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Modelling the Effects of Chemical Dispersant on the Fate of Spilled Oil: Case Study 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, due to increased tanker traffic. While environmental conditions such as strong tide and current could pose challenges for using mechanical recovery methods if a spill occurs in the area, chemical dispersant could be an alternative oil spill countermeasure. However, the application of chemical dispersant in shallow water and costal zones remains an issue of debate. To study if chemical dispersant could be effective for potential oil spills in Saint John, a 3-dimensional model was used to simulate the transport of oil following a hypothetical release of 1000 m^3 Arabian Light crude under winter conditions. A stochastic approach was used to take into account the uncertainties of environmental inputs. The results show a significant reduction of oil ashore, and enhanced biodegradation with dispersant application, but these effects were accompanied by an increase of oil in sediment and water column, which is a concern. While the results are only conclusive for the selected scenarios of winter release, the method could be extended to other months and seasons of the year to support more detailed net environmental benefit analysis regarding dispersant application.

Keywords: Oil spills, modelling, chemical dispersant application, fate and behaviour, Saint John harbour, biodegradation

Introduction

Canada has the world's third largest oil reserves, and 97% of it's 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, spells a bright future for the development of Canada's oil sands (International Energy Agency, 2012; Conference Board of Canada, 2012). Currently, the takeaway capacity of oil sand product is 3.5 mmbd from the Western Canadian Sediment Basin (WCSB). With the forecasted production of >5 mmbd by 2035, there is a requirement of additional transportation capacity 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 Quebec City, QC, and Saint John, NB.

As long as oil is produced and transported, there is a risk of spills with the potential to cause significant environmental damage. Notable, recent examples are the Deepwater Horizon oil spill in the Gulf of Mexico, the Kalamazoo River oil spill in Michigan, and the Lac-Mégantic oil spill in Quebec. When 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 cleanup 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 were 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 breakup 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 and 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 an oil 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 needed 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 and Warner, 2011). A clearly established national dispersant decision policy is critical to streamline the approval process and prevent unnecessary regulatory delays, because failure to make such a timely decision often results in a decision not to use dispersant. Some countries, such as France, Norway, the United Kingdom, and the United States have established regulations and guidelines regarding dispersant use. 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 use. If a spill were to occur today, a leading agency (LA) would need to be identified first and the LA 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 with dispersant use decision making, 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 dispersant application on the fate and behaviour of spilled oil, and evaluate potential environmental impacts and benefits, as demonstrated by Reed et al. (2004). The Port of Saint John is under an increased risk of oil spills due to the greater shipping traffic that will arise as a result of the Energy East pipeline development, It is the purpose of this paper to describe a modelling effort to understand the probable distribution of oil in the Port of Saint John and surround areas following a hypothetical release of oil to which dispersant is applied.

Study Area

The Port of Saint John is located at the mouth of the Saint John River in the city of Saint John, NB (Figure 1). The port is Eastern Canada's largest port. The port, through its Canaport terminal, receives crude oil by supertankers (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 deepwater marine terminal in the port would provide Alberta crude oil access 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.

Sant John lies on the north side of the Bay of Fundy, famous for some of the world's largest tides, reaching over 6 m in amplitude in the Minas Basin. The depth-integrated current is very strong, reaching over 3m/s through the Minas passage (Karsten et al., 2008; Wu et al., 2011). As suggested by Nuka Research and Planning (2006), strong tide and currents can greatly impair mechanical response and cleanup operations, so there is a need to investigate alternative response methods, such as chemical dispersant application, and to determine the effects on oil fate and behavior for this study area.

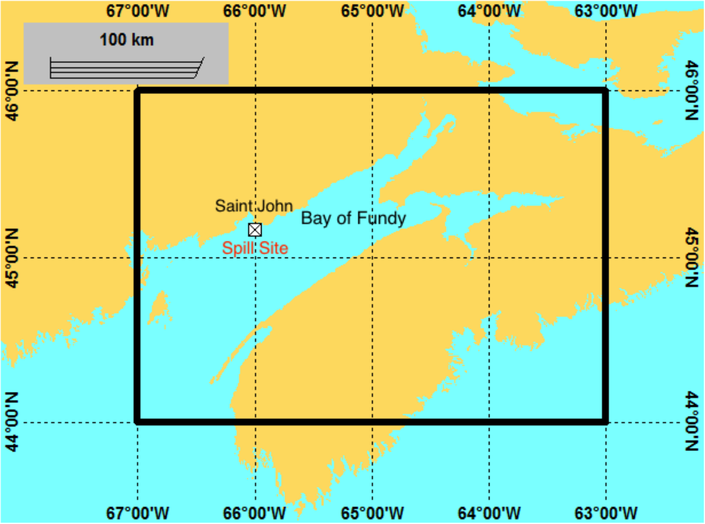

Figure 1. Study area and model domain outlined by black box.

Modeling Approach

Oil spill model

The oil spill contingency and response (OSCAR) model (Reed *et al.*, 1995; Aamo *et al.*, 1997; Reed *et al*. 1999; Reed *et al.*, 2004), which was specifically designed to support oil spill contingency and response decision making, was used to simulate the behaviour and fate of the hypothetical oil spill in the Saint John Harbour. This is a 3-dimensional particle-based model that simulates the evolution of oil on the water surface, along shorelines, and dispersed and dissolved oil concentrations in the water column. The processes included are spreading, drifting, natural dispersion, chemical dispersion, evaporation, stranding, dissolution, adsorption, settling, emulsification and biodegradation (Figure 2). The model has three key components: a databased oil-weathering model, a three-dimensional fate/trajectory model, and an oil spill response/combat model. OSCAR has been validated in considerable detail (Reed et al. 1996; 2000).

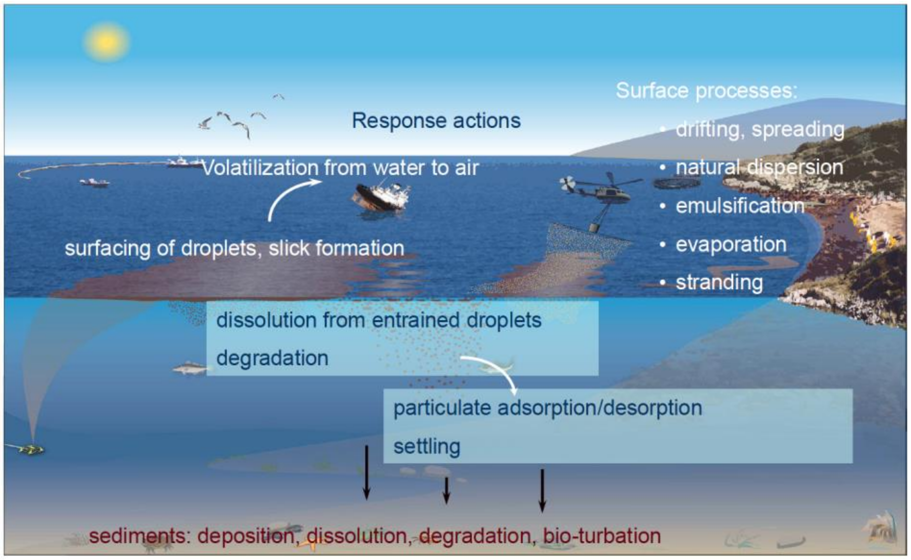

Figure 2. Processes included in the OSCAR model (Courtesy of SINTEF).

Model inputs and setup

The ocean currents for oil spill modelling are from 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 et al., 2007). The model was evaluated against independent observational data, which include tidal elevation, tidal current (in the water column and bottom layer), tidal residual current and tidal asymmetry indicators. The evaluation shows that the model is 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 and Eakins, 2009). The maximum depth is 286 m. Climate data, such as wind and air temperature for the study area are downloaded from Environment Canada (2014). Waves are calculated internally by the model as a function of wind speed, fetch and duration.

Scenarios

As mentioned, many different crude and refined petroleum products are transported to and from the Port of Saint John. Based on a recent report to Transport Canada prepared by WSP Canada

Inc. (2014), the Environmental Risk Index (ERI) for crude oil spills in the study area, which is based on a combination of the probability and environmental sensitivity calculations, is medium to high. The ERI for refined product spills is high to very high. The ERI for fuel oil spills is very low. Based on this analysis, spills from both crude oil and refine products are needed. However, due to the unavailability of oil properties data for refined product, only spills from a crude oil (assuming that it has properties similar to Arabian Light) will be studied here. The analysis by WSP Canada Inc. (2014) also shows that the frequency of spills is much higher for spills less than 1,000 m^3 than for spills over 1,000 m^3. Therefore, a spill volume of 1,000 m^3 was selected to represent the most frequent spill event. The location of the spill was assumed to be 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, only winter scenarios from January 1 to 31, 2013, were chosen to study the effects of chemical dispersant application. The same approach can be applied using environmental inputs for other seasons. The dominant wind for the study period is shown in Figure 3.

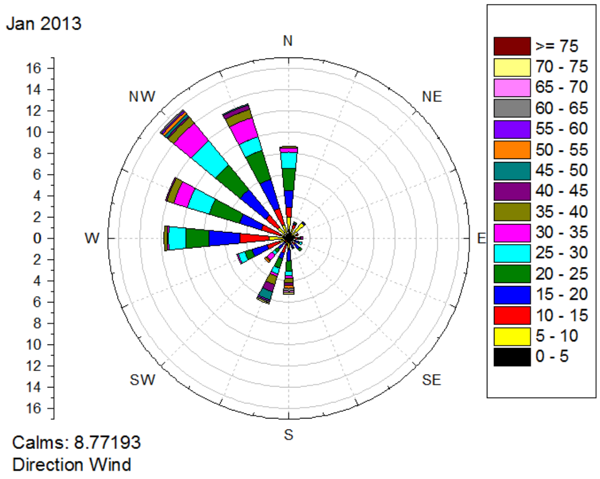

Figure 3. Windrose plot showing wind speed, direction and frequency.

To study the effects of chemical dispersant application, scenarios with and without chemical dispersant were selected for both winter and summer conditions (Table 1). Dispersant application begins almost immediately after the spill occurs, and continues throughout the simulation period to treat the under-dosed fraction. This approach ensures that the treatment is 100% efficient (not limited by dispersant quantity), and enables us to study the maximum likely effects of dispersant on oil fate/behaviour. For example, if the maximum likely reduction of oil ashore is insignificant under ideal application conditions, the application of dispersant is less justifiable for this site under the selected scenarios. The dispersant used was Corexit 9500 with a dispersant effectiveness of about 40% for Arabian Light (Blondina et al., 1999).

A stochastic approach was used in this study to estimate the likelihood of particular trajectories occurring, based on historical wind speed and direction data. The model ran a series of trajectories under various wind conditions from the historic wind records, and then combined the results to produce an overall result illustrating the probability of where oil may travel. In this study, a 10-day simulation period was selected based on preliminary simulations to ensure that spilled oil could potentially reach the shoreline. For each scenario, 20 stochastic runs were performed.

Results and Discussions

Mass balances for the 20 stochastic runs were computed and an example, Run No.3, is given in Figure 4 to show the effects of chemical dispersant application. The case without dispersant application (Figure 4 - left) shows that a large amount of oil remains in the surface initially and then gradually disappears 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 (Figure 4 - right), surface oil was effectively dispersed soon after the spill and a significant amount was transferred to the water column. Due to this effect, the evaporation was reduced and oil started to reach the sediment earlier (3 days after spill) compared with the case without dispersant (6.5 days). Biodegradation was significantly enhanced because of more oil being in the water column. The extent of the oil coverage for Run No.3 are shown in Figure 5.

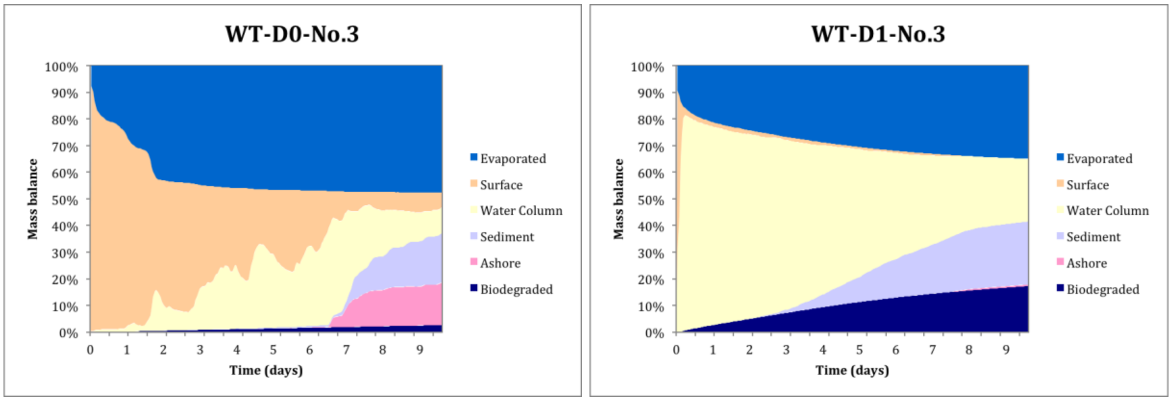

Figure 4. Mass balance for run No.3. WT: Winter, D0: without dispersant, D1: with dispersant.

The mass balances for the 20 runs at the end of each 10-day simulation period are given in Figure 6. Overall, a visual comparison indicates that a higher percentage of oil reached the shoreline and very little remains in the water column after 10 days for the case without dispersant application (Figure 6 - left). For the case with dispersant application, oil reaching the shoreline was reduced for all 20 runs. The amount in the water column and sediment increased for a majority of the runs (Figure 6 - right). Quantitative comparisons of the effects are presented in Figure 7. On average, 25.9% of the total spilled oil was prevented from reaching shore after 10 days due to dispersant application. This application also helped to enhance biodegradation. The increase in biodegradation was on average 11.6% of the total spilled oil. This is beneficial if the shoreline is of high priority for protection. However, it should be noted that the application of chemical dispersant increased the amount of oil in sediment for all 20 simulations. The range of increase was from 2.7% (No.20) to 24.3% (No.8), with a mean value 13.6% (Figure 8). There was also an increased amount in the water column averaging 8.4% of the total spilled oil. These increases are of concern if the fisheries are of higher priority than shoreline. A net environmental benefit study using the results generated from this study could provide recommendations on dispersant use for the selected scenarios.

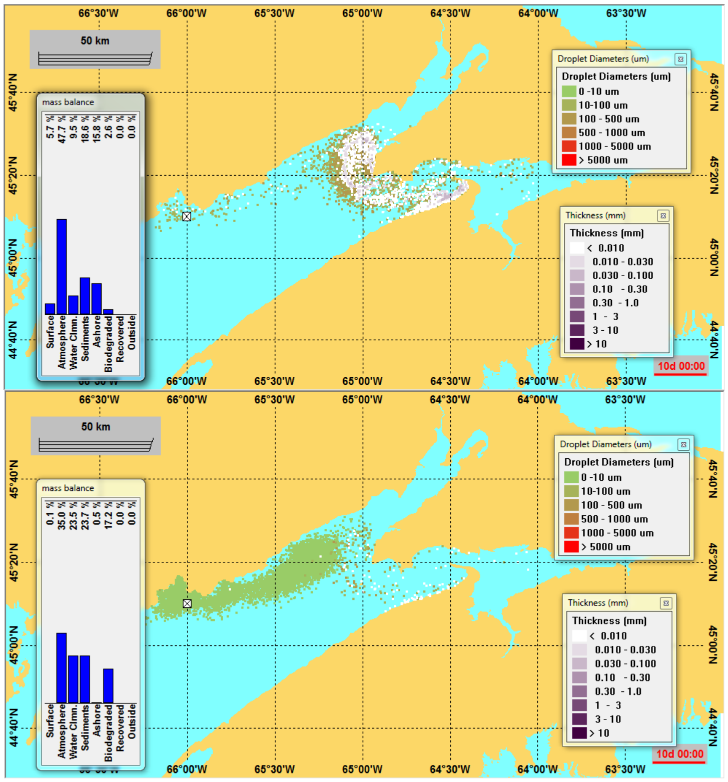

Figure 5. Extent of oil coverage for run No.3. Top: without dispersant, bottom: with dispersant. The bottom figure shows that a significant amount of oil remains in water column and much less remains on the surface compared with the case without dispersant application.

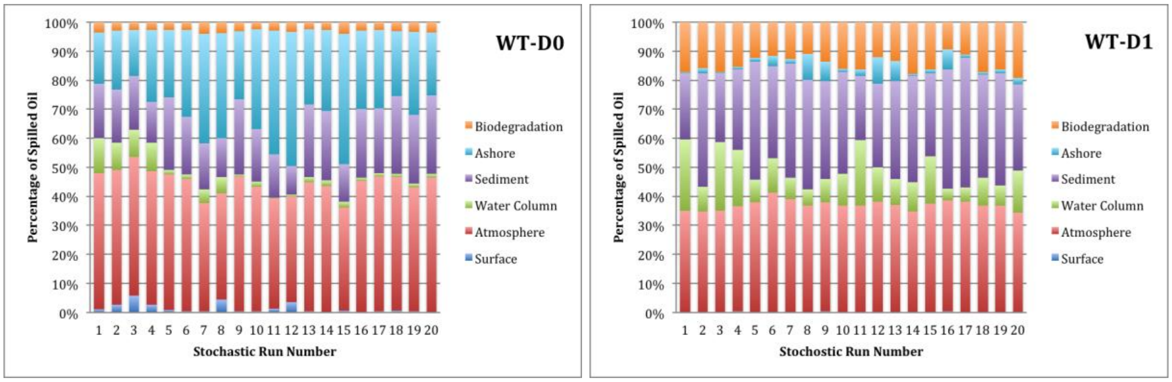

Figure 6. Mass balance at the end of each 10-day simulation period for the 20 stochastic runs (Jan 2013). Left: without dispersant, right: with dispersant.

Finally, the individual trajectories of the 20 runs were combined together to produce a probability of contamination to show the likelihood of surface and shoreline contamination (Figures 9 and 10). The results show that the application of dispersant helped to lower the probability of surface and shoreline contamination in many areas. The total impacted area is reduced from 6,996 km^2 to 5,980 km^2. The impacted shoreline is reduced from 172 km^2 to 95 km^2. If we assume that the species in the study area are of some 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), this reduction suggests that dispersant application would be beneficial resulting in a reduction of the overall impacted area.

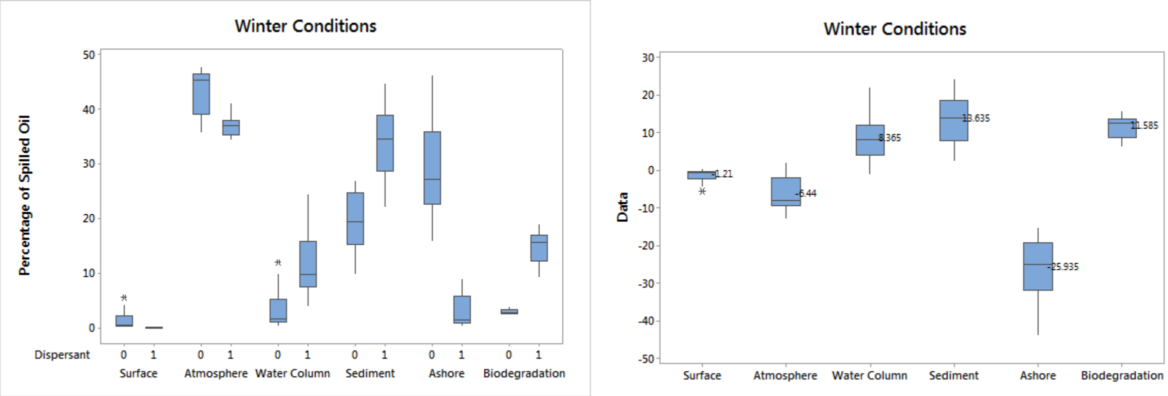

Figure 7. Quantitative comparison of the effects of dispersant on mass balance at the end of each 10-day simulation period. Left: box plot of the descriptive statistics of mass balance for the 20 runs without (0) and with (1) dispersant, right: box plot of the descriptive statistics of percentage of reduction.

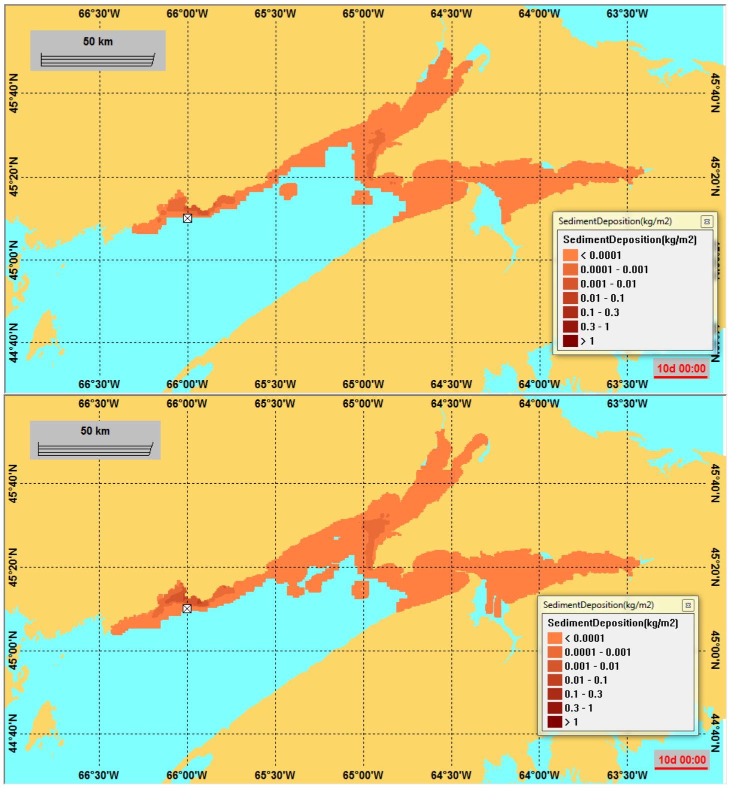

Figure 8. Sediment oil concentration for run No. 8. Top: without dispersant, bottom: with dispersant.

It should be noted that the results shown above 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 that shown above. In this study, a dispersant effectiveness of 40% from laboratory experiments was used. This was 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.

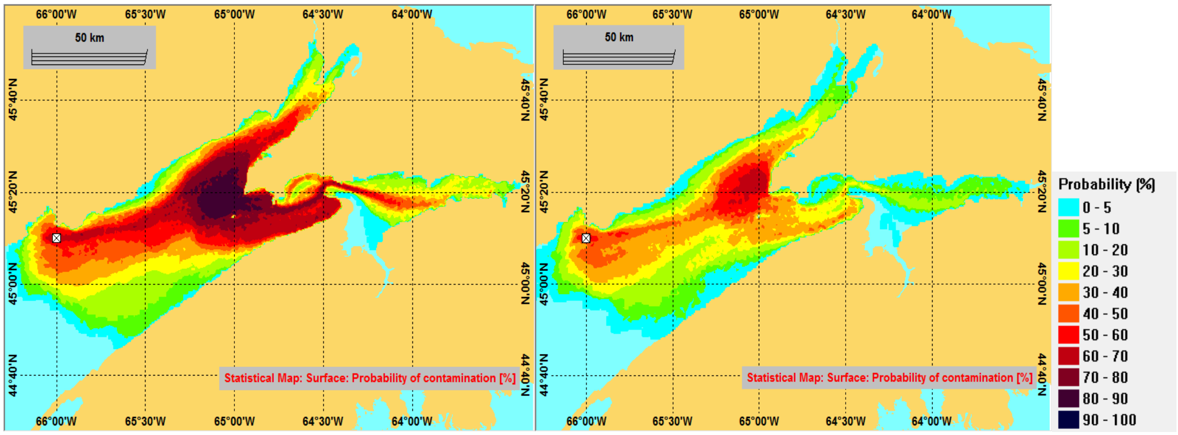

Figure 9. Probability of surface contamination. Left: without dispersant, right: with dispersant.

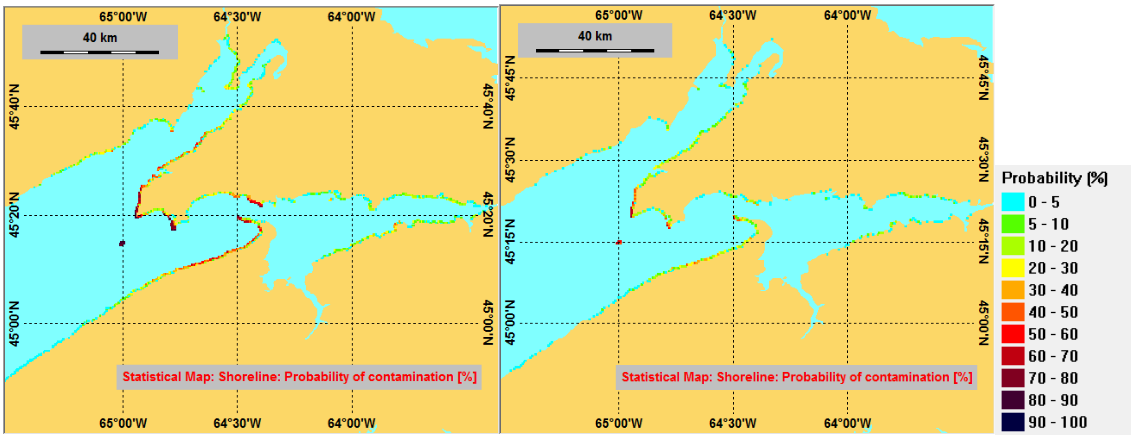

Figure 10. Probability of contamination of shoreline. Left: without dispersant, right: with dispersant.

Conclusions

The OSCAR model was used in this study to simulate a hypothetical oil spill of 1000 m3 of Arabian Light oil near the offloading terminal in Saint John, NB, in winter 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 employed to consider the uncertainties associated with environmental inputs such as wind and currents.

The dispersant application was found to have effects on all 20 stochastic runs and significantly reduced the amount of oil that could have reached the shoreline. The mean reduction was from

25.9% (15.3% to 43.7%) of the total spilled oil after 10 days. The application of dispersant also helped to promote biodegradation with a mean increase of 11.6% (6.5% to 15.6%) of the spilled oil. Together with 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 13.6% and 8.4% of total spilled oil, respectively. If the importance of the shoreline and the water column are the same, the results indicate that dispersant application would be a suitable countermeasure under the study conditions because of an overall reduction of impacted sea surface and shore area from 6,996 km^2 to 5,980 km^2.

The results from this study could be used to conduct more detailed net environmental benefit analysis to give recommendations on dispersant application for the study area. Such a study should consider the short- and long-term fate and effects of chemical dispersant component on oil impacted ecosystems. Unfortunately, with the exception of two recent studies (Baelum et al., 2012; Campo et al., 2013), no information has been published about the fate of the active surfactant in dispersant in the environment when subject microbial activities. More research on the fate and effects of dispersants are clearly needed.

Acknowledgement

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