Effects of chemical dispersant and seasonal conditions on the fate of spilled oil – modelling of a hypothetical spill near Saint John, NB

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ABSTRACT

The proposed Energy East pipeline project has raised concerns about potential oil spills in Saint John, New Brunswick. While environmental conditions could pose challenges for using mechanical recovery methods if a spill occurs, chemical dispersant could be an alternative. However, the application of chemical dispersant in shallow water and coastal zones remains an issue of debate. Furthermore, the effectiveness of chemical dispersant under different seasonal conditions is yet to be determined. This study attempts to describe a modelling effort to understand the probable distribution of petroleum hydrocarbons in Port Saint John following a hypothetical release of crude oil to which dispersant is applied during different seasons. A three-dimensional model was used to simulate the transport of oil with a release of 1,000 m³ of Arabian light crude in the summer and winter. A stochastic approach took into account the uncertainties of environmental inputs. The results were a significant reduction of oil ashore, and enhanced biodegradation with dispersant application. However, these effects were accompanied by an increase of oil in the sediment and water column, which is a concern. While the results are only conclusive for the selected scenarios of summer and winter, the method could be applied to other months and seasons to support more detailed analysis regarding dispersant application.

Key words | Arabian Light crude, biodegradation, chemical dispersant application, fate and behaviour, modelling, oil spills, Saint John Harbour

INTRODUCTION

Canada has the world’s third largest oil reserves and 97% of its oil reserves are in the oil sands (Canadian Association of Petroleum Producers 2013). Rising oil demand in the long-term, and the fact that the new supplies will be hard to reach, spell a bright future for the development of Canada’s oil sands (Conference Board of Canada 2012; International Energy Agency 2012). Currently, the takeaway capacity of oil sand product is 3.5 mmbd from the Western Canadian Sediment Basin (WCSB). With a forecasted production of >5 mmbd by 2035, there is a requirement of additional capacity in transportation through rail or pipeline (Conference Board of Canada 2012). Increased export of oil sand product has already been proposed by industries including the Enbridge Northern Gateway pipeline to Kitmat, BC, the Kinder Morgan Trans Mountain pipeline to Vancouver, BC, and the TransCanada Energy East pipeline to Canada’s east coast.

When oil is produced and transported, there is a risk of spills with the potential to cause significant environmental damage (Alves et al. 2014). Notable recent examples are the Deepwater Horizon oil spill in the Gulf of Mexico, and the Lac-Mégantic spill in Quebec. Once oil is spilled into an aquatic environment, the major steps involved in controlling oil spills are containment and recovery. Mechanical equipment, such as booms and skimmers, are often used to block the spreading of oil, concentrate it into one area,
and remove it from the water. In cases where mechanical containment and clean-up prove difficult or impossible, such as areas where untreated oil may reach shorelines and sensitive habitats causing more damage, or when the sea is rough, alternative oil spill countermeasures, such as chemical dispersant application, may be considered (US Environmental Protection Agency 1999). For example, during the Deepwater Horizon incident in which the release of oil was under extreme pressure and depth, a total of 43,884 barrels of dispersant was used (The Federal Interagency Solutions Group 2010).

Chemical dispersant contains surfactant compounds that can reduce the oil-water interfacial tension and cause oil slicks to break up into droplets and enter the water column. This process helps to remove oil from the surface and make it less likely to reach the shoreline (US Environmental Protection Agency 1999). Chemical dispersion can also help to stimulate biodegradation and further removal of oil from the environment (Swannell & Daniel 1999). The effectiveness of dispersant depends on many factors such as dispersant type, oil type, temperature, salinity, and mixing energy. Furthermore, the physical and chemical weathering of spilled oil over time can lead to the formation of stable oil and water emulsions which resist chemical dispersion. The window of opportunity for the effective use of dispersant before oil becomes more difficult to disperse is relatively short, typically within hours to 1 or 2 days after the spill (National Research Council 2005).

Many factors may contribute to delayed application, such as travel time to a spill site, darkness, dangerous sea state, as well as the regulatory approval process. Regulatory approval is required for application of dispersants, because their use has not been without controversy despite the wide use of dispersant in over sixty documented spills worldwide (Franklin & Warner 2011). A clearly established national dispersant decision policy is critical to streamline the approval process and prevent unnecessary regulatory delays, because failure to act quickly often results in a decision not to use dispersant. Some countries, such as France, Norway, the UK, and the United States have established regulations and guidelines regarding dispersant application. For example, some US regulations have ‘pre-authorized’ dispersant use in some areas depending on water depth and distance from shore. In Canada, unfortunately, there is no written policy on dispersant application. If a spill were to occur today, a lead agency (LA) would need to be identified first, which would consult with other agencies and regional environmental emergency teams (REET) to make a decision on a case-by-case basis. As suggested by the Arctic Oil Spill Response Technology Joint Industry Programme (2013), ‘Canada should revise/update the existing dispersant use guidelines and streamline the spill-specific dispersant approval/endorsement process.’

To help support decision making for dispersant application, and to evaluate the pre-approval options in selected scenarios or selected areas in Canada, numerical models may be used to study the effects of applied dispersant on the fate and behaviour of spilled oil, and evaluate potential environmental impacts and benefits, as demonstrated by Reed et al. (2004). The risk of an oil spill in the Port of Saint John will increase as a direct result of increased shipping traffic for the Energy East pipeline. The objective of this study was to describe a modelling effort to understand the probable distribution of petroleum hydrocarbons in Port Saint John and its environs following a hypothetical release of crude oil to which dispersant is applied.

**STUDY AREA**

Saint John, eastern Canada’s largest port, is located at the mouth of the Saint John River in New Brunswick (Figure 1). It receives crude oil at its Canaport terminal by supertanker (including the Acropolis, the world’s largest crude carrier capable of holding 2.8 million barrels of oil) from various regions around the world, such as Saudi Arabia, the North Sea, and nearby Newfoundland and Labrador. After passing through the Irving Refinery, finished product, such as jet fuel, bunker, and heating oil are exported by different means including ships to Canada and the US. The recently proposed deep-water marine terminal in the port would facilitate the export of Alberta crude oil to foreign markets. This has raised concerns about the increased risk of oil spills due to increased tanker traffic in the ecologically important Bay of Fundy.
Saint John, located on the north side of the Bay of Fundy, is famous for some of the world’s largest tides, reaching over 6 m in amplitude in the Minas Basin. The depth-integrated current can often exceed 3 m/s through the Minas passage (Karsten et al. 2008; Wu et al. 2011). As suggested by Nuka Research & Planning (2006), strong tide and currents can greatly impair mechanical response and clean-up operations. So there is clearly a need to investigate alternative response methods, such as chemical dispersant application, and to determine the fate and behaviour of spilled oil in this study area.

MODELLING APPROACH

Oil spill model

The Oil Spill Contingency And Response (OSCAR) model (Reed et al. 1995, 1999, 2004; Aamo et al. 1997), which is specifically designed to support decision making, was used to forecast the fate and behaviour of hypothetical oil spills in Saint John Harbour. This three-dimensional, particle-based model simulates the evolution of oil on the water surface, along shorelines, and dispersed and dissolved in the water column. The processes include spreading, drifting, physical dispersion, chemical dispersion, evaporation, stranding, dissolution, adsorption, settling, emulsification and biodegradation (Figure 2). The model has three key components: a databased oil-weathering module, a three-dimensional fate/trajectory module, and an oil spill response/combat module. The OSCAR model has been validated in considerable detail (Reed et al. 1996, 2000).

Model inputs and setup

The ocean currents that were used were generated by a hydrodynamic model based on the Finite-Volume Coastal Ocean Model (FVCOM), which is a proven three-dimensional, finite-volume, unstructured grid ocean model (Chen
The outputs from FVCOM are high-resolution data (spatial resolution up to 10 m and temporal resolution of 1 hour) with triangular mesh which is highly capable in characterized complex topographies such as rivers and shorelines. The model was evaluated against independent observational data, including tidal elevation, tidal current (in the water column and bottom layer), tidal residual current and tidal asymmetry indicators. Simulated results were in good agreement with the observations. Details on the hydrodynamic model setup and validation can be found in Wu et al. (2011).

The model domain for the study area is shown in Figure 1. The area is 4 degrees by 2 degrees divided into 700 by 500 grid cells. Depths in the simulation are taken from the high-resolution 1-arc minute global bathymetry database, ETOPO1 (Amante & Eakins 2009). The maximum depth is 286 m. Climate data, such as wind and air temperature, for the study area were downloaded from Environment Canada (2014). Waves were calculated internally by the model as a function of wind speed, fetch and duration. In order to fit the data formats to the OSCAR model, the water current data from FVCOM were interpolated based on the defined grid cells and modelling domain. After interpolation, the horizontal resolution for current was 50 m. Furthermore, 10 layers were set for the vertical grids with resolution of 1 m. The temporal resolution was 1 hour.

Scenarios

As mentioned, different crude and refined petroleum products are transported to and from the Port of Saint John. An environmental risk index (ERI), which takes account of the main factors including spill size, oil type, oil dispersion and environmental sensitivity, is usually utilized to represent the risk of oil spills in the marine environment (Australian Maritime Safety Authority (AMSA) 2011). In a recent report to Transport Canada prepared by WSP Canada Inc. (2014), the ERI for crude oil spills in the study area is medium to high, based on a combination of probability and environmental sensitivity calculations. According to the report, the ERI for refined product spills is high to very high. Comparatively, the ERI for fuel oil spills is much lower. Therefore, the potential for spills from both crude oil and refine products requires investigation. Since data on oil properties for refined products were unavailable, only spills from crude oils with properties similar to Arabian Light were studied.

The analysis by WSP Canada Inc. (2014) revealed that the spills of less than 1,000 m$^3$ occur most frequently. In addition, the maximum spill amount for Tier 2 response (usually a regional response) is 1,000 tonnes, which is approximately 1,000 m$^3$ (Transport Canada 1995). Thus, a 1,000 m$^3$ spill represents the worst case scenario of the most frequent type of oil spill for the region, and the worst case scenario for the Tier 2 response scheme in Canada, which is why this volume was used. It was assumed that a spill would be most likely to occur near the offloading terminals at 45°10’N, 66°0’W (Figure 1).

Environmental conditions, especially wind, play an important role on the fate and transport of spilled oil. Since the dominant wind for a particular season of the year varies significantly, the effects need to be investigated separately. In this study, two series of scenarios, winter from January 1–31, 2014 and summer from July 1–31, 2014 were chosen to study the effects of chemical dispersant application under different seasonal conditions. These two months were selected in an attempt to capture the extremes in climate of the study area. The same approach can be applied using environmental inputs for other seasons. The dominant wind for the study period is shown in Figure 3. The wind roses for January and July indicate that the prevailing wind direction in winter is from the northwest, and which in summer is from the southwest. In addition, the wind direction in winter is more differentiated than that in summer. Furthermore, the wind speed in winter is significantly higher than that in summer.

To study the effects of chemical dispersant application, scenarios with and without chemical dispersant were selected for both winter and summer conditions. Corexit 9500 with a dispersant effectiveness of about 40% for Arabian Light was used (Blondina et al. 1999). Dispersant application begins almost immediately after the spill occurs, and continues throughout the simulation period to treat the under-dosed fraction. This approach ensures the highest treatment efficiency (not limited by dispersant quantity), and enables us to study the maximum likely effects of dispersant on oil fate and behaviour. For example, if the maximum likely reduction of oil ashore is insignificant
under ideal application conditions, the application of disper-
sant is less justifiable for this site under the prescribed
scenarios.

A stochastic approach was applied in this study to esti-
mate the likelihood of particular trajectories occurring,
based on historical wind speed and direction data. The
model ran a series of trajectories under various wind con-
ditions from the historic wind records, and then combined
the results to produce an overall picture, illustrating the
probability of where oil may travel.
Figure 5 | Oil at the water surface, in the atmosphere, in the water column, in the sediment, onshore, biodegraded, recovered and transported outside the study area for (a) winter without dispersant, (b) winter with dispersant, (c) summer without dispersant, and (d) summer with dispersant in a single stochastic run (No. 3).
In this study, the period for any individual model run was 10 days. This was selected based on preliminary simulations to ensure that spilled oil could potentially reach the shoreline and considering the reality of oil spills and the window of opportunity for the application of dispersant. It is well known that spill dispersion occurs within the first 10 days, after which the oil in the water column generally becomes undetectable. The stochastic simulation incorporates a randomized spill date, which was set to occur within the first 20 days of the complete 30 day modelled period.

RESULTS AND DISCUSSION

Mass balances for the 20 stochastic runs were computed. As an example, the mass balances from Run No. 3 are given in Figure 4 to show the effects of chemical dispersant application under different seasonal conditions (winter and summer). The case without dispersant application in winter (Figure 4(a)) indicates that a large amount of oil remained in the surface initially and then gradually disappeared due to evaporation and natural dispersion. After 6.5 days, oil in both the surface and water column started to decrease rapidly due to contact with the seabed and shoreline and became stranded. For the case with dispersant application in winter (Figure 4(b)), surface oil was effectively dispersed soon after the spill and a significant amount was transferred to the water column, so that evaporation was reduced and oil started to reach the sediment earlier (3 days after the spill) compared with the absence of dispersant (6.5 days).

In summer scenarios, the prevailing southerly wind moved the oil towards the shoreline and it quickly became stranded onshore (Figure 4(c)). After application of dispersant, most of the spilled oil entered the water column before reaching the shore (Figure 4(d)). Biodegradation was significantly enhanced because more oil entered the water column. The extent of oil coverage for Run No. 3 is shown in Figure 5. A significant amount of oil remained in the water column. Far less remained at the surface after the use of dispersant compared with the case without dispersant application.

The mass balances for the 20 runs at the end of each 10-day simulation period are given in Figure 6. A higher
percentage of oil reached the shoreline and very little remained in the water column after 10 days for the cases without dispersant application (Figure 6(a) and (c)). When dispersant was applied, the percentage of oil reaching the shoreline was reduced in all 20 runs. The amount in the water column and sediment increased for a majority of the runs (Figure 6(b) and (d)). The sharply increasing percentage of chemically dispersed oil in the early stage was due to the reduced and unstable oil-water interfacial tension. A fraction of the dispersed oil droplets continued to move between the surface and the water column until this flux stabilized. The dispersion rate kept decreasing after the initial application of dispersant until it became stable after about 7 days. Before significant loading of oil ashore and to the sediment, dispersion rates were sustained at about 40% in both winter and summer scenarios.

Compared with winter, more significant sedimentation occurred in the summer. The study has found that most of the oil was transported and trapped in the northeast, in Chignecto Bay which is a comparatively shallow area. Here, entrained oil particles tended to make contact with the seabed and remain adhered to the sediment. There is also the possibility of oil remaining with the sediment through the formation of oil-mineral aggregates, but this was not part of the present model. Quantitative comparisons of the effects are presented in Figure 7. On average, 25.9% and 35.6% of the total spilled oil was prevented from reaching shore after 10 days due to dispersant application in winter and summer, respectively. This application also helped enhance biodegradation. The increase in biodegradation was on average 11.6% and 3.1% of the total spilled oil in winter and summer, respectively. This is beneficial if the shoreline is of high priority for protection. Compared with the winter scenario, strong shore retention occurred in the summer, reducing the amount available for biodegradation in the water column, which is why the biodegradation rate in summer was lower than in winter.

It should be noted that the application of chemical dispersant increased the amount of oil in sediment for all 20

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**Figure 7** | Quantitative comparison of the effects of dispersant: (a) mass balance with/without dispersant application in winter, (b) difference in mass balance between natural dispersion and chemical dispersion in winter, (c) mass balance with/without dispersant application in summer, and (d) difference in mass balance between natural dispersion and chemical dispersion in summer. Note: 0 in the x-axis indicates no application of dispersant or just natural dispersion; while 1 indicates application of dispersant or chemical dispersion.
Figure 8 | Sediment oil concentration for Mass balance for (a) winter without dispersant, (b) winter with dispersant, (c) summer without dispersant, and (d) summer with dispersant in a single stochastic run (No. 3).
simulations. In winter, the range of increase was from 2.7 (No. 20) to 24.3% (No. 8), with a mean of 13.6% (Figure 7(a) and (b)). Sedimentation was more significant in summer with a range of 28.1 (No. 8) to 58.6% (No. 18) and mean of 42.2% (Figure 7(c) and (d)). The distribution of oil in the sediment in both seasons with and without dispersant is shown in Figure 8. There was also an increased amount in the water column averaging 8.4% and 8.8% of the total spilled oil in winter and summer conditions, respectively. These increases are of concern if the fisheries are of higher priority than shoreline. A net environmental benefit analysis using the results generated from this study could provide recommendations on dispersant use for the selected scenarios.

Finally, the individual trajectories of the 20 runs were combined to produce a probability of surface and shoreline contamination (Figures 9 and 10). Figure 9 indicates that the area in winter was significantly larger than in summer. As mentioned previously, the reasons for this are mainly the more varied wind direction and higher wind speed in winter (Figure 3) than in summer. The environmental impact factor (EIF) was used to represent the risk to different habitats (e.g. water column, water surface, and shoreline) and the whole region. The water column is defined as the area of the horizontal cross section of the spill plume in water column.

Impacted areas with risk greater than 5% are shown in Table 1. The application of dispersant helped lower the probability of surface and shoreline contamination in many areas. The total impacted area was reduced from 6,996 to 5,980 km² in winter. The impacted sea surface area was significantly reduced from 6,385 to 898 km² (Figure 9(a) and (b)). Furthermore, the impacted shoreline was reduced from 172 to 95 km² (Figure 10(a) and (b)). The total impact area in summer was significantly smaller than in winter. However, the total impacted area in summer was slightly increased from 2,078 to 2,859 km².
after application of dispersant, which was caused by a significant increase in affected water column (121% increase). In contrast, the total impacted sea surface area in summer was decreased from 1,604 to 897 km² (Figure 9(c) and (d)) and the impacted shoreline area was decreased from 61 to 29 km² (Figure 10(c) and (d)).

If we assume that the species in the study area are of equal importance and the toxicity of oil/dispersant mixtures are about the same as or less than that of oil alone (Fuller et al. 2009; Hemmer et al. 2011), it suggests that dispersant application would be beneficial, resulting in a reduction in the overall impacted area in winter. The application of dispersant in summer would require more caution. If the major concern for the impacted areas is focusing on sea surface and shoreline (i.e. ecological reserves and residence areas), dispersant would be recommended. In contrast, the application of dispersant would not be recommended in summer when the concern is for the water column (e.g. fishery areas).

The results in Table 1 are based on a 10-day simulation period. For some runs, especially those with a higher percentage of oil remaining in the water column, oil might continue to transfer to the sediment and shoreline, and the final mass balance may be different from what is shown. In this study, the 40% dispersant effectiveness that was used was based on laboratory experiments under controlled conditions with effective oil-dispersant interaction and mixing. In reality, field effectiveness could be much lower due to many factors such as ineffective slick encounters and spraying of oil, delayed application resulting in reduced effectiveness due to oil weathering and emulsion formation, and effects of low water temperature and salinity.

CONCLUSIONS

The OSCAR model was used in this study to simulate a hypothetical oil spill of 1,000 m³ of Arabian Light oil near the offloading terminal in Saint John, NB, in winter and summer conditions, and to study the effects of chemical dispersant application on the fate and distribution of oil in different environmental partitions. A stochastic approach
was also employed to consider the uncertainties associated with environmental inputs such as wind and currents. The effects of dispersant application were detected in all 20 stochastic runs. The application of dispersant significantly reduced the amount of oil that could have reached the shoreline. The mean reduction of stranded oil was between 25.9% and 35.6% of the total spilled after 10 days in winter and summer, respectively. The application of dispersant also helped promote biodegradation with a mean increase of 11.6% and 3.1% of biodegraded oil during winter and summer, respectively. Besides these positive effects, the application of dispersant did have some negative effects: an increased amount of oil in the sediment and water column by an average of 15.6 and 8.4% in winter, and 42.4 and 8.8% in summer. If the importance attributed to shoreline and water column are equal, the results indicate that dispersant application would be a suitable countermeasure under winter conditions because of reductions of all impacted areas. The application of dispersant in the summertime would lead to a significant increase in impact to the water column, but decreased impact to the sea surface and shoreline areas; therefore, the application of dispersant would be suitable in the summer when the major concerns are the sea surface and shoreline areas. However, it would not be suitable when the major concern is the water column. The results of this study could be used to conduct more detailed net environmental benefit analysis to furnish recommendations on dispersant application for the study area. Such a study should consider the short- and long-term fate and effects of chemically dispersed oil on impacted ecosystems. Unfortunately, with the exception of two recent studies (Baelum et al. 2012; Campo et al. 2013), no information has been published on the environmental fate of the active surfactant in dispersant with regard to microbial degradation. More research on the fate and effects of dispersants are clearly needed. Future studies, should address refined products.

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