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Uncertainty in predictions of oil spill trajectories in a coastal zone

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Abstract

A method is introduced to determine the uncertainties in the predictions of oil spill trajectories using a classic oil spill model. The method considers the output of the oil spill model as a function of random variables, which are the input parameters, and calculates the standard deviation of the output results which provides a measure of the uncertainty of the model as a result of the uncertainties of the input parameters.

In addition to a single trajectory that is calculated by the oil spill model using the mean values of the parameters, a band of trajectories can be defined when various simulations are done taking into account the uncertainties of the input parameters. This band of trajectories defines envelopes of the trajectories that are likely to be followed by the spill given the uncertainties of the input.

The method was applied to an oil spill that occurred in 1989 near Sines in the southwestern coast of Portugal. This model represented well the distinction between a wind driven part that remained offshore, and a tide driven part that went ashore. For both parts, the method defined two trajectory envelopes, one calculated exclusively with the wind fields, and the other using wind and tidal currents. In both cases reasonable approximation to the observed results was obtained.

The envelope of likely trajectories that is obtained with the uncertainty modelling proved to give a better interpretation of the trajectories that were simulated by the oil spill model.

Keywords: Oil spill; Trajectory model; Uncertainty modelling

1. Introduction

Oil spill modelling can be used for several different purposes, depending on which the choice of the type of the appropriate oil spill model should be made. Different models will include different detail in the description of different physical processes, which imply that they will need different extent of input data and that the accuracy of their output results will be different.

Oil spill models can be used retrospectively to analyse or to reconstruct a given event. In this situation, it may be possible that all the required information is available about the meteorological conditions at the location, as well as about the characteristics of the spilled product. In this case it can be appropriate to use a very sophisticated tool that models the details of the physical process. However if some of the details of the input data are missing, the use of such a sophisticated model will

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invariably lead to results that will deviate from the correct ones by an uncertain value.

A simpler model that only represents the most important physical processes may provide relatively accurate results. By representing only the dominant processes and having the appropriate input data for them avoids that the results of not well characterised secondary processes may spoil the quality of the output data.

Oil spill modelling can provide useful information to assist spill response at sea since it can predict the fate, and in particular, the trajectory that the spilled product will follow. This information is useful before observations are available, as most of the times it is the only information that exists for some time, but it is also useful together with observations, since it introduces the possibility of forecasting and therefore of anticipating the developments in the near future.

A typical situation in which uncertainties are present is the use of oil spill models in the forecast model in which case the objective of the trajectory forecasts is to support oil spill emergency plans to be put in place (Guedes Soares and Sebastião, 2002). The uncertainty in the trajectory resulting from the uncertainty in the prediction of the future meteorological and oceanographic data is independent of the type of oil spill model and adds to the uncertainty implicit in the oil model. Presently weather forecasts have a good predictive skill for periods up to 4 days, but it degrades gradually as time progresses.

There are presently many oil spill models with different degrees of complexity to compute the trajectory of spills. However, the success of the application of each model is dependent on the formulation of the model itself, on the accuracy of the input data, and finally on how the results are interpreted.

The input data is subject to many sources of error and some of the environmental variables have a stochastic behaviour. Hence, there is always some degree of uncertainty associated to the input parameters that should not be neglected.

This paper introduces a method to calculate the uncertainties of the predicted oil spill trajectory that results from the uncertainties in the input parameters, such as the wind and currents fields, and applies it to a case study that occurred in the south-western coast of Portugal in 1989.

The method of uncertainty quantification considers each output of the oil spill model as a function of random variables, which are the input parameters, and models the uncertainty by calculating the standard deviation of the output results as a function of the standard deviation of the input parameters. These statistical parameters give a measure of the uncertainty of the model results given the uncertainties of the input parameters. This uncertainty can be represented by an interval band similar to the confidence intervals associated with statistical inference.

When the above procedure is applied to the prediction of oil spill trajectories one obtains a range of possible trajectories instead of a single one that is given by the oil spill model output to a single set of input variables. These results are able to reflect the uncertainty in the prediction process and allow decision to take it into consideration, increasing the confidence when analysing the results.

The method will be applied to a case study by using the oil spill system described in Guedes Soares et al. (2000) and in Sebastião and Guedes Soares (2003). The oil spill model calculates the transport of the oil slick as a function of the wind and the local current as the velocity of the centre of the oil slick. A physical–chemical weathering module computes the evolution of the physical parameters of the spilled oil using a Fay type formula (Fay, 1969) to compute the area of the spill and several other formulae to describe the additional processes (Sebastião and Guedes Soares, 1995).

As stated before the results of the model depend obviously on the quality of the model itself. An important weakness of this type of models comes from the use of the formulation of spreading due to Fay (1969). This was developed essentially for calm sea conditions and it includes formulas to determine the growth of a circular spill, considering the physical–chemical properties of the crude. Although this approach can be appropriate to estimate the area just after the spill, in practice, a crude oil also spreads through the action of the currents and the turbulence that exist in the upper layers of the sea.

The output of this model involves a so-called model uncertainty, which results from using this limited model of the reality and also the uncertainty due to the uncertain conditions of the meteorological forcing as well as of the current and wave fields, which will need to be quantified in each specific case. In this work only the latter is addressed, as the first one would require very detailed and controlled experiments to assess the accuracy of the model.

The next section describes briefly the principles of the oil spill model and in Section 3 the method of uncertainty modelling is described. Finally in Section 4 the example case is described.

2. Oil spill model

The oil spill computational system that was used comprises the modules to calculate the weathering of the spill, its trajectory, and a database where the required information is stored. The database has geo-referenced information of the bathymetry and the properties of the most common crude oils. At the moment the data covers the Exclusive 6 Economic Zone of Portugal that comprises the regions of Azores and Madeira, with a resolution of 1°×1°. Monthly average data for wind and residual currents are stored in the database allowing preliminary estimates while other met-ocean data are not available (Guedes Soares et al., 2000). When measured met-ocean data are available the system uses those data to perform the calculations (Sebastião and Guedes Soares, 2003).

The modules to compute the weathering of the spills are described in detail in Sebastião and Guedes Soares (1995, 1998). They take into account the processes of spreading, evaporation, dispersion and emulsification and compute the evolution of the viscosity and density of the spilled oil. These processes are described in detail in those references and they will determine the physical–chemical characteristics of the oil slick as a function of time.

This work is more interested on the trajectory of the oil slicks and thus spreading becomes of importance as it governs the size of the oil slick with time. The spreading process, which is described in more detail below, is determined by a rate of area growth given by Mackay et al. (1980)

$$\frac{\mathrm{d}A}{\mathrm{d}t} = K_1 A^{1/3}\left[\frac{V}{A}\right]^{4/3} \quad (1)$$

where

A = Spill area (m^2)
K_1 = Constant default value = 150 s^{-1} (Mackay et al., 1980)
V = Spilled volume (m^3)
t = time (s)

The trajectory of the slick is calculated by following equation:

$$V_R = V_c + w_f . W \quad (2)$$

where the resultant drift velocity, V_R, is the vectorial addition of the local current, V_c, to a fraction, w_f, of the wind velocity, approximately 3–4%. A drift angle can also be considered either depending on the wind speed either constant, between 0° and 20°, typically 10–17° (Spaulding, 1988).

In fact, currently there is still no definitely accepted way of estimating the deflection angle. Samuels et al. (1982) made a literature review where they mention more than thirty studies about this topic that produced as many formulas to calculate the deflection angle, including the theoretical classical solution given by Ekman (1905), which indicates an angle of 45° to the right of the movement in the Northern Hemisphere. In that paper they proposed the new empirical formula (3) based on field observations and theoretical arguments.

$$\theta = 25°\exp(-10^{-8} W^3 / \nu g) \quad (3)$$

where

θ = deflection angle (degrees, clockwise in Northern Hemisphere)
W = wind speed ($m\ s^{-1}$)
g = gravitational acceleration ($m\ s^{-2}$)
ν = kinematic viscosity of seawater ($m^2\ s^{-1}$)

In the present work formula (3) was adopted since it showed good agreement with the field observations.

Therefore the lack of knowledge about the appropriate deflection angle and the ambiguity of the wind factor of 2–4% represent another strong enough reason to model uncertainty.

The velocity of the current, V_c, is supposed to include all components of the local current, except the wind induced surface component. Therefore, excluding the last one V_c will be the resultant of the vectorial addition of the large-scale mean circulation (residual current) and the tidal currents.

The trajectory of the oil spill is then calculated according to the available values of W and V_c on a given time step, as a straight-line segment. Starting from a certain point, expressed in geodesic co-ordinates, the co-ordinates of the arrival point are calculated, taking into account the distance covered.

3. Uncertainty modelling

Oil spill models include various mechanisms that are described by differential equations relating several parameters. The values of those parameters have associated uncertainties and in the case of environmental variables they have a stochastic nature.

The deterministic models represent neither the uncertainty of the parameters nor the variability of the environmental processes, because they use deterministic values of the parameters. If these values are the best estimates of the input variables as given by their expected values, the model will predict the expected or mean output, including for example, the expected trajectory.

To increase the amount of information provided by the model it is necessary to represent the variability that is associated to various parameters. For that purpose, the uncertain parameters and the variables of stochastic behaviour can be modelled by random variables. In this case, the trajectory or any of the other results of the model become functions of random variables.

The simplest way of describing a random variable is through its mean value and standard deviation, without indicating the type of probabilistic distribution that describes it. In fact, when the values are close to the mean value, the results are not very sensitive to the type of probabilistic distribution and in this case it is frequently assumed that the normal distribution is appropriate to describe the random variable. This distribution is completely described by its mean and variance.

Assuming the simplest description of the variables based on the first and the second statistical moments, it is possible to use classic formulations of the theory of the error to calculate the mean value and the standard deviation of the function of random variables $f(x)$ (e.g. Benjamin and Cornell, 1970).

Generally, $f(x)$ will be a non-linear function that can be linearized around a reference point by a first order Taylor expansion:

$$f(x)=f(x^*)+\sum\left(\frac{\partial f}{\partial x_i}\right)_{x^*}(x_i-x_{i^*}) \tag{4}$$

Its first two statistical moments are given by

$$E[f(x^*)]=f(x^*) \tag{5}$$

$$V[f(x^*)]=\sum_i\sum_j\left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right)\sigma_i\sigma_j\rho_{ij} \tag{6}$$

where $E[f(x^*)]$ and $V[f(x^*)]$ represent, respectively, the expected value and the variance, x^* is the point around which f is linearized, σ_i is the standard deviation of x_i and, ρ_{ij} is the correlation coefficient of the variables i and j.

If there is no correlation between the variables i and j then expression (6) simplifies to

$$V[f(x^*)]=\sum_i\left(\frac{\partial f}{\partial x_i}\right)^2\sigma_i^2 \tag{7}$$

that is the conventional formula for the propagation of the uncertainty. Therefore, $V[f(x^*)]=\sigma_R^2$, where σ_R is the standard deviation of the model result, $f(x)$.

The contribution of the uncertainty of a parameter x_i to the global uncertainty of the model σ_R is a measure of the sensitivity of the uncertainty of the model to that variable. Thus, for parameter x_i, a relative sensitivity S' can be defined by normalizing $\partial f/\partial x_i$ with σ_i/σ_R, leading to:

$$S'(f|x_i)=\left(\frac{\partial f}{\partial x_i}\right)\Big/\frac{\sigma_R}{\sigma_i} \tag{8}$$

Substituting σ_R by Eq. (7) one obtains

$$\alpha_i=\frac{\sigma_i}{\sqrt{\sum_i\left(\frac{\partial f}{\partial x_i}\right)^2\sigma_i^2}}\left(\frac{\partial f(x)}{\partial x_i}\right). \tag{9}$$

where α_i is the importance factor or relative sensitivity of variable x_i. After normalizing, equality (10) is verified:

$$\sum_i\alpha_i^2=1. \tag{10}$$

In the application of this method, the result of the model is determined for a set of values of the input parameters chosen *a priori* (the reference situation). The value of the derivative $\partial f/\partial x_i$ is calculated by finite differences determined from deterministic small variations of the parameters in relation to their reference values considering the approximation:

$$\left(\frac{\partial f}{\partial x_i}\right)\approx\frac{\Delta f}{\Delta x_i} \tag{11}$$

Using forward differences the derivative of f in relation to the parameter x_i $(1\le i\le n)$ *is* calculated numerically by:

$$\frac{\partial f(x_1,x_2,\ldots x_i,\ldots,x_n)}{\partial x_i}\approx\frac{f(x_i,x_2,\ldots,x_i+\Delta x_i\ldots,x_n)-f(x_i,x_2,\ldots x_i,\ldots,x_n)}{\Delta x_i} \tag{12}$$

The backward differences are defined in a similar way. Central differences are determined by

$$\frac{\partial f(x_1,x_2,\ldots,x_n)}{\partial x_i}\approx\frac{f(x_1,x_2,\ldots,x_i+\Delta x_i\ldots,x_n)-f(x_1,x_2,\ldots x_i-\Delta x_i\ldots,x_n)}{2\Delta x_i}. \tag{13}$$

Using the general formula of the expansion of Taylor series it is verified that the calculation of the derivative through central differences has a second order truncation error, while the forward and backward differences have first order truncation. However these last ones just need one evaluation of the function, if $f(x^*)$ is known.

In this work forward differences were used in the calculation of the derivatives. An uncertainty analysis provides two types of information: first it calculates the relative importance of the uncertainty of each input parameter in the uncertainty of the global results of the model second, it calculates the global uncertainty of the model in function of the uncertainties of each input parameter.

4. Simulation of the Marão oil spill

4.1. Description of the accident

At 14:35 h of July 14, 1989, the Portuguese flagged tanker *Marão*, carrying 124,500 tons of Iranian Heavy crude oil was approaching the oil terminal of Sines. Due to the fog, it collided with the head of the western quay making two holes below the waterline that affected the tanks 1 and 4 on the portside. About 1000 l of crude were spilled in the place.

During the following hours the ship released ca. 4500 tons of crude oil, that polluted the coastline from Sines to Zambujeira do Mar in the south western coast of Portugal, until the ship reached the oil terminal and begun emptying the damaged tanks. The 13 approximate locations and shapes of the part of the spill that remained at sea are schematically shown in Fig. 1. The shape and location of the spilled oil are based on aerial and ship visual observations in the days after the spill and as they are constructed based on information from different sources and at different instants of time. Therefore they need to be interpreted with some care and not as very exact information. The arrows indicate the zones of larger incidence in the coast.

The approximate area covered by the spill, remaining at sea (ca. 2 miles offshore) on the 15th July at 20:30 h, was ca. 3–4 miles long. On 17th July the area was 7 miles long per 2 miles wide, located 2 miles away from the coast. On the 18th July it was observed that the spillet broke into two. One of them was going ashore and the other one moving away from the coast towards SW.

4.2. Simulation of the evolution of the physical-chemical properties of the Marão oil spill

The accident has been simulated with the system of Guedes Soares et al. (2000) briefly described earlier here. The conditions used in the simulation of the Marão oil spill were the following:

Approximate position of the spill 37°.55′ N 8°.53′ W
Date (beginning of the simulation) 14-07-89 12:00 h
Spilled volume 4.500 ton
Product Iranian heavy crude
Temperature 19.4 °C

Table 1 and 2 list properties of the crude and Table 3 shows the properties of the seawater that were used in the calculations.

The simulation of the evolution physical–chemical properties of the spilled crude, which was made on the basis of the model described in Sebastião and Guedes Soares (1995), included the fraction evaporated, water content, viscosity, density, area, volume and thickness. The plots of these results for the first 100 h of spill are

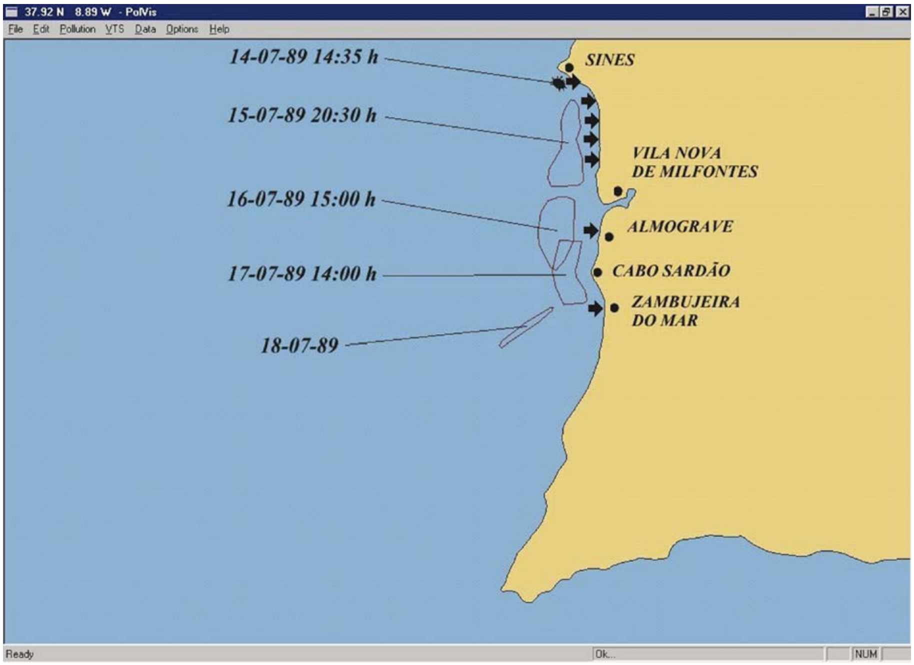

Fig. 1. Approximate locations of the spill produced by the *Marão* oil spill obtained by aerial and ship observations between 15 and July 18, 1989. The arrows indicate the zones of larger incidence in the coast.

Table 1
Distillation parameters of the Iranian heavy crude for evaporative exposure method (Stiver and Mackay, 1984[a] Jokuty et al., 1999[b])

A	6.3[a]
B	10.3[a]
T_0	302.623 K[b]
T_G	600.0761[b]

shown in Fig. 2a)–g). The use of this model is relevant for determining the size of the oil slick as time progresses. This study is concentrated on the uncertainty in the prediction of the trajectories and thus, although the weathering module was used, it did not provide estimates of the uncertainties involved in those variables.

4.3. Simulation of the trajectory of the offshore spill

From the observations drawn in Fig. 1 it seems evident that the processes that originate the transport and spreading of the spilled oil led to a separation of the total mass into two main parts: one that was displaced towards the coast, and, the other one that remained offshore. These observations suggested that two distinct main driving forces have transported each of the parts of the spill: the wind would dominate one of them while the other would start sinking, becoming protected from the influence of wind and was then transported by the tidal current. In order to test these hypothesis two simulations were done: one using the wind fields only, and the other using wind and tidal currents.

The simulation of the trajectory using only wind fields was based on Eq. (2). A wind factor w_f=0.04 was considered and a defection angle depending of the wind speed calculated by Eq. (3) was used in order to account for the Coriolis effect.

Wind fields supplied by the European Center of Medium Range Weather Forecast (ECMWF) were used, with space and time resolution of 2.5°×2.5° and 6 h, respectively. The wind vectors for each location of the spill were obtained by interpolation. Fig. 3 shows the wind vectors between 14-07-89, 12 h and 31-07-89, 18 h interpolated for the simulated locations of the spill. For comparison, Fig. 4 shows the mean direction and frequency of the wind in the month of July measured between 1967 and 1980 in the station Zambujeira (INMG, 1991).

Table 2
Properties of the Iranian heavy crude (Jokuty et al., 1999)

Maximum absorbed water fraction, C_3	0.7
Crude viscosity, μ_c	17.22 cP (19.4 °C)
Crude density, ρ_c	870 kg m^{-3}
Oil–water interfacial tension, γ_{ow}	22.5 dyn cm^{-1} (15 °C)

Table 3
Properties of seawater (Horne, 1969[c])

Relative viscosity, $\mu_{rel\ w}$	0.6815 (35‰ S at 15 °C)[c]
Specific gravity, ρ_w	1024 kg m^{-3}

In Fig. 5, the continuous line that is approximately parallel to the coastline shows a simulated trajectory of the *Marão* oil spill between 14-08-89,12:00 h and 18-07-89,18:00 h. The calculated trajectory approximately follows the observed trajectory that is shown in Fig. 1.

4.4. Simulation of the trajectory considering tidal currents

In Fig. 5 the calculated trajectory forced by the wind field shows good agreement with the observed trajectory of the spill that remained offshore, but the trajectory of the part of the spill that reached the coast is not reproduced. Therefore another simulation was done using now the tidal currents and the wind forcing.

The current fields were calculated by the 2D hydrodynamic model developed by García and Kahawita (1986) that simulates the currents due to the tide and the wind, using a 16 shallow water approach. The hydrodynamic equations are solved through an explicit discretization based on the method of finite differences of Mac Cormack.

Vertically integrated models can give wrong estimates of the surface currents in situations where the current velocity changes much along the vertical axis. However these models give good results in cases where velocity of the current is almost uniform in the vertical, as happens in shallow water areas where the tidal currents dominate (García-Martínez and Flores-Tovar, 1999).

The computational domain considered extends to an area of 61 km along the coast per 27 km (perpendicularly to the coast) approximately from the North limit of Fig. 1 to Almograve. In the considered area the isobaths are reasonably parallel to the coast and the maximum depth does not exceed 200 m in most of the area, and therefore it was considered that the shallow water approach could be applied. The domain was discretized in cells of 1×1 km. The currents are induced by the wind and the tide. The tide was imposed as boundary condition in the Southern border of the domain (on the left in Fig. 6). This boundary was chosen because the results obtained were reasonable in most of the domain, and it presented less abrupt variations of depth than the Northern border, due to the proximity of the Cape of Sines. It was not possible, however, to compare the results obtained with measurements, what would be important to validate the model.

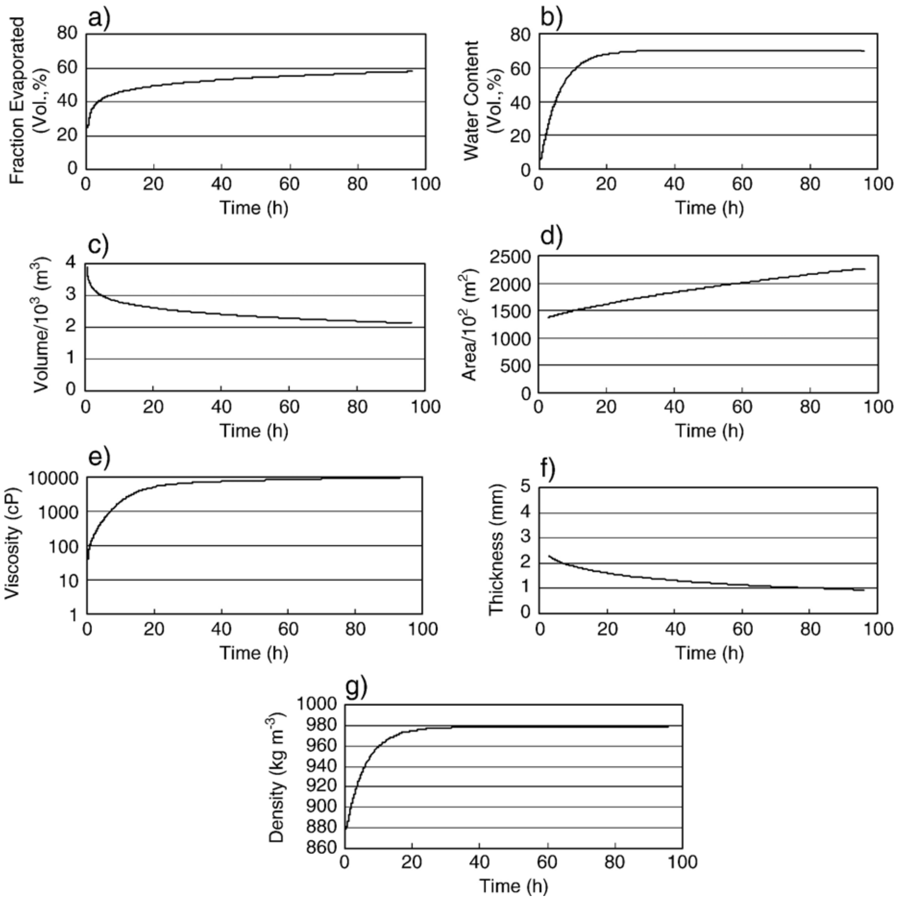

Fig. 2. Simulation of the evolution of the physical–chemical properties of the *Marão* oil spill between 14-07-89 12 h and 18-07-89 12 h.

Fig. 6 shows the velocity field of the current calculated at 12 h 14-07-89-2.5 h before the accident. Fig. 7 shows the calculated trajectory of the spill using expression (2) (without the observations— a) and with the observed spillets, b)), but considering, now, the tidal currents calculated by the hydrodynamic model, in intervals 17 of 30 min, and the 6 hourly wind as used in the first example. In the same way, the values of the currents and the wind were interpolated for each location of the spill.

No deflection angle due to the Coriolis force was considered here. In fact, the conditions that originate an integrated vertical current with a theoretical angle of 45° to the right of the wind are not satisfied near the coast (Elliott, 1986). And, as will be seen below, when considering a zero angle the results obtained agree with the observations.

The calculated area of the spill is represented by ellipses with the larger axis lined up with the wind direction and with double length of the smaller axis. The intersection of the ellipses with the coastline gives the indication that the spill has contacted land.

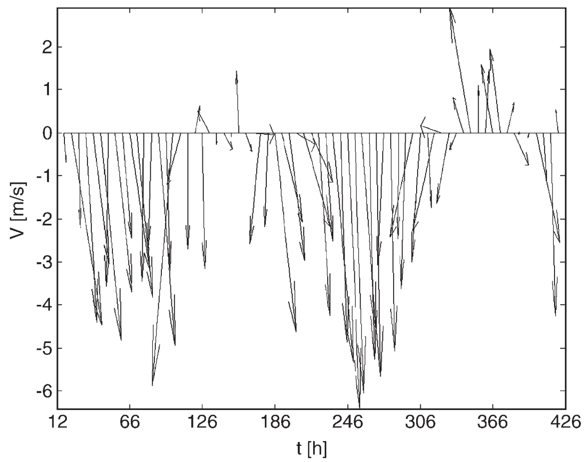

Fig. 3. Wind velocity vectors between 14-07-89,12 h and 31-07-89,18 h interpolated for the calculated locations of the spill. Data supplied by European Center (ECMWF) with a resolution of 2.5°×2.5°.

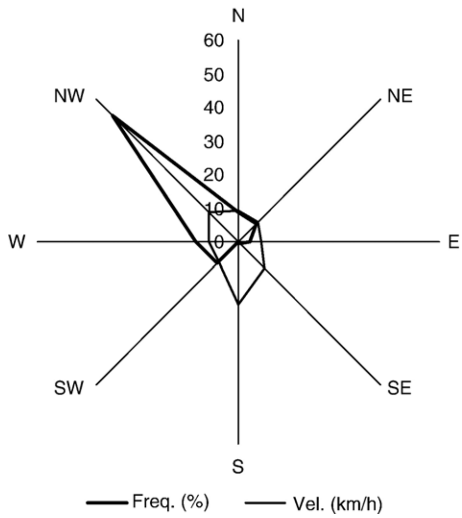

Fig. 4. Direction and mean frequency of the wind for the month of July between 1967 and 1980 measured in the station of Zambujeira (INMG, 1991).

Fig. 7 shows again a good agreement between the simulated trajectory and the incidence on the coast that was verified from Sines to Almograve, as shown by the arrows in Fig. 1. It is verified unequivocally that the model predicts the contact of the spill with the coast. Furthermore the model predicts that the spill would not reach Vila Nova de Milfontes (Fig. 1), as indeed it did not happen. But, on the other hand, the first contact with land that was predicted by the model, occurs lower to the South than the observations and it did not predict that the spill would reach Almograve.

Thus, it can be concluded that the model predicts well the global displacement of the spill, however it does not explain some details. For example, it is not able to predict the division of the main spill into smaller parts, that later move independently, and, it does not take into account the mass loss that is retained in the coast and that later will be removed by the cleaning operations. However these handicaps are part of the intrinsic limitations of the model.

It is evident in Fig. 7b) that the calculated area of the spill is much smaller than the observations suggest. However the observations were mainly visual with low precision and no scientific control. Therefore a more accurate study would be needed in order to evaluate the performance of the model concerning the calculation of the area. In any case, as was stated before, the Fay type formula that is used in the model is not suitable for non-circular spills that occur under the stress of wind and turbulence of the sea.

4.5. Application of the uncertainty model to the trajectory of the spill

The simulation shown in Fig. 7 was done between 14-07-89, 14:30 h and 18-07-89, 18 h using the mean value of

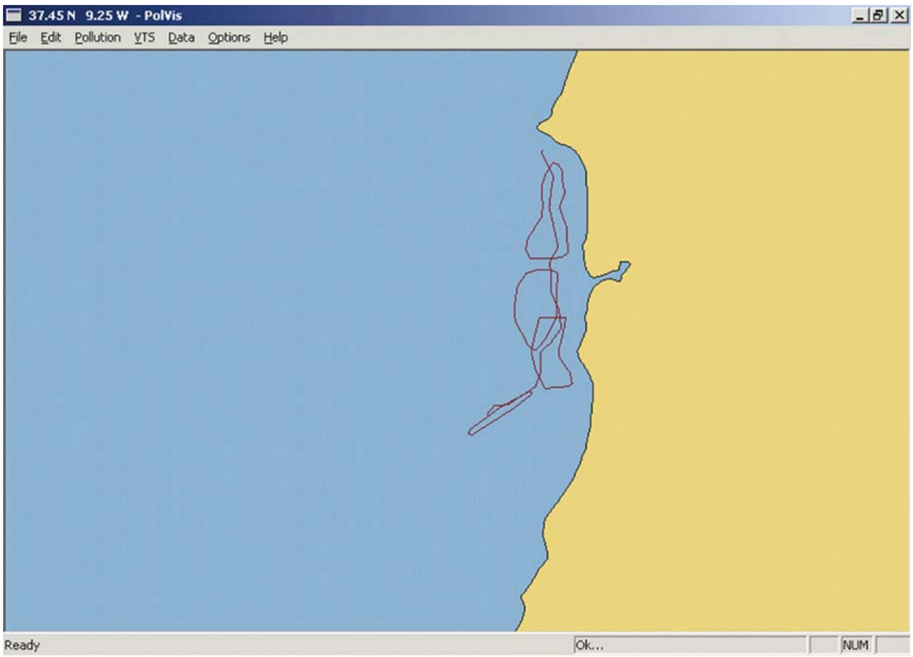

Fig. 5. Simulated trajectory of the *Marão* oil spill using wind fields only: the continuous line approximately parallel to the coast. The trajectory follows the observed offshore surface spill as is represented in Fig. 1. Simulation between 14-08-89 12:00 h and 18-07-89 18:00 h.

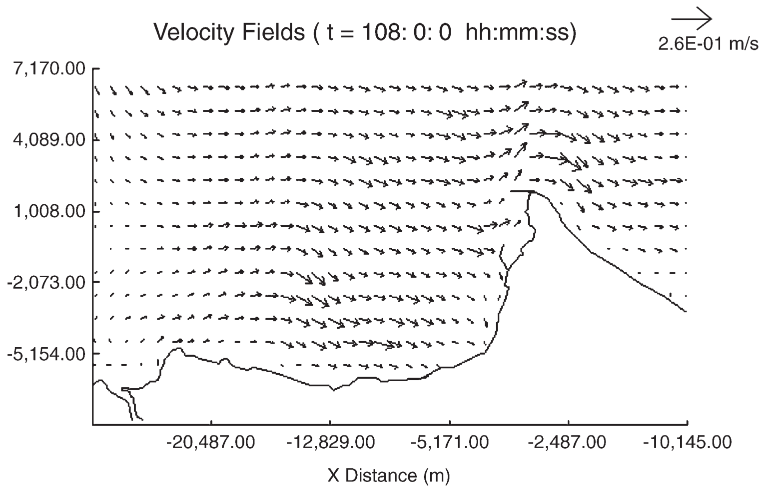

Fig. 6. Velocity field of current calculated by the 2D model (García and Kahawita, 1986) at 12:00 h 14-07-89.

the parameters presented in Table 4, namely the x and y components of the wind velocity (V_x, V_y) and the respective components of the current (C_x, C_y). Also w_f from Eq. (2) was considered as uncertain. New simulations were done introducing ±10% deviations in the parameters relative to the mean values. In principle the various input variables would have different level of uncertainty but there is no data available in this respect and thus it was decided that equal values would be used to all. In fact the objective was basically to verify how the results would be sensitive to this

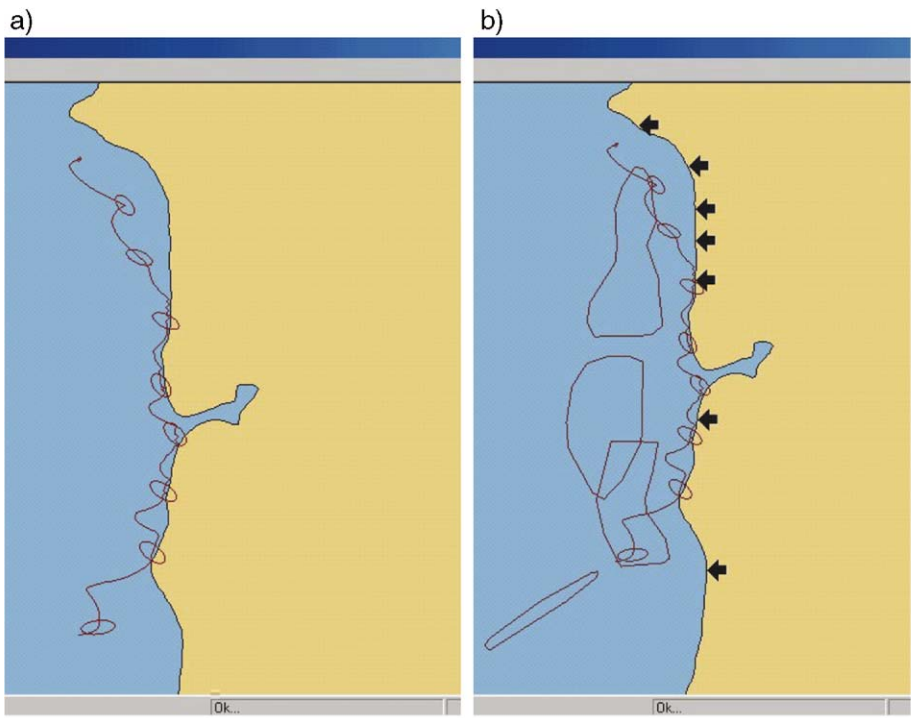

Fig. 7. Simulation of the *Marão* oil spill using the tidal currents calculated by the hydrodynamic model between 14-07-89 14:30 h and 18-07-89 18:00 h. The ellipses represent the calculated area of the spill. a) results of the model; b) observed spillets. The arrows indicate schematically the zones of larger incidence in the coast.

Table 4
Mean values of the wind and current and of the errors along the calculated trajectory of the *Marão* oil spill in 1989

	Mean	$\overline{\sigma}i$	α_i
V_x (ms^{-1})	1.09	0.17	0.11
V_y (ms^{-1})	−3.49	0.35	0.69
$\lvert C_x \rvert$ (ms^{-1})	0.086	0.0086	0.095
$\lvert C_y \rvert$ (ms^{-1})	0.029	0.0029	0.0025
W_f	0.035	0.0035	0.71

Factors of importance of V_x, V_y, C_x, C_y e w_f.

input uncertainty and which level of uncertainty would lead to a better adjustment with the field data.

Those simulations, shown in Fig. 10, allowed analyzing the uncertainty of the distance of the final point of the trajectory, in relation to the point obtained for the mean parameters, as a function of the variations of each parameter. The factors of importance are presented in Table 4 and Fig. 8. The calculated global error was: $\sigma_R = 3.48$ km.

These values were calculated based in the mean error of each parameter ($\overline{\sigma}i$), which was considered to be 10% of its value, along the trajectory of the spill.

If instead of forward differences, central differences are used in the calculation of the partial derivatives in Eq. (6) a global error (σ_R) of 3.14 km is obtained and the respective factors of importance are shown graphically in Fig. 9. Some variation in the factors of importance is found: the importance of V_y dominates, while the importance of C_x rises while the one of V_x, decreases.

The next simulations were conducted to determine what would be the trajectory when it is calculated with parameters perturbed by the deviations considered. Considering deviations of ±10 % in relation to the mean values of each parameter the trajectories obtained are shown in Fig. 10a) and b), respectively without and with representation of the calculated area. The overlap of the ellipses corresponding to the area of the spill in the different locations originates a denser "band" that defines an area that the model foresees to be potentially reached by the spill.

Proceeding in the same way but now considering deviations of ±25% in relation to the mean values of each parameter the trajectories represented in Fig. 11a) and b) are obtained. In this calculation the areas of the ellipses were also calculated considering $K_1 = 187.5\ s^{-1}$ (increase of 25% in relation to its default value). The width of the "band" obtained is obviously larger.

Applying the same procedure of performing simulations introducing ±10% deviations in the parameters relative to the mean values, to the simulation illustrated in Fig. 5 and 11 is obtained. It is observed that the band of likely trajectories gives a good estimation of the observed trajectory.

5. Conclusions

A method to calculate and account for the uncertainties associated to the trajectory predicted by an oil spill model was introduced. It allows identifying the weight that the uncertainty of each parameter has in the uncertainty of the result of the simulation and to calculate the uncertainties associated to the trajectory. This can be useful to help making decisions on spill response operations, since the user has access not only to best estimates given by the oil spill model but also to the intervals of variation of the results.

The importance of considering uncertainty aspects should not be neglected since the oil spill model has to be fed with the input of data that has always some degree of uncertainty. Furthermore, when the modelling capability is limited, the calculation of the uncertainty of the results gives a more realistic result to be interpreted.

The application of the method to the *Marão* oil spill that occurred in a coastal zone showed that when

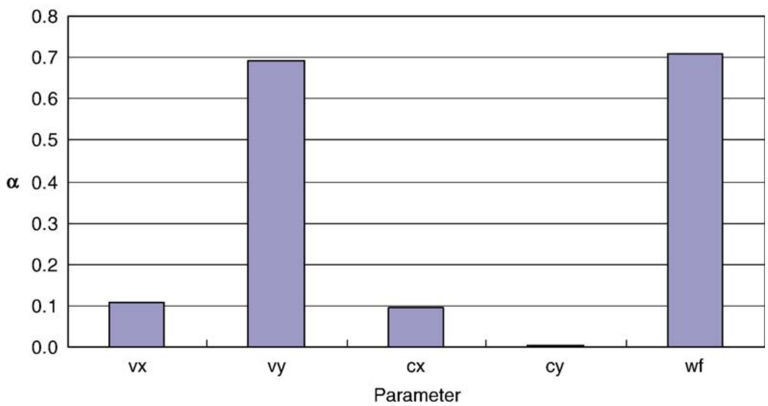

Fig. 8. Factors of importance of V_x, V_y, C_x, C_y and w_f in the uncertainty in the uncertainty of the final destiny of the trajectory of the *Marão* oil spill of taking as reference the final point calculated with mean parameters. The derivatives were calculation using forward differences.

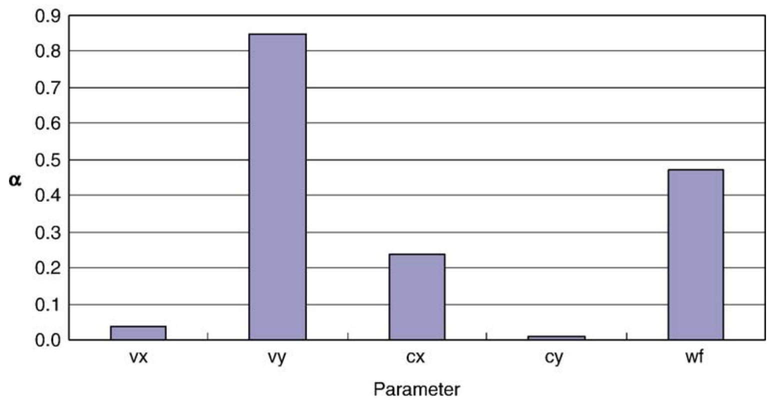

Fig. 9. Factors of importance of V_x, V_y, C_x, C_y and w_f in the uncertainty in the uncertainty of the final destiny of the trajectory of the *Marão* oil spill of taking as reference the final point calculated with mean parameters. The derivatives were calculation using central differences.

considering the existence of errors in the input parameters the corresponding ranges of the output results allow obtaining a more realistic picture of the evolution of the oil spill.

The simulation of the *Marão* oil spill with the input of wind fields reproduced well the parcel of the spill that remained offshore (Fig. 12). The simulation with the input of both currents and wind predicted the trajectory of the parcel of the spill that has reached the coast (Fig. 11). Since the wind has stronger effect on the upper layer of the water column, and because near the coast the tide has effect over the entire water column, it is reasonable to consider that the parcel of the oil spill that was mainly driven by the wind was predominantly at the surface. The other parcel was more dispersed below the surface driven mainly by the tidal current.

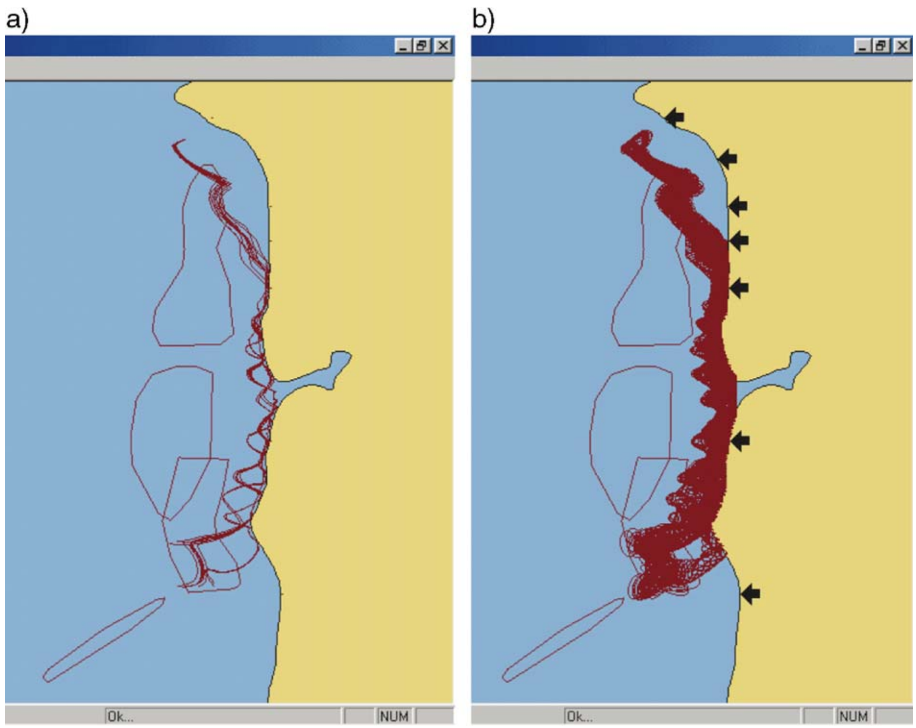

Fig. 10. The *Marão* oil spill. Trajectories considering the parameters V_x, V_y, C_x, C_y and w_f affected by variations of ±10%. a) trajectories; b) trajectories and area of the spill.

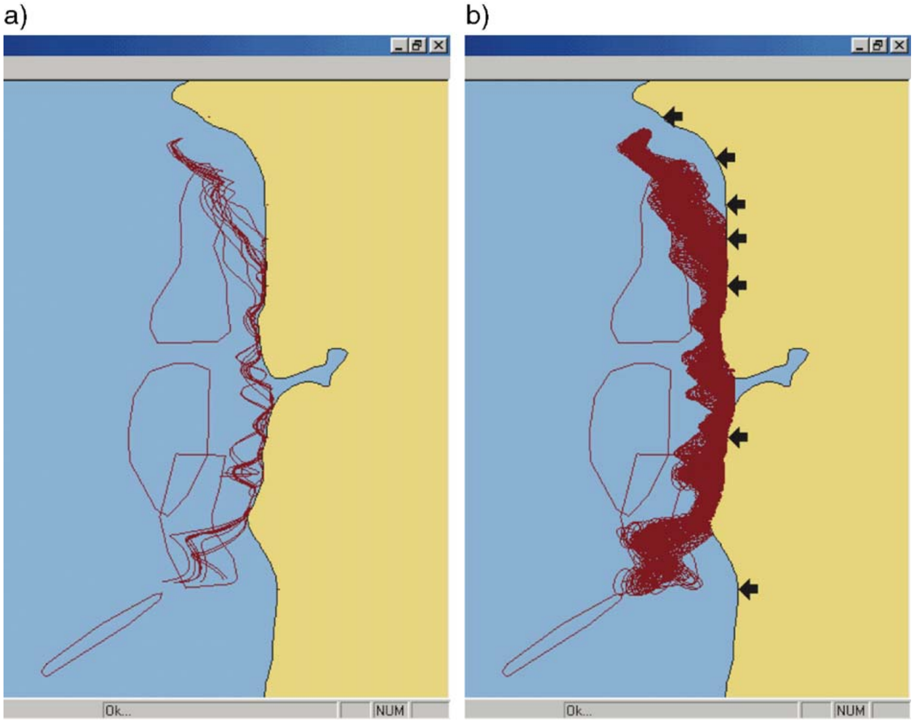

Fig. 11. The *Marão* oil spill. Trajectories considering the parameters V_x, V_y, C_x, C_y and w_f affected by variations of ±25%. a) trajectories; b) trajectories and area of the spill.

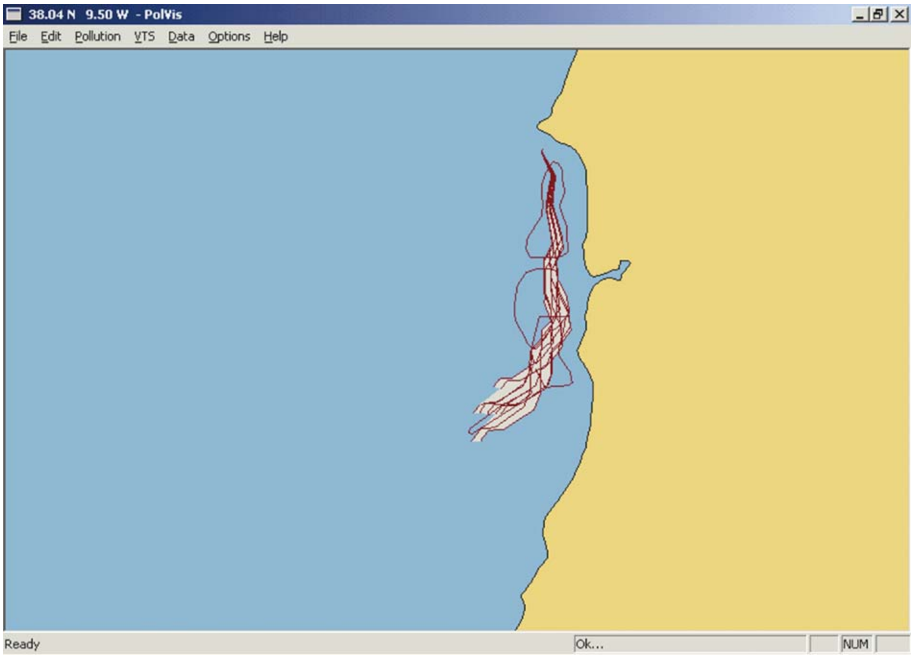

Fig. 12. Simulated trajectory of the *Marão* oil spill using wind fields only: and considering the parameters V_x, V_y, w_f and θ, affected by variations of ±10%. Simulation between 14-08-89 12:00 h and 18-07-89 18:00 h.

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