A numerical model to simulate the tidal dispersion of radionuclides in the English Channel

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Abstract

A numerical model to simulate the tide-induced dispersion of conservative radionuclides in the English Channel has been developed. The model solves the shallow-water hydrodynamic equations and, simultaneously, the advection diffusion dispersion equation. The hydrodynamic model has been tested by comparing measured and computed currents for medium, neap and spring tides over the Channel and the dispersion part of the model has been tested by comparing measured and computed concentrations of ^{125}Sb, ^{99}Tc and ^{137}Cs in the Channel. These radionuclides are released from a nuclear fuel reprocessing plant. Model results are in good agreement with observations. The effect of wind on the dispersion patterns has also been studied.

1. Introduction

A nuclear fuel reprocessing plant releases radionuclides (^{125}Sb, ^{99}Tc, ^{137}Cs, ^{239,240}Pu) to the sea at Cap de La Hague, located on the French shore of the English Channel (see Fig. 1). Some models have been developed to simulate the dispersion of conservative radionuclides (mainly ^{125}Sb and ^{99}Tc) in part of the Channel (Salomon et al., 1988) and in the whole Channel plus the southern North Sea (Breton & Salomon, 1995; Salomon et al., 1995; Janin, 1996). However, these models work with residual (averaged) circulation and, as a consequence, they can only be used to obtain the long-term dispersion of radionuclides (temporal scale in the order of years).

The objective of this paper is to present a model that can be used as a predictive instrument, and that can predict the radionuclide dispersion pattern shortly after a discharge has occurred. The model may be useful in the event of an accident since it

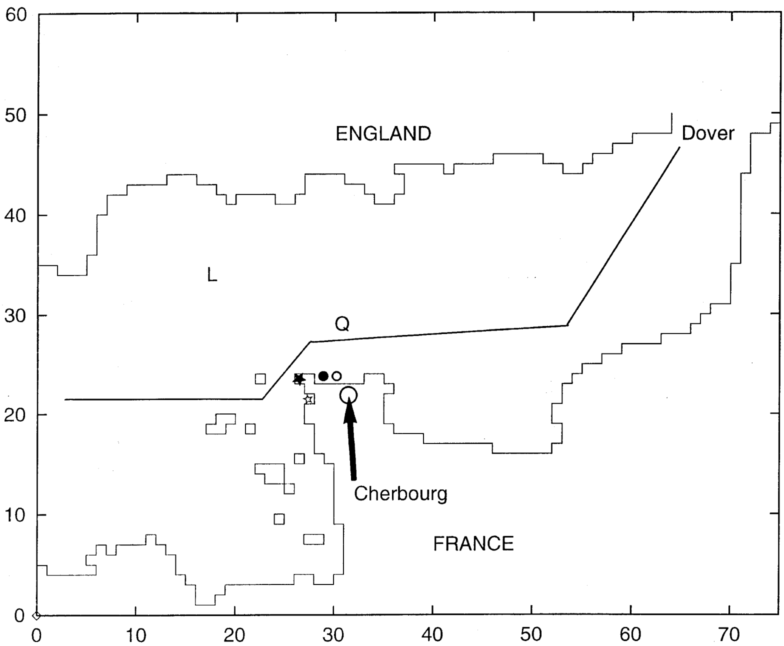

Fig. 1. Computational domain. Letters are two of the points where currents have been measured and the black star is La Hague nuclear fuel reprocessing plant. The line is the section along which radionuclide concentrations are obtained (see Section 3.2). The white star is compartment (28, 22) , the black circle is (29, 24) and the white circle is (30, 24) (see Section 3.3).

can give the concentration of radionuclides at any place in the Channel minutes, hours, days and even months after the accident. Models that give the tide-induced dispersion of pollutants are often developed for small coastal regions or estuaries (Periáñez et al., 1994; Ng et al., 1996) and few models (see, for instance, Proctor et al., 1994) have been developed to simulate tidal dispersion in a larger marine environment. The model presented in this work, although it has been applied and tested in the English Channel, could be used in other marine environments.

The model solves the shallow water hydrodynamic equations to obtain the instantaneous water velocities over the Channel and, simultaneously, the advective–diffusive dispersion equation is also solved. The hydrodynamic part of the model, which uses a non-uniform bed friction coefficient, is validated by comparing computed and measured water velocities and the dispersion equation is calibrated by comparing computed and measured radionuclide distributions.

The model is two-dimensional. This is justified by the dominance of barotropic over baroclinic mechanisms in the shallow and well-mixed waters of the Channel (Breton & Salomon, 1995).

The model equations and the method used to solve them are presented in the next section. Then, model results are presented and discussed. Finally, the effect of wind upon the radionuclide distribution patterns is studied.

2. Model description

The two-dimensional shallow water hydrodynamic equations are (see for instance Pugh, 1987):

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial x}[(D+z)u] + \frac{\partial}{\partial y}[(D+z)v] = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial z}{\partial x} - \Omega v + K\frac{u\sqrt{u^2+v^2}}{D+z} = 0, \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + + g\frac{\partial z}{\partial y} + \Omega u + K\frac{v\sqrt{u^2+v^2}}{D+z} = 0, \tag{3}$$

where u and v are the depth-averaged water velocities along the x- and y-axis, respectively, D is the depth of water below the mean sea level, z is the elevation of the water surface above the mean level due to tidal oscillations, Ω is the Coriolis parameter ($\Omega = 2w \sin \beta$, where w is the earth's rotational angular velocity and β is the latitude), g is the accleration due to gravity and K is the bed friction coefficient. The effect of wind has not been considered since currents in agreement with observations are obtained, as will be seen. However, the effect of wind has been investigated in the final section since the wind-driven flow may affect the radionuclide dispersion pattern.

The dispersion of a conservative radionuclide is governed by the advection–diffusion dispersion equation, which in the case of a two-dimensional incompressible flow can be written (see, for instance, Prandle, 1984) as

$$\frac{\partial(HC)}{\partial t} + \frac{\partial(uHC)}{\partial x} + \frac{\partial(vHC)}{\partial y} = \frac{\partial}{\partial x}\left(HK_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(HK_y\frac{\partial C}{\partial y}\right) - \lambda HC, \tag{4}$$

where $H = D + z$ is the instantaneous water level, C is the radionuclide concentration, λ is the radioactive decay constant and K_x and K_y are the diffusion coefficients along the x and y directions, respectively.

To solve these equations, a spatial and temporal discretization is carried out: the Channel was divided into 3750 grid cells (forming a matrix 75×50). The grid extends from 48.3° N to 51.0° N and from 4° W to 1.5° E; the grid cell size is $\Delta x = \Delta y = 5000$ m and temporal resolution is $\Delta t = 60$ s.

The explicit finite differences scheme described in Flather and Heaps (1975) was used to solve the hydrodynamic equations. Second-order accuracy finite difference schemes (Kowalick & Murty, 1993) are used to solve the advection and diffusion terms in the dispersion equation. All the stability conditions (Kowalick & Murty, 1993) are satisfied by the spatial and temporal resolutions of the model.

The model is started from rest. Thus, some time must elapse before discharging the contaminants in order to allow the tidal regime to become established.

The computational domain is shown in Fig. 1. Along the open western boundary, water elevations were specified for each time step from observations (Howarth & Pugh, 1983). A radiation condition (Kowalick & Murty, 1993) is applied along the northeastern open boundary (Dover Strait). Boundary conditions along the coast consist of setting to zero the component of the water current normal to the boundary. Only the two main tidal components ($M_2 + S_2$) were considered when specifying water elevations along the western boundary. This way, the different effect of a discharge on neap or spring tides could be simulated. Good agreement with observations is obtained although only the M_2 and S_2 components are used, as will be seen.

In the case of the dispersion equation, there is no flux of radionuclides through a closed boundary. Along open boundaries, the condition described in Periáñez et al. (1994) was applied:

$$C_i = \phi C_{i-1}, \tag{5}$$

where C_i is the concentration of radionuclides in the open boundary and C_{i-1} represents the concentration just inside the computational domain. The nondimensional number ϕ is obtained from calibration.

Water depths were introduced as input data for each grid cell from bathymetric maps.

3. Results

3.1. Water circulation

Observed and computed water velocities have been compared to test the hydrodynamic part of the model.

Instead of using a constant value for the bed friction coefficient, as is usual in most models, the value of K has been increased from 0.0015 in the west Channel to 0.0875 in the Dover Strait to obtain a better agreement between computed and observed currents. Indeed, Prandle (1975) has found in previous modelling work that friction increases in the region around Dover Strait and has noted that the value of K must be selected with care in this area so as to account for such an increase in the bottom friction.

The magnitude and direction of computed and observed currents have been compared for 12 points in the Channel for medium, neap and spring tides. Observed tidal currents have been obtained from Admiralty Chart 2675. There is good agreement between observed and computed currents, in both magnitude and direction, for all points. As an example, results for points L, and Q (see Fig. 1) in medium tides are presented in Figs. 2 and 3, respectively. It can be observed that the tidal phases are also reproduced by the model, since the times when maximum and minimum currents are measured are given by the model. Observed and computed current magnitudes at Q in neap and spring tides are presented in Fig. 4. Again, there is a good agreement between observed and computed values. Current directions are also well reproduced by the model.

A computed corange chart for the M_2 tide is presented in Fig. 5. It is in good agreement with that obtained from observations (Howarth & Pugh, 1983), showing amplitudes over 3 m in the Gulf Normand-Breton and over 2 m in Dover. Also, there

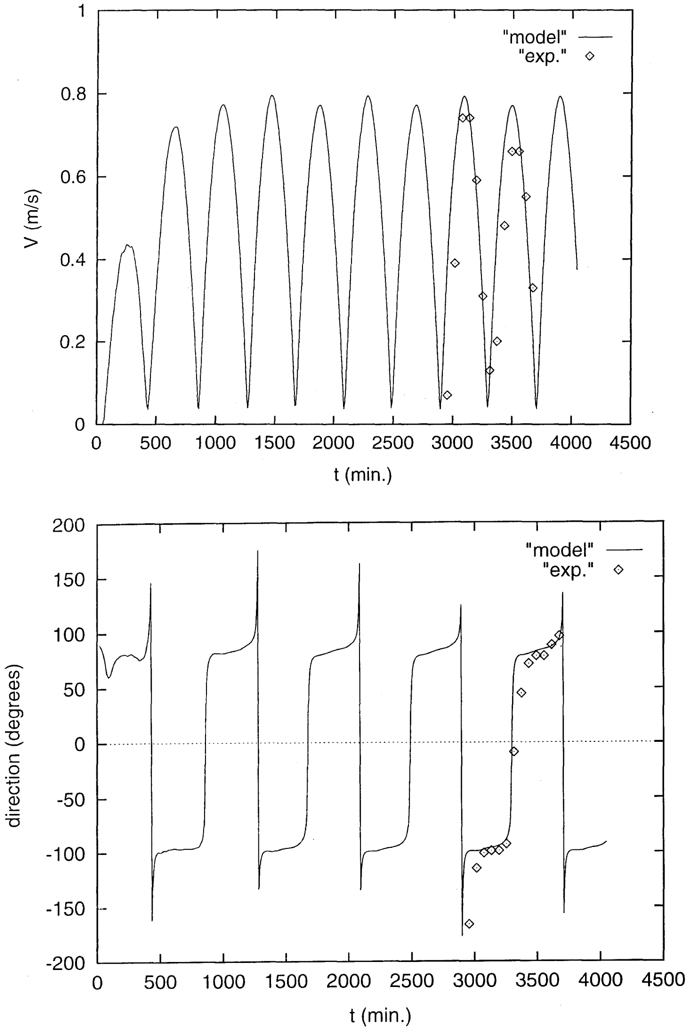

Fig. 2. Observed (points) and computed (lines) time evolution of magnitude and direction of current at point L. The direction is measured clockwise from north in degrees.

is clear evidence of a degenerate amphidrome inland of the English coast. Tidal phases are also well reproduced by the model.

The computed tidal residual flux through Dover to the North Sea is $77\times10^3\ m^3\,s^{-1}$. Other estimations include: Pingree and Maddock (1977) calculated a net tidal flow of $55\times10^3\ m^3\,s^{-1}$, Prandle et al. (1996) obtained a value of $41\times10^3\ m^3\,s^{-1}$ from HF (high-frequency) radar observations and Breton and Salomon (1995) computed an average flow of $114\times10^3\ m^3\,s^{-1}$.

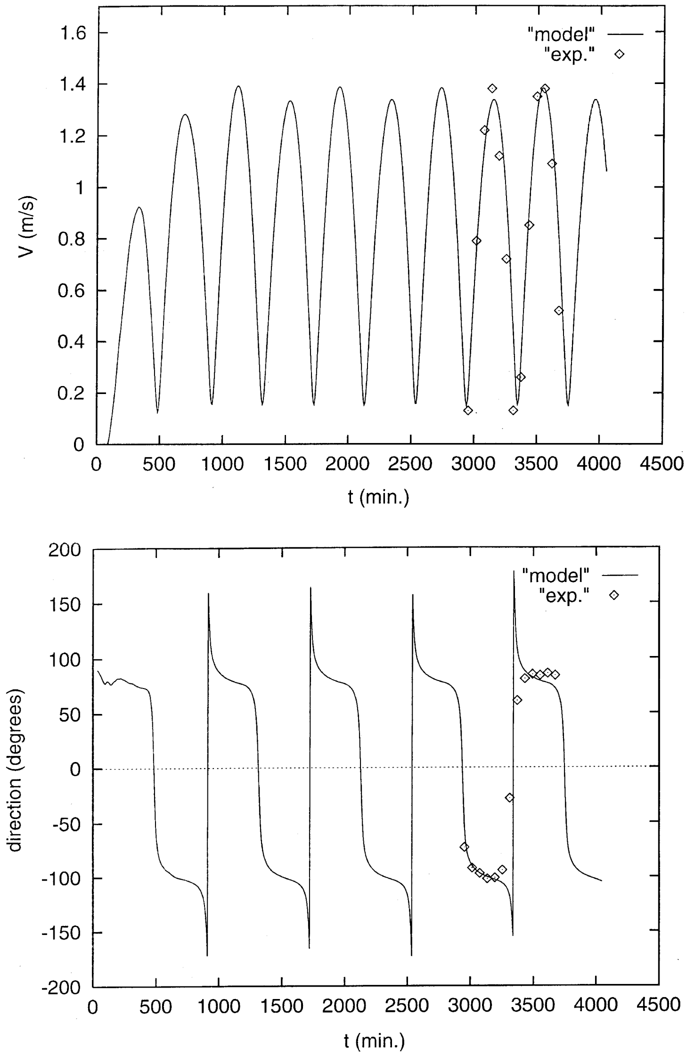

Fig. 3. Same as Fig. 2 but for point Q.

3.2. Dispersion of radionuclides

Since tidal mixing is explicitly calculated, the diffusion coefficients must be chosen with respect to the real dispersion coefficient, evaluated using Elder's formula for instance (in Fisher et al., 1979), and to that of the subgrid, required to diffuse patches which become too small to be correctly described by the grid size and the numerical scheme. After Okubo (1971), Lam et al. (1984) gave an empirical relationship linking

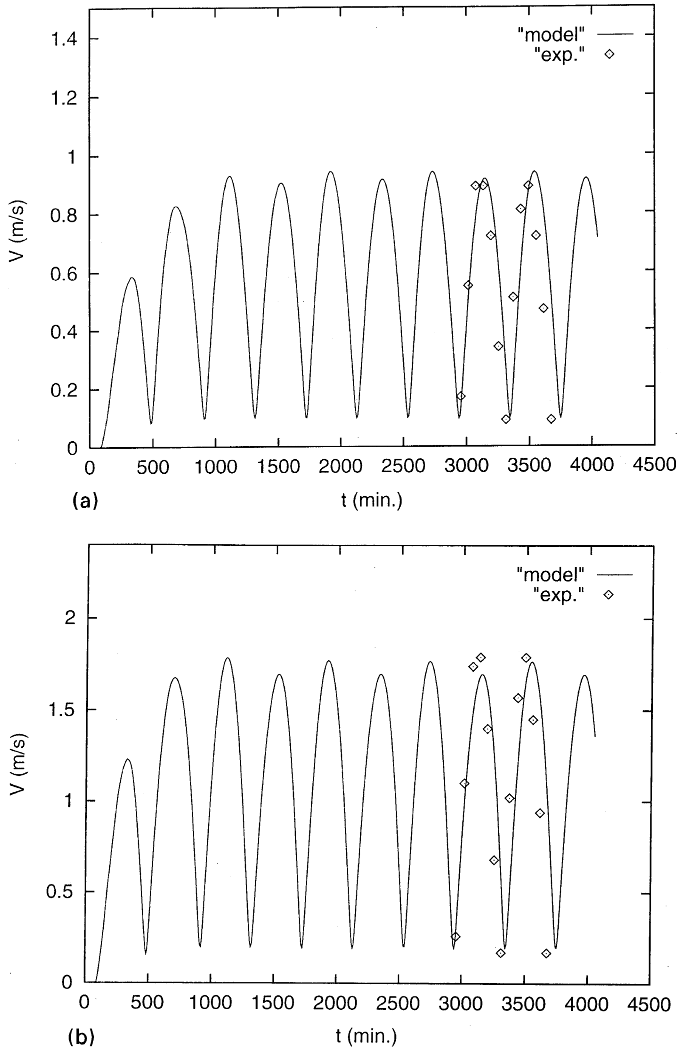

Fig. 4. Observed (points) and computed (lines) time evolution of current magnitude in the case of neap (a) and spring (b) tides.

a given patch size to a dispersion coefficient:

$$K_d = 5 \times 10^{-4} d^{1.2}, \tag{6}$$

where K_d is the dispersion coefficient ($m^2\,s^{-1}$) and d is the diameter of the patch. Considering that three grid cells are an acceptable lower limit for the smaller patches described by the model (Breton & Salomon, 1995), the present grid size corresponds to a dispersion coefficient equal to $51\,m^2\,s^{-1}$. This value is of the same order of

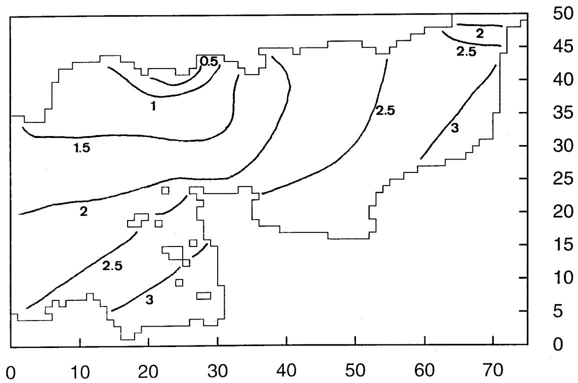

Fig. 5. Computed corange chart for the M_2 tide. Amplitudes are given in m.

magnitude as that obtained from Elder's formula. Thus, $K_x = K_y = 51\ \text{m}^2\,\text{s}^{-1}$ has been considered in all simulations.

The model was also tested by balancing, at each time step, the amount of radionuclides in the system (Periáñez et al., 1994). Good results are obtained taking $\phi = 0.9$ in Eq. (5).

The model has been tested for ^{125}Sb, ^{99}Tc and ^{137}Cs; they are considered to behave conservatively in sea water, that is, no fraction is removed from the water column by geochemical or biological processes. Indeed, radiochemists have found that ^{125}Sb and ^{99}Tc behave almost conservatively in sea water (Dahlgaard et al., 1995). ^{137}Cs, although less conservative than ^{125}Sb and ^{99}Tc (IAEA, 1985), can be considered to remain in solution.

Distribution patterns of the radionuclides of interest were obtained from several research cruises carried out from 1990 to 1993 (Herrmann et al., 1995) in the Channel.

The discharges of radionuclides started some years before the simulated periods. Thus, the model cannot be started from zero concentration: a uniform radioactivity background, which represents the effect of previous discharges, has been assumed over the Channel. This technique has been used before (Periáñez et al., 1994), where it was shown that model results do not depend upon the way the backgroud is created. Thus, the same results are obtained by assuming a uniform background over the study area or by releasing a large discharge and allowing some time to elapse so that this discharge is dispersed through the study area. The magnitude of the background level has been obtained from measured average concentrations of radionuclides in the Channel: in the case of ^{125}Sb, the mean concentration obtained from a cruise performed in September 1990 is used as the uniform background for the simulation. The computed and measured distributions obtained in February 1991 (when another cruise was carried out) are compared. Real discharges correponding to that period of time are used (Gueguenia t et al., 1996). In the case of ^{99}Tc, the initial condition (background magnitude) corresponds to November 1990 and computed and observed distributions obtained in February 1991 are compared. Finally, in the case of ^{137}Cs, initial conditions correspond to September 1990 and results are compared with measurements of February 1991. It can be seen that 5, 3 and 5 months have been simulated for each radionuclide.

Results for ^{99}Tc are presented in Fig. 6. In Fig. 6a, a map of computed concentrations is presented. It can be seen that maximum concentrations are obtained close to the source, as expected. However, concentrations are higher on the French side of the Channel than on the English side, which is in agreement with previous modelling work (Breton & Salomon, 1995). The banded structure, showing decreasing activities away from the French coast, has been observed by Gueguenat et al. (1996)

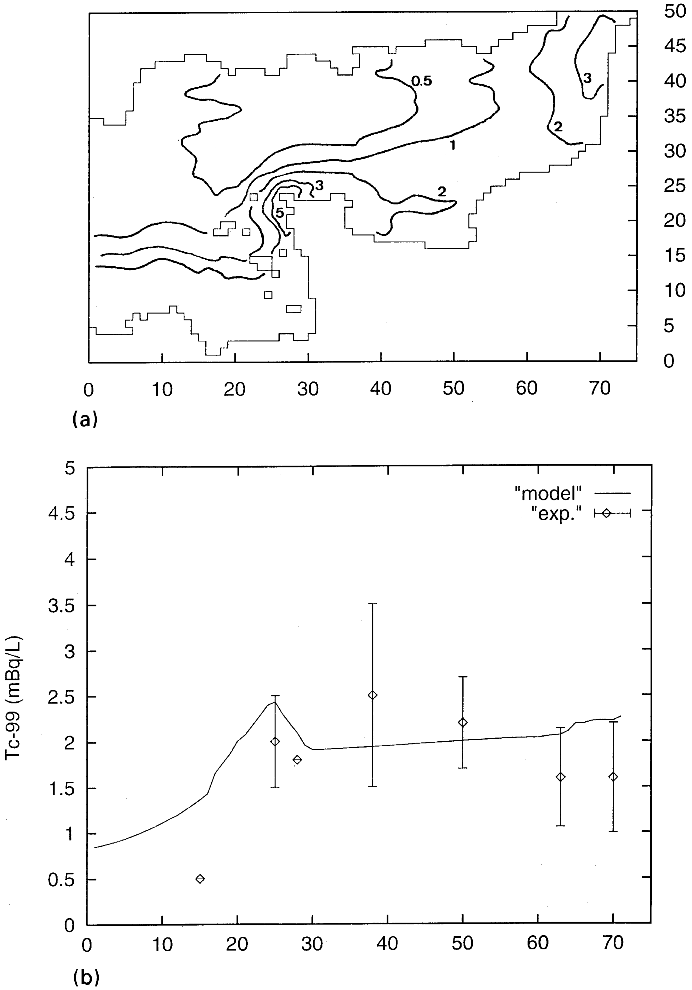

Fig. 6. (a) Computed ^{99}Tc distribution map. (b) Measured and computed profiles along the Channel. The *x* axis indicates the compartment number measured from the western boundary to Dover, thus, each unit is 5000 m.

and is also apparent here. To a certain extent, the southern coast of England is protected from the discharges due to the input of Atlantic waters towards the east (Breton & Salomon, 1995). Waters of the Normand-Breton Gulf are affected by the discharges from La Hague due to the existence of gyres around the Channel Islands (Orbi & Salomon, 1988). The strait of Dover acts as a bottleneck and, thus, gradients are slightly enhanced in this area. This effect has also been found by Breton and Salomon (1995). A profile of ^{99}Tc specific activity along the Channel is presented in Fig. 6b. The line represents the computed concentration, from the western open boundary to Dover Strait, approximately along the central channel (see Fig. 1). During the research cruises, samples were collected from a large number of locations (Herrmann et al., 1995). Thus, experimental points in Fig. 6b represent the mean value of the measured concentrations, in such a way that this mean value is calculated by averaging the sampling points that are located in the same transversal section (from coast to coast) of the channel. Error bars represent the standard deviation of the mean value. These mean values have been calculated because the experimental results are widely dispersed (even for samples collected very close to each other) and errors were not provided by the authors (Herrmann et al., 1995). It can be seen in Fig. 6b that model results are in good agreement with the measured mean concentrations along the Channel.

Results for ^{125}Sb are presented in Fig. 7. The computed profile is again in good agreement with the mean concentrations measured along the Channel.

Finally, results for ^{137}Cs are presented in Fig. 8. It seems that the model slightly underestimates the ^{137}Cs concentrations. It must be noted that ^{137}Cs is less conservative than ^{125}Sb and ^{99}Tc (IAEA, 1985), thus, part of the released ^{137}Cs is fixed to the bottom sediment. In previous modelling work (Periáñez et al., 1996; Hofer & Bayer, 1997), it was found that bottom sediments are a source of radionuclides to the water

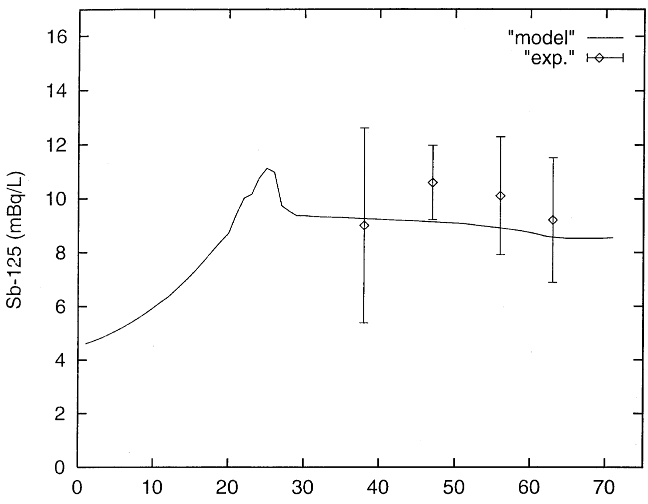

Fig. 7. Same as Fig. 6b but for ^{125}Sb.

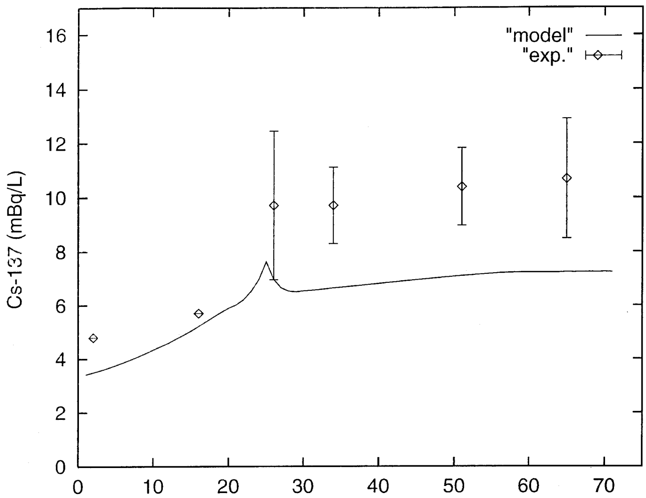

Fig. 8. Same as Fig. 6b but for ^{137}Cs.

column when concentrations in water are low enough to allow the desorption reaction to dominate adsorption. During the simulated period the input of ^{137}Cs was smaller than some months before (Guegueniat et al., 1996); thus the ^{137}Cs contribution from the sediment may be higher than the input from the source. This effect is not considered in the model and, thus, could explain the underestimation of the ^{137}Cs concentrations. Nevertheless, another possibility is the existence of other sources of ^{137}Cs to the area, like the existence of a component of Sellafield discharges coming out of the southern Irish Sea and leakage from radioactive waste dumped in the central Channel (in Fosse Centrale de la Manche), although the significance of this last source is negligible for the moment (Guegueniat et al., 1996). ^{137}Cs was measured in the Celtic Sea and the western Channel, in a zone unaffected by releases from La Hague, in September 1994 (Guegueniat et al., 1996). An excess of ^{137}Cs activity, with respect to the North Atlantic background, was found in these waters. This suggests the influence of an additional source term that could correspond to a contribution of Sellafield releases that have taken a southerly route (Guegueniat et al., 1996).

3.3. *Effect of wind*

No wind effects have been considered when calibrating the model since previous computations have already shown that wind-induced currents are relatively weak (compared to tidal currents) and essentially restricted to regions along the coast (Le Hir et al., 1986; Salomon, 1988). However, these weak currents may affect the long-term dispersion of radionuclides. Indeed, Breton and Salomon (1995) include wind effects in their long-term dispersion model. The influence of wind-induced currents on the near-field dispersion of radionuclides released from La Hague has now been investigated.

The effect of wind is included by adding the terms

$$-\frac{\rho_a}{\rho_w}\frac{C_D}{D+z}|W|W\cos\theta \tag{7}$$

$$-\frac{\rho_a}{\rho_w}\frac{C_D}{D+z}|W|W\sin\theta \tag{8}$$

to the left-hand side of Eqs. (2) and (3) respectively. ρ_a and ρ_w are the air and water densities, W the wind velocity, θ the direction to which the wind blows measured anticlockwise from the east and C_D is a dimensionless drag coefficient. An acceptable value for C_D is (Pugh, 1987):

$$C_D = (0.63 + 0.066W) \times 10^{-3} \tag{9}$$

for $2.5 < W < 21$, with W measured in ms^{-1}, 10 m above the sea surface.

An arbitrary discharge was released at La Hague at the beginning of a tidal cycle and distribution maps were obtained 4 days later for different wind directions and speeds. Results are summarized in Table 1, where the position column indicates the location (compartment coordinates) of the activity peak after the simulation. The location of these compartments is also indicated in the map of Fig. 1. In no wind conditions, the peak flows round Cap de La Hague in the direction of Cherbourg due to the eastward residual flow. Results show that for light winds (5 ms^{-1}) the dispersion pattern is not significantly affected by the wind (for 4 days of simulation) since the peak is located in the same compartment as before. In the case of a wind speed of 10 ms^{-1}, there is no significant effect if the wind blows from the west or from the south. However, if the wind blows from the north or from the east, the activity maximum does not pass the cape and is retained in the Gulf Normand-Breton. Similar

Table 1
Effect of wind on the dispersion of an intantaneous discharge of radionuclides at La Hague. Numbers in paranthesis denote the compartment where the activity peak is located after each experiment

Speed (ms^{-1})	Direction	Position
Calm	—	(29, 24)
20	North	(28, 22)
	West	(30, 24)
	South	(29, 24)
	East	(28, 22)
10	North	(28, 22)
	West	(29, 24)
	South	(29, 24)
	East	(28, 22)
5	North	(29, 24)
	West	(29, 24)
	South	(29, 24)
	East	(29, 24)

results are obtained for a wind speed of 20 ms^{-1}. Neverthless, when the wind blows from the west, the eastward transport is obviously increased and, as a consequence, the maximum moves closer to Cherbourg.

4. Conclusions

A numerical model to simulate the tide-induced dispersion of conservative radionuclides in the English Channel has been developed. The model solves the shallow water hydrodynamic equations and, simultaneously, the advection diffusion dispersion equation. The hydrodynamic part of the model uses a bed friction coefficient that changes with position and has been tested by comparing observed and computed magnitudes and directions of tidal currents. Both sets of data are in good agreement. The dispersion model has been tested by comparing measured and computed ^{125}Sb, ^{99}Tc and ^{137}Cs concentrations over the Channel. Model predictions are in good agreement with observations in the case of ^{125}Sb and ^{99}Tc. In the case of ^{137}Cs, the model underestimates the concentrations, which could be due to the fact that this radionuclide is less conservative and to the existence of an additional ^{137}Cs source to the Channel, that could correspond to a contribution of Sellafield releases following a southerly route. It has also been observed that wind has little effect on the dispersion patterns, which is in agreement with previous observations. The most relevant result is the higher input of contaminated water in the Gulf Normand-Breton when the wind is blowing from the north and from the east. After testing, the model may be used as a predictive tool that could be applied, for instance, in the case of an accidental release of radionuclides from the reprocessing plant. The model has applicability to cases where the two-dimensional approach is valid.

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