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DEVELOPMENT OF SYSTEM OF HYDRODYNAMIC-ENVIRONMENTAL MODELS FOR COASTAL AREA

(Case study in Quang Ninh - Hai Phong region)

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ABSTRACT. The system of three-dimensional hydrodynamic-environmental models could simulate full advection and dispersion processes of the dissolved and particulate matter as suspended sediment and all oil phases in the realistic marine conditions. The hydrodynamic model provides temperature, salinity and current structure and water level. These variables will be used in the environmental model simulating the advection and diffusion processes for suspended matter concentration, bottom sediment thickness and all oil spill phases in the water and bottom sediment. This model includes two-dimensional (2D) sub-model for surface oil slick, dissolved and particulate oil, the thickness change in the bottom sediment layer and three-dimensional (3D) sub-model for the suspended matter, dissolved, emulsified and particulate oil in the water column.

Preliminary results for the EDC, PCB transport in Ha Long Bay region, for surface oil spill in the Hai Phong area show that the system of models could be used to simulate and predict the spreading of the contaminant matter in the coastal and estuarine waters and to resolve the problem of sediment transport and morphological change.

1. Introduction

The computation and forecasting of the displacement of the contaminant matters and oil in the sea environment are very difficult due to the different phases of these pollutants: oil slick at the surface, dissolved and suspended in water and bottom sediment. The previous models for the contaminant matters and oil slick are built on the basis of applying the semi-empirical formulas, developed in integration with the marine dynamic models. In practice, the Euler approach is traditional in hydrodynamics and the Lagrange approach is used in studying the contaminant spreading trajectories.

In the future, the Euler approach will become more and more popular due to the need to combine the dynamic equations of polluted substances transportation with the thermal hydrodynamic model. The use of similar techniques as in thermo-hydrodynamics allows us to enhance the modeling capability of water quality as well as the precision of environmental studies in general. The integration of dynamic principles and experimental data opens up a possibility of application of the model to several marine environmental problems.

Based on the study of dynamic principles of interactions between oil phases and environmental compound, we can build the dynamic model of oil compound as well as the marine environment.

2. MDEC hydrodynamic model

The MDEC hydrodynamic model is a full three-dimensional thermo-hydrodynamic model using system of primitive equations for water current $\vec{v}$, temperature T, salinity S and turbulent kinetic energy k with Boussinesq approximation and hydrostatic approximation. The general description of this model is given by Dinh Van Uu (2003).

3. Model for suspended particulate matter transport and bottom bathymetry evolution

The model for SPM and bottom bathymetry evolution includes 2 sub-models: 3D SPM Model for water column and 2D model for bottom layer evolution. The description of this model is given by Dinh Van Uu et al (2005, 2006), where the simulated variables are SPM concentration (C) and bottom layer thickness (ζ).

4. Model for oil fate and transport

In this model, there is four oil phases in the marine environment: oil slick, emulsion, particulate and dissolved oil. Among those, the oil slick only exists on the sea surface and the remaining phases exist in the water column. In the sediment, there are only two phases: the dissolved oil and particulate oil.

The physical, chemical and biological processes govern the transportation and degradation of oil in the environment. It also depends on properties of the oil and hydrodynamic, meteorological, and environmental conditions. These processes include: advection, turbulent diffusion, spreading, evaporation, dissolution, emulsification, hydrolysis, oxidation, biodegradation, and sedimentation.

When the oil begins spill over the sea, it spreads to make a thin oil slick. The transportation of the oil slick depends mainly on the advection and turbulent diffusion by the wind and currents. In this dispersion process, the oil slick also changes its form. The lighter oils tend to evaporate, the dissolvable oils blend into water, the under-water oils will be emulsified and transported as oil droplets. The emulsification or water-in-oil process depends on turbulences and often appears a couple of days after the oil spill. They tend to form several thin films and will be very sticky when transferred to the shoreline. As time goes by these thin films will stick together to form a thick mousse. The heavier oils can combine with the suspended sediment and go down to the bottom and is biodegraded by the bacteria. The oil slick and particles have relatively small contact area compare to their volume, therefore, their degradation process is quite slow.

The dynamics of the oil phases is established based on the principle of matter transformation as well as the diffusion advection process and matter transformation process.

In the static condition, the amount of oils on the sea is correlative to the thickness of the oil slick. The change in the thickness of the oil slick is influenced by three processes: evaporation, emulsification, dissolution into the under water. All these processes will lead to the decrease of amount of oil and the thickness of the oil slick, and there exists no reverse dynamical process.

This leads to a result: for the marine environment under the oil slick, there is an incoming source of oils which exhibits in the corresponding increase.

At the same time, from the water environment there will be an exchange flux of oils to the bottom sediment, the direction of this flux depends on the difference between concentration of dissolved and particulate oils in the water (C_d, C_p) and in the bed sediment (C_{db}, C_{pb}) respectively. The transformation of the oil phases mainly happens in the water and in the bottom sediment.

All of the oils, water layer in the emulsion (water-in-oil or oil-in-water) and dissolved oils have the tendency to transform into particulate due to the present of suspended matters in water. This process depends on the difference in concentration of the oil phases and concentration of the suspended matters S_w, where the suspended matters can have natural or artificial origin due to the use of oil dispersant substances. Therefore, this transformation process is the same as a source for making particulate oils in water.

A similar process can be applied to two main oil phases in the bottom sediment which are particulate oils and dissolved oils. This means that certain amount of dissolved oils will be transformed into particulate oils.

The natural condition of sea environment with the existence of dynamic phenomena such as wave, current, advection, convection and dispersion will play a crucial role to the transformation rules as well as the distribution displacement of oils in the oil slick, water column, bottom and shoreline sediment.

Since the transformation, advection and diffusion of oils in each environment are different, we need to build a system of models for each environment which is related to each other through the boundary conditions. In this case, we can introduce the system of models for oil slick, oil-in-water environment and bottom sediment.

Though there are many formulas, we can use the *equation of thickness variation of oil slick (h)* based on the generalization of the diffusion advection process and the exchange process between oil slick and air, and water through the evaporation of lighter oils and the emulsification, as well as the dissolution of the heavier oils:

$$\frac{\partial h}{\partial t} + \overline{\nabla}(h\vec{v}) - \overline{\nabla}\left(D\overline{\nabla}h\right) = Q, \tag{1}$$

where: $\overline{\nabla} = \frac{\partial}{\partial x} + \frac{\partial}{\partial y}$.

This equation is constructed based on the principle of conservation of mass for the moving oil slick (Benque et al, 1982; Fingas and Fieldhouse, 2004). ***Q*** is the loss rate due to evaporation, emulsification and dissolution in water.

In Equation (1), the diffusion advection process only happen on the horizontal direction and are described through operator $\overline{\nabla}$. The velocity in the advection factor consists of two components: general regular current and wind-driven current. The wind-driven current can be computed according to the wind speed with the coefficient approximately equal 3%. There are many ways to evaluate the horizontal diffusion coefficient ***D***, however, we choose the following (Cuesta et al., 1990): $D = \frac{gh^2(\rho - \rho_o)\rho_o}{\rho f}$, where *f* is the friction coefficient between oil slick and surface water.

Therefore, the model for thickness variation of the oil slick can be solved through the impact of wind field and current on the sea surface.

This is a 2D model with the initial condition of the oil slick is given by the thickness h. In addition to the boundary condition for the oil slick at the shoreline and sea open boundaries, the model required the concentration of oil emulsion C_e and oil dissolution C_d in the water layer which contacts with the oil slick. These are the conditions associated to the model of oil in water environment.

For the whole water column, the 3D model of the marine environmental components (Dinh Van Uu et al., 2005, 2006), which apply *for three different oil phases* related to each other by the laws of dynamics and diffusion-advection:

$$\frac{\partial C_i}{\partial t} + \vec{\nabla}(C_i \vec{v}_i) - \vec{\nabla}(D_i \vec{\nabla} C_i) = Q_i,\ i = e,d,p \qquad (2)$$

where the velocity ($\vec{v}_i$) consists of the current velocity ($\vec{v}_c$) and the setting velocity (w_i) of the corresponding oil phases. D_i is the diffusion coefficient of the oil phases in water environment.

According to the law of dynamical transformation, the production and destruction of each phase are specified by the corresponding function:

$$Q_e = Q_e(S_w, C_e, C_p),\ Q_d = Q_d(S_w, C_d, C_p),\ Q_p = Q_p(C_e, C_d, C_p).$$

So we obtain a set of equations for the oil models in the system of 3D thermo-hydrodynamic environmental models MDEC which have been previously developed and applied. To implement this model, it is important to deal with the boundary conditions in the water environment.

As explained above, on the interface between water and oil slick, the flux of emulsion oil is going into water depends on the amount of present emulsion C_e. The flux of dissolved oil depends on the correlation between present concentration and saturation of the lighter oil phase. For the interface between water and sediment, the exchange oil flux depends on the difference between concentration of oils in sediment and in the near-bottom water layer. This is also the relation between model of oils in water environment and in the bottom sediment.

We assume that the *bottom sediment layer* that contains the oil phases is not significant, so their concentration can be taken as the average value of the thickness of the surface sediment. So we can build the model of oil in the sediment with the laws of dynamical transformation mainly between dissolved oil and particulate oil. The horizontal advection and diffusion process will play a key role, so this is a 2D model:

$$\frac{\partial C_{ib}}{\partial t} + \overline{\nabla}\left(C_{ib}\vec{v}_{ib}\right) - \overline{\nabla}\left(D_{ib}\overline{\nabla}C_{ib}\right) = Q_{ib} \tag{3}$$

In this model, the velocity of the bed sediment can be specified through the bed flux or dynamic velocity v_{*b}.

The production and destruction rates get from the transformation and exchange flux through the water-sediment interface.

So we obtain a system of three models for the oil slick, oil in water column and in the bottom sediment environments. Since these models are related to each other through the boundary conditions, we can solve independently when these conditions are given.

The MDEC hydrodynamic and SPM transport models will provide the hydrodynamic factors, such as current, wave, water density, SPM concentration and bottom stress for implementation of the oil transport model.

By combining all of these models, we can give an apprehensive solution to the oil spreading problem in marine environment and create an environmental-ecological model which can fulfill the forecasting, impact assessment and oil spill recovery task.

5. Preliminary results of application of the models in Quang Ninh - Hai Phong region

It is well-known that the construction and development of 3D marine hydrodynamic models allow to describe, in a quite accurate way, the current, temperature, salinity fields and other environmental components as SPM concentration for the whole water layer. So the system of models should be based on the 3D thermo-hydrodynamical models for each particular environment that contains interested matter.

The marine thermo-hydrodynamical models can provide characteristics for the 2D model of oil slick on sea surface. The concentration of dissolved, particulate oils and emulsion in water is the result of implementation of the 3D model for oils in the water environment. The 2D model will be constructed and implemented in order to compute horizontal distribution of oil in the bottom sediment and bottom layer thickness. The oil and SPM fluxes exchanged among different environment (oil slick, water column and bottom sediment) are the boundary conditions for each sub-model.

The system of MDEC models has been applied for simulating hydrodynamic, suspended matter and environmental components included oil in Ha Long Bay and Hai Phong estuarine area. For all of these regions, the simulated fields of water circulation and water level show mostly well for as very complicated coastal and estuarine condition as combined river- air-sea interaction.

The simulated results of SPM transport sub-model for Ha Long Bay show that the SPM concentration in water is generally higher in the area near the coast than that is in the central and north - east region. The deposition of the SPM at the bottom is more in the area near Ha Long, Bai Chay and Cat Ba coasts than it is in the central area. The seasonal variation of SPM concentration and the sedimentation rate is significant for the open sea area between Bai Chay and Cat Ba (Fig. 1a, 1c and 1b, 1d).

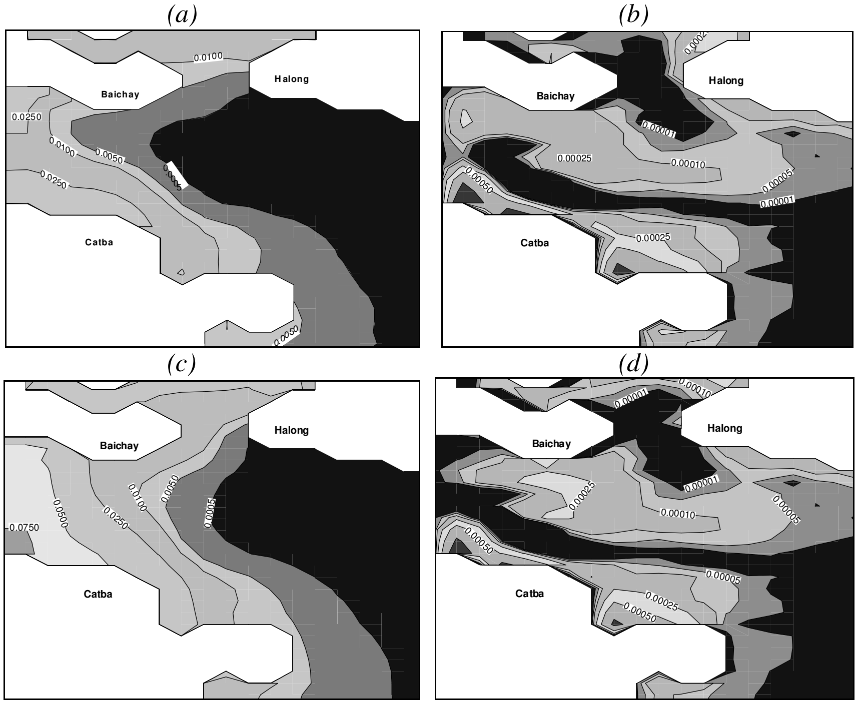

Figure 1. Simulated SPM concentration (a, c) and bottom layer thickness (b, d) after 12 days in Ha Long Bay area: a, b - SE wind, c, d - NE wind

The field sampling results in September 2005 show that the distribution of EDC (Phenol and 4-NP) concentration in the water (Fig. 2a) and in the sediment has the same features as resulting from model simulation (Fig. 1a and 1b).

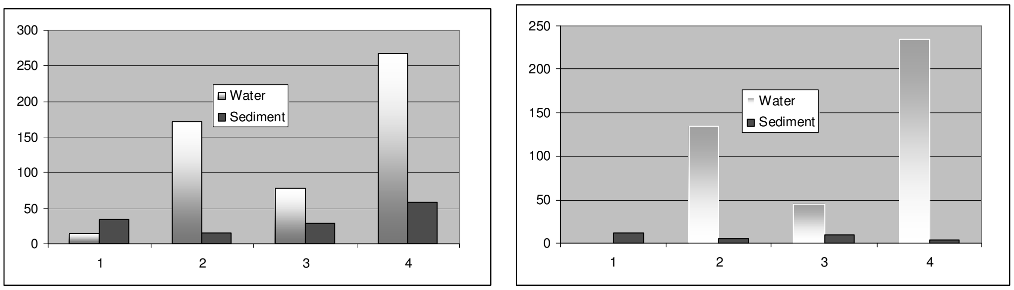
(a) *(b)*

Figure 2. Distribution of total Phenol (a) and 4-NP (b) concentration in water and sediment for Bai Chay (1), Cat Ba North (2), Cat Ba East (3) and Hon Gai (4) coastal area during September 2005

The recent sampling results in 2006 for Polyclobisphenyls (PCBs) in Ha Long Bay area show significant seasonal variation of PCBs concentration in water and in sediment (Figure 3a). Figure 3b shows that there is repartition of average PCBs concentration in different regions.

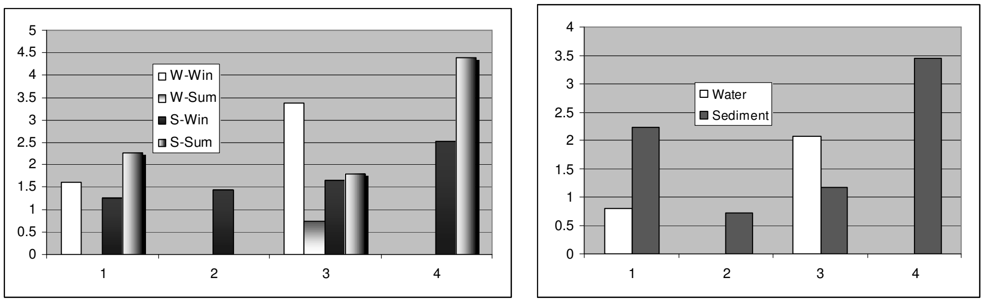
(a) *(b)*

Figure 3. Seasonal (a) and average (b) PCB concentration in water (W) and sediment (S) at Bai Chay (1), Centre (2), Cat Ba (3) and Hon Gai (4) area in 2006 *(Win: Winter, Sum: Summer)*

For the oil sub-model, the testing is carried out in Hai Phong estuary by using parameters which originated in the work of Tkalich et al. (2003). The obtained results for spreading oil slick show that the model has been successfully simulated in time and shape of the oil spill as in the classical models as well as in reality (Cuesta et al., 1990). Figure 4 shows the positions of the oil slick after 6 and 24 hours in the case of SE wind for the source of oil spill in the area between Do Son and Cat Hai. In this case, the oil slick is transformed into shape of an ellipse with centre in the oil slick origin.

In the case of NE wind, the oil slick is quickly approached Do Son - Hai Phong shoreline, where there is strong nearshore current (Figure 5).

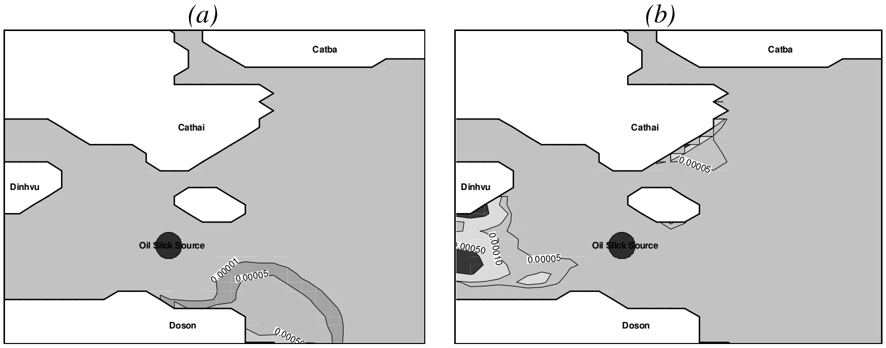

Figure 4. Distribution of the thickness of oil slick on sea surface after 6 (a) and 24 (b) hours in the SE wind

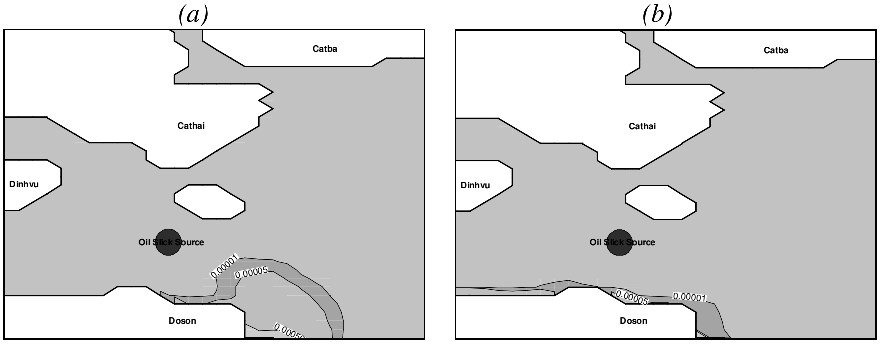

Figure 5. Distribution of the thickness of oil slick on sea surface after 6 (a) and 24 (b) hours in the NE wind

For oil phases in the water environment, though concentrations of each component are different, the distribution regions of them have similar shape and the result is the gathering of oils in Cat Hai area and Bach Dang estuary. Figure 6 shows diagrams of distribution of particulate concentration in water at depth of 0.5m and similarly for oil slick in the SE wind field after 6 and 24 hours.

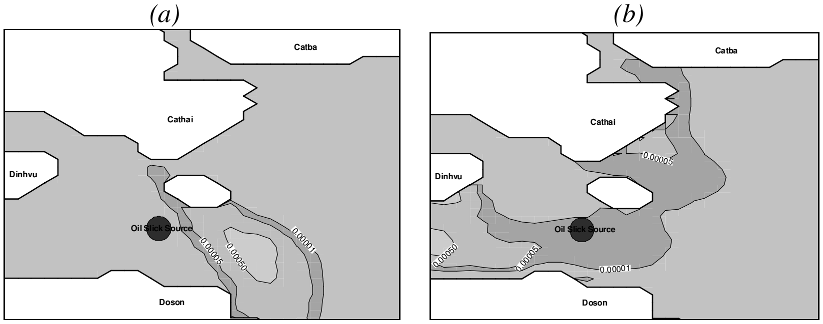

Figure 6. Distribution of particulate concentration in water (depth 0.5m) after 6 (a) and 24 (b) hours in the SE direction wind

In the case of NE wind, the oils also had tendency to approach Hai Phong - Do Son shoreline and to extend the affected area in East-West direction (Figure 7).

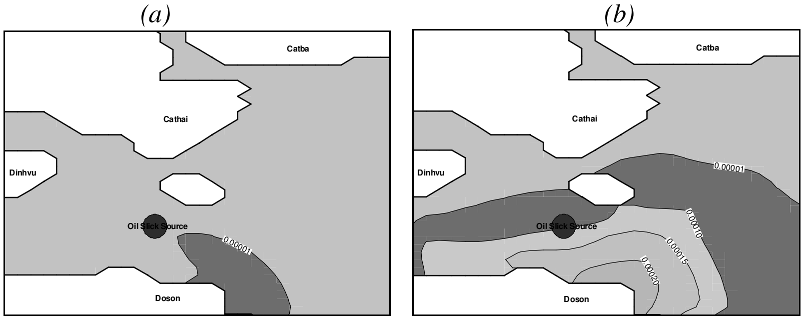
(a) *(b)*

Figure 7. Distribution of particulate oil concentration in water (0.5m layer) after 6 (a) and 24 (b) hours in the NE wind

The amount of particulate oil in the bottom sediment increases as time goes by and the position has relatively small variation compare to oils in water and oil slick (Figure 8).

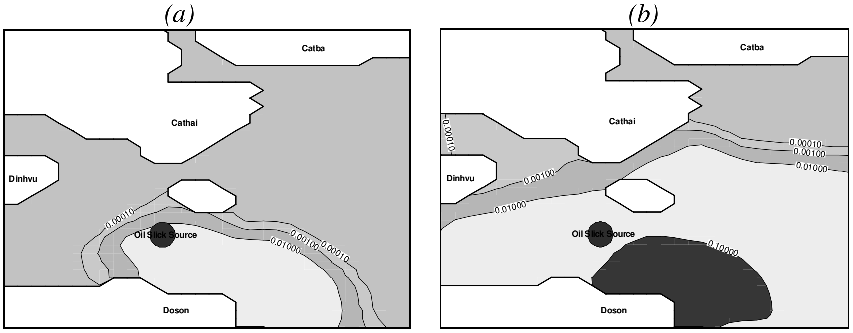
(a) *(b)*

Figure 8. Distribution of particulate oil concentration in sediment after 6 (a) and 24 (b) hours in the NE wind

6. Conclusion

The preliminary results for the combined system of 2D, 3D hydrodynamic-environmental models for SPM and bottom layer change show the ability to forecast the fate and transport of contaminants and sediment, and the impact to the sea and nearshore environment. By making more comprehensive tests for several oil spill cases, this system of models can be developed and applied, together with the recovery strategies, for the case of oil pollution sources in water or seabed. This system of models also allow to integrate with models of ecological components and water quality, therefore open up the application in monitoring and forecasting coastal and marine environment.

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