Oil spills in coastal zones: Environmental impacts and practical mitigating solutions

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ABSTRACT: A computational structure that has been developed to forecast the time-space evolution of oil spills in marine environments is presented. This structure was developed considering widely used mathematical formulations for oil spreading and weathering processes. A Eulerian transport model, that uses hydrodynamic results obtained with a two-dimensional and a *quasi* three-dimensional hydrodynamic model, was used to predict the oil slick transport and spread. General characteristics of the computational structure and the results of its application to a real case study - the "Cercal" accident in October 1994 - are presented. Georeferenced data are processed via a Geographical Information System tool. Data on the N/T "Prestige" oil spill processed by means of this information system and simulation results are also included.

1 INTRODUCTION

Petroleum products that enter the marine environment have distinct effects, according to their composition, concentration and the elements in the environment that are taken into consideration. Some effects can be related to transformations of the chemical composition of the environment and alterations in its physical properties, the destruction of the nutritional capital of the marine biomass, danger to human health, and changes in the environmental biological equilibrium.

The Iberian coastal waters are noted for their intense oil tanker traffic and, as a consequence, the risk of an oil spill occurring in these coastal waters is high. The Prestige oil tanker disaster, in the Atlantic Ocean off the coast of Spain on November 19, 2002, when the vessel sank after leaking about 30 000 *tons* of fuel oil, is just one recent example of an accident with dramatic environmental consequences for the Iberian coastal zone.

Numerical models are intrinsically able to predict the evolution and behaviour of oil spilled at sea, regardless of the atmospheric conditions, hence the vast interest in them. Mathematical modelling is thus a very powerful tool for management assessment after an oil spill accident, particularly for determining preventive measures and to help monitoring accident evolution.

The latest information technologies have provided us with new tools and different strategies in the field of environmental management that are capable of efficiently processing the great quantity of information needed to support accidental hydrocarbon spill management.

These modelling tools are now of paramount interest in the forecasting of oil slick evolution at sea, as they allow measures to mitigate the negative impacts associated with hydrocarbon spills to be put in place. When integrated into Geographical Information Systems tools, the information yielded by the models' simulations can be analysed easily and appropriately.

2 ENVIRONMENTAL IMPACTS OF THE SPILLS

The petroleum products that enter the marine environment have distinct effects, according to their physical and chemical composition, and the environmental elements that are considered. The mechanisms of toxic action depend on the petroleum's characteristics. The toxicity of the various fractions of the pollutants is directly related to the distilled products, on a short-term basis, and related to the slow-action products, on a long-term basis. It is also related secondarily to the products degraded either biologically, through the action of bacteria, or through physical-chemical processes.

Petroleum pollution can be detected through the modification of the environmental conditions and can be described by:

- transformations of the chemical composition of the environment and alterations in its physical properties;
- destruction of the biomass' nutritional budget;
- changes in the environmental biological equilibrium.

From the physical point of view, hydrocarbons directly influence the marine environment, since gas transfer mechanisms are disturbed by the presence of a pollutant layer on the surface. Self-purification processes are thus reduced. These processes can be aggravated by the increased oxygen consumption by growing micro-organisms, depending on the quantity of biodegradable organic matter present. This oxygen deficit could even create conditions for anaerobic life, giving rise to the death and disappearance of certain species and permitting the fermentation of organic residues.

From a biological point of view, the environmental effects of oil are varied and complex. While some are immediately obvious, others only manifest themselves after a long period. The degree of the effect is therefore different, whether in the animal or in the plant kingdom. In the case of crude oil, the volatile components and the aromatic compounds are the most toxic.

In addition to possible direct intoxication resulting from the inhalation or ingestion of petroleum products, there is an indirect risk to humans from the consumption of certain marine animals (fish, crustaceans, shellfish, etc.) that have been in close contact with the oil.

The pollution's noxious effects can also be felt indirectly through its environmental and economic impacts: damage to biological resources (flora and fauna), affecting biodiversity; deterioration in seawater and shoreline quality, with negative effects on economic activities.

The first and hardest influences to gauge are those that take a broader view of the oceans as one of humanity's last resources. In a narrower sense, it is important to keep in mind that an oil spill affects all the people who directly or indirectly exploit marine resources, particularly those related to tourism, fishing and fish farming.

3 OIL SPILL DETECTION AND CONTROL

In order to efficiently combat the permanent danger of marine pollution caused by hydrocarbon spills, it is extremely important, once a spill has been detected, to be able to predict both the discharge location and the transformations that the hydrocarbons undergo in time, quickly and precisely.

Tele-detection is a widely-used technique employed with considerable success to define the affected zones, to determine the extent of the spill and to help the ships combat pollution. For that purpose, aerial detection sensors have been developed. However, under adverse meteorological conditions, they only provide sufficient information when used in combination.

Under favourable conditions, the tele-detection technique is capable of defining the zones affected and the extent of the spills. It could even help guidance for ships combating pollution. Tele-detection data could also serve as entry data to verify the results obtained from previsional models of spill evolution. However, this technique is difficult to use in unfavourable atmospheric conditions, which are the most likely ones to prevail during accidents at sea.

Containing operations at sea generally involve the use of floating barriers that can be used to confine, concentrate or manage oil slicks. Various types of collection equipment may be used, the choice of which will depend on the following factors: spill location and dimension, movement of the spill, meteorological conditions, hydrographic conditions, and protection priorities.

The elimination of surface hydrocarbons is one of the main goals of pollution-control actions and various methods have been tried to tackle the problem. The physical removal of the oil is generally considered preferable to chemical removal, since it does not introduce additional substances into the marine environment, involves a smaller quantity of irrevocably lost hydrocarbons and permits the reuse of the collected products.

4 NUMERICAL MODELLING OF THE BEHAVIOUR AND EVOLUTION OF HYDROCARBON SPILLS AT SEA

Spreading and weathering processes (i.e. evaporation, dissolution, dispersion into the water column, emulsification, changes in viscosity and density) can be simulated by numerical models based on mathematical formulations that describe these processes, according to their physical and chemical properties.

It is important to keep in mind that the numerical model to be used should be sufficiently simple and fast, from a computational point of view, to allow information to be gathered in real time, and for the following reasons:

- the evolution of hydrocarbon spills depends on environmental processes and factors that are still poorly understood and whose mathematical description is complicated, and depends on more or less empirical hypotheses;
- in real accident cases, important factors are generally unknown, such as the real quantity of oil spilt and some of its properties.

In preventive terms, these models could even be the only method of planning the implementation of means of combating pollution at sea. In the meantime, predictions provided by the numerical models should, whenever possible, be accompanied by direct observations. In this way, the model's predictions will help to guide direct observations, and, with the necessary precautions, direct observation will permit the recalculation of prediction data from that point on.

4.1 *Mathematical formulations*

Most oil spill transport models have adopted a Lagrangean description. However, it is likely that Eulerian models will be used more frequently in the future as they need to be coupled with the (Eulerian) hydrodynamic models and (Eulerian) meteorological models of the lower atmospheric boundary layer. In this work, numerical models for oil spill simulation use the hydrodynamic data required for the Eulerian transport approach to describe the spreading and weathering processes. Hydrodynamic data are obtained by applying the Saint-Venant or *shallow-water equations,* using either a two-dimensional (2DH) or a *quasi*-three-dimensional (*quasi*-3D) form of the equations.

4.1.1 *Hydrodynamic models*

A 2DH hydrodynamic model is implemented using a programme based on the finite element method (WES-HL, 1996), and a *quasi*-3D hydrodynamic model is developed using a finite difference hydrodynamic model, which corresponds to a modified version of the POM-Princeton Ocean Model (Mellor, 1998; Pinho, 2001).

The 2DH model is used in situations where the water flow does not exhibit a significant vertical variation, and the *quasi*-3D hydrodynamic model is used to calculate the surface water currents when a significant vertical variation is associated with the water flow pattern.

$$\frac{\partial \eta}{\partial t} + \frac{\partial[(h+\eta)U]}{\partial x} + \frac{\partial[(h+\eta)V]}{\partial y} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = +fV - g\frac{\partial \eta}{\partial x} - \frac{g}{\rho}\frac{\partial \rho}{\partial X}\frac{h+\eta}{2} + \\ + \frac{\rho_a k W_v^2 \cos\varphi}{h+\eta} - \frac{gU\sqrt{U^2+V^2}}{(h+\eta)C^2} + \frac{\varepsilon}{\rho}\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) \quad (2)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -fU - g\frac{\partial \eta}{\partial y} - \frac{g}{\rho}\frac{\partial \rho}{\partial y}\frac{h+\eta}{2} + \\ + \frac{\rho_a k W_v^2 sen\varphi}{h+\eta} - \frac{gV\sqrt{U^2+V^2}}{(h+\eta)C^2} + \frac{\varepsilon}{\rho}\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) \quad (3)$$

where x and y are the horizontal Cartesian coordinates, t is the time, U and V are the vertical average of the horizontal velocity components, ρ_a is the air density, W_v is the wind velocity, φ is the wind direction, C is the Chezy coefficient and ε is the turbulent viscosity coefficient.

The *quasi*-3D model contains a basic improvement whereby the external model is calculated using a finite element method technique to enhance its overall performance when applied to geometrically complex problems in which specific boundary conditions are considered. The following mass and momentum conservation equations are solved:

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}(uH) + \frac{\partial}{\partial y}(vH) + \frac{\partial w}{\partial \sigma} = 0 \quad (4)$$

$$\frac{\partial}{\partial t}(uH) + \frac{\partial(uuH)}{\partial x} + \frac{\partial(vuH)}{\partial y} + \frac{\partial}{\partial \sigma}(wu) - fvH = \\ = -HP_1 + \frac{\partial}{\partial \sigma}\left(\frac{K_M}{H}\frac{\partial u}{\partial \sigma}\right) + HF_1 \quad (5)$$

$$\frac{\partial}{\partial t}(vH) + \frac{\partial(uvH)}{\partial x} + \frac{\partial(vvH)}{\partial x} + \frac{\partial}{\partial \sigma}(wv) + fuH = \\ = -HP_2 + \frac{\partial}{\partial \sigma}\left(\frac{K_M}{H}\frac{\partial v}{\partial \sigma}\right) + HF_2 \quad (6)$$

where σ is the sigma vertical coordinate, u and v are the horizontal velocity components, w is the transformed vertical velocity (physically, w is the velocity component normal to sigma surfaces), $H \equiv h+\sigma$ is the total depth [$h(x,y)$ is the bottom topography and $\sigma(x,y,t)$ is the surface elevation], f is the Coriolis parameter, P_1 and P_2 are the horizontal pressure gradient terms, F_1 and F_2 are the horizontal diffusion terms, and K_M is the vertical kinematic viscosity.

The transformation of w to the cartesian vertical velocity is:

$$W = w + u\left(\sigma\frac{\partial H}{\partial x} + \frac{\partial \eta}{\partial x}\right) + \\ + v\left(\sigma\frac{\partial H}{\partial y} + \frac{\partial \eta}{\partial y}\right) + \sigma\frac{\partial H}{\partial t} + \frac{\partial \eta}{\partial t} \quad (7)$$

4.1.2 *Transport model*

The Eulerian surface oil slick transport equation is used, which is a mass conservation equation for the surface oil layer:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(UC) + \frac{\partial}{\partial y}(VC) - \\ - \frac{\partial}{\partial x}\left(E_x\frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial y}\left(E_y\frac{\partial C}{\partial y}\right) + k_C C = 0 \quad (8)$$

where, $C = \rho\delta$ is the local concentration of surface oil, t is time, ρ is the local mass density of oil, δ is the local thickness of the oil layer, E_x and E_y are the local dispersion coefficients in the x and y direction, respectively, and k_C is the local mass transfer rate from source/sink processes.

This equation is solved numerically using a modified version of the RMA4 programme (Pinho, 2001).

4.1.3 *Weathering processes*

The weathering processes can be modelled considering the overall effects of evaporation, vertical dispersion (volume and area variation), emulsification, and viscosity changes.

The evaporative loss fraction (F_e) of a given hydrocarbon is described by the following equation (Buchanan & Hurford, 1988):

$$\frac{dF_e}{dt} = \frac{K\,A_o}{V_o}\,exp\left[A - \frac{B}{T}\left(T_0 + T_G F_e\right)\right] \qquad (9)$$

where K = 2.5x10^{-3} U$_v^{0.78}$; T = product temperature (^oK); T_0 = initial temperature (when $F_e = 0$); A = 6.3; B = 10.3; T_G = distillation curve gradient (^oK); μ = dynamic viscosity (cP); A_o = oil slick area (m^2); and V_o = oil volume (m^3).

Vertical dispersion losses are modelled considering the rate proposed by Mackay *et al*., 1980):

$$Y_d = \frac{0.11\;\left(U_v + 1\right)^2}{1 + 50\mu\,\delta\,\gamma_{ow}} \qquad (10)$$

where μ = dynamic viscosity (cP); δ = pollutant slick thickness (cm); and γ_{ow}= oil-water surface stress ($dyne/cm$).

Taking the previous formulations for the oil losses, the volume variation can be expressed by (considering V_{o0}= initial oil volume):

$$\frac{dV_o}{dt} = -V_{o0}\frac{dF_e}{dt} - \mathrm{Y}_d V_o \qquad (11)$$

The area rate growth is modelled using the following expression (Mackay *et al.*, 1980),

$$\frac{dA_o}{dt} = K_1 A_o^{1/3}\left[\frac{V_o}{A_o}\right]^{4/3} \qquad (12)$$

Emulsification is modelled by means of the expression (where Y is the water in oil fraction),

$$\frac{d\mathrm{Y}}{dt} = 2.0\times10^{-6}\left(U_v + 1\right)^2\left(1 - \frac{Y}{Y^F}\right) \qquad (13)$$

where Y^F= 0.70 (crude oils, heavy oils) to 0.25 (light fractions).

Changes in dynamic viscosity and density are modelled by the following expressions:

$$\frac{d\mu}{dt} = C_\mu \mu_0 \frac{dF_e}{dt} + \frac{2.5\mu_0}{\left(1 - \mathrm{Y}^F\mathrm{Y}\right)^2}\frac{d\mathrm{Y}}{dt} \qquad (14)$$

$$\rho_e = \mathrm{Y}\rho_w + \left(1 - \mathrm{Y}\right)\left(\rho_o + \mathrm{Y}^F F_e\right) \qquad (15)$$

where μ_0 = initial viscosity (cP) and C_μ is the mechanical oil rate recovery time. C_μ = 1 (gasoline) to 15 (heavy crude oils). A numerical tool based on the Runge-Kutta method was developed to solve these equations.

4.2 *Case Study: "Cercal" Accident Modelling*

On the 2nd October 1994 the Panamanian oil tanker Cercal struck a rock while entering the harbour of Leixões - Porto (Portugal), releasing about 2 500 *tons* of crude oil (Arabian Light) into the sea. Figure 1 shows a satellite-acquired image two days after the accident.

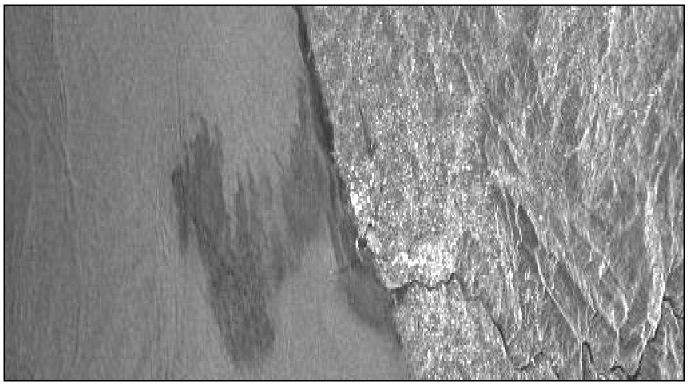


Figure 1. Satellite-acquired image two days after the Cercal accident at the Leixões - Porto harbour.

The spill could be seen floating along the coast and out to sea. The coastal city of Porto, lying near the centre of the oil spill, appears as a cluster of white dots. The rainy and foggy weather prevailing in that region of Portugal on the date of the accident made it very difficult to evaluate the spill from an aircraft. However, thanks to the all-weather capabilities of the satellite instrument it was possible to acquire this very useful scene through the cloud cover.

The Portuguese authorities monitored the accident and some laboratory work was carried out to analyse the physical properties of the crude oil.

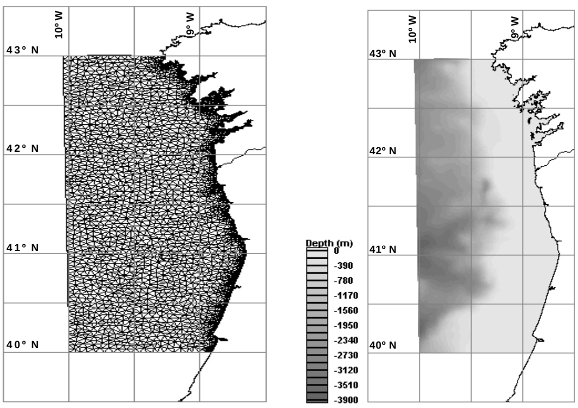
This case has been studied by Antunes do Carmo & Costa (2000) considering only the wind action (without current), a Lagrangian transport model and equations (9) - (15) to simulate the oil spill evolution properties. The following crude oil parameters ρ_o = 857 $kg\ m^{-3}$, ν (at 25 ºC) = 6.30 cSt, Y^F= 65%, T_0= 292 ºK, T_G = 624 ºK and γ_{ow} (at 20 ºC) = 0.0309 Nm^{-1} have been assumed. The accident simulation starts at coordinates 41.16º N and 8.92º W. Comparisons between the measured and simulated results are shown in Table 1.

Table 1. Volume and geometry changes of the pollutant cloud from the N/T "Cercal" (Antunes do Carmo & Costa, 2000).

Day	Volume (m^3)	Volume (m^3)	Area (km^2)	Area (km^2)	Radius (Km)	Thickness (mm)
	Real	Preview	Real	Preview	Preview	Preview
3-Oct	2 400	2 335	16	15.5	2.222	0.1506
5-Oct	1 530	1 457	70	68.65	4.572	0.0222
7-Oct	1 400	1 332	136	133.91	6.529	0.0099
9-Oct	1 290	1 256	220	215.56	8.283	0.0058
11-Oct	1 200	1 199	315	308.5	9.91	0.0038

As water currents at the accident site can play an important role in the oil transport process, a second simulation of this accident was performed to analyse their influence and also to test another surface oil slick transport model [equation (8)]. The 2DH hydrodynamic model (1)–(3) was used to quantify the water currents' velocity at the northern Iberian Peninsula coastal zone during the accident.

Figure 2 shows the geographical extent, the finite element mesh (with 5294 quadratic triangular elements) and the bottom topography. It must be emphasized that this model is still in the implementation phase, and, since there is no data available for model calibration and validation purposes, its parameters were established taking values used in similar studies.



a) b)

Figure 2. DH hydrodynamic model: a) finite element mesh, b) bottom topography (Pinho *et al.*, 2002).

A hydrodynamic simulation was carried out imposing predicted tidewater surface elevations (JPL, 1996) at the open ocean boundary (Figure 3). Figure 4 displays the instantaneous maximum tide current velocities (during ebb and flood) at the accident area.

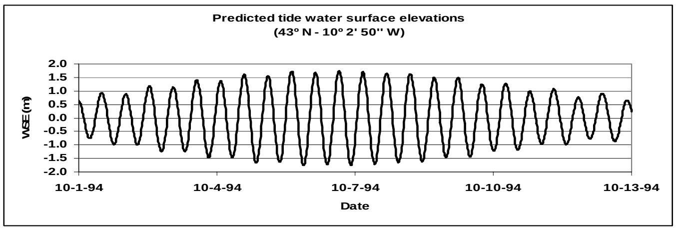
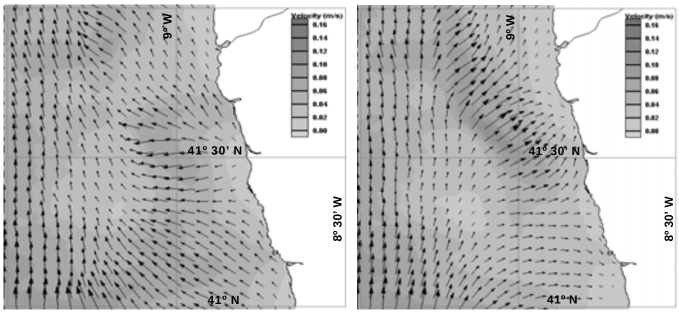


Figure 3. Predicted tide water surface elevations at 43º N – 10º 2' 50'' W from 1 to 13 October, 1994.



a) b)

Figure 4. Instantaneous maximum tide current velocities for: a) ebb, b) flood (Pinho *et al.*, 2002).

The hydrodynamic model results were used to calculate the daily residual tide current velocities during the accident period. Figure 5 presents the results for each day of the accident period. As Figure 5 shows, the daily residual tide current velocities at the oil slick positions are lower than 2 cm^{-1} (the results were similar for other days not shown in this figure). The wind therefore appears to have most influence on the oil transport process (compared with other types of current).

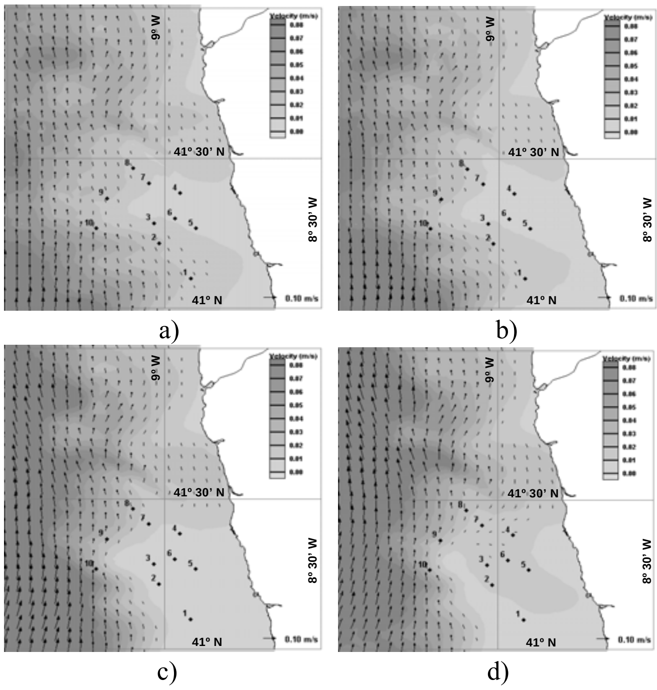


Figure 5. Daily residual tide current velocities: a) 2 Oct 1994, b) 5 Oct 1994, c) 9 Oct 1994, and d) 12 Oct 1994 (Pinho *et al.*, 2002).

In order to quantify the velocities to be used in the Eulerian transport model, the C_v coefficient value must be established. According to the positions observed for the oil slick, the daily C_v value varies between 0.015 and 0.025 (ignoring water flow current velocities, which is close to the real situation, if tide currents are assumed to be the most important flow currents).

To show the general capabilities of the transport model, a simulation was carried out taking the values calculated for C_v. Figure 6 presents the calculated oil slick thickness at different oil slick positions.

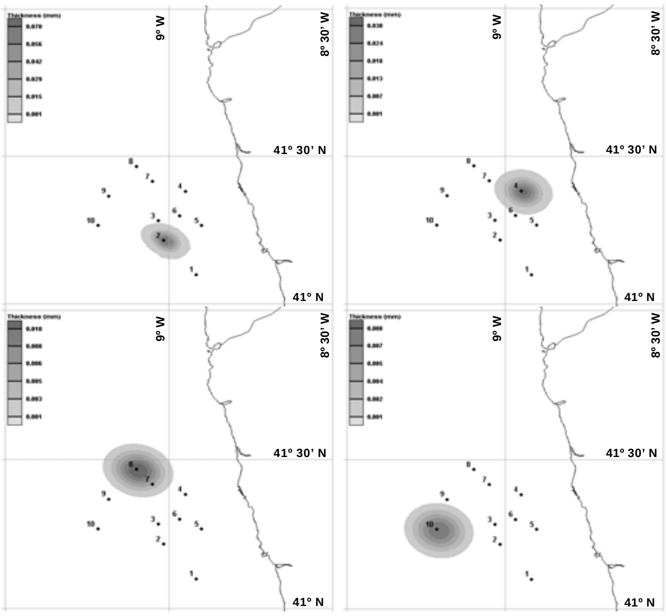


Figure 6. Eulerian transport model results: oil slick thickness at different observed positions (Pinho *et al.*, 2002).

Several simulations were carried out considering different C_v values during the simulation period. The results obtained have shown a high sensitivity to this parameter. The Eulerian model results were further corroborated by calculating the volume of oil within the spatial integration domain (Figure 7).

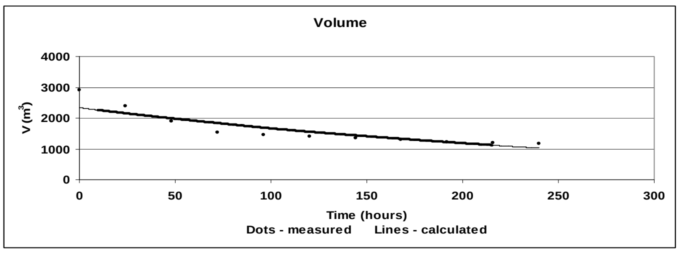


Figure 7. Comparison between the observed oil volumes (points) and the calculated volumes (Pinho *et al.*, 2002).

5 INFORMATION SYSTEM COMPONENTS

An Information System (IS) has been developed to serve as a supporting tool for hydrocarbon spill management in the Iberian Peninsula Atlantic coastal waters. The IS (Figure 8) has three main components: basic information for data organisation and handling; hydrodynamics modelling for the spreading and weathering processes simulation and spilled oil transport; and a GIS tool to analyse, visualise and edit the results.

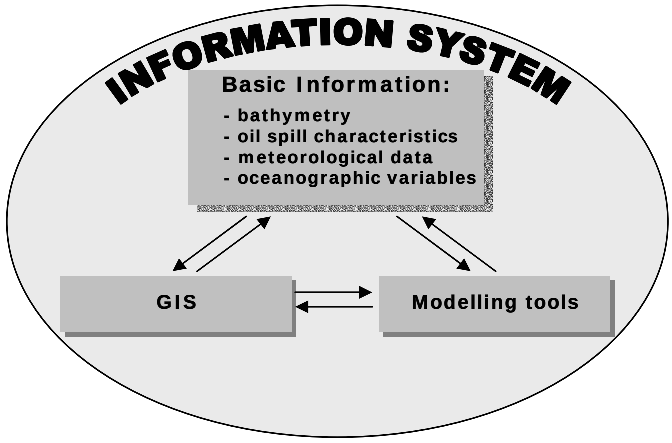


Figure 8. Main components of the Information System (Pinho *et al.*, 2004).

The modular approach adopted in the development of this Information System appears to be a versatile methodology, well-suited to the decision support systems to be applied in coastal zone environment management, particularly when appropriate measures have to be implemented after the occurrence of an oil spill.

The hydrodynamics can be simulated by the following main components: *i*) two-dimensional hydrodynamic model [equations (1)–(3)], and/or three-dimensional model [equations (4)–(7)] (or *quasi*-3D, as the hydrostatic condition is assumed).

A 2DH model has been applied to the NW of Iberian Peninsula, as a component of the Information System for studying the hydrodynamics at the instant of the N/T Prestige accident. Figure 9 shows the finite elements grid and the simulated field currents.

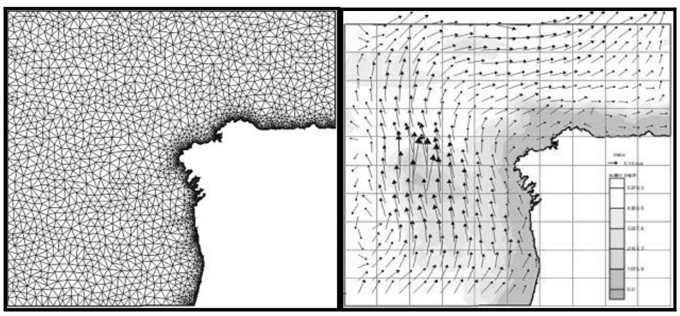


Figure 9. Study area: finite elements grid and field currents obtained after simulation.

A *quasi*-3D model has also been applied to the NW of Iberian Peninsula to study the wind action at the precise moment of the N/T Prestige accident. Some numerical results are shown in Figure 10, where the circulation mechanism caused by the northerly wind is close to the known seasonal variation of the summer circulation scheme in the coastal zone of Iberian Peninsula, as presented in Figure 11.

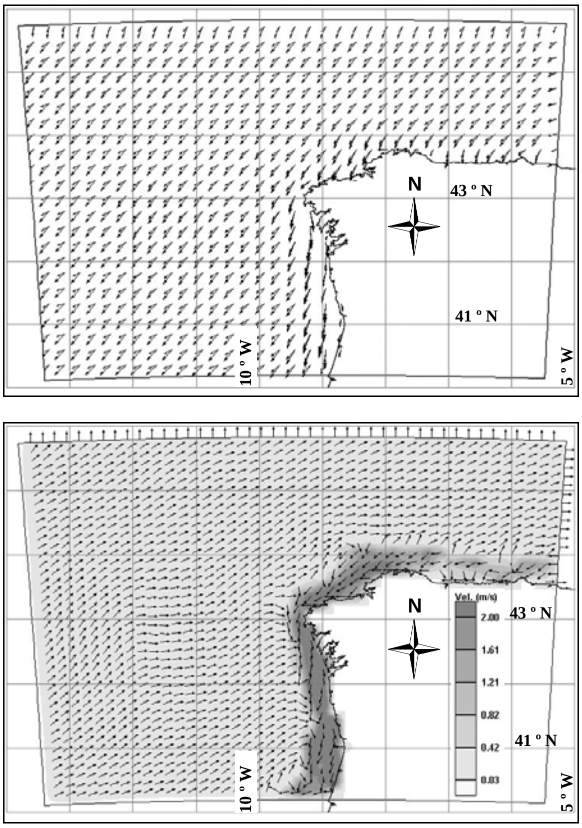


Figure 10. *Quasi*-3D hydrodynamic results: wind currents, a) at layers 1 and 5 (1% depth), and b) at layer 10 (23% depth) (Pinho *et al.*, 2004).

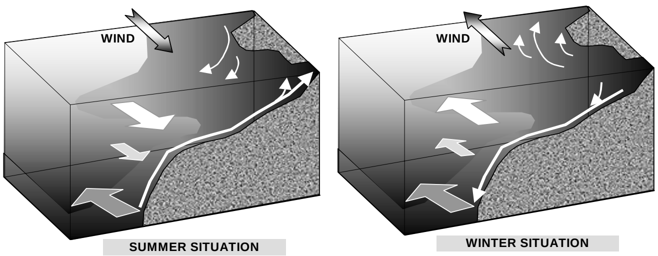


Figure 11. Seasonal variation of the circulation scheme at NW of Iberian Peninsula (Pinho *et al.*, 2004).

6 N/T "PRESTIGE" ACCIDENT

The N/T Prestige accident occurred on 13th November 2002. The oil tanker transporting about 77000 *tons* M-100 fuel oil leaked an amount in excess of 30000 (CCMM, 2003). This is a very heavy viscosity product, practically insoluble and having a characteristic petroleum colour (CEDRE, 2003). As an illustration, Figure 12 presents the results obtained for the mass evolution of the spilled fuel oil. The following surface field currents were considered in the simulation: a SW uniform current for the first 6 hours and a W current for the subsequent 18 hours. Further work consists of reproducing the trajectories of deriving systems introduced during the incident, with the objective of calibrating the models utilized in the Information System.

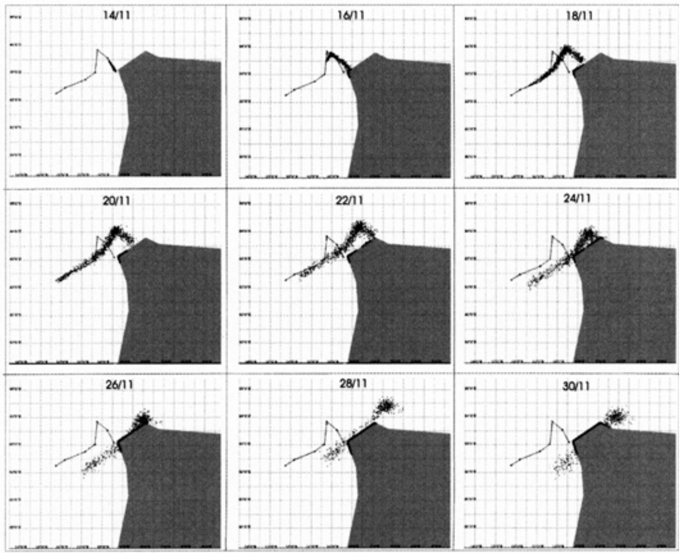


Figure 12. Simulated results of the spilled fuel oil mass.

7 CONCLUSIONS

The computational structure described here is based on either a 2DH or a *quasi*-3D hydrodynamic model, on the Eulerian surface oil slick transport model, and on classical empirical formulations for spreading and weathering processes. It proved to be satisfactory for modelling an oil spill accident. Some widely applied expressions for oil spill characteristics (evaporation loss, volume and area) showed its suitability for modelling the Cercal oil spill. For forecasting purposes, special care must be taken in the prediction of the C_v coefficient. Furthermore, wind characteristics (velocity and direction) must be properly recorded (or anticipated).

This work also presents an intermediate stage of an Information System that is being developed as a management support tool for accidental hydrocarbon spills in Atlantic coastal waters. The main information sources have been characterized, as have the modelling tools, which confer high potentialities on the IS in terms of its ability to anticipate the evolution and transport of hydrocarbon spills. The main specific applications for processing the information utilized in the different IS components have been developed. A common structure, based on GIS technology, allowing an efficient utilization when dealing with all the aspects concerned, facilitates the integration and the information analysis involved.

8 ACKNOWLEDGEMENTS

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