

3D Oil Spill Model: Application to the “Happy Bride” Accident

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Abstract The application of the European Water Framework Directive and the monitoring obligation on water quality for human consumption and industrial activities create a need for water quality assessment and monitoring systems. The MIGR’Hycar research project (see: <http://www.migrhycar.com>), partly funded by the French National Agency for Research (ANR), was initiated to provide decisional tools and fulfil operational needs for risks connected to oil spill drifts in continental waters (river, lakes, estuaries). Within the framework of the Migr’Hycar project, a three-dimensional (3D) numerical oil spill model has been developed. A Lagrangian model describes the transport of an oil spill near the free surface. The oil slick is represented by a large set of small particles. The model enables us to simulate the main transport process that acts on the spilled oil: advection (wind, current), diffusion (turbulence) and the shoreline oiling model. In order to validate the 3D Ouary 2006, the tanker “Sigmagas” suffering technical damage collided with another tanker “Happy Bride”. 60 t of heavy fuel has been spilled in Loire estuary because of tanker collision. The oil slick drift in the estuary and the affected area location have been followed with aerial and land

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observations. These observations allow us to assess the quality of the numerical predictions. Promising results are found and presented in this paper.

Keywords Lagrangian model · Oil spill modelling · Stochastic diffusion · Shoreline oiling model · Loire estuary

1 Introduction

Although in almost half of all instances of contamination, the exact cause is never determined, oil spills can be due to human error, accidental or voluntary discharge of cargo residues, domestic or industrial tank overflow, leakage from fuel stations, traffic accidents or fire, and among other causes.

When faced with hydrocarbon contamination of inland waterways, authorities and other organizations can seldom rely on dedicated decision-making tools to intervene in an effective way.

Whereas considerable management and monitoring resources are rapidly deployed for off- or inshore oil incidents, the more frequent occurrence of continental water pollution is dealt with relatively modest means. A limited grasp of the nature and magnitude of such events often renders both industry and government powerless in controlling their impact.

The Migr'Hycar research project (www.migrhycar.com) was initiated to provide decisional tools and fulfil operational needs, for risks connected to oil spill drifts in continental waters (rivers, lakes, estuaries). These tools are meant to be used in the decision-making process after oil spill pollution and/or as reference tools to study scenarios of potential impacts of pollution on a given site. The Migr'Hycar consortium has been organized to closely match project objectives and comprises modelling technology developers (EDF, Saint-Venant Laboratory for Hydraulics, ARTELIA, VEOLIA), researchers with long-standing experience of hydrocarbon physicochemical behaviour (Agribusiness laboratory LCA, CEDRE), engineering consultants liaising closely with local and regional authorities (ARTELIA), two water intake operators directly concerned with project-related issues and well experienced in applying protective warning systems (EDF, VEOLIA) and a major player in the oil industry (TOTAL). The consortium has therefore the expertise required to develop a surface water risk monitoring and prevention system against oil spillage contamination.

The proposed application of the deterministic model developed for this project is the modelling of the collision that took place between two butane carriers in the Loire estuary on 14 January 2006. On this date, the Happy Bride's heavy fuel oil tank was struck by the Sigmagas and subsequently spilt its 60 m³ reservoir of IFO 380. This event is presented below alongside a discussion of the results obtained and the areas for improvement to be considered. This will be preceded by a discussion of the bases of the hydraulics and transport models of the Loire estuary.

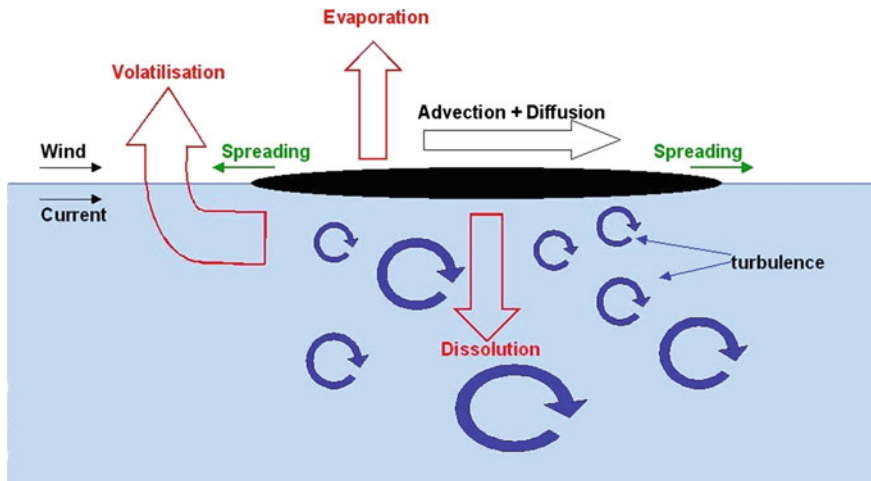


Fig. 1 Fate and transport oil surface slick processes

2 Presentation of the 3D Oil Spill Model

Within the framework of the Migr’Hycar project, a three-dimensional (3D) oil spill model has been developed by combining Lagrangian and Eulerian methods. This model enables us to simulate the main processes that act on the spilled oil: advection, diffusion, evaporation, dissolution, spreading and volatilization (Fig. 1). Though generally considered as a minor process, dissolution is important from the point of view of toxicity. The Lagrangian model describes the transport of an oil spill near the free surface.

To model the dissolved oil in water, an Eulerian advection–diffusion model is used. The fraction of dissolved oil is represented by a passive Eulerian scalar. This model is able to follow dissolved hydrocarbons in the water column (PAH: polycyclic aromatic hydrocarbons). The Eulerian model is coupled with the Lagrangian model.

In this work, only oil slick transport processes are described.

2.1 3D Hydrodynamic Model

Hydrodynamics is provided to the oil spill model using the TELEMAC-3D hydrodynamics model. TELEMAC-3D was developed by the National Hydraulics and Environment Laboratory, a department of Electricité de France’s Research and Development Division.

This open source freeware program (www.opentelemac.org) solves the following governing equations:

$$\frac{\partial U_i}{\partial x_i} = 0, \quad (1)$$

$$\frac{\partial U_i}{\partial t} + \frac{\partial U_j U_i}{\partial x_j} = F_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} - \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j}, \quad (2)$$

where $x_i = (x, y, z)$ denotes the spatial coordinates, t the time, $U_i = (U, V, W)$ the local time-averaged components of the flow velocity, F_i the component of external forces (gravity, Coriolis force,...), p the mean pressure, ρ the fluid density and τ_{ij} the component of the stress tensor calculated with the Boussinesq approximation and related to the gradient of the velocity and the turbulent eddy viscosity ν_t .

TELEMAC-3D solves the previous equation system using the finite element method on superimposed triangular meshes, the resulting elements being prisms. TELEMAC-3D can take into account the bed friction, the influence of the Coriolis force and meteorological factors, the turbulence, sub- and super-critical flows, river and marine flows, the influence of temperature or salinity gradient on density and dry areas in the computational domain, and among other processes [1].

2.2 Lagrangian Model

Eddies generated by turbulence affect the motion of petroleum particles in water and randomize their trajectory. Consequently, a stochastic approach is adopted to take this phenomenon into account. The advection–diffusion Eq. (3) is well adapted to modelling transport and dispersion of continuous contaminants, but since the present model uses a discrete particle description of contaminant transport and dispersion, a transformation must be applied to obtain a Lagrangian description.

$$\frac{\partial C}{\partial t} + \nabla \cdot (C\mathbf{U}) = \nabla \cdot \left(\frac{\nu_t}{\sigma_c} \nabla C \right), \quad (3)$$

where C is the pollutant concentration, σ_c the neutral turbulent Schmidt number and ν_t the turbulent viscosity. The turbulent Schmidt number can be set to $\sigma_c = 0.72$ [2].

The first transformation step consists of interpreting the concentration $C(\mathbf{X}, t)$ as a probability $P(\mathbf{X}, t)$ of finding a particle at a location \mathbf{X} at a time t . Then, the non-conservative formulation of Eq. (3) leads to the Fokker–Planck equation:

$$\frac{\partial P}{\partial t} = - \left[\mathbf{U} - \nabla \left(\frac{\nu_t}{\sigma_c} \right) \right] \nabla P + \nabla \cdot \left(\frac{\nu_t}{\sigma_c} \nabla P \right), \quad (4)$$

A stochastic solution to Eq. (4) is obtained by specifying the hydrocarbon particle position $\mathbf{X}(t)$ according to the following Langevin equation [3]:

$$\mathbf{X}(t + \delta t) = \mathbf{X}(t) + \left[\mathbf{U} - \nabla \left(\frac{v_t}{\sigma_c} \right) \right] \cdot \delta t + \sqrt{\frac{2v_t}{\sigma_c}} \cdot \delta t \boldsymbol{\zeta}(t), \quad (5)$$

where δt is the time step and $\boldsymbol{\zeta}(t)$ a vector with independent, standardized random components. In the above relationship, v_t and \mathbf{U} are computed by TELEMAC-3D using a k - ϵ turbulence closure model. The velocity vector \mathbf{U} takes the wind effect into account through the two-dimensional condition at the surface:

$$v \frac{\partial \mathbf{U}_h}{\partial n} = \frac{\rho_{\text{air}}}{\rho} a_{\text{wind}} \mathbf{W} \|\mathbf{W}\|, \quad (6)$$

with $\rho_{\text{air}} = 1.29 \text{ kg/m}^3$, \mathbf{U}_h the horizontal velocity at the surface and \mathbf{W} the wind velocity 10 m above the water. The coefficient a_{wind} (dimensionless) is given by Flather [4].

2.3 Shoreline Oiling Model

2.3.1 Oil Beaching on Shoreline

When an oil slick reaches a shoreline, it may deposit if

- The slick thickness is greater than the water level under the oil slick.
- The size of the bottom roughness is greater than the water level.
- The deposited oil volume does not exceed the maximum surface loading and maximum sub-surface loading which is given by Cheng et al. [5]:

$$M^* = \rho_o (\text{Surf}_{\text{shore}} \cdot T_m + C_v D_p L_s), \quad (7)$$

where M^* is the maximum oil mass deposited on the shore, $\text{Surf}_{\text{shore}}$ the shore surface, ρ_o the oil density, T_m the maximum oil thickness, C_v the sediment oil content, L_s the width of the shore, and D_p the depth of oil penetration on the shore.

The oil-holding capacity of a shore depends on both oil and beach characteristics. The parameters C_v , D_p and T_m are derived from real oil spill observations, and their values are summarized in Table 1 [6]:

2.3.2 Oil Refloating in the Water Current

The deposited spilled oil may be reentrained into the sea current if

- The water level under the oil slick is greater than the slick thickness.
- The water level is greater than the size of the bottom roughness.

Table 1 Oil-holding capacity [6]

Shoreline type	Maximum surface oil thickness (T_m) (mm) by oil viscosity			Oil loading capacity (C_v) ($m^3 \text{ oil}/m^2 \text{ sediment}$)			Depth of oil penetration (D_p) (mm)
	Light viscosity	Medium viscosity	High viscosity	Light viscosity	Medium viscosity	High viscosity	
Sandy beach	4	17	25	0.004	0.017	0.025	50
Gravel	2	9	15	0.0021	0.0091	0.0151	180
Rocky shore	1	5	10	0.001	0.005	0.01	0

- Random phenomena, such as gusts of wind, waves induced by boats, act on the spilled oil. This condition is taken into account using the probabilistic approach suggested by Danchuk [7].

The oil removal rate k_f is used to determine the probability of a particle of oil refloating P_{refloat} .

$$P_{\text{refloat}} = 1 - e^{-k_f t} \quad (8)$$

where k_f is the oil removal rate (day^{-1}) which depends on shore characteristics (sand: $k_f = 0.25$; gravel: $k_f = 0.15$; rock: $k_f = 0.85$).

Refloating for a particle is determined by choosing a random number $R_{(0,1)}$. The particle refloats if $R_{(0,1)} < P_{\text{refloat}}$.

3 The 3D Loire Estuary Hydraulic Model

Given its physical configuration and demographics, the Loire estuary is subject to considerable constraints and constitutes an area in which different human activities overlap. For the most part, the various industrial and commercial centres are concentrated around the major urban areas. The activity of the Nantes Saint-Nazaire port (now known as the Grand Port Maritime), in particular, has allowed several industries to settle in the industrial port area of Montoir-Donges.

At the same time, the organization and distribution of the drinking water production network reflect the specificities of the physical environment and as such consist of relatively few production units in relation to the population served. Water is supplied predominantly from surface sources.

Together, all of these elements make the estuary a sensitive environment where hydrocarbon pollution could have a serious impact both on the water and, by extension, on its use for agriculture, drinking water supply and industrial use at the EDF power plant at Cordemais.

The GIP Loire estuaire (GIPLE) (<http://www.loire-estuaire.org>) commissioned ARTELIA with a study to develop and operate a 3D hydrosedimentary model of the Loire estuary in the context of its “Programme to restore the Loire estuary

downstream of Nantes”. This hydrodynamics model was reused in the context of the Migr’Hycar project. It correctly reproduces the tide propagation in the estuary and upstream as far as Nantes. A brief description of the model is given below.

3.1 Presentation of the Model

This model covers an area that extends from Ancenis upstream to the Grande Baie downstream, including the Bourgneuf Bay to the south and the headland of Le Croisic to the north, totalling around 90 km of river and 40 km of coastal waters out to sea. The horizontal finite element mesh consists of approximately 7,052 nodes and 12,855 triangles of size in the range 50–2500 m. The mesh is refined in the main channel of the Loire estuary. Ten horizontal meshes are stacked to generate the 3D mesh (Fig. 2).

The daily flow rate measured at Montjean was imposed at the upstream limit of the model (Ancenis). During floods, it includes the flow rates from the Sèvre and

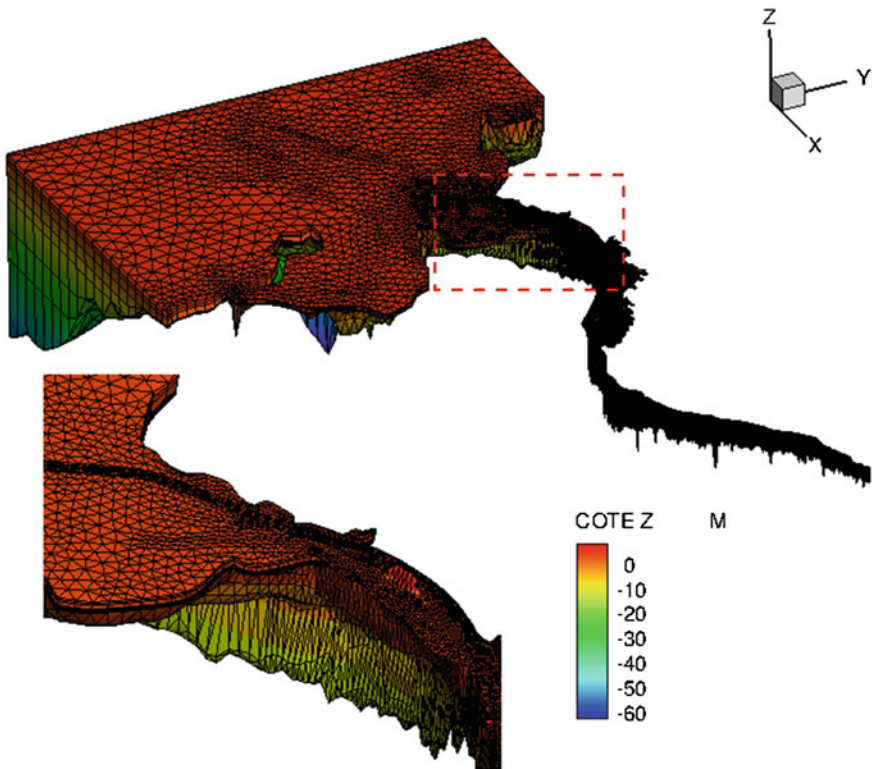


Fig. 2 Three-dimensional mesh of the Loire estuary

the Erdre rivers. The astronomical tide is imposed at the maritime limit of the model, with the average level calculated using tidal measurements from Saint-Nazaire for the period simulated.

3.2 Calibration

For the calibration of the model, the value of wind intensity at sea (as extracted from point CROISIC1 in the Prévimer database) is applied equally across the maritime part of the model and is then interpolated from the downstream limit of the Saint-Nazaire port access channel to downstream of Donges, where its value is considered negligible. The aim of taking wind into account in the model is not simulating tidal surges in the estuary, as this would require a more elaborate hydrometeorological model. In any case, surge is taken into account by the temporal evolution of the average level in the boundary conditions. The aim of including wind factors in the 3D model is to generate the 3D water circulation in the external estuary that is likely to lead to significant changes in the residual circulation of the astronomic tide. Such effects are in contrast negligible in the internal estuary, where the effects of turbid and haline stratification together with those of the tide and the flow rate of the Loire dominate. Later, to study the oil spill event, a spatially interpolated wind from the climate forecast system reanalysis (CFSR) model has been used [CFSR (<ftp://nomads.ncdc.noaa.gov/CFSR>)].

The main aim of the hydrodynamic calibration was to adjust the friction coefficients per zone in order to correctly represent tidal propagation within the estuary. The friction laws chosen are the Nikuradse law downstream of Sainte-Luce-sur-Loire and the Strickler law upstream of this point. The Nikuradse formulation depends on the grain size of sediment and on the velocity profile over the bottom, whereas the Strickler formulation only deals with the vertically averaged velocity. The Strickler formulation is preferable to include in friction other head losses, such as vegetation on the banks, groynes, weirs, bridge piers.

Taking liquid mud into account in the calibration stage required the use of a lower friction coefficient (in relation to the standard friction coefficient for a sandy river bed) in the area in which liquid mud is assumed to be present. This coefficient varies with the flow rate. The results obtained for tidal propagation in the estuary are presented in Fig. 3 for a flooding period.

Salinity and hydrodynamics were controlled using measurements from fixed stations for the low- and medium-flow periods in mid-October 2000 and for the flood in January 2004.

The period of October 2000, in which flow rate varied between 300 and 1,100 m³/s, is very interesting as far as salinity measurements are concerned. Indeed, the measurement points at surface and bottom level clearly demonstrate:

- During spring tide: a period of significant mixing associated with a large amplitude in salinity in the downstream sections of the estuary.

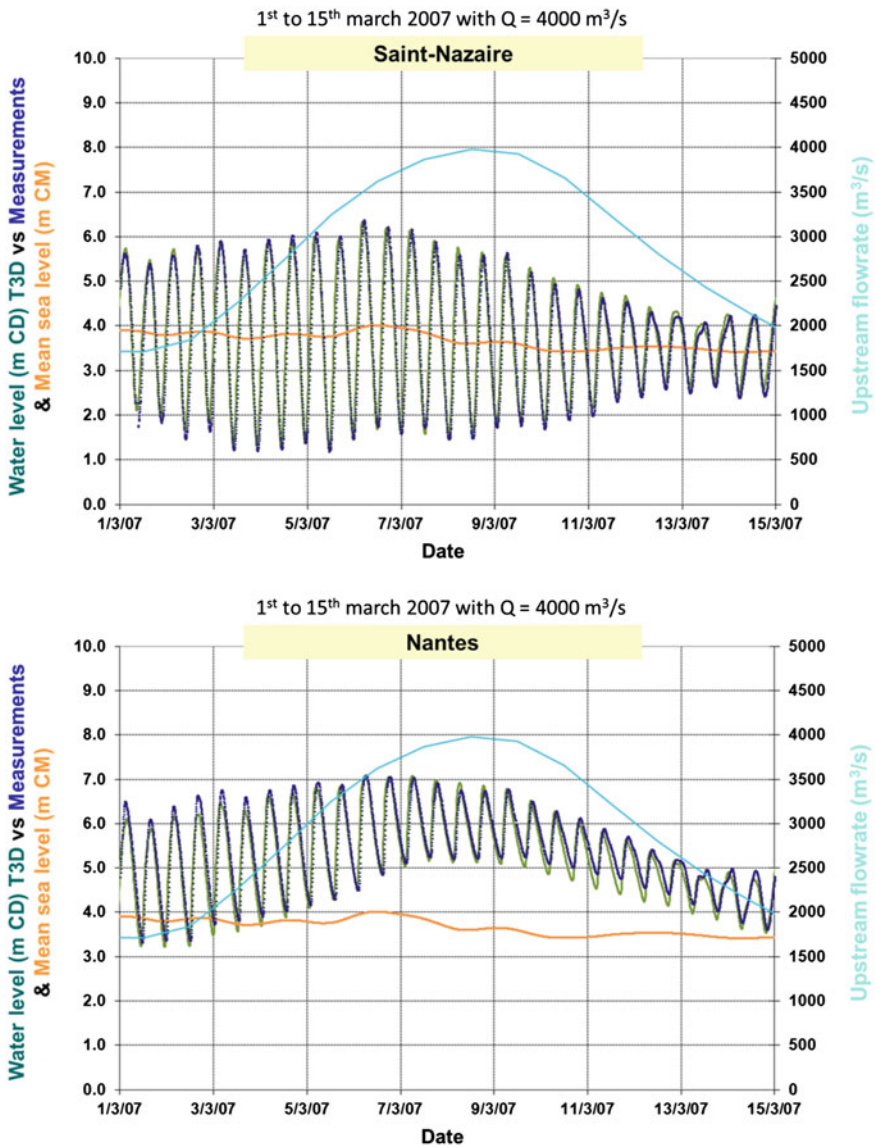


Fig. 3 Comparison of the water level between model and measurements at Saint-Nazaire (top) and Nantes (bottom) for a flooding period

- During neap tide: very different measurements at surface and bottom level, with a particularly large saline penetration upstream due to density effects when flow rates are low.

The flood period of January 2004 shows strong haline stratification in the navigation channel, particularly at Montoir during neap tide (Fig. 4). During spring tide, this stratification is present but less noticeable. Salinity, even during periods in which flow rates exceeded 4,000 m³/s, penetrates along the bottom of the navigation channel due to its density. The short periods of vertical mixing are due to gusts of wind in excess of 10 m/s. The model reproduces the mixing caused by wind relatively well.

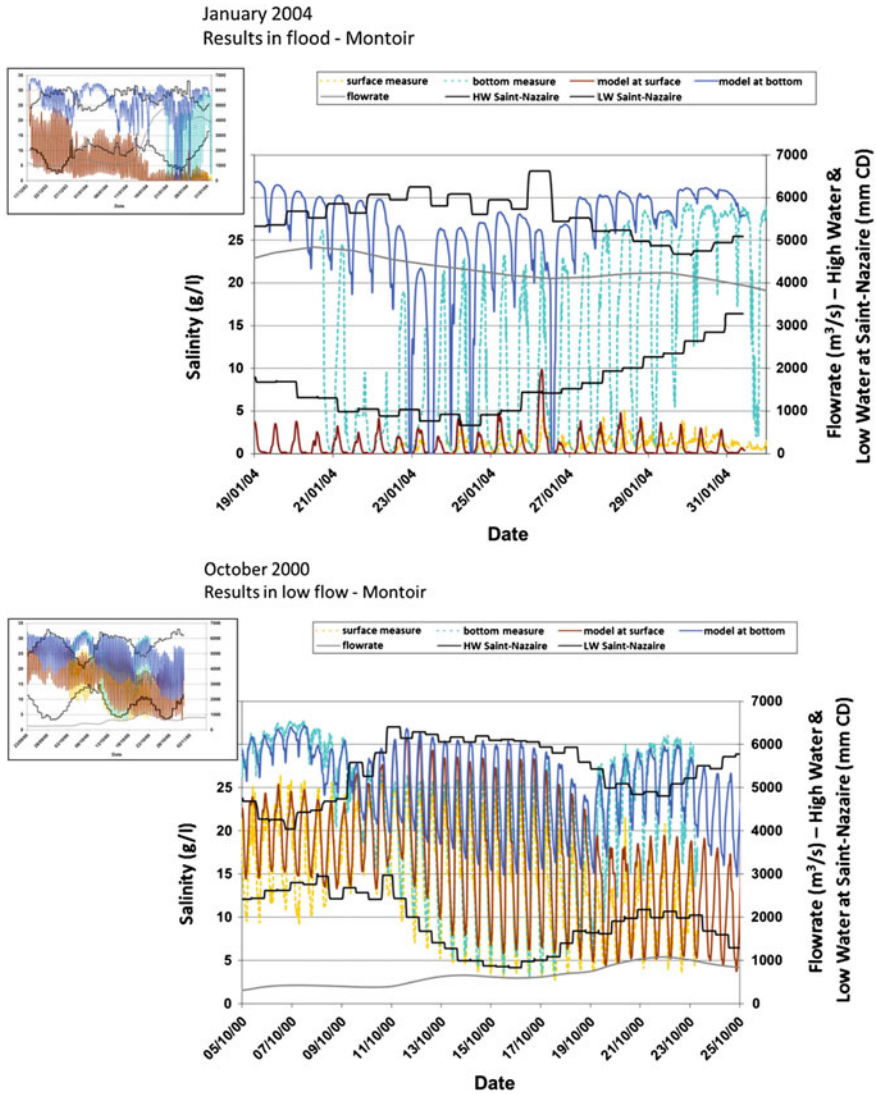


Fig. 4 Salinity varying with time at Montoir during flood (top) and low flow (bottom)

We can therefore conclude that the model reproduces the high levels of salinity stratification measured during the flood, as well as the saline penetration due to density as measured during neap tide.

4 Application to the Happy Bride and Sigmagas Collision

4.1 Description of the Accident

The Donges refinery produces liquid butane gas, part of which is transported by sea. Consequently, LPG tankers regularly transit through the Loire estuary. On 4 January 2006, the LPG tanker “Sigmagas” left the refinery after having loaded its cargo of butane, while the LPG tanker “Happy Bride” entered the channel on its way to the refinery. A few minutes before they crossed each other, the Sigmagas experienced a rudder problem which caused the vessel to veer to port on a collision course with the Happy Bride. At 8.20 pm, the Sigmagas hit the middle port side of the Happy Bride, rupturing a bunker oil tank. All the fuel oil contained in this tank (60 m³ of IFO 380) subsequently spilled into the estuary. On 5 January, an aircraft operated by the French customs authorities reported a 17 km-long, 300 m-wide oil slick (with an estimated quantity of 13 m³) running from Saint-Nazaire bridge in a west/south-westerly direction. The oil slick drift in the estuary and the affected area were followed with aerial and land observations. These observations allow the quality of the numerical predictions to be assessed.

4.2 Numerical Results

The mathematical model of oil slick drift developed in the Migr’Hycar project and the 3D hydrodynamic model of the estuary were used to simulate the drift of the polluting slick caused by the collision between the two liquid butane carriers.

1. Situation on Thursday 5 January 2006 (Fig. 5)

At the time of the collision, the current was directed downstream towards the Loire estuary outlet (high tide at 7.50 pm) and the slick was therefore carried towards the estuary outlet. This phenomenon was no doubt amplified by the saline stratification of the water. In the first few hours following the spill, the oil slick remained located in the northern part of the estuary, as shown on the maps produced by the accident crisis management teams [8]. This result was mirrored by the simulations, especially under the effect of a south-westerly wind.



Fig. 5 Summary of observations and simulations on the 05 January 2006

2. Situation on Saturday 7 January 2006 (Fig. 6)

Observations taken on land indicate the presence of small lumps of solidified oil in La Baule Bay and residues at the mouth of the estuary. The results obtained by the model match these observations.

Residual deposits are observed in the upstream and downstream vicinity of Donges refinery and on the right bank of the estuary. These deposits are probably due to lumps of oil previously deposited on the shore being picked up again as a



Fig. 6 Summary of observations and simulations on the 07 January 06

result of tidal-level variations. These pollution points are not detected by the model. The results show that improvements can be made by refining data on the adherence of the oil slick to the estuary banks. However, this parameter is very delicate because it depends not just on the location (distinguishing between different types of bank) but also on the date on which the simulated spill took place (different vegetation depending on the season).

The results obtained from this oil slick modelling procedure are encouraging and demonstrate the forecasting feasibility of the model with a view to preventing pollution of installations that might be affected in continental waters. In this same

area dominated by tidal currents and the Loire river flow, oil slick drift is affected to a large extent by wind conditions. By making better allowance for wind, and by processing more detailed data in time and in space, it should be possible to represent oil slick drift more accurately. The results can also be improved by a more detailed analysis of the adherence of the oil slick to the estuary banks.

5 Conclusions

While major oil spill catastrophes, occurring mainly in an oceanic or coastal environment, result in the rapid deployment of large-scale crisis monitoring and management tools, accidents of lesser importance, despite occurring much more frequently, are more often than not managed with only limited facilities, especially with regard to pollutant spills affecting continental waters. Given the limited knowledge of the nature and importance of such events, local authorities charged with taking the necessary health or economic protection measures are generally powerless when confronted with the environmental consequences. Accidents involving the oil pollution of continental waters are increasing at an alarming rate, with an average of one spill every 40 h over the 2008–2010 periods [9].

Application of the Water Framework Directive and the obligation to monitor the quality of water used for human consumption and for recreational or industrial activities have led to a massive rise in demand for water quality assessment and monitoring systems.

The Migr'Hycar project was set up in this context and has been used to develop a modelling tool to simulate the migration of oil slicks in continental and estuary waters. Linked to a database for hydrocarbon physical–chemical characterization, this tool is destined for operational use.

The Loire estuary test site, following the Happy Bride accident, was chosen in order to evaluate the relevance of the tools developed. This application illustrates the hydrodynamic complexity of the environment in these stratified areas where sea water mixes with freshwater from the river. A further difficulty is the need to properly reproduce the transport of oil pollution which is governed by currents and weather conditions. Given the complex dynamics of estuaries, 3D modelling seemed to be the only valid means of adequately predicting hydrocarbon drift and of assessing the impacts of dissolved compounds contained in the water from the surface to the bed.

The results obtained are encouraging and demonstrate the feasibility of pollution prevention for installations that could be affected by this type of pollution.

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