Hydrodynamic modeling of the Bay of La Rochelle to support the control of accidental oil spills

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EXTENDED ABSTRACT OF THE DISSERTATION SUBMITTED TO OBTAIN THE DEGREE OF MASTER IN:

ENVIRONMENTAL ENGINEERING

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Abstract

We validate a hydrodynamic system of the Bay of La Rochelle, providing Historical observations and predictions of several atmospheric and water conditions, including hydrodynamic properties.

We characterize the system application area, mainly his circulation patterns. Modeling system framework is explained, as well as main tools involved and developed are described. Different components of data acquisition are analyzed, and water modeling system applied – MOHID – is studied.

The model was implemented by using Mohid Water modelling system. The report describes data used to implement the model and their preprocessing. The hydrodynamic model was implemented by using downscaling technique including nested domains.

We make an analysis of modeling scheme configuration, and main options taken in that subject. Modeling results are compared with information obtained from automatic stations, monitoring campaigns, acoustic Doppler profilers (ADCP) and empirical data estimated from historical measurements made by tidal gauges.

The hydrodynamic model will provide hydrodynamic forecasts which will be used to assess the best location of oil booms in the occurrence of oil spill. The model is used to predict the movement and dispersion of small patches of oil to support the use of containment barriers. Scenarios are simulated to study most typical consequences of spill occurring on local with more marine traffic.

Key Words: MOHID, modeling, La Rochelle Bay, hydrodynamics, oil spill.

1. Introduction

The Charente coast is located in the middle of the French Atlantic coast along the Bay of Biscay, surrounded by the rocky coastline of South Brittany, in the north, and that of Aquitaine, straight and sandy, the south. It consists of approximately 460 km of coastline, mainly due to the presence of two major islands that are the island of Ré and Oléron Island (about 200 km coastline).

These islands are separated from the mainland by maritime areas locally called «Pertuis», which correspond to segments of incised valleys (Chaumillon & Weber, 2006).

From north to south, we can characterize the Pertuis Charentais in three different areas:

- The Pertuis Breton, between the Ile de Ré and the South Vendee coast, represents an area of 360 km^2;
- The Pertuis of Antioch, between the island of Ré and Oléron Island, represents an area of 350 km^2;
- The Pertuis of Maumusson, between the southern tip of the island of Oléron and the coast, represents an area of 260 km^2.

Figure 1 – Study area

The two main islands of Ré and Oléron, oriented Northeast / Southwest protect the areas from ocean swell forming tidal bays. The main one is the Bay of Marennes-Oléron (160 km2), located south of the Pertuis of Antioch between Oléron Island and the mainland. It is characterized by numerous and extensive intertidal flats (about 60% of the total area) interspersed with small tidal creeks. This semi-closed environment is identical to estuaries of mixed type dominant tide. (Gouriou,2012).

The Pertuis Charentais are subjected to strong anthropogenic impacts, especially because it is one of the largest shellfish farming areas in Europe. Bay of Marennes-Oléron is one of the most important European centers with an oyster shellfish stock about 95 000 tons with an annual production of about 35 000 to 40 000 tons (Modéran, 2010).

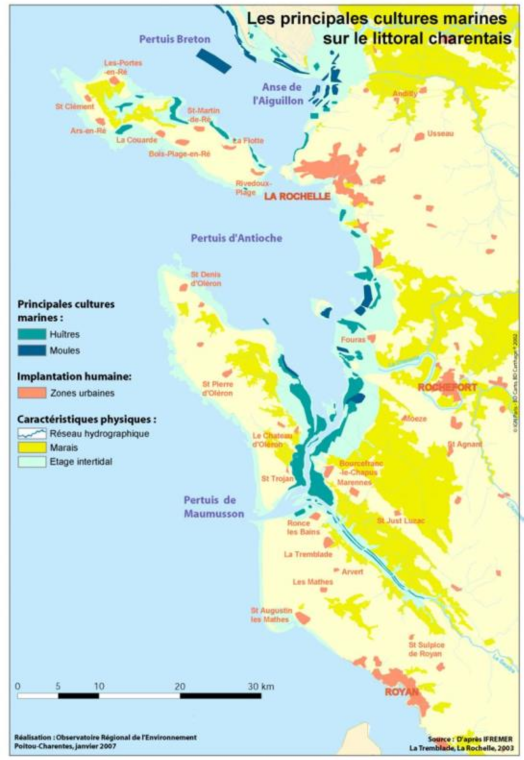

Figure 2 – Main marine cultures in the Pertuis charentais (legend: oyster, mussel, urban area, hydrografic network, swamp, tide zone) – (©ORE 2007)

The Figure 2 show the geographical extend of those cultures. Shellfish farms are distributed throughout the region, mostly on the lower part of the tidal flats, an area of over 175 km2. Mussel areas (38%) are concentrated in the Pertuis Breton while oyster areas (62%) are more abundant in the Bay of Marennes-Oléron (Bertin, 2005).

2. Model implementation

The numerical model used in this study is MOHID Water modelling system, a three-dimensional hydrodynamic model which solves the Navier-Stokes equations, considering the Boussinesq and hydrostatic approximations. The description of the hydrodynamic model is given in Martins et al. (2001). The simulation domain covers a large part of the Biscay bay (Figure 33).

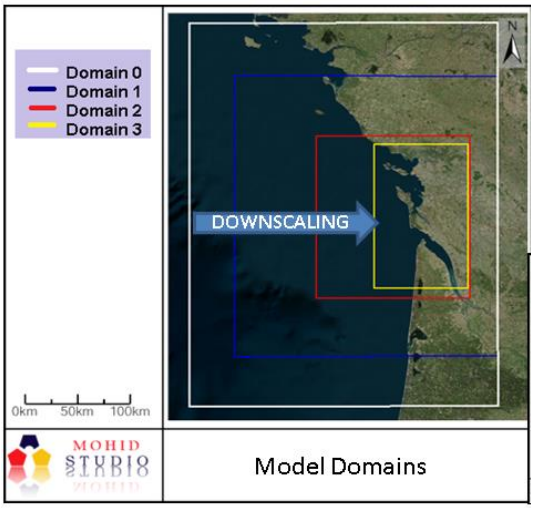

Figure 3 – Overview of model domains and bathymetries

The spatial resolution of the model is implemented by using a downscaling technique (Campuzano et al., 2013; Leitão et al., 2005). This technique consists of simulating local scale hydrodynamics on the basis of information provided by larger scale models. Four grids were implemented, called Domains and numbered from 0 to 3, with fixed horizontal resolution of 7x13 km, 7x13 km, 2.5 km, and 0.5 km, respectively. Local scale hydrodynamics were represented by the highest resolution domain (Domain 3), including Pertuis Bretons, Pertuis d'Antioche, and the Gironde Estuary. Domain 0 corresponds to the coarser grid and has a 2D vertical geometry consisting of one sigma layer extending between the surface and the maximum depth. For Domains 1-3 a vertical grid is used, consisting of 50 vertical layers. The time step used in the model Domain 0-3 was 180, 90, 30, and 15 sec, respectively.

2.1. Boundary conditions

Open boundary conditions for temperature, salinity, velocity, and free surface elevation are based on modelling results produced by the Mercator-Ocean Global Monitoring and Forecast System (Lellouche et al., 2013). Mercator-Ocean results do not include tide, and for this reason the tide boundary conditions were obtained from the model corresponding to Domain 0, and then linearly added to the solution of Domain 1. The tide is imposed at the open boundary of Domain 0, using the FES2004 solution (Lyard et al., 2006). River boundary conditions for Gironde and Charente Rivers were imposed by using historical time series of freshwater inputs, available at daily frequency from the French freshwater office database (www.hydro.eaufrance.fr). The average freshwater input in the year 2012 from the Gironde and Charente Rivers were 570 m^3/s and 60 m^3/s respectively. There are a few studies published about river temperature in the Garonne. The temperature imposed at the river boundary condition for the Gironde estuary was based on monthly averages obtained from historical data from the year 1978 (Croze et al., 2007).

2.2. Meteorological forcing

Meteorological forcing was provided by the French meteorological service Meteofrance (www.meteofrance.com). The available information includes fields of atmospheric pressure, wind velocity, solar radiation, air temperature, relative humidity, downward long wave radiation, and cloud cover at a resolution of 2.5 km and at 3 hour frequency for the period 01/01/2012-01-07/2012.

The Meteofrance results were interpolated over the model grids and used to compute wind shear stress, radiation balances, and latent and sensible heat fluxes.

3. Model validation

The hydrodynamic model will be validated by comparing simulated results with observed data available for the period 01/01/2012 – 01/07-2012. Presently, measured data available for model validation include water levels, temperature and salinity.

3.1. Water level and Tidal Harmonic Analysis

Water level data from SHOM were provided by EIGSI La Rochelle ("Industrial systems engineering school") at seven gauges in the area. Four of these locations fall in the model domain and will be used to validate water level. The map with gauges location is provided in figure 4.

Figure 4 – Water level gauge location

In order to compare the model's result with the field data, which has only tidal data, one has to remove the non-tidal interactions from the model's timeseries to be able to compare solely the tide. This procedure is done by performing a harmonic analysis on the model's timeseries, and then reconstruct it based on the resulting harmonic components. This was computed with the T_Tide package (Pawlowicz 2002; Foreman, 1977) using MatLab. The analysis can be made by comparing the timeseries (statistical analysis) and by comparing the harmonic components (harmonic analysis).

The tidal simulation of the coastal gauges is reasonably accurate. The figure 5 shows an example of comparison between simulated and measured gauges for La Rochelle showing a good agreement.

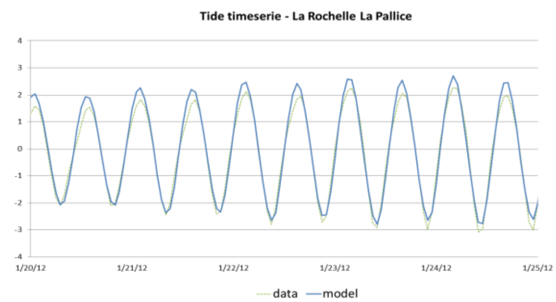

Figure 5 – Example of comparison between simulated and measured gauges for La Rochelle.

From the resulting two timeseries, a statistic analysis was made using several descriptors. The descriptors are based on Chambel-Leitao (2007):

- Correlation coefficient: also known as the Pearson product-moment correlation coefficient;
- RMSE: Root Mean Square Root.

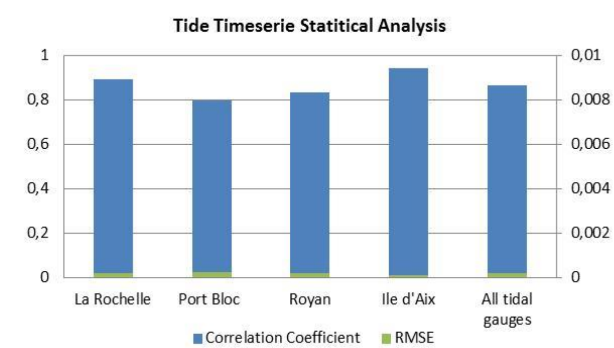

Figure 6 – Model vs field data timeseries statistical analysis (left scale : Correlation Coefficient, right scale : RMSE)

Figure 6 shows the results of the descriptors, for all 4 tidal gauges analyzed. The model generally agrees with the observations. It presents a good correlation coefficient (>80%), indicating that there is a linear correspondence between the two timeseries.

For the selected gauges, a comparison between the model's harmonic components and the field data is done. Figure 7 – Example of comparison between simulated and measured tidal gauge harmonic analysis for La Rochelle7 show an example for La Rochelle with the 8 main harmonic components, based on the model's amplitude. When the error is taken into account, the differences between the model and the field data are quite satisfactory for most tidal gauges: each lies on the others' error margin and vice-versa. From the results it is possible to conclude that we retrieve harmonic components characteristic for a semi-diurnal tide as expected from the context analysis (M2, S2, N2).

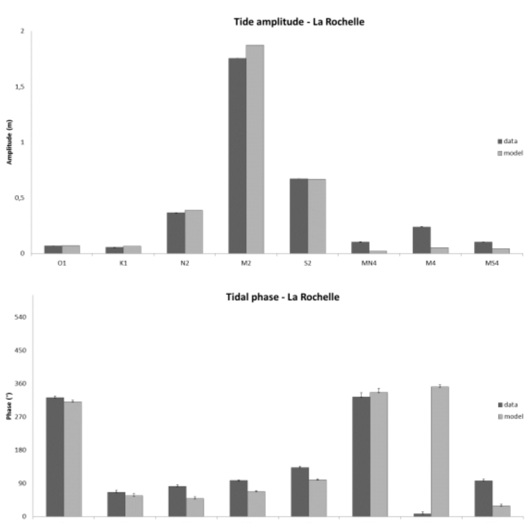

Figure 7 – Example of comparison between simulated and measured tidal gauge harmonic analysis for La Rochelle

3.2. Temperature and salinity data

The comparison with data was done by selecting CTD profiles located inside the area of Domain 3, because this is the domain where freshwater inputs are imposed. The vertical profiles were compared at the same depths of the model results. In overall, MOHID results are similar to MyOcean results, showing that open boundary conditions are transferred consistently along the domains, thus validating the downscaling methodology (Mateus et al., 2012). Simulated salinity were compared with CTD vertical profiles available for the month of may-june 2012, collected by Pelgas Cruises, and provided by Ifremer. The figure 8 shows examples of comparison between simulated and measured vertical profiles in the study area, showing a good agreement.

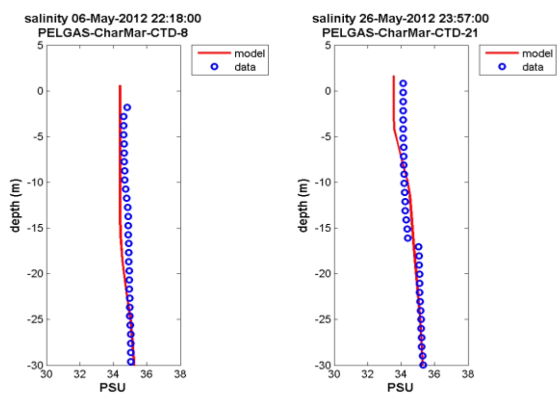

Figure 8 – Examples of comparison between simulated and measured vertical profiles

3.3. Sea Surface Temperature

Comparison with satellite images shows good agreement between model results and satellite images in the offshore area. Close to the coast, the model tends to underestimate temperature. The temperature imposed at the river boundary was based on the analysis of historical data for the years

1978-2005. Following this, one of the reasons of the error can be lack of information in the model about actual temperature of the waters discharged by the rivers. Another source of error can be due to the approximations done in the model to calculate heat fluxes at the interface water-air (Ascione 2014).

4. Oil spill simulation

This chapter describes the oil spill submodel, which is a 0D submodel coupled with solution imposed from the hydrodynamical model described previously.

In this submodel we use a lagrangean module that simulates the oil spill evolution in the two domains area, domain 2 and 3. The description of the hydrodynamic model is given in Fernandes (2012).

The objective here is to determine existence of spatial pattern, identify areas of shoreline affected by oil spills, and analyze the weathering processes affecting oil spills evolution.

4.1. Oil spill location

To choose the oil spill location, we analyze major maritime traffic road in the area. Historical information were obtained from MarineTrafic website showing all vessel positions recorded during last semester 2013, as show in Figure 9.

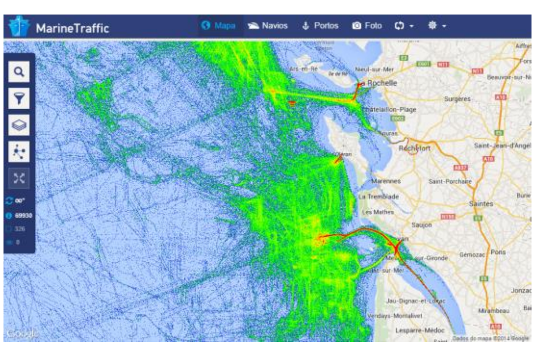

Figure 9 – Density map of all vessel positions (MarineTraffic, 2013)

Three locations origins were chosen to simulate oil spills. One origin is located near La Rochelle La Palice harbor where vessels are stationing before going to oil wharf terminal. Another one is located at the entry of Gironde estuary near Royan where we can see a crossing between local road (passenger ferry) and vessel traffic. The last origin is inside the estuary.

4.2. Oil type

Oil types differ from each other in their viscosity, volatility, and toxicity. Generally we can group oil into four basic types from Group 1 (Very light oils) to Group 4 (Heavy oils). Two representative kind of oil have been chosen for oil spill simulation. Their characteristics are provided in Table 1 below.

Oil name	Carpinteria	West Delta
Group	Medium oil (Group 3)	Very light oil (Group 1)
API	22.9	50.2
Pourpoint (ºC)	-21	-27
Viscosity at 15ºC (cP)	164	1
Aromatic (% weight)	30	7
Saturates (% weight)	44	92
Resins (% weight)	17	1
Asphaltene (% weight)	9	-
Maximum water content of the emulsion (%)	72	-

Table 1 – Oil characteristics for spill simulation

4.3. Model Results

This chapter describes the results obtained with oil simulation.

4.3.1. Spatial analysis

The following images depict a synoptic view over the domain area at surface depth (0-5 m). An instant in winter season (February 2012) and another one in summer (june 2012) was selected for this purpose.

The winter scenario presents a typical wind driven movement of the plume. This meteorological scenario is typical for this season as we seen in previous chapter, with light winds coming mostly from the continent (NE to SE) for a cumulative frequency inferior a 48% of the time.

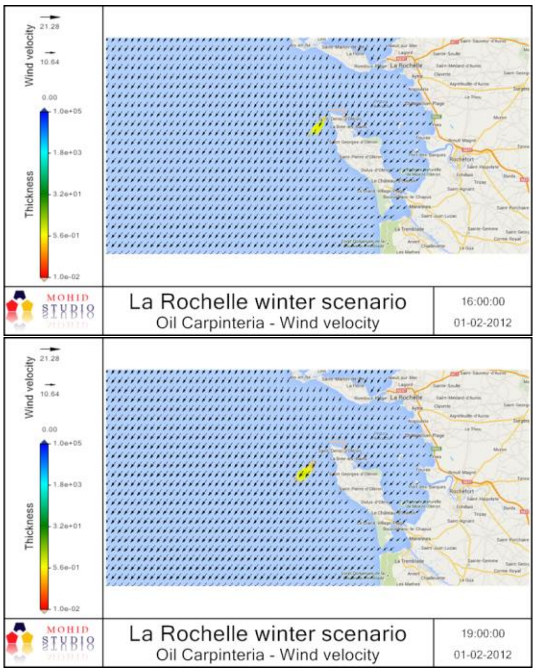

Figure 10 – La Rochelle winter scenario showing wind stress

Figure 10 is coupling the oil spill tracers with the wind stress which represents the wind at the surface. We can notice that the tracers are exactly following the wind stress direction South-West.

The summer scenario presents a typical case with almost absence of wind stress. This meteorological scenario is typical for this season as we seen in previous chapter where weak winds are present near 60% of the time, mainly to West North East (NW 15% of the time Chassiron, N 14% of the time and W 13.5% of the time in La Rochelle). The summer scenario presents a typical hydrodynamic driven movement of the spill. Figure 11 is coupling the oil spill tracer with the hydrodynamic velocity which represents the current at the surface. We can notice that the tracers of oil plume are transported following the tide movement.

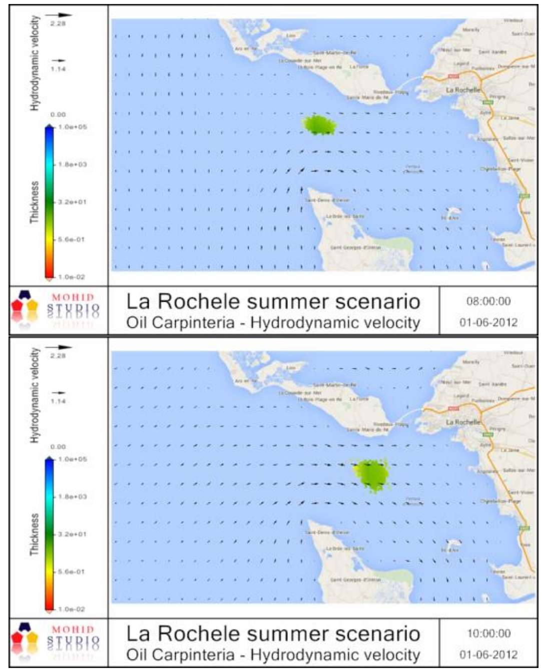

Figure 11 – La Rochelle summer scenario showing hydrodynamic velocity

4.3.2. Areas of shoreline affected by oil spills

While activating the parameter beaching in our model we can determine zones affected by this spill. Figure 12 presents an example of result for La Rochelle summer scenario.

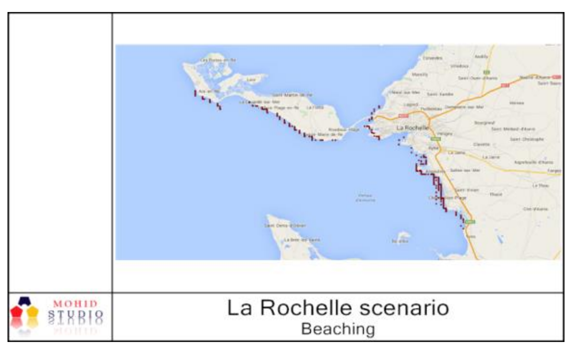

Figure 12 – Beaching simulation for La Rochelle summer scenario

4.3.3. Oil arrival time

Another way to study trajectory and evolution of spill can be represented by the oil arrival time. Trajectories of tracers are represented by different colors in function of time. This approach can help to determine best position for oil barrier in oil spill response. An example of result for La Rochelle scenario is presented in figure 13.

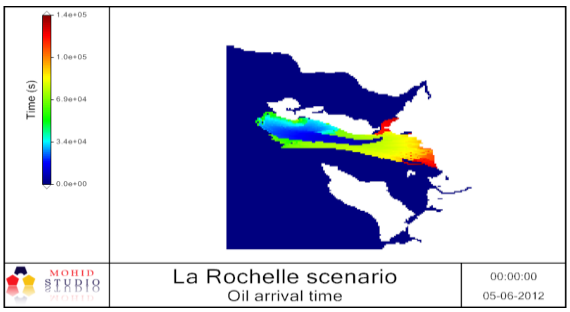

Figure 13 – Oil arrival time result for La Rochelle in summer scenario

4.3.4. Oil weathering process

The behavior of oil depends closely on the type of product spilled. Oil is also subject to the effects of the environment resulting to its dispersion in the marine environment and at the same time changing its physical and chemical characteristics, the so-called "aging" of oil. The behavior of oil spill is the result of a set of interactions between the spill and the external environment.

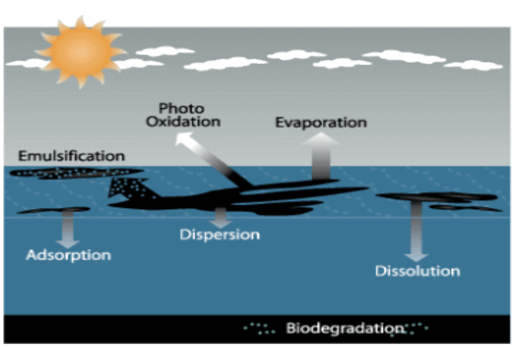

Figure 14 – Weathering processes affecting oil spills

A phase of short-term evolution occurs in the first days after the spill marked by process resumed in figure 14.

The following figures show the weathering processes affecting oil spills for two selected representative's kind of oil: a medium oil (Carpinteria) and a very light oil (West Delta).

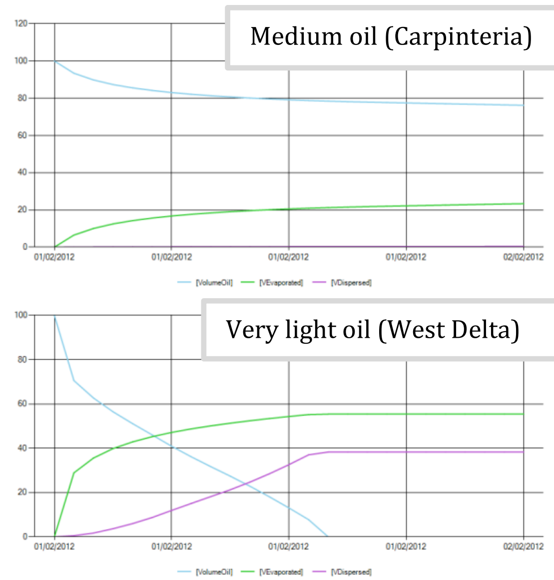

Figure 15 – Volume of oil total, evaporated and dispersed in m3

Figure 15 resumes the oil weathering processes previously explained with the evolution in term of total volumes, evaporated and dispersed. We notice here that for medium oil almost 80% will persist as floating oil. Contrary to light oil that is either evaporated or naturally dispersed into the water column in time frames of a couple of hours.

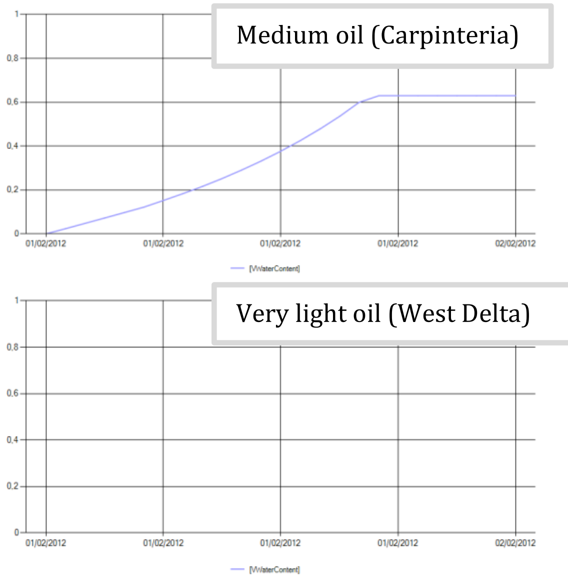

Figure 16 – Water content % in oil plume

The water content is characteristic of the emulsification process whereby one liquid is dispersed into another liquid in the form of small droplets. Emulsification is responsible for the incorporation of water droplets in oil, changing substantially the oil viscosity and therefore its behaviour at sea. In fact, after evaporation, emulsification can be considered the most important transformation process (Fingas, 2008). Figure 14 demonstrates that the water content of oil is increased for the medium oil (Carpinteria) up to 60%. If we compare the analysis made in terms of behavior and impact for the two oil type, light oil and medium oil, it shows that we are dealing with two completely different events. This result agrees with literature telling us that most crude oil blends will emulsify quickly when spilled, creating a stable mousse that presents a more persistent cleanup and removal challenge. Even in high winds, usually over 80% of a Medium Oil spill will persist as floating or beached oil for some days or longer (Marchand, 2002).

Group	I	III
Oil type	Light oil (West Delta)	Medium oil (Carpinteria)
Behavior and effects	Low persistence Short-term toxicity	Medium / high Persistence Toxic effect and smothering Effects
Spill response	None	Contain, recover, dispersing

Table 2 – Evolution of accidentally spilled oil and ecological consequences

Conclusion

The model was applied using a nested configuration which enabled to transfer boundary conditions from the large scale to the local scale. A lagrangian model was coupled to the hydrodynamic model.

In term of plume trajectory, two main scenarios stand out. A winter scenario, where the oil spill is pushed off the coast due to wind stress. A summer scenario, where the oil spill follow tide current and tends to beach in coastal area. Wind appears to be the most important factor driving the oil spill trajectory. Nevertheless the scenario can become totally opposite in function of wind force and direction. Wind will be a major parameter to take into account for oil boom barrier location.

In term of oil weathering process, the types of oil spilled will completely transform the scenario in term of evolution of the spill, ecological consequences and emergency spill response.

Some process of oil weathering have been excluded for this analysis like dissolution and sedimentation, it can be interesting to study this process.

We can ameliorate this study by integrating different climatological scenarios for currents and weather of the last 10 years in La Rochelle, and also different kind of oil.

Future works to develop are the simulation of the oil barrier impact on the plume for different scenarios.

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