Modeling and Assessment of the Produced Water Discharges from Offshore Petroleum Platforms

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There has been a growing interest in assessing the risks to the marine environment from produced water discharges. This study describes the development of a numerical approach, POM-RW, based on an integration of the Princeton Ocean Model (POM) and a Random Walk (RW) simulation of pollutant transport. Specifically, the POM is employed to simulate local ocean currents. It provides three-dimensional hydrodynamic input to a Random Walk model focused on the dispersion of toxic components within the produced water stream on a regional spatial scale. Model development and field validation of the predicted current field and pollutant concentrations were conducted in conjunction with a water quality and ecological monitoring program for an offshore facility located on the Grand Banks of Canada. Results indicate that the POM-RW approach is useful to address environmental risks associated with the produced water discharges.

Key words: POM, Random Walk model, simulation, produced water, heavy metal

Introduction

Produced water is the largest effluent discharge associated with offshore oil and gas production. The total volume of produced water effluent is expected to increase with future anticipated development of offshore oil and gas reserves worldwide (Gordon et al. 2000). The environmental impact potentially caused by produced water is related to the fate and transport of its individual components including organic and inorganic compounds (e.g., petroleum hydrocarbons, heavy metals, nutrients, natural radionuclides) associated with the formation water and treating chemicals (Hodgins 1993). Although produced water discharges are associated with rapid dilution and low-to-trace levels of pollutants, the potential for cumulative toxic effects under regional ocean currents warrants a need to assess the long-term risks to the marine ecosystems (Lee et al. 2005).

There is increasing environmental concern over the ocean discharge of contaminants, such as metals and hydrocarbons, in produced water because of their potential for bioaccumulation and toxicity, particularly by those dissolved in the water phase (Neff 2002; Neff et al. 2006). It is noted that hydrocarbons and heavy metals show different fate and transport mechanisms due to their differences in physicochemical properties. Low-concentrations of hydrocarbons in a large discharge of produced water can be rapidly diluted by tidal currents and decay over time due to aerobic degradation. Thus, the effects of hydrocarbons associated with produced water discharges are primarily linked to localized areas and unlikely to cause large-scale environmental impacts (National Research Council 1985). In contrast, a large number of heavy metals are stable, environmentally persistent, and highly toxic. Furthermore, they can be accumulated by marine life in concentrations several thousand times higher than those in the surrounding seawater (Foster 1976; Bryan and Langston 1982). For example, lead (Pb) is a highly toxic metal with persistent adverse effects in the marine ecosystem, and the toxic effects on shellfish can occur even in the presence of a very low concentration of Pb (Dojlido and Best 1993).

Previous models have been developed to predict the dispersion and transport of produced water discharges in the coastal environment, especially for sites around the North Sea and the Gulf of Mexico (Ray and Engelhardt 1992; Reed and Johnsen 1996). For example, McFarlane (2005) applied chemometrics to describe the contamination of produced water by soluble organic compounds based on a partial least-squares statistical model. Rye et al. (1996) proposed a dispersion-dilution model to study the transport and dilution of produced water and the resulting uptake and biomagnification in marine biota. Smith et al. (2004) conducted a field verification of the Offshore Operators Committee Mud and Produced Water Discharge Model. In recent years, the Random Walk method has been used as a means to model the dispersion of pollutants in the aquatic system. Gillibrand et al. (1995) simulated the dispersion of produced water in the northern North Sea (the East Shetland area) using a Random Walk model. Riddle et al. (2001) also developed a Random Walk model to compute the concentration distribution of dispersed oil in the North Sea resulting from produced water discharges. The above-reviewed studies provide a basis for new model development for managing offshore produced water discharges.

The hydrodynamic nature of the marine environment, namely the changing current field, is known to govern the transport and dispersion of discharged produced...
water constituents linked with potential environmental impacts. Unfortunately, to date, there has been a lack of consideration given to current data inputs in fate and transport models. To address this issue, we propose a new modeling approach, POM-RW, that integrates a hydrodynamic ocean current model (POM) with a dispersion model (Random Walk [RW] model) to simulate the fate and transport of contaminants associated with produced water discharges. The POM (Princeton Ocean Model) three-dimensional (3D) hydrodynamic model was employed to provide the current field data within a produced water discharge area of Atlantic Canada to support the application of the Random Walk model to simulate the dispersion of produced water discharges in three dimensions. A field validation study for the integrated current simulation and dispersion model was conducted as part of an environment effects monitoring program for a representative offshore platform facility (i.e., Hibernia), which is located on the Grand Banks of Newfoundland along the east coast of Canada.

**Development of a POM-RW Modeling Approach**

Integration of Ocean Current Model and Pollutant Dispersion Model

The ocean current is the most important factor determining the direction and rate at which produced water disperses. In the present study, POM, as a sigma-coordinate, free-surface coastal ocean model, is implemented to simulate the velocity field of the coastal area under study.

A new pollutant dispersion modeling approach that integrates the pollutant dispersion model (Random Walk model) with the 3D ocean current modeling components from POM has been developed. It is hereafter called the POM-RW approach. The framework of the developed POM-RW approach is presented in Figure 1. As shown in the figure, the POM-RW method includes three major components: data collection and input processing, flow field simulation, and 3D pollutant dispersion modeling.

Ocean Circulation Model – POM

POM is a three-dimensional, sigma coordinate, free-surface estuarine and coastal ocean circulation model. Its apparently unique feature is the imbedded turbulent closure submodel, which yields realistic, Ekman surface and bottom layers (Blumberg and Mellor 1987). The model represents ocean physics as realistically as possible and addresses large-scale and long-term phenomena, depending on the basin size and grid resolution.

The main governing equations used in POM are as follows (Blumberg and Mellor 1987; Mellor 2004):

The continuity equation:

\[
\frac{\partial DU}{\partial x} + \frac{\partial DV}{\partial y} + \frac{\partial D\omega}{\partial \sigma} + \frac{\partial D\eta}{\partial t} = 0
\]  \hspace{1cm} (1)

The momentum equations:

\[
\frac{\partial UD}{\partial t} + \frac{\partial U^2 D}{\partial x} + \frac{\partial UVD}{\partial y} + \frac{\partial U\omega D}{\partial \sigma} - fVD + gD \frac{\partial \eta}{\partial x} + \frac{\partial D^2}{\partial x^2} = \frac{\partial}{\partial \sigma} \left[ \frac{K_u}{D} \frac{\partial U}{\partial \sigma} \right] + F_x
\]  \hspace{1cm} (2)

\[
\frac{\partial VD}{\partial t} + \frac{\partial V^2 D}{\partial x} + \frac{\partial UVD}{\partial y} + \frac{\partial V\omega D}{\partial \sigma} + fUD + gD \frac{\partial \eta}{\partial y} + \frac{\partial D^2}{\partial y^2} = \frac{\partial}{\partial \sigma} \left[ \frac{K_v}{D} \frac{\partial V}{\partial \sigma} \right] + F_y
\]  \hspace{1cm} (3)

The turbulence closure equations:

\[
\frac{\partial Dq_1^2 D}{\partial t} + \frac{\partial Uq_1^2 D}{\partial x} + \frac{\partial Vq_1^2 D}{\partial y} + \frac{\partial D\omega q_1^2}{\partial \sigma} = \frac{\partial}{\partial \sigma} \left[ \frac{K_u}{D} \frac{\partial q_1^2}{\partial \sigma} \right] + 2K_u \frac{\partial U}{\partial \sigma} \frac{\partial \omega q_1^2}{\partial \sigma} + \frac{2g}{\rho_o} K_u \frac{\partial \bar{q}}{\partial \sigma} + 2Dq_2^3 \beta l + F_q
\]  \hspace{1cm} (4)

\[
\frac{\partial q_1^2 D}{\partial t} + \frac{\partial Uq_1^2 D}{\partial x} + \frac{\partial Vq_1^2 D}{\partial y} + \frac{\partial D\omega q_1^2}{\partial \sigma} = \frac{\partial}{\partial \sigma} \left[ \frac{K_u}{D} \frac{\partial q_1^2}{\partial \sigma} \right] + \frac{1}{\rho_o} \frac{\partial}{\partial \sigma} \left[ \frac{K_u}{D} \frac{\partial \bar{q}}{\partial \sigma} \right] \left( \frac{Dq_2^3}{B_1} \frac{\partial D}{\partial \sigma} + \tilde{W} + F_i \right)
\]  \hspace{1cm} (5)

where:

- \(U, V\) are the horizontal velocities (m·s\(^{-1}\));
- \(\omega\) is the velocity component normal to sigma surfaces (m·s\(^{-1}\));
- \(\eta\) is the surface elevation (m);
- \(D \equiv H + \eta\) is the total elevation of the surface water (m);
- \(x, y\) are the horizontal Cartesian coordinates (m);
- \(\sigma\) is the sigma vertical coordinate (m);
where:
- $t$ is time (s);
- $f$ is the Coriolis parameter ($s^{-1}$);
- $g$ is gravitational acceleration;
- $\rho' = \rho - \rho_{\text{mean}}$ before the integration is carried out;
- $\rho_{\text{mean}}$ is generally the initial density field which is area averaged on z-levels and then transferred to sigma coordinates in the exact same way as the initial density field;
- $K_M$ is vertical kinematic viscosity ($m^2\cdot s^{-1}$);
- $F_x, F_y$ are the horizontal diffusion terms ($m^2\cdot s^{-2}$);
- $K_h$ is vertical diffusivity ($m^2\cdot s^{-1}$);
- $\alpha^2$ is twice the turbulence kinetic energy ($m^2\cdot s^{-2}$);
- $l$ is turbulence length scale (m).

### Pollutant Dispersion – A Random Walk Model

The Random Walk model is based on the particle tracking approach, which follows the concept of the random movement of particles. Specifically, particles are represented as real entities spread across the computational domain rather than as concentrations. The effluent discharge is represented by placing a fixed number of “particles”, converted from the discharge rate and concentration, at the outfall position at each timestep (Riddle 1998). The POM is implemented to seamlessly provide the velocity components at each coordinate. These particles are therefore moved during each subsequent timestep (Webb 1982):

\[
X_{\text{new}} = X_{\text{old}} + U dt + f_x \alpha \\
Y_{\text{new}} = Y_{\text{old}} + V dt + f_y \beta \\
Z_{\text{new}} = Z_{\text{old}} + W dt + f_z \gamma
\]  

(6)

where:
- $X, Y$ and $Z$ represent the position of a particle and the subscripts “old” and “new” represent the positions at the start and end of a model timestep;
- $dt$ is the timestep, and $U, V$ and $W$ are the horizontal and vertical velocity components at time $t$ from the POM model and the effect of wind, respectively;
- The functions $f_x, f_y$ and $f_z$ define the mixing process;
- $\alpha, \beta$ and $\gamma$ are random numbers from a standard normal distribution.

Each particle represents a fixed mass of effluent, and it is assumed that no reaction takes place.

A constant diffusion coefficient based on the Fickian equation is used to characterize the horizontal and vertical diffusion as follows:

\[
f_x = f_y = \sqrt{2K_a dt} \\
f_z = \sqrt{2K_v dt}
\]  

(7)

where
- $K_x$ and $K_v$ are the horizontal and vertical mixing coefficients ($m^2\cdot s^{-1}$).

Conversion of particle numbers and locations into concentrations is straightforward. The concentration distribution of a pollutant in the water is quantified using a counting cell. The number of particles in a grid cell over a depth interval from the water surface down to a specified depth is counted, giving the mass of the pollutant in a known volume, and therefore the concentration is computed. We can write the following expression for the concentration calculation under the assumption that each particle has the same mass (Suh 2006):

\[
C = \frac{m}{A h}
\]  

(8)

where:
- $C$ is the average concentration in a cell ($\mu g/L$);
- $m$ is the mass of a particle in mg (i.e. total mass of the system divided by the number of particles);
- $P$ is the number of particles in the cell;
- $A$ is the area of the cell ($m^2$);
- $h$ is the average depth of the cell (m).

### Application of the POM-RW Approach

The developed POM-RW approach was validated with data collected around an offshore platform facility located in the Atlantic Ocean off the east coast of Canada. A large-scale area for the ocean current simulation has been configured to eliminate the influence of open boundaries on the study area. Within the simulations, the concentrations of Pb were used to track the 3D discharge pattern of the produced water. Corresponding 3D field monitoring data were provided from a field-based environmental effects monitoring program to validate the POM-RW approach.

### Overview of the Study Site

The Hibernia platform is located at 46°75’N, 48°78’W off Canada’s east coast, on the Grand Banks of Newfoundland, 315 km off the coast of Newfoundland (Fig. 2). It is situated in relatively shallow water, approximately 80 meters deep. The Hibernia oil field was discovered in 1979. It began producing oil in November 1997. Figure 2 presents the Hibernia platform location and the chosen modeling area. The small inside square around the Hibernia site is the study area for the present research. The area measures 50 km by 50 km with the Hibernia platform in the centre.

The major issue involved in the ocean current simulation in the present research is that the Hibernia platform is located in an open sea; four lateral boundaries are completely unbounded in the study area as shown in Fig. 2. There are no existing current monitoring stations (or existing field observation data) for each lateral boundary. Thus, the situation leaves no choice but to use numerical open boundary conditions for each lateral boundary.
However, no matter which kinds of open boundary conditions have been chosen, numerical errors will exist and may create an unrealistic flow across the boundary, consequently affecting the simulation results. Therefore, in order to eliminate the numerical errors for the study area, simulating ocean current on a larger scale covering the study area at the centre is proposed in the present paper. A large-scale area was chosen from 60°W, 44°N to 45°W, 45°N as shown in Fig. 2. The left boundary is along the shore of Canada's east coast. Only the portion of ocean current modeling results related to the study area was used for pollutant dispersion simulation, which is from 49°135’W, 46°54’N to 48°475’W, 47°02’N.

Fig. 2. Study site and modeling area.

The model grid and bottom topography are shown in Fig. 3. The solution of the horizontal grid is modified into Cartesian coordinate grids, which have 90 by 93 nodes for the large-scale area. The size of the model grids is generated as Δx = Δy = 2 km in the study area. Outside the study area, the size of the model grids is designed to be larger than the inside study area, where the grids vary between Δx = 8 km to Δx = 50 km, Δy = 12 km for the irregular mesh as shown in Fig. 3.

The constructed sigma coordinate for the study site has 21 vertical layers, σ = (0.0, -0.0263, -0.0526, -0.1053, -0.1579, -0.2105, -0.2632, -0.3158, -0.3684, -0.4211, -0.4737, -0.5263, -0.5789, -0.6316, -0.6842, -0.7368, -0.7895, -0.8421, -0.8947, -0.9474, -1.0) and σ = (z-η)/(H+η). The vertical resolution is higher near the surface. For example, for a grid point where the water depth is 80 m, Δz is around 2 m at the surface and 4 m in the other layers.

The current model was initialized by mainly using the climatological data of June 2005 and was run for 30 days. The data set includes sea surface temperature obtained from the Fisheries and Oceans Canada Oceanographic database and includes the hourly averaged wind speed and directions of June 2005 from the Environment Canada climatic database, the National Data Buoy Centre database, and the Hibernia Annual Environmental Data Summary Report in 2005 (Lee et al. 2005). The wind data were collected from 28 locations, including the Hibernia platform. Most of the wind monitoring stations are distributed along the west and south boundaries of the large-scale area (Fig. 2).

Samples of produced water and ambient sea water at 3 depths from the surface to the ocean bottom were collected by the Bedford Institute of Oceanography research cruise during the period of 27 June 2005 to 7 July 2005. The analysis of the sea water samples was conducted by the Centre for Offshore Oil and Gas Environmental Research at the Bedford Institute of Oceanography. The Pb concentration in produced water was analyzed by the Trace Analysis Facility at the University of Regina.

Among those contaminants in the produced water, the dispersion of Pb was used as a tracer in this study to validate the POM-RW model due to its conservative nature. The background dissolved Pb concentration in seawater was 0.001 μg·L⁻¹ based on the measurement, and a continuous point discharge of produced water at a depth of 40 m below the surface at the Hibernia platform was identified and considered for dispersion modeling. The emission rate of produced water was 882 m³/hr at 456.7 μg·L⁻¹ of Pb, assuming that Pb is conservative. Based on the comparison with the field observation data and the values published in the literature (Riddle 1998; Riddle et al. 2001), the horizontal mixing coefficient of 50 m²·s⁻¹ and vertical coefficient of 1 × 10⁻³ m²·s⁻¹ were adopted in this paper.

3D Current Simulation and the Comparison with Field Data

The first step of the current simulation was to generate the model grid with a set of 90 by 93 nodes for the larger-scale area as shown in Fig. 3, which contains the Hibernia site from 49°30’W, 46°40’N to 48°20’W, 47°20’N. The topography, temperature, salinity, and hourly wind data for the larger domain containing the study site were interpolated into Cartesian horizontal grids and vertical sigma coordinate layers as the input conditions. At the four lateral open boundaries (the locations where the water depths were lower than 10 m were considered

Fig. 3. Model grid and bottom topography contour map (The diamond point is the location of Hibernia, the square around the Hibernia platform is the study area).
as closed boundaries in the model), Sommerfeld-type radiation conditions were used (Mellor 2004; Palma and Matano 1998).

The current modeling results were obtained as daily averaged velocities and visualized through vector fields. Comparisons with the observed current vector data were conducted at three depths: the surface, 9 meters from the surface, and 42 meters from the surface. Figures 4a and b show the surface modeling results of the current vector field after a model run of 5 days and 15 days, respectively. Corresponding to each day, the field observations are real-time velocities, which were measured by a MIROS Directional Wave and Current Radar installed on the Hibernia Platform (Oceans Ltd. 2006). Figures 4a and b, with a comparison of both magnitude and direction, indicate that POM can provide a reasonable simulation of the surface current in the Hibernia area.

Figures 5a and b give the velocity vector comparisons at 9 m of depth in the water after a model run of 16 days and of 23 days, corresponding to the observed current velocity data that occurred during the period from 16 June 2005 to 24 June 2005 at locations indicated in Fig. 5. Figures 6a and b give the current velocity vector comparisons at 42 m of depth after a model run of 16 days and 23 days, corresponding to the field data that occurred during the period from 16 June 2005 to 24 June 2005 for this depth measured by the Oceans Ltd. in 2005 (Oceans Ltd. 2006). The comparisons between simulation and monitoring results in 3D indicate that the modeling of ocean currents in the Hibernia area is satisfactory using POM, which accounts for local hydrodynamic effects and is in direct support of assessing the dispersion of pollutants resulting from the coastal petroleum production process.

Pb Dispersion Modeling Results and a Comparison with Field Monitoring Data

The POM-RW method was formulated to simulate the dispersion of Pb in the produced water effluent in the present study. The model ran for 30 days with a timestep of 180 s and a release of 200 particles per timestep. The Pb dispersion results compared with field data at 10, 35, and 60 m are shown in Fig. 7a, b, and c, respectively. The modeling results are the distribution of average concentration for the model run from 21 days to 30 days. It shows that the model results have good agreement with the field observations at the depth of 35 m, which is the closest layer to the emission source point. Figure 7b also clearly shows the emission source location with the highest concentration in the resulting plume at that layer. The flow modeling results for the layer at the depths of 10 and 60 m confirm that the effects of the turbulent currents have been quantified to support a field modeling of pollutant dispersion. This explains why the dispersed pollutants move slightly to the north of the Hibernia site as indicated in Fig. 7a and c.

The predicted concentrations for field locations far away from the emission source are generally lower than the sample concentrations as shown in Fig. 7a and c. This could be explained as follows: i) the computational grid cells were set at 2 km by 2 km by 4 m for the study region, which can be refined with high performance computational facility; ii) there are uncertainties associated with the natural marine condition as well as the possible operational changes of produced water discharges from the source; iii) the model ran for only 30 days; most of the particles could still accumulate in the near field and possibly only a small number of particles reached the surface and the bottom; and iv) the mixing coefficients were assumed constant in this study; different values of the coefficients will affect the dispersion pattern (Chen and Huang 2003).

Discussion and Uncertainty Analysis

Determination of boundary conditions is critical for a successful simulation of the coastal current field. Modeling and verification results in this study confirm that the development of a radiation-type open boundary condition is appropriate for modeling the ocean current fields in the study area. Additionally, a much larger and
wider area containing the study region (Fig. 2) is considered to minimize the influence of boundary conditions for the study region. An integrated effort was made in this study for 3D field sampling and measurement, which directly supported the field validation of the developed POM-RW. More regular monitoring of the local ocean current conditions will further help to configure the complex model boundary conditions.

Field validation indicates that the developed POM-RW approach can provide better prediction of pollutant concentration close to the emission source (Fig. 7b), but modeling outputs for locations near to the surface and the ocean bottom do not match with monitoring data very well (Fig. 7b and c). This can be further attributed to the following: (i) the Random Walk approach provides better results in the near-field region, and it might result in erroneous particle distributions in the far-field locations (Suh 2006); (ii) the tide was not considered in this study, which could contribute to more dilution and to carrying pollutants to different locations from the predicted results; and (iii) instantaneous changes of current in the study area due to aquatic life activities, sailing ships, and oil and gas production and transportation activities would also change the pattern of dispersion. Nevertheless, this study shows that the developed POM-RW approach is capable of examining both regional circulation conditions and pollutant dispersal for the study site.

Additionally, determination of key dispersion model parameters was a difficult task during the model application study. Especially, the horizontal and vertical mixing coefficients, $K_h$ and $K_z$ given in equation 7, are among the most important factors to determine the concentrations of pollutants in the environment. A thorough analysis of the model and site uncertainties is suggested in future studies (Chen and Huang 2003).

Conclusions

A POM-RW approach has been developed in this study based on a Princeton Ocean Model and a Random Walk simulation. Notably, the effects of ocean current on the dispersion of pollutants in the natural marine
environment can be fully considered for addressing potential environmental impacts associated with large waste effluents from offshore oil production activities.

Based on the full consideration of boundary conditions, the modeling results of the flow field indicate that POM can provide satisfactory current simulations for the study region. Therefore, it not only helps to understand the ocean current circulation pattern in the Atlantic Ocean off the east coast of Canada, but also provides hydrodynamic inputs to the model of pollutant dispersal.

A field program has been conducted to supply monitoring data of the ambient ocean water quality. Comparing the field data with the modeling results shows a relationship that the developed POM-RW approach can provide an environmental assessment of the produced water discharge activities near its source. Although Pb was used in this research as a model contaminant

**Fig. 7.** Modeling results for the dispersion of Pb with a comparison with monitoring data at (a) a 10-meter depth (μg/L), (b) a 35-meter depth (μg/L), and (c) a 60-meter depth (μg/L).
tracer, the dispersion and risks of other contaminants to the regional marine environment may be examined using the developed modeling approach. This research will contribute to the development of effective decision tools for the long-term management of produced water discharges in the ocean environment.

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