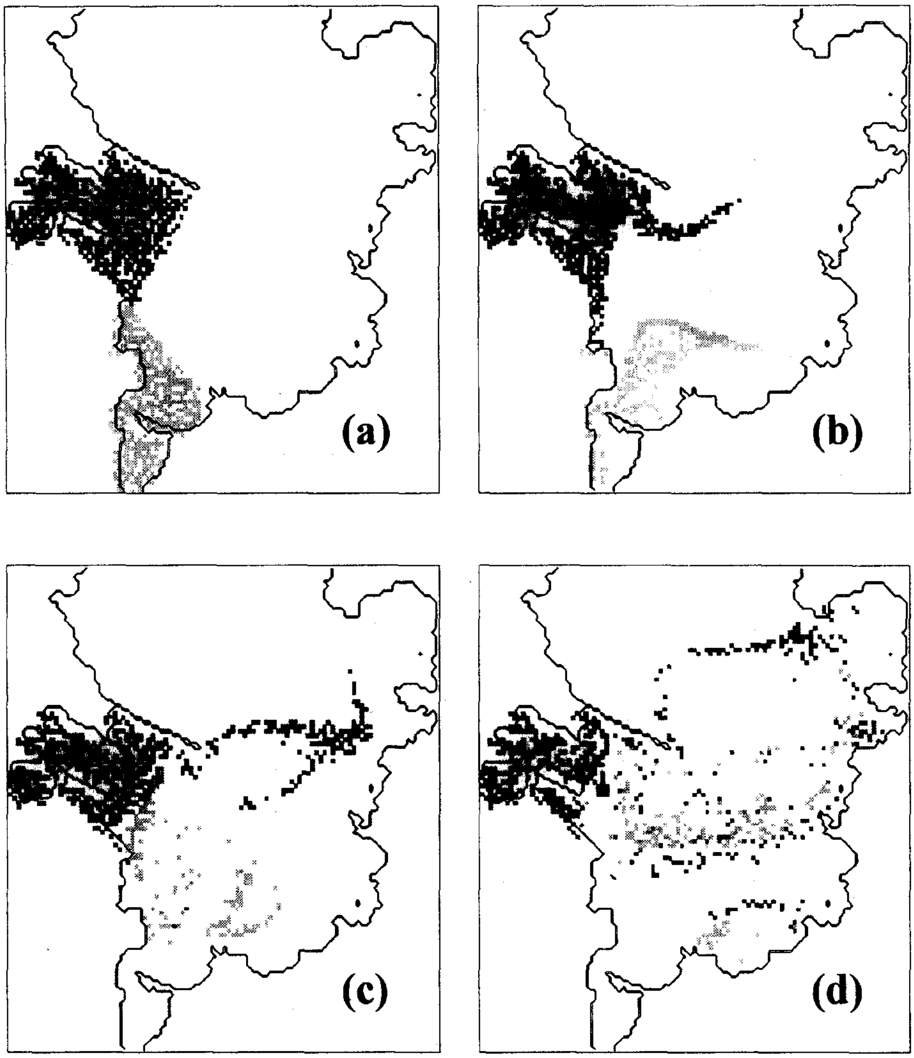

Figure 3. Particle tracking result in A Coruña Bay at (a) beginning of the calculation, where the particles in the river area are represented in a lighter colour, and particles in the harbour area are represented in darker colour, (b) 5th day, (c) 11th day and (d) 14th day.

Once again, the emission boxes (*figure 6*) can provide additional information that helps to clarify conclusions obtained analyzing the residual flow. A considerable percentage of the particles initially placed in the harbour area (lighter coloured particles in *figure 6a*) leave it during the first week (*figure 6b*). These particles spread inwards and outwards (*figures 6c, 6d*) due to the existence of the small eddies mentioned above. The particles initially placed in the river area (San Simon Bay) (darker colour in *figure 6a*), start leaving the area during the two first weeks (*figures 6b, 6c*), but they tend to accumulate in the Rande Strait afterwards (*figure 6d*).

Figure 7 provides some additional information, which may highlight that given in *figure 6*. After the first week a particle will have left the harbour area with a probability of almost 0.5. During the following weeks, particles continue to leave the area very slowly, in fact, the probability barely increases. A similar behaviour is observed near the river area, during the first two weeks the probability

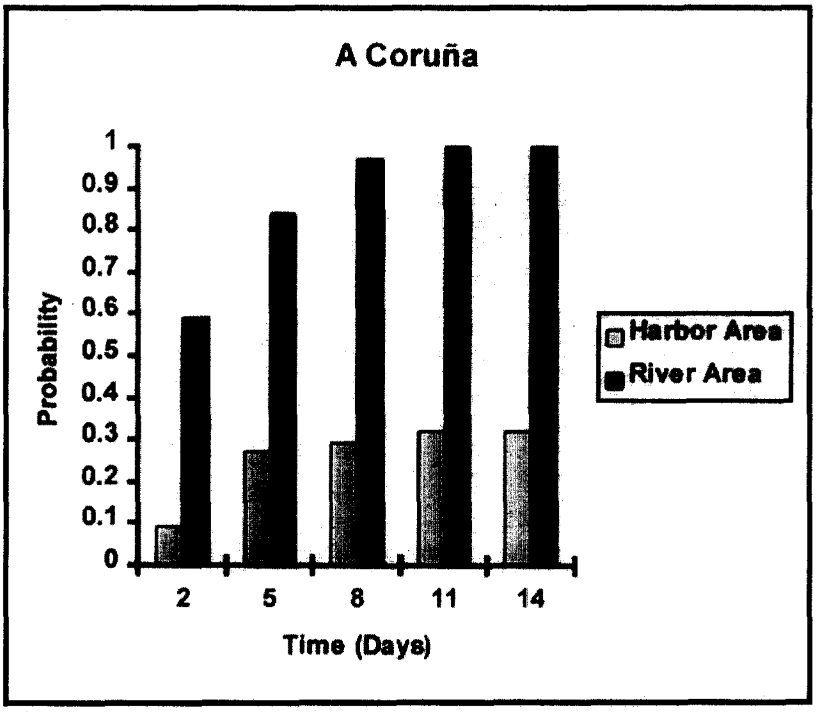

Figure 4. Probability of a particle leaving the area (harbour or river) where initially placed in A Coruña Bay.

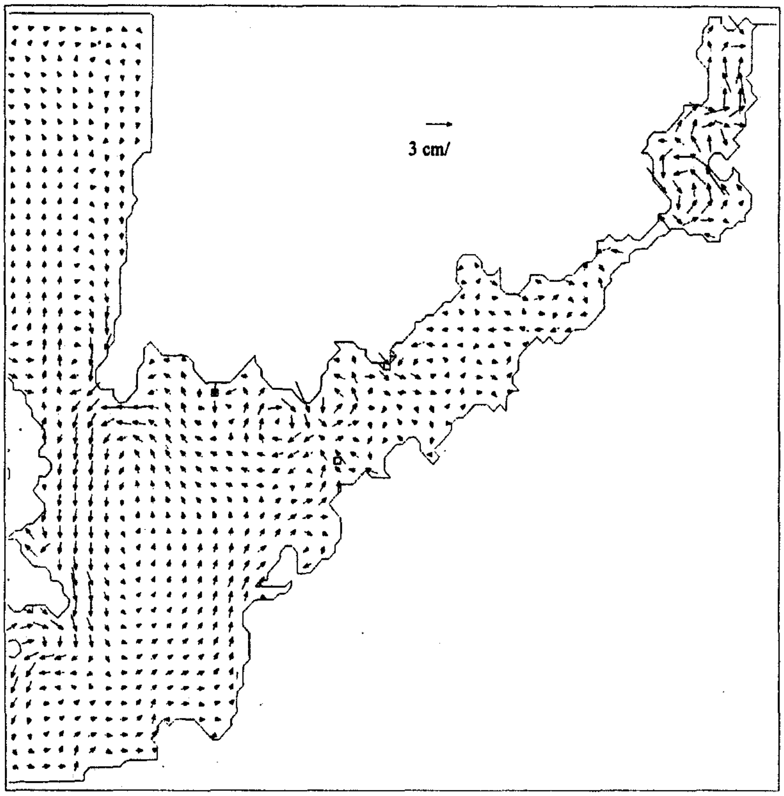

Figure 5. Residual current calculated in Vigo Ria during 28 days.

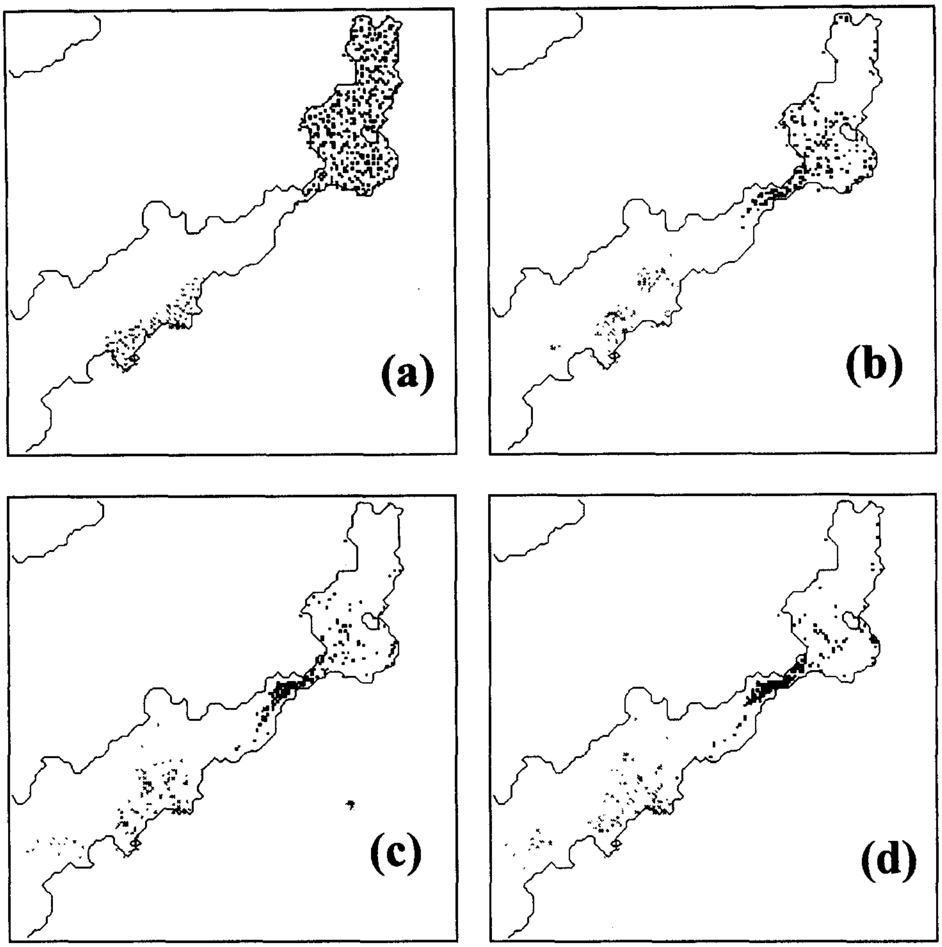

Figure 6. Particle tracking result in Vigo Ria at (a) beginning of the calculation, where the particles in the harbour area are represented in a lighter colour, and particles in the river area are represented in darker colour, (b) 7th day, (c) 14th day and (d) 21st day.

grows to 0.2, but it stabilizes around that value for the rest of the calculation.

5. CONCLUSIONS

A 2D barotropic model coupled to a particle tracking model was used to investigate contaminant dispersion in two Galician rias. This study was carried out under low river discharge conditions, corresponding to the longest residence time. Under these conditions, estuaries are well mixed and a 2D model can be used accurately.

A passive tracer can be assigned to a water mass transporting any contaminant released in that water mass. In this way, the probability of a given tracer to remain in the area where it was initially placed is related to the residence time of the water in that area.

In A Coruña Ria, where the oceanic influence is strong in every season, the river area showed a short residence time (in eight days the probability of a particle remaining in the area is negligible). On the contrary, the harbour area had a long residence time. Actually, most of the particles in the innermost part of the harbour hardly moved out. This is due to the presence of a dock, which affects the circulation of the southernmost zone of the estuary.

The ria of Vigo has three different zones as mentioned above, the harbour area showed a residence time shorter than the one corresponding to A Coruña, but the particles coming from the river tend to accumulate around the Rande Strait despite the existence of strong tidal currents in that area. This is due to the low river discharge and to

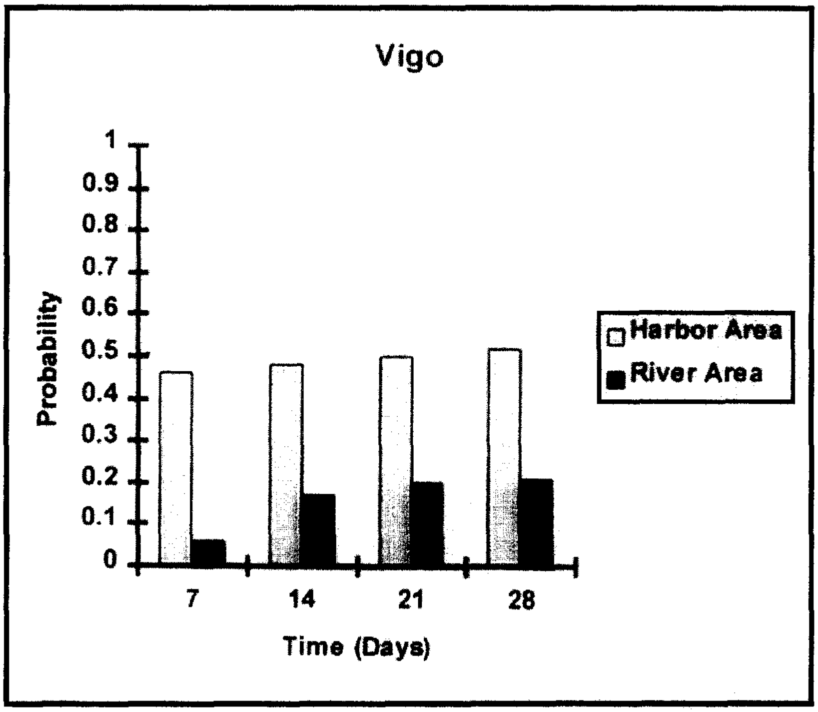

Figure 7. Probability of a particle leaving the area (harbour or river) where initially placed in Vigo Ria.

the narrowness of the Rande Strait, which avoids the creation of large gyres in the area. The situation would be completely different under winter conditions, since the high river flow induces the appearance of more complex two layer dynamics as reported both experimentally [30] and numerically in a preliminary 3D study by Montero et al. [21].

In summary, the presented particle tracking model has proved to be a powerful tool for studying dispersion phenomena. It allows the residence time in the estuaries to be estimated, which can be used to analyze water quality, at a low computational cost.

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