

# **State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 2, Saint John and Bay of Fundy, New Brunswick**

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## **ABSTRACT**

Ryan, S.A., Wohlgeschaffen, G., Jahan, N., Niu, H., Ortmann, A.C., Brown, T.N., King, T.L., and Clyburne, J. 2019. State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 2, Saint John and Bay of Fundy, New Brunswick. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: x + 67 p.

Increasing Canadian oil production and tanker traffic elevates the risk of accidental oil spills in Canadian waters. In response, the Government of Canada announced the World Class Tanker Safety System and created the independent Tanker Safety Expert Panel to review Canada's ship-source oil spill preparedness and response. Using the panel's recommendations, the Government of Canada is establishing response plans for four pilot areas which have the highest tanker traffic in Canada: Saint John, NB, Port Hawkesbury and Canso Strait, NS, St. Lawrence Seaway, Qc, and the southern portion of British Columbia.

This is the second volume of a five volume report and contains information relevant to developing an area response plan for Saint John, NB. The first volume of this report contains introductory information on oil products and spills and should accompany subsequent volumes.

## RÉSUMÉ

Ryan, S.A., Wohlgeschaffen, G., Jahan, N., Niu, H., Ortmann, A.C., Brown, T.N., King, T.L., and Clyburne, J. 2019. State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 2, Saint John and Bay of Fundy, New Brunswick. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: x + 67 p.

L'augmentation de la production de pétrole et du trafic de navires-citernes au Canada accroît le risque de déversements accidentels de produits pétroliers dans les eaux canadiennes. En réponse, le gouvernement du Canada a annoncé le système de sécurité de classe mondiale pour les navires-citernes et créé le Comité d'experts indépendant sur la sécurité des navires-citernes pour examiner la préparation et l'intervention du Canada en cas de déversement de produits pétroliers provenant de navires. Suivant les recommandations du Comité, le gouvernement du Canada établit des plans d'intervention pour quatre zones pilotes où le trafic de navires-citernes est le plus élevé au Canada : Saint John (Nouveau-Brunswick), Port Hawkesbury et le détroit de Canso (Nouvelle-Écosse), la Voie maritime du Saint-Laurent (Québec) et la partie sud de la Colombie-Britannique.

Il s'agit du deuxième volume d'un rapport en cinq volumes qui contient de l'information pertinente pour l'élaboration d'un plan d'intervention localisée pour Saint John, au Nouveau-Brunswick. Le premier volume du présent rapport contient des renseignements introductifs sur les produits pétroliers et les déversements et devrait accompagner les volumes suivants.

# 1 INTRODUCTION

In November 2013, the Expert Panel of the World Class Tanker Safety System (WCTSS) produced its first report (Houston, Gaudreau, & Sinclair, 2013). In response to the Panel's recommendations, the Government of Canada aims to develop and implement fitted oil spill response plans in the following four pilot areas:

- Saint John and Bay of Fundy, New Brunswick
- Port Hawkesbury-Canso Strait, Nova Scotia
- St. Lawrence Seaway, Montreal to Anticosti, Québec
- Strait of Georgia and the Juan de Fuca Strait, British Columbia

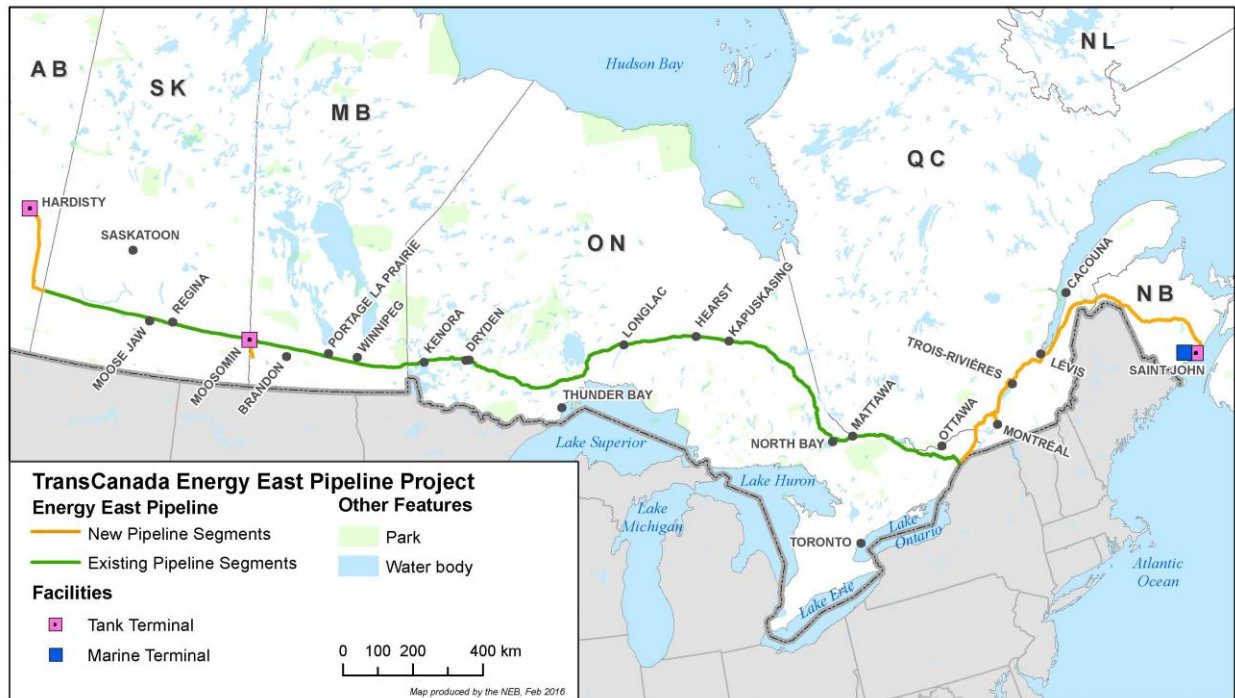
As part of this initiative, a five-volume report has been produced in order to provide a general review of factors that may influence oil spills and response in the four pilot areas. This report is intended to be practical in nature and not a detailed examination of the science of oil spills or specific scenarios that may be encountered.

Volume 1 of this report provides information that is common to the study as a whole, including oil products handled by the ports, oil spill fate and transport, fate and behaviour modelling of spilled oil, a synopsis of the methods currently employed in operational response, techniques used to monitor and track spills, and a glimpse of technologies under development. Four additional volumes provide information on the hydrography, oceanography, climate, case studies of spills, and, when available, spill modelling for each of the four selected pilot ports in the order listed above.

This volume focuses on the Port of Saint John which hosts approximately 80 cruise ships with over 200,000 passengers each year, and handles over 26 million metric tonnes of cargo annually through its two principal channels (Saint John Port Authority, 2015). Tankers of 200,000 deadweight tonnage and larger transit the lower Bay of Fundy bringing crude oil from various foreign sources into the Port of Saint John which is the busiest Canadian port for oil tanker traffic. The Saint John Port Authority has noted that 12,382,874 metric tons (MT) of crude oil, 11,770,564 MT of petroleum, 656,556 MT of refined petroleum products, and 239,640 MT of natural gas passed through the port during 2016 (Somerville, 2017). With respect to the volume of oil products being transported through the port, the Port of Saint John is considered to have the highest risk of an oil spill of any port in Canada (SL Ross Environmental Research, 1999).

The proposed Energy East pipeline that could transport Alberta's Athabasca blended bitumen products (e.g. crude bitumen diluted with a light fluid to meet pipeline specification) to the marine export terminal in Saint John would result in a significant increase in oil tanker traffic in the Bay of Fundy (Figure 1). The risk of spills would increase and a spill of diluted bitumen would be particularly devastating as it has been shown that some products sink and form tar balls in marine conditions (e.g. brackish water) like the Bay of Fundy (Environment Canada, Fisheries and Oceans Canada, & Natural Resources Canada, 2013; King, Robinson, Boufadel, & Lee, 2014; King et al., 2015).

To date, however, no spills of sufficient size to cause major damage have occurred in the Port of Saint John.



**Figure 1. Existing pipeline and proposed Energy East extension (National Energy Board, 2016)**

## 2 GEOGRAPHY

### 2.1 LOCATION

The Port of Saint John is located along the Atlantic coast of Canada in the city of Saint John, New Brunswick. Saint John Harbour is situated in the Bay of Fundy which occupies the area between New Brunswick and Nova Scotia. A small portion of the study area (Figure 2, blue outline) extends along the coast of Maine, USA.



**Figure 2. Saint John and the Bay of Fundy: Regional Response Plan boundary in darker blue**

The Port of Saint John facilities are situated at the mouth of the Saint John River where it flows into Saint John Harbour and ultimately the Bay of Fundy (Figure 3). As the Saint John River approaches Saint John Harbour it flows into the upstream end of Long Reach then takes a 90° turn into Grand Bay where it meets a major tributary, the Kennebecasis River. From Grand Bay, the river drains through a narrow rocky gorge and over a geological sill, called the Reversing Falls, into the relatively broad Saint John Harbour. Depth in these sections of the Saint John River estuary varies considerably from 5 m at the Reversing Falls to greater than 60 m in Kennebecasis Bay (Toodesh, 2012; Trites, 1960). In addition to the Reversing Falls which connects the Saint John



River to Saint John Harbour, the system also features two other sills, Long Reach sill and Boars Head sill, which further restrict circulation within the estuary (Figure 3).

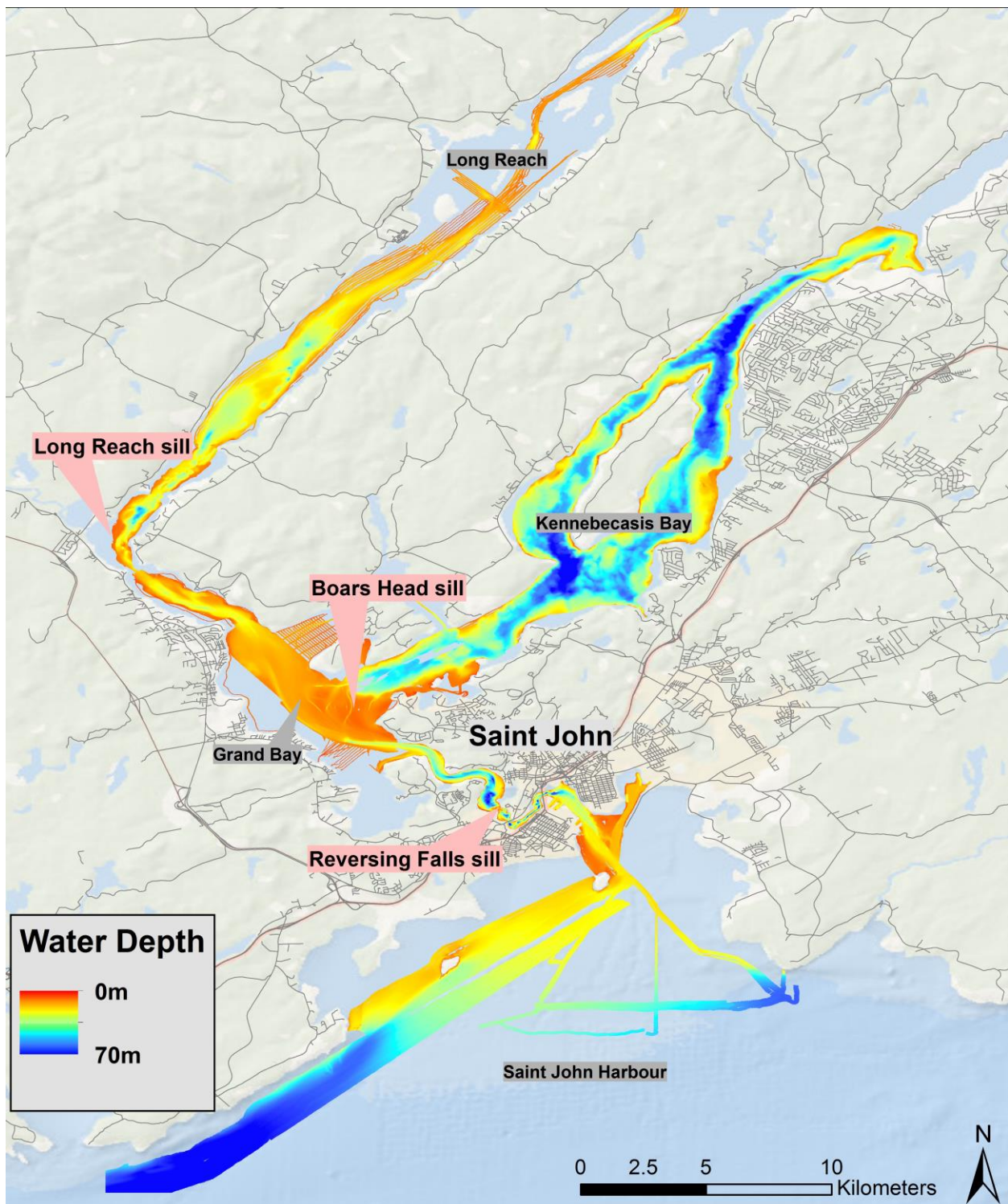


Figure 3. Saint John River Estuary, bathymetry data from Church (2017)



## 2.2 SHORELINES

Although roads line both sides of the Saint John River over much of its length, shorelines remain mostly natural with the exception of areas within the City of Saint John. Near Saint John, developed residential areas occupy much of the shoreline and active industrial areas flank both sides of the river where the estuary flows into Saint John Harbour (Figure 4).

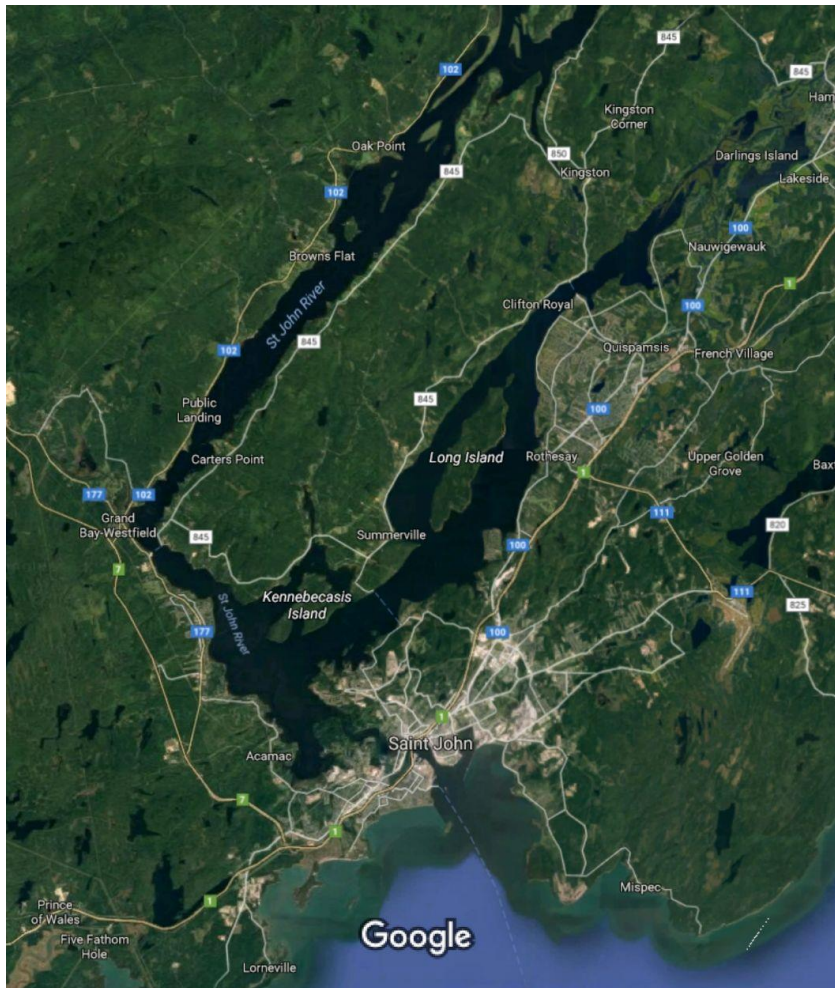


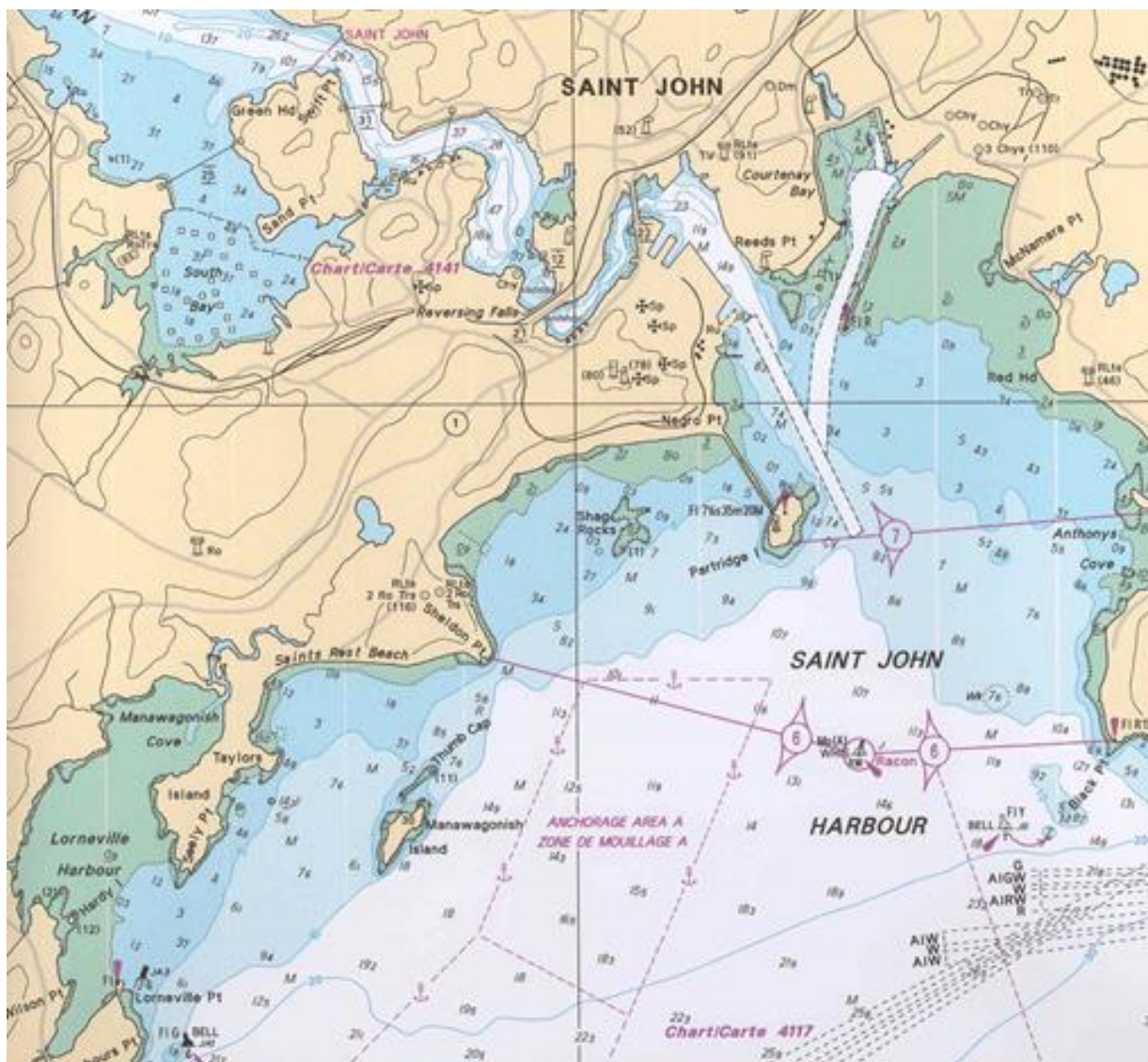
Figure 4. Saint John River Estuary (Google Maps, 2017)

### 3 HYDROGRAPHY

The Saint John River contributes 60% of the total freshwater input to the Gulf of Maine, gathering water from a 55,100 km<sup>2</sup> watershed originating in Quebec (13% of the drainage basin) and Maine (36% of the basin), and flowing 720 km southeast through New Brunswick (51% of the drainage basin) to the Bay of Fundy (Environment and Climate Change Canada, 2014).

The Saint John River Estuary is defined by the presence of a salt water wedge overlain by a freshwater plume and covers the area from the Reversing Falls sill to Gagetown which is 60 km inland from Saint John Harbour (Metcalf, Dadswell, Gillis, & Thomas, 1976; Trites, 1960). Characteristics of the freshwater plume in this stratified system primarily depend on river discharge volume, temperature, bathymetry, tidal amplitude, mixing from waves, longshore currents, and sediment load (Toodesh, 2012). High levels of suspended sediments (clay and silt) present in freshwater flowing from the Saint John River results in a plume that is often easily identified as it has a brown colour relative to the sea water.

Saint John Harbour is relatively broad and deep at its outer reaches, however the inner harbour tends to be shallow and laden with sediment (Figure 5). The main channel in Saint John Harbour is dredged annually to maintain a depth of at least 9 m while other areas of Saint John Harbour, such as Courtenay Bay, have depths maintained at 5 m at low tide for safe navigation (Toodesh, 2012).



**Figure 5. Canadian Hydrographic Service chart of Saint John Harbour**

Information regarding circulation patterns is critical if an oil spill were to occur, especially if water stratification will play a vital role in determining where heavy oil products might sink, and perhaps resurface, in more dense saline waters. The Bay of Fundy is famous for having high tides and Saint John Harbour is no exception with a tidal range of up to ~8.5 m (mean of ~6.5 m) at the mouth of the estuary (N. C. Delpeche, Soomere, & Lilover, 2010; Trites, 1960). That being said, restricted circulation due to the Reversing Falls reduces the tidal ranges upstream in the estuary to generally less than 0.5 m (Hachey, 1935; Hughes Clarke & Haigh, 2005). Although the Reversing Falls is the single biggest factor affecting circulation within the Saint John River Estuary, there are two other geographic sills, Boars Head sill and Long Reach sill, which are situated upstream of the falls.



### 3.1 SILLS

#### 3.1.1 Reversing Falls Sill

The Reversing Falls sill (Figure 6) is located at the mouth of the Saint John River estuary within a 200m wide gorge and extends upwards to a depth of 5 m below the surface of the water. The Reversing Falls heavily restricts the amount of water that can pass between the river and the harbour (N. Delpeche, 2006); water levels in the harbour can be up to ~3.5 m higher at high tide, or ~4.5 m lower at low tide than that of the estuary depending on tidal amplitude (Trites, 1960).



**Figure 6. Incoming tide at the Reversing Falls (Kenner, 2002)**

Interaction of the sill with the tide causes variation in water levels on either side of the sill. With an incoming tide and normal river levels, the water level on the seaward side of the Reversing Falls is higher than the river, causing a net inflow of seawater from the Bay of Fundy and at ebb tide, river flow reverses. During high river discharge of the spring freshet, the water level on the landward side of the sill is always higher at all phases of the tide such that the net flow is always seaward and the falls do not reverse (Toodesh, 2012).

The restriction at the Reversing Falls creates currents of 10 knots or more and almost completely homogenizes the incoming water, resulting in a characteristic salinity of 23-26‰ (H. A. Neu, 1960; Trites, 1960). This brackish water penetrates another 20 miles upriver, beyond the sill. The Reversing Falls are also the primary factor affecting salt water stratification in the system. A salt wedge extends from Reversing Falls into Long Reach and the Kennebecasis (Metcalf et al., 1976; Toodesh, 2012) with replenishment of the lower salt layer occurring by intermittent exchange over the sill during neap tides (Hughes Clarke & Haigh, 2005). Also, the pycnocline (a layer of water where density

increases quickly with depth, restricting vertical mixing) of Saint John Harbour is always at or below the level of the sill (Metcalf et al., 1976; Trites, 1960).

### **3.1.2 Boars Head Sill**

Approximately 6 km upstream from the Reversing Falls the Kennebecasis River system meets the Saint John River forming Grand Bay. Grand Bay is the location of the Boars Head sill which is very shallow and governs the circulation and flow of waters through the bay (Figure 3). Water flowing out of Kennebecasis Bay exits a 30-50 m deep gorge into the shallower Grand Bay (<15m) and Boars Head Sill (~6m) (Hughes Clarke & Haigh, 2005).

The oceanographic characteristics of both the Saint John River (upstream of Boars Head sill) and Kennebecasis Bay are determined by the volume and extent of dilution of saline water as it makes its way over this second sill. Multibeam and oceanographic surveys performed from 2000 to 2004 indicated that this sill lies at or above the mean level of the pycnocline, which would vary seasonally and tidally (N. Delpeche, 2006). Advancing water from the Reversing Falls Gorge can cross Boars Head Sill and flow into Westfield Channel and Kennebecasis Bay during the summer and winter months (which experience low river discharge) as the flood tide causes the pycnocline to rise over the top of the sill. During periods of high river discharge the sill top is never exposed to saline waters, so salt water does not flow into the Kennebecasis.

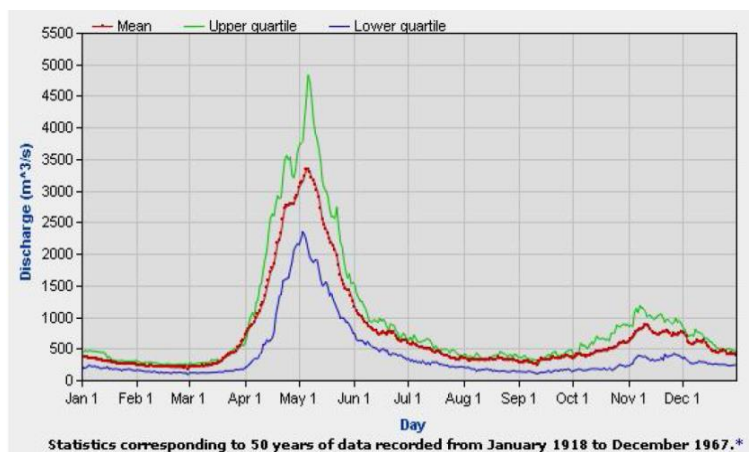
### **3.1.3 Long Reach Sill**

According to multibeam surveys performed in May 2004 by the class of the University of New Brunswick Geodesy and Geomatics Engineering (N. Delpeche, 2006), from the upstream end of Grand Bay to the entrance of Long Reach, the depth of the thalweg (the line defining the deepest points along the length of a river bed) decreases from 17 m to 11 m, and near the banks it is about 6 m. However, like the Reversing Falls and Boars Head sill, it is expected that the sill located at the entrance to Long Reach (Figure 3) will influence the flow of fresh and salt water. Oceanographic measurements at the sill have been restricted by the West Field ferry service that operates immediately downstream of the Long Reach sill.

## **3.2 SAINT JOHN RIVER DISCHARGE**

The Saint John River drains about 55,100 km<sup>2</sup> of New Brunswick, Quebec, and the State of Maine (Environment and Climate Change Canada, 2014). Discharge varies annually and according to the season, however there is usually one peak in fall due to heavy rains from about August to November or late December, and another in April or May from snowmelt (Figure 7). In summer (June – August) the flow is about 500 m<sup>3</sup>/s, whereas the spring freshet (April – May) is six times as much, being about 3400 m<sup>3</sup>/s

(Toodesh, 2012). Minimum discharge occurs during freezing winter weather, and mid-summer times of minimum precipitation.



**Figure 7. Discharge of the Saint John River at Pokiok averaged from January 1915 to December 1967 (HYDAT-Environment Canada, 2009).**

### 3.3 SALINITY & TEMPERATURE

The water at the mouth of the Bay of Fundy is stratified and salinity in summer is ~33‰, but tends to be lower at the surface and at the head of the bay (David A. Greenberg, 1984). It is about 31‰ at Cape Chignecto, about 30‰ in Chignecto Bay, and 28‰ in upper Minas Basin. Less fresh water input in fall and winter leads to a more uniform salinity regime throughout the Bay of Fundy. Surface temperatures in late summer tend to be 11°C at the mouth of the Bay of Fundy, 14°C at Cape Chignecto, 17°C in Chignecto Bay, and 21°C in upper Minas Basin, while temperatures are cooler but more uniform in fall (David A. Greenberg, 1984). The gradient is reversed in the winter: 0°C in Chignecto Bay and Minas Basin, and 3 to 4°C at the mouth.

Salinity observations made by both Trites (1960) and Metcalfe et al. (1976) in the Saint John River Estuary have shown seasonal variations in the position of the salinity front in addition to variability from one year to the next depending on conditions. In the spring, salt water is flushed out of the river due to ice melt and a corresponding increase in freshwater discharge. During this period the saline front typically ends in Long Reach (near Oak Point). During summer and winter, freshwater discharge is usually at a minimum due to low rainfall which results in the salinity front advancing further upstream in the estuary. Overall surface and bottom salinities are highest during the summer months. Fall and winter salt water intrusion into Long Reach through a deep channel linking the Gorge to Westfield is limited by the height of the halocline at Boars Head Sill (N. Delpeche, 2006; Hughes Clarke & Haigh, 2005). In all seasons, as the saline front progresses upstream, the salinity decreases, with the greatest change occurring from the Gorge to the entrance of Long Reach (Metcalfe et al., 1976; Trites, 1960).

### 3.4 TIDES

The Bay of Fundy has semi-diurnal tides that are the highest in the world. The primary reasons for such high tidal ranges are the length of the coastline, the V-shape tapering of the coastline, the drastic change in depth from the Atlantic Ocean to the Bay of Fundy, and a resonance effect that occurs due to coinciding high and low tide times with the adjoining Atlantic Ocean (N. Delpeche, 2006; D.A. Greenberg, 1979). The range of the tide within the Bay from the southern end of Nova Scotia is 6 m, increasing to 16 m as it flows into the Minas Basin. At Saint John Harbour the tidal range is 8 m. The rapidly changing tides would introduce a challenge for spill responders, if an oil spill occurred in the Bay of Fundy (Toodesh, 2012).

Although the Reversing Falls sill tempers the effect of Bay of Fundy tides on the Saint John River Estuary, their influence reaches as far upriver as Fredericton. Tidal range decreases from 0.7 m near the mouth of the river, to 0.4 m in Long Reach, and 0.15 m at Fredericton (Trites, 1960). Compared to the time of the tide in St John Harbour, there is a delay by 1.5 hours at the Reversing Falls, 3 hours at Long Reach, and 10 hours at Fredericton (N. Delpeche, 2006).

A physical model of the Reversing Falls (Hansen 1977) demonstrated that high freshwater outflow caused river water levels to increase. Density currents were ignored, but it was still evident that variation in river discharge was superimposed on the daily tidal variation. When density currents are accounted for, increased discharge above the Reversing Falls results in reduced tidal range, the time of low water is earlier, and high water is later (Godin, 1985). Below the falls, increased discharge results in decreased friction at flood tide, but increased friction during ebb tide, which causes low water to occur later and high water to occur sooner, so density currents affect tidal range and duration of tidal phase.

### 3.5 WAVES

There have been some wave measurements made in the upper Bay of Fundy, but winter observations are difficult because of ice conditions. At Tiner Point, between Point Lepreau and Saint John, significant wave height (the mean height of the highest third of all waves in a wave record, so nearly a sixth of all the waves are larger than this value) during the winter months, November to April, exceeds 1 m 25 percent of the time and exceeds 2 m four percent of the time (H. J. A. Neu & Vandall Jr., 1976). From May to October wave energy is reduced, and minimum heights are approximately half the winter values. For a storm, depending on its duration, the maximum wave height can be up to twice the significant wave height with a predicted 100-year extreme wave of 16 m (H. J. A. Neu & Vandall Jr., 1976). Prediction of wave height in the Bay of Fundy prior to a storm can be difficult and inaccurate (H. J. A. Neu & Vandall Jr., 1976).

## 4 CLIMATE

New Brunswick's climate tends to be continental, though tempered by proximity to the ocean. It is harshest in the northwest, where more than one-third of the precipitation arrives as snow, and temperatures are several degrees colder than the central interior.

### 4.1 TEMPERATURE

The average annual temperature in Saint John is a cool 4.9°C (Table 1). The mean monthly temperatures throughout the year vary by ~25°C. The average annual diurnal temperature variation is 10°C. July is the warmest month with a mean temperature of about 17°C. January is the coldest month with an average temperature of -8.2°C.

**Table 1. Average monthly and annual temperature for Saint John, New Brunswick (Climatemps.com, 2014)**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max °C (°F)	-2.8 (27)	-2.3 (27.9)	2.1 (35.8)	7.9 (46.2)	14.4 (57.9)	19.2 (66.6)	22.1 (71.8)	21.8 (71.2)	17.6 (63.7)	12.1 (53.8)	6 (42.8)	-0.2 (31.6)	9.8 (49.7)
Average °C (°F)	-8.2 (17.2)	-7.7 (18.1)	-2.6 (27.3)	3.2 (37.8)	9.1 (48.4)	13.8 (56.8)	16.9 (62.4)	16.7 (61.2)	12.7 (54.9)	7.5 (45.5)	2.1 (35.8)	-5 (23)	4.9 (40.8)
Average Min °C (°F)	-13.6 (7.5)	-13.3 (8.1)	-7.5 (18.5)	-1.5 (29.3)	3.7 (38.7)	8.4 (47.1)	11.6 (52.9)	11.5 (52.7)	7.6 (45.7)	2.9 (37.2)	-1.9 (28.6)	-9.9 (14.2)	-0.2 (31.7)

Saint John Harbour and the Bay of Fundy remain ice free throughout the year. The Bay of Fundy average summer surface water temperature is 8-12°C and winter temperature is 0-4°C, which make for cooler summers and warmer winters than inland (Toodesh, 2012).

### 4.2 PRECIPITATION

Saint John receives an average of 1432.7 mm of precipitation annually (Table 2), or 119.4 mm per month. On average there are 166 days with more than 0.1 mm of precipitation per year, which is about 13.8 days in each month with some form of precipitation (Table 2). The driest month of the year is February which has an average of 102.6 mm of precipitation, while the wettest month is December with an average of 167.6 mm.

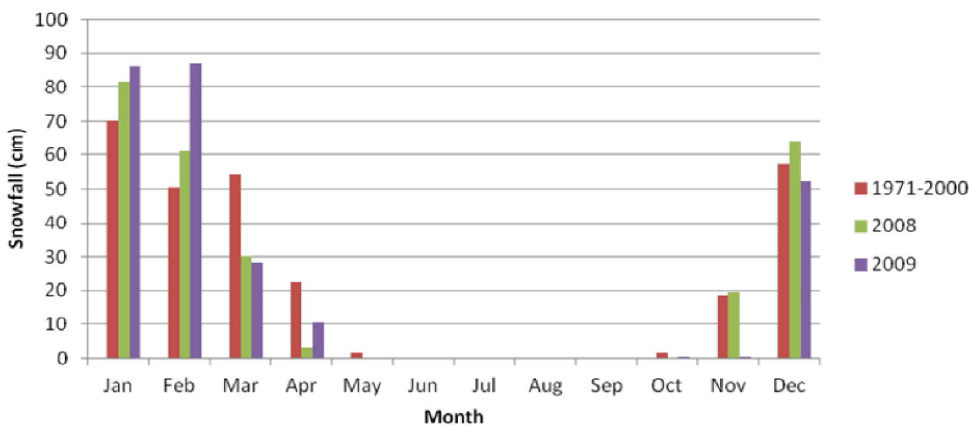


**Table 2. Average annual precipitation, precipitation days, sun and cloud for Saint John, New Brunswick 2009-2014 (Climatemps.com, 2014)**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average precip mm or L/m <sup>2</sup> (gal/ft <sup>2</sup> )	128.3 (3.15)	102.6 (2.52)	109.9 (2.7)	109.7 (2.69)	123.1 (3.02)	104.8 (2.57)	103.7 (2.54)	103 (2.53)	111.3 (2.73)	122.5 (3)	146.2 (3.59)	167.6 (4.11)	1432.7 (35.14)
Number of precip. days (probability of precip. on a day)	15 (48%)	13 (46%)	14 (45%)	14 (47%)	14 (45%)	14 (47%)	13 (42%)	13 (42%)	13 (43%)	13 (42%)	15 (50%)	15 (48%)	166 (45%)
Percentage sunny (cloudy) daylight hours	38 (62)	39 (61)	42 (58)	39 (61)	44 (56)	42 (58)	48 (52)	50 (50)	44 (56)	45 (55)	33 (67)	3 (62)	43 (57)

Precipitation can fluctuate greatly from year to year in the Saint John area, for example, there was almost twice the amount of rainfall in July and October 2009 than in the same months in 2008. Total annual rainfall in 2008 (1352 mm) and 2009 (1308 mm) exceeded the historical mean of 886 mm (Toodesh, 2012).

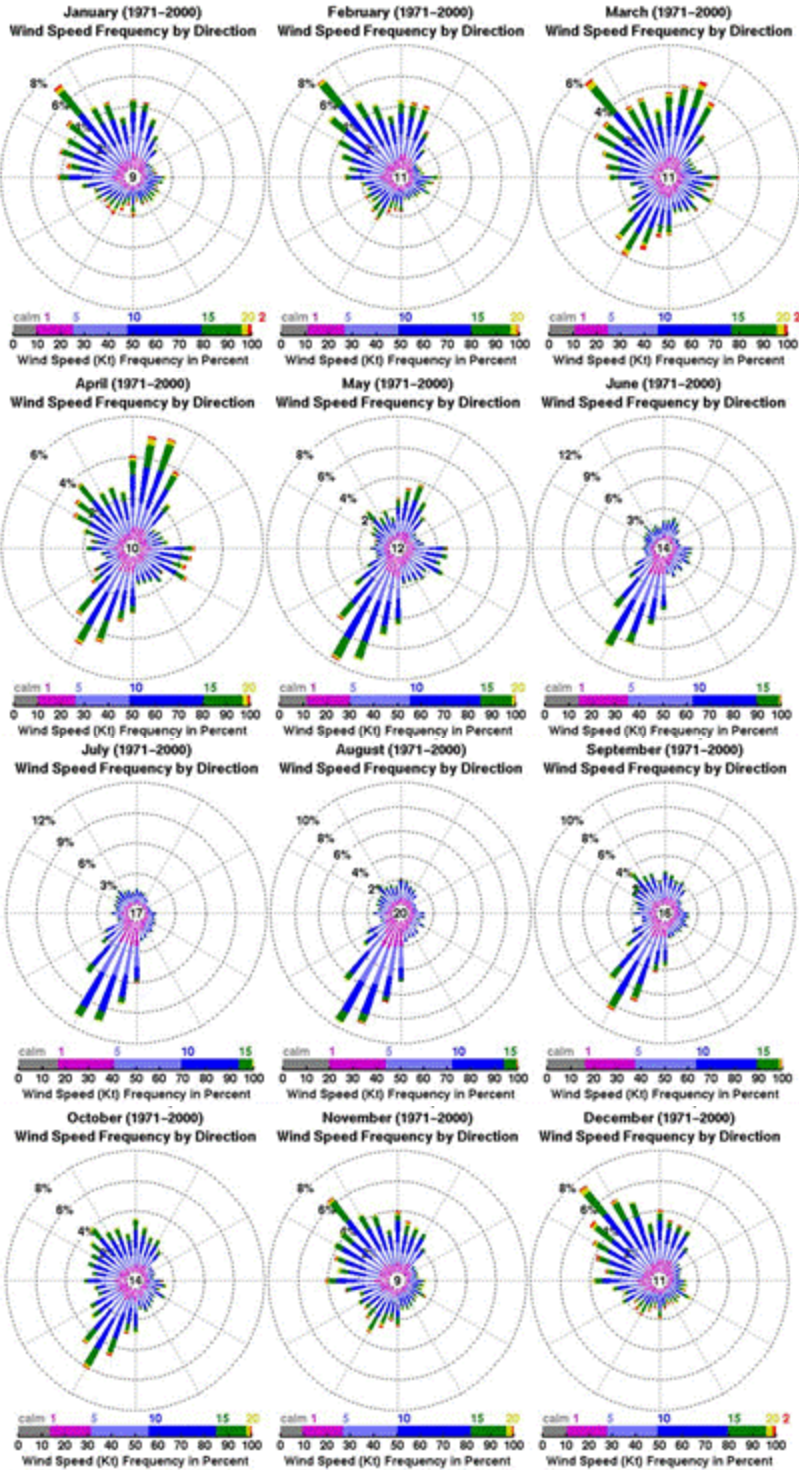
Average snowfall values for Saint John can be found in Figure 8.



**Figure 8. Environment Canada total snowfall in Saint John 2008, 2009 and 1971-2000 (Environment and Climate Change Canada, 2009)**

### 4.3 WIND

Winds have been found to be strongest, but variable, from October to March (Toodesh, 2012). Wind roses for extended data periods are shown in Figure 9.



**Figure 9. Wind roses compiled from data collected at Saint John airport 1971-2000 (Fleetwood, 2015)**

From November to March the prevailing winter winds from the northwest (Figure 9) bring cold Arctic air. April is a month of change in wind direction and in May to October the winds are predominantly from the southwest.

Wind has not been found to have a significant impact on circulation of the tidal cycle, which demonstrates the protected nature of Saint John Harbour; however, this could change in a serious storm (Toodesh, 2012).

## 5 PAST OIL SPILLS

The Transportation Safety Board of Canada (TSBC) maintains a database of air, marine, rail, and pipeline incidents and accidents, collectively called occurrences, and publishes annual reports with statistics (Transportation Safety Board of Canada, 2018). The marine occurrences database contains information on the vessels involved, cargo, location, reported pollution and more. As reporting requirements have changed over time the number of marine occurrences entered into the database per year has increased. The most recent update of TSBC reporting requirements was 2014 (Transportation Safety Board of Canada, 2014), and data for many more occurrences are available from that time onward. Statistics have been compiled here for occurrences of interest for the entire span of the database (1975-2018) and on an annual average basis for full years since the new reporting requirements (2015-2017).

Statistics for four different types of marine occurrences have been compiled: 1) occurrences involving cargo vessels, either tankers or barges, that transport petroleum products; 2) occurrences in which pollution was reported or any type of cargo was lost overboard; 3) occurrences in which petroleum products were reported spilled on board or into the water; and 4) occurrences in which vessels were sunk, capsized or otherwise seriously damaged beyond repair, and expected to release fuel into the environment.

Statistics for the Port of Saint John were compiled by filtering for occurrences in the province of New Brunswick, or Nova Scotia or international waters, within the latitudinal range of 44.0°N to 45.65°N, and within the longitudinal range of 64.8°W to 67.5°W. This area corresponds to most of Bay of Fundy, and out into the Gulf of Maine. See Table 3 for statistics.

**Table 3. Transportation Safety Board incident and accident occurrences in the Port of Saint John shipping lane**

<b>Occurrences involving...</b>	<b>All years (1975-2018)</b>	<b>Annual average (2015-2017)</b>
All occurrences	419	51.3
Petroleum cargo vessels	8	0.7
Pollution or cargo lost overboard	27	0.7
Petroleum spills onboard or overboard	3	0.7
Vessels sunk, capsized or destroyed	23	1.3

The occurrences involving cargo vessels carrying petroleum products are minor; most of them are reports of tankers dragging anchor in bad weather. All 23 reports of vessels sunk or lost are fishing vessels, which are relatively small vessels with median length 12.09m. Reports of pollution and petroleum spills are mostly due to sunk or lost fishing vessels, or due to passenger ferries making bottom contact. The three petroleum spills reported are all from passenger ferries with maximum spill size of 682 litres.

The following are a collection of some of the more noteworthy spills that have occurred in this area for which documentation was obtained during our review of the literature.

## **5.1 IRVING OIL CANAPORT**

Three small oil spills in the Bay of Fundy halted the offloading of crude from an offshore buoy at the Canaport facility in Saint John Harbour (CBC News, 2008). The spills, estimated to have released approximately 25 litres of oil into the bay, occurred in early August 2008. The Canadian Coast Guard first reported them as “mystery oil sheens” on the water that dissipated quickly. However, the sheens were noticed on two other occasions within less than a week. They appeared whenever a ship delivered oil. Tankers unload crude oil on the east side of Saint John Harbour at a buoy where an underwater pipeline carries the oil from ship to shore. The three leaks seemed to originate from a junction on the underwater pipe while ships were unloading crude oil (CBC News, 2008).

Irving Oil has recorded at least 19 accidents classified by regulators as environmental emergencies at its existing facilities in eastern Canada since 2012, one of which amounted to 3,000 barrels (Reuters, 2015).

## **5.2 MACTAQUAC GENERATION STATION**

On April 15, 2014 about 3,000 litres of ‘non-hazardous’ oil spilled into the Saint John River at Mactaquac Generating Station, Fredericton (CBC News, 2014). NB Power attributed it to a broken seal on an underwater turbine hub at the station. The company said the leak was biodegradable Teresso 32 lubricating oil, which was not expected to be harmful to aquatic organisms. The company added that the fast-moving spring river water quickly moved the oil downstream, and made it impossible for cleanup crews to collect and remove it.

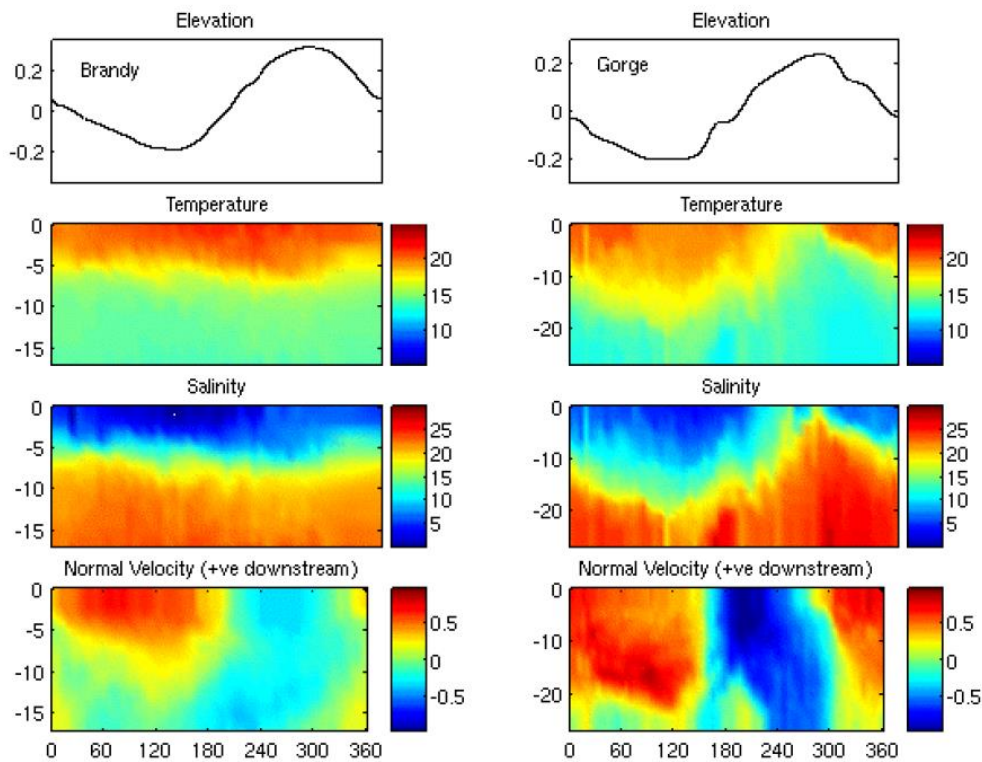
## **5.3 IRVING OIL SPILLS**

Findings show that Irving Oil's Saint John refinery which borders on the outer Saint John Harbour experienced 19 incidents between Jan 1, 2012 and Dec 31, 2014 (Ecology Action Centre, 2015). Of the 19 incidents, 12 occurred in 2012, four in 2013, and three in 2014. Four involved the dumping of petroleum sludge above permitted amounts. Three involved crude oil. The other measured incidents were smaller, with spills between 1,000-2,000 L, and excess dumping of petroleum sludge. The largest of the Irving incidents occurred in 2014, when 10,000 L of vacuum gas oil and 40,000 L of diesel spilled due to overfilling of holding tanks.

## 6 MODELLING

### 6.1 SALINITY AND TEMPERATURE IN GRAND BAY, KENNEBECASIS AND SAINT JOHN RIVER ESTUARY

The Reversing Falls Sill and Boars Head Sill exert significant control over mixing and exchange of salt and fresh water between the Saint John River, Kennebecasis Bay, and the open sea. This area of extreme salinity and temperature variation was examined using QUODDY, a three-dimensional, finite element, baroclinic, shelf circulation model (S. P. Haigh & Hughes Clarke, 2005). The model had upstream and downstream open boundaries. Time series of temperature, salinity, and normal velocity were obtained at Brandy and Gorge (Figure 10).



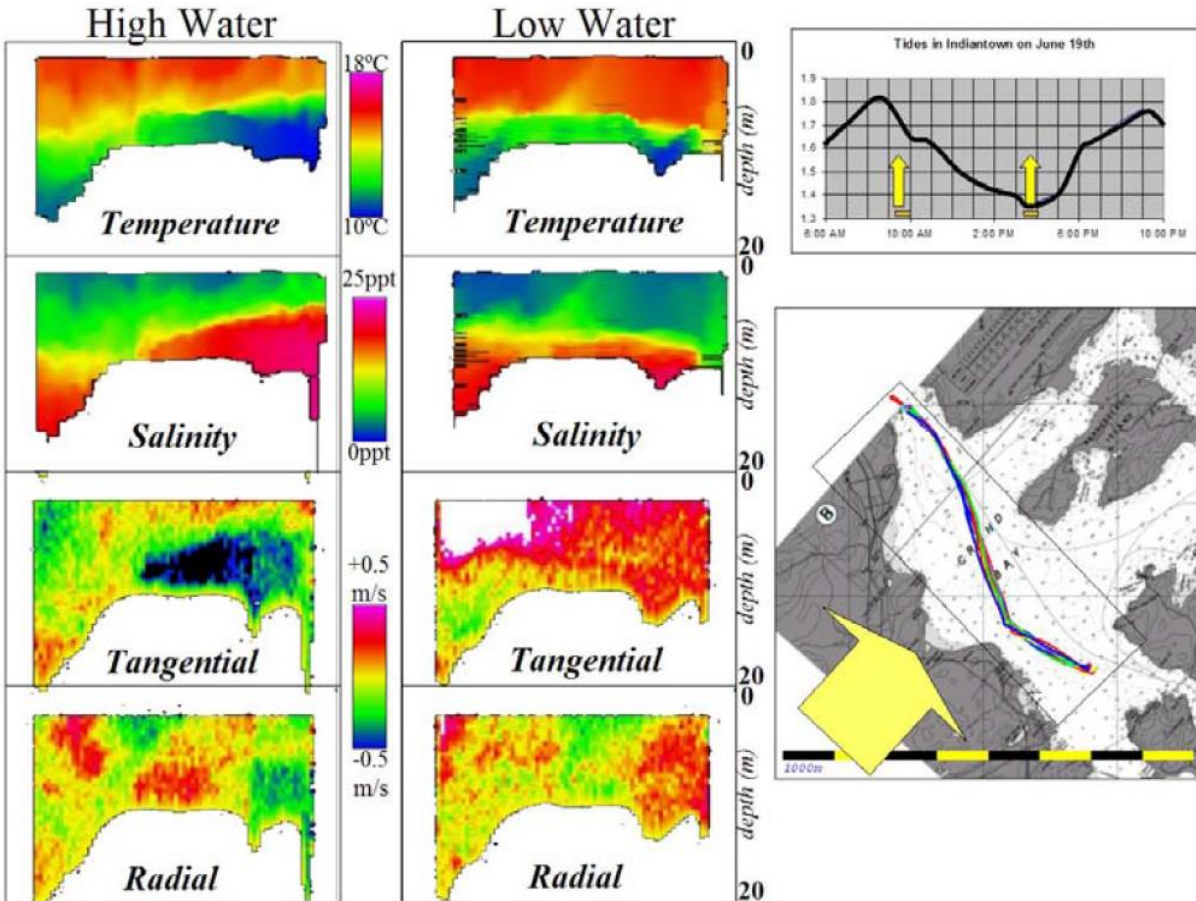
**Figure 10.** July 2001 empirical data for elevation (m), temperature (°C), salinity (ppt) and normal velocity (m/s) at Brandy (left panels) and Gorge (right panels) as a function of the M2 tidal phase in degrees on the x-axis (S. P. Haigh & Hughes Clarke, 2005)

The river flows downstream at both boundaries on the ebb tide, with greater velocity at Gorge, which is located at the narrows above the Reversing Falls. There is also a top, warm, freshwater layer of water from the river and the Bay of Fundy that has been mixed in the Reversing Falls, and a bottom, cool, salt water layer. Currents at both boundaries reverse in flood tide. Temperature and salinity patterns at Brandy remain the

similar throughout the tidal cycle, whereas at Gorge there is an influx of cool salt water and the fresh water layer momentarily disappears.

In another survey conducted in June 2003 from just north of Gorge to Brandy (Figure 11), tangential and radial velocities were positive downstream (toward the right in Figure 11) and eastward (into the page; currents over  $-0.5$  m/s appear black and over  $+0.5$  m/s are white). At high tide, a cold salt water wedge from the Reversing Falls flows upstream along the bottom. At Gorge, the salt water actually reaches the surface, briefly. This salt wedge does not completely surmount the sill to replenish the saline layer at Brandy (Figure 11), demonstrating that the salt water at Brandy is not always replenished every tidal cycle. At low tide, the warm, upper, fresh water flows downstream. Essentially, during ebb tide, the salt intrusion becomes a stationary layer over the sill of less than 2 m thick which never disappears.





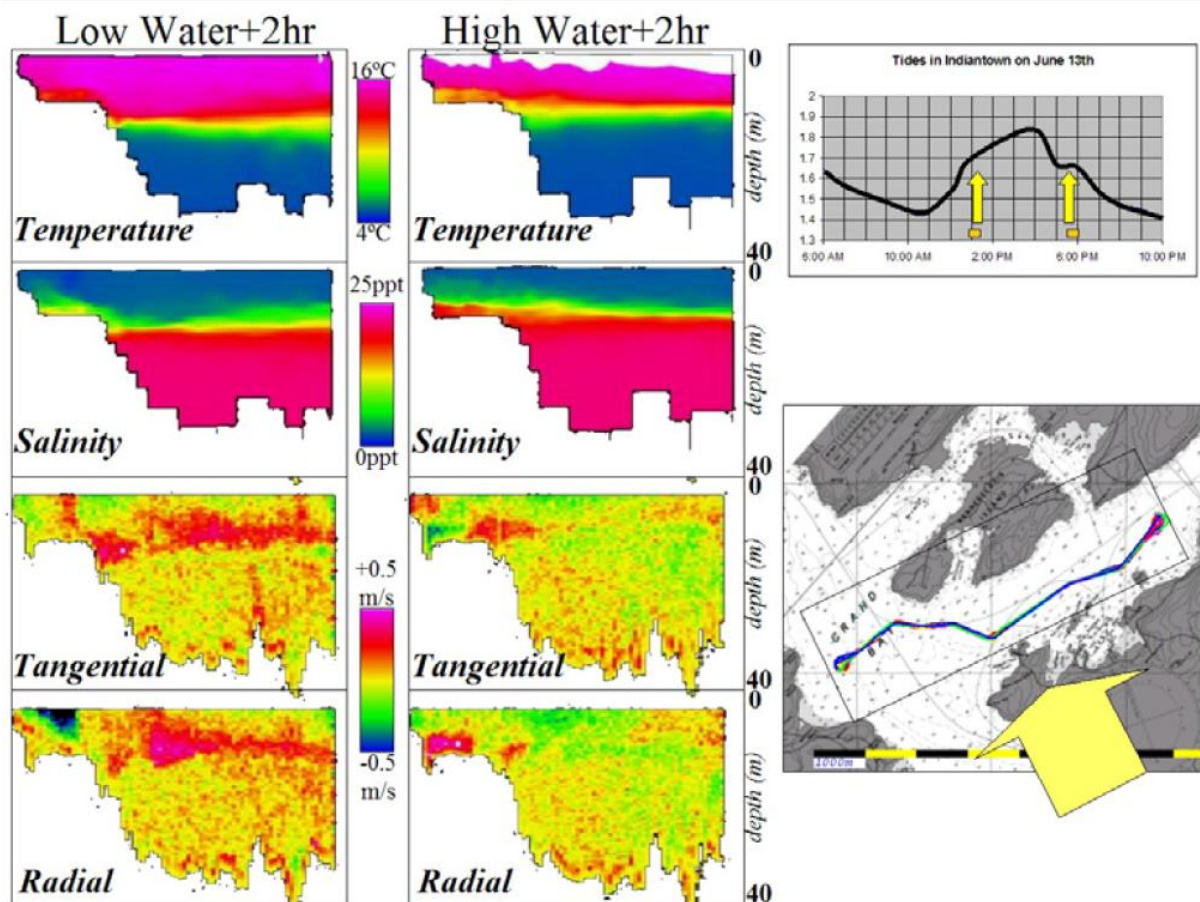
**Figure 11.** Temperature, salinity, tangential and radial current velocities made at Brandy (left) and Gorge (right) in the Saint John River Estuary on 19 June 2003, during tidal phases indicated by yellow arrows on the elevation plot at top right, and along a transect shown on the chart at bottom right (S. P. Haigh & Hughes Clarke, 2005)

Measurements from two hours after low water until two hours after high water in Grand Bay, over the Boars Head Sill, and into Kennebecasis Bay on June 13, 2003 (Figure 12) revealed a permanent pycnocline in Kennebecasis. This was early summer, so the high discharge of fresh water from the Saint John River would have prevented the intrusion and renewal of salt water into Kennebecasis Bay (S. P. Haigh & Hughes Clarke, 2005). The deep water remained at 4.9°C and 21.8‰. The pycnocline migrated up to approximately 9 m and down to 15 m with the tide. It was noted that an internal wave at the pycnocline might be the result of water spilling over the sill into Kennebecasis Bay at high tide.

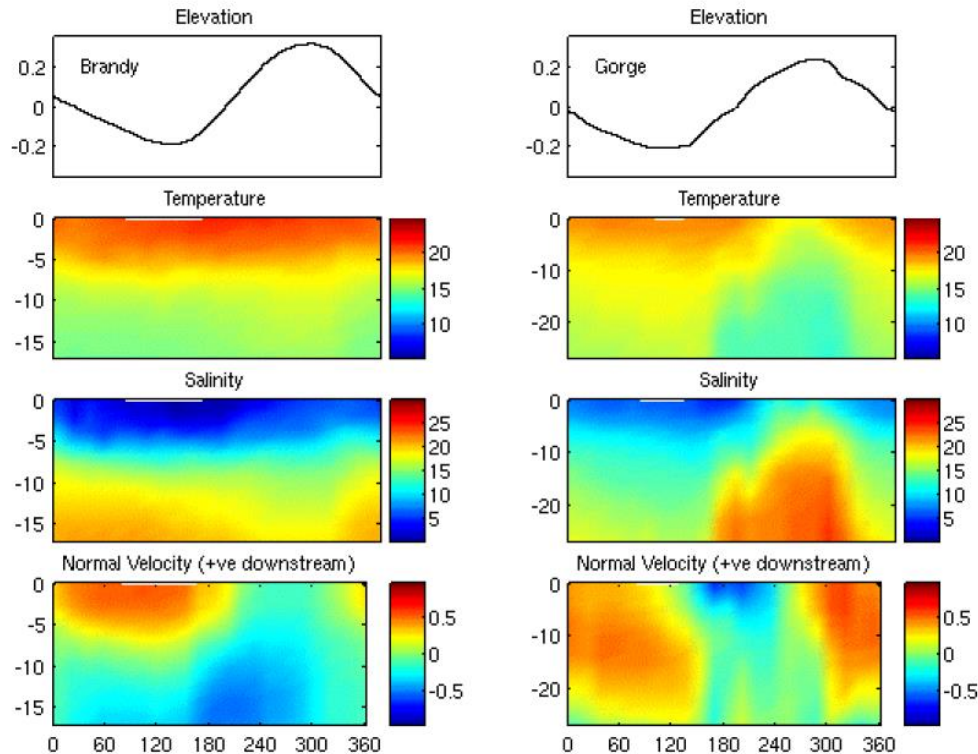
Modelled elevation, temperature, salinity and normal velocity at the Brandy and Gorge boundaries (Figure 13) were comparable with empirical data (Figure 10) when water was flowed into the domain, which occurs during ebb tide at Brandy and flood tide at Gorge (S. P. Haigh & Hughes Clarke, 2005); however, modelled bottom water salinity



was lower than observed, and bottom temperatures were higher. The model should be in equilibrium and should not show a loss or gain of heat or salt water (S. P. Haigh & Hughes Clarke, 2005). When water was flowing out of the model boundary, temperature and salinity inside the domain did not match the observed values and the modelled lower salt layer at Gorge almost disappeared. The model produced acceptable normal velocities, which at Gorge were weaker for all phases of tidal cycle, while at Brandy the flood tide flow upstream was stronger than observed values (S. P. Haigh & Hughes Clarke, 2005).



**Figure 12.** Positive tangential (to the right) and radial velocities (into the page) in Grand Bay at left, and Kennebecasis Bay at right (S. P. Haigh & Hughes Clarke, 2005)



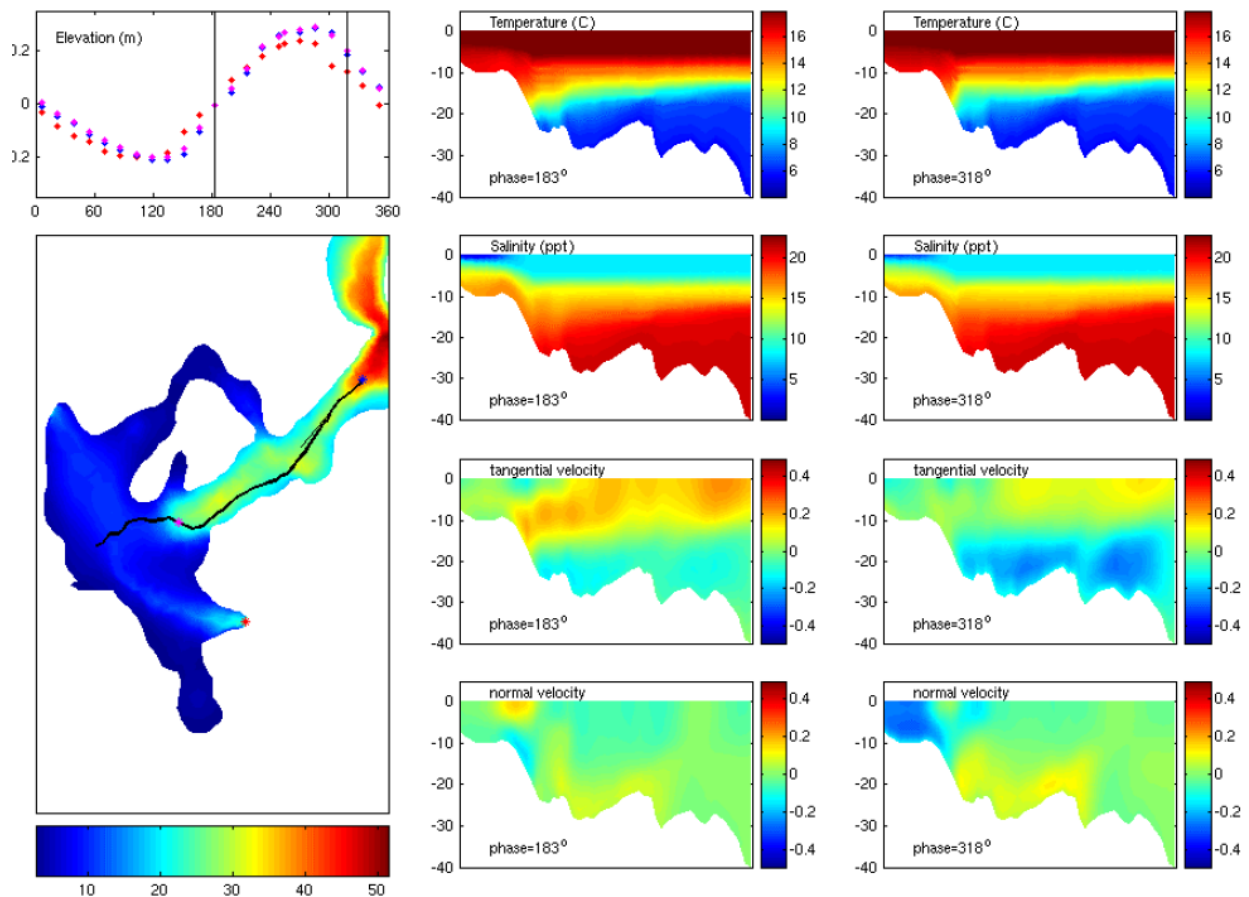
**Figure 13. Modelled elevation, temperature ( $^{\circ}\text{C}$ ), salinity (ppt) and normal velocity (m/s) for Brandy at left, and Gorge at right (S. P. Haigh & Hughes Clarke, 2005)**

Kennebecasis Bay is a deep (up to 60 m) fjord shaped estuary with a permanent pycnocline separating warm, fresh water above from cold, salt water below (S. P. Haigh & Hughes Clarke, 2005). Water flow in the bay can be up to 30 cm/s in the upper 30 m, with slight movement of the surface layer toward the sea, and flow of cold, salt water from the Reversing Falls into the bay in deeper waters during flood tide (S. P. Haigh & Hughes Clarke, 2005; Trites, 1960).

When compared with empirical data from the Brandy-Gorge transect on 19 June 2003 (for the two phases of the tide shown in Figure 11), the behaviour of the model along a transect at high tide simulated a simultaneous intrusion of cool, salt water from the Reversing Falls moving upstream (though not enough to replenish the salt water layer at Brandy) while surface waters flowed in the opposite direction, downstream (S. P. Haigh & Hughes Clarke, 2005). The model did not completely mimic nature: the salt wedge upstream velocity was less in the model, at low tide the model depicted a thinner fresh layer and a thicker salt layer, and the pycnocline remained thicker throughout the tidal cycle.

Flows in Kennebecasis Bay were modelled (Figure 14) for the same tidal phases as in Figure 12, two hours past low water when the pycnocline is at its lowest, and two hours past high water when it is at its highest. Comparing Figure 12 with Figure 14, the

modelled temperatures and salinity are warmer and fresher than the observed values (S. P. Haigh & Hughes Clarke, 2005).



**Figure 14. Temperature, salinity and velocity (tangential is positive to the right, normal is positive into the page) along transect (black line in bathymetric map at bottom left; \* correspond to tide height at top left) at two tidal phases, with the St John River in left panels and Kennebecasis Bay in the right (S. P. Haigh & Hughes Clarke, 2005)**

Figure 14 shows salt water of about 16‰ from the Saint John River estuary connected with salt water in the pycnocline of Kennebecasis Bay just like the empirical data (Figure 12), although the model (Figure 14) does not show clearly the direction of flow, and this salt water remains present in the river estuary throughout the tidal cycle, always attached to the water in Kennebecasis Bay. However, observations on 13 June 2003 (Figure 12) showed that the salt water layer disappeared in the estuary during ebb tide and did not reappear until high tide. Although the numerical model does predict a rise and fall of the pycnocline with the tide, due to its thickness, a portion of the pycnocline is always level with the sill, so that in the model it is always connected to the Saint John River Estuary.

The model does not exactly reproduce the observed nature of the salt water connection between the Reversing Falls and upstream of Brandy, nor the circulation in Kennebecasis Bay due to limitations of the coordinate system (S. P. Haigh & Hughes Clarke, 2005). On the other hand, the flow of saline water along the pycnocline, rather than along the bottom, is reproduced in the model (S. P. Haigh & Hughes Clarke, 2005).

## **6.2 CIRCULATION IN THE PORT OF SAINT JOHN**

Another multi-disciplinary study funded by the Saint John Port Authority and National Sciences and Engineering Research Council of Canada is underway at the University of New Brunswick (Ocean Mapping Group) and the Institut national de la recherche scientifique to better understand the sedimentation, circulation and ecology of Saint John Harbour (S. Haigh & Hughes-Clarke, 2010). The model has open boundaries, one approximately 150 m wide at the sill just above the Reversing Falls in Saint John River (this made the implementation of boundary conditions easier) and the other from Sheldon Point to Black Point (approximately 7 km wide) opening up into the Bay of Fundy.

Archival (1996, 2000, 2001, 2005) multibeam bathymetric data (one metre resolution), in addition to the most complete multibeam survey (one metre resolution) of the harbour completed in April 2008, were used to create the bathymetric model from which the numerical hydrodynamic model was derived. Data for the coastline and areas not included in any of the surveys were obtained from Canadian Hydrographic Service digital chart 4117. All data were reduced to a 4 metre grid. The WebTide tidal prediction model, developed by Fisheries and Oceans Canada, has a Scotia-Fundy-Maine model domain which was used to determine the elevation along the open boundary (Dupont, Hannah, & Greenberg, 2005).

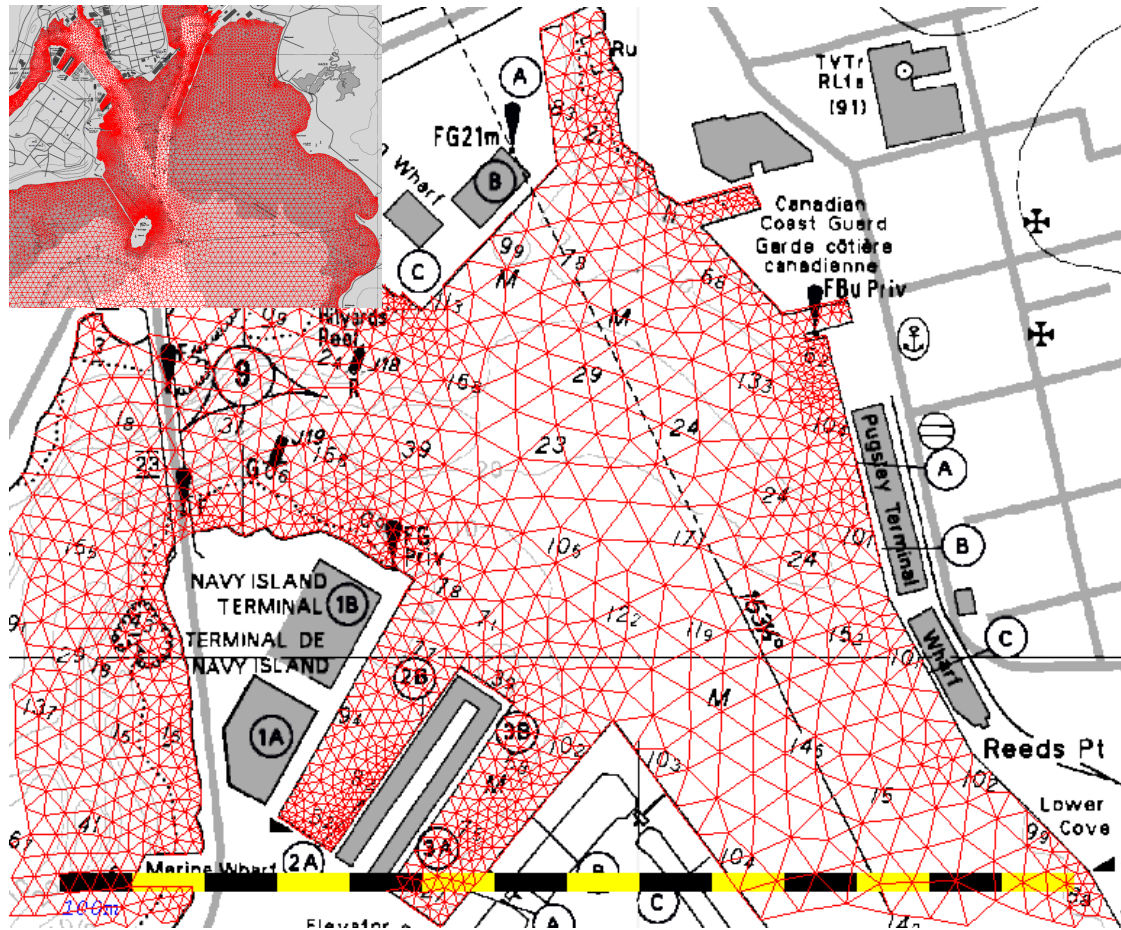
The Finite Volume Coastal Ocean Model (FVCOM) is a prognostic, finite-volume, free-surface, three-dimensional primitive equation ocean model (Chen, Liu, & Beardsley, 2003), and was employed because its unstructured, horizontal, triangular grid has computing advantage for modelling estuarine flow, as it permits resolution of fine details without requiring a high resolution grid throughout the entire domain. Bottom topography is well represented by a vertical  $\sigma$ -coordinate system. Since the main forces affecting harbour circulation are tides and Saint John River discharge, effects of wind, heat, precipitation, evaporation and groundwater were ignored.

The horizontal triangular grid (cells from 4.4 m<sup>2</sup> to 6350 m<sup>2</sup>) was able to resolve small features (Figure 15). Depths ranged from negative 4.4 m (dry and exposed at low tide) to positive 44.2 m.

The circulation of the individual fresh and salt water masses were examined by producing three-dimensional, baroclinic, model simulations with conditions corresponding to the four oceanographic surveys conducted on the 22 April 2008



(spring freshet), 14 November 2008 (fall freshet), 26 March 2009 (winter minimum) and 11 June 2009 (summer minimum).



**Figure 15. High resolution detail of the inset low resolution grid (S. Haigh & Hughes-Clarke, 2010).**

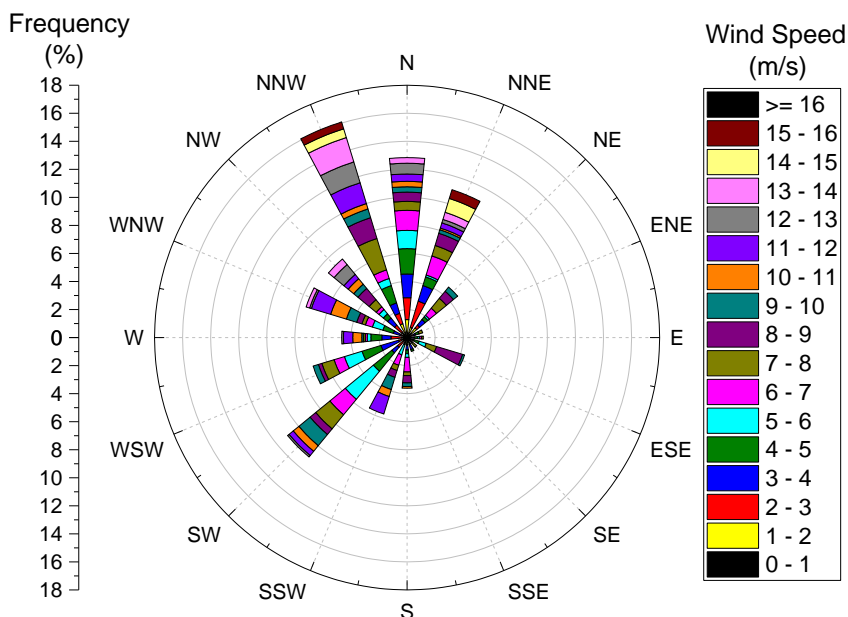
### 6.3 OIL BEHAVIOUR

The potential behaviour of different spills in the Port of Saint John was simulated by the Automated Data Inquiry for Oil Spills (ADIOS2), with consideration of winter and summer conditions. The ADIOS2 software package is an oil weathering model provided by the National Oceanic and Atmospheric Administration. The ADIOS2 database includes estimates of the physical properties of oils and products compiled from different sources, including industry, Environment and Climate Change Canada, and the U.S. Department of Energy. The model uses mathematical equations and information from the database to predict changes over time in the density, viscosity, and water content of oil or oil product, the rate at which it evaporates from the sea surface and disperses into the water, and the rate at which an oil-in-water emulsion may form (Samuels, Amstutz, Bahadur, & Ziemniak, 2013). Output of the model in graphical and textual format can be used to address questions that typically arise during spill response

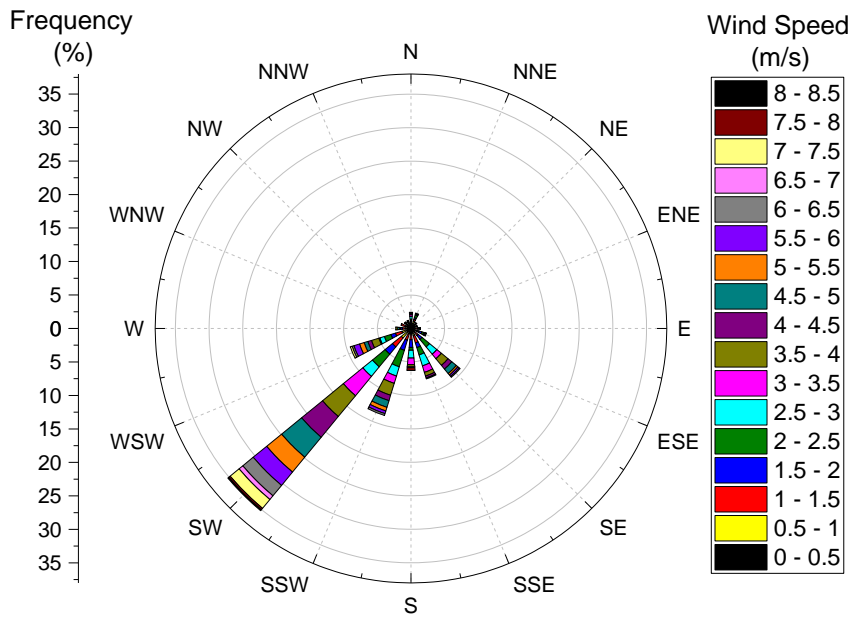
and cleanup. For example, by predicting change in oil viscosity (resistance to flow) over time, ADIOS2 can provide information on whether chemical oil dispersants can be used with success.

### 6.3.1 Environmental Conditions at the Port of Saint John

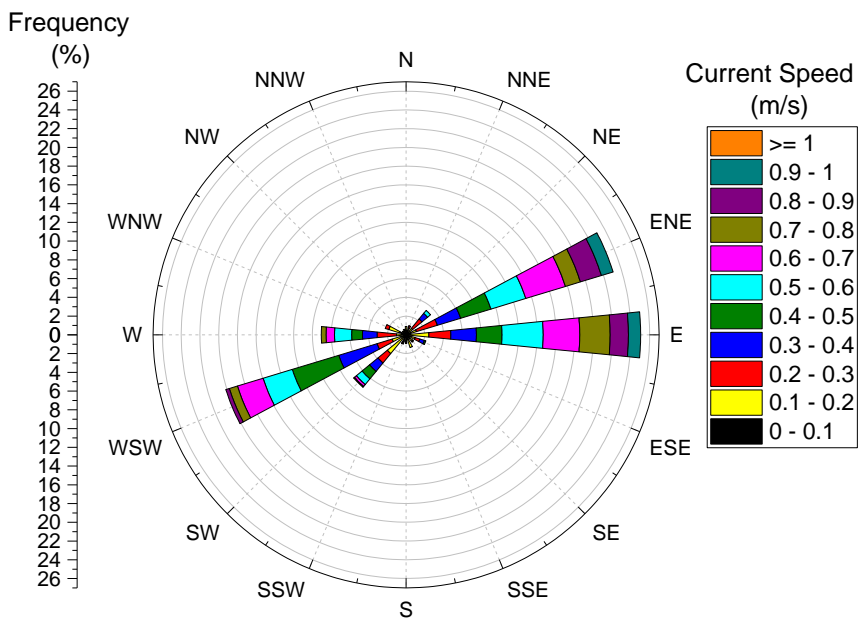
For comparative purposes, oil weathering scenarios were prepared using ADIOS2 software for winter and summer conditions of the Port of Saint John, according to buoy data from SmartAtlantic for the port, which included water temperature, wind speed, wind direction, current speed, and current direction. Due to limited data, winter conditions were represented by half-hour data from March 15 - 31, 2015, and summer conditions were represented by data from July 1 - 15, 2015 (Figure 16 to Figure 21).



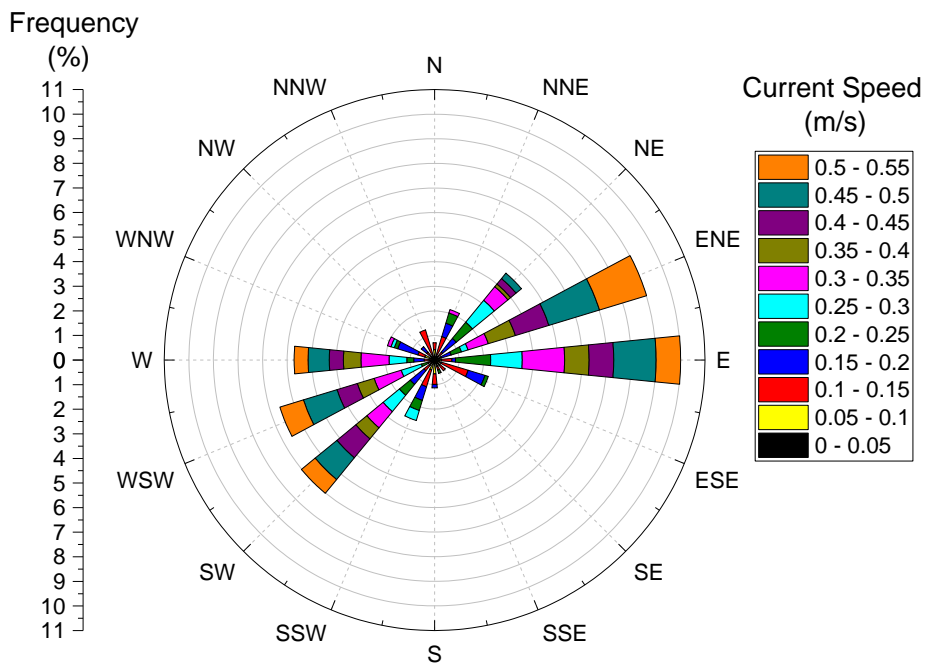
**Figure 16. Port of Saint John wind rose 15-31 March 2015**



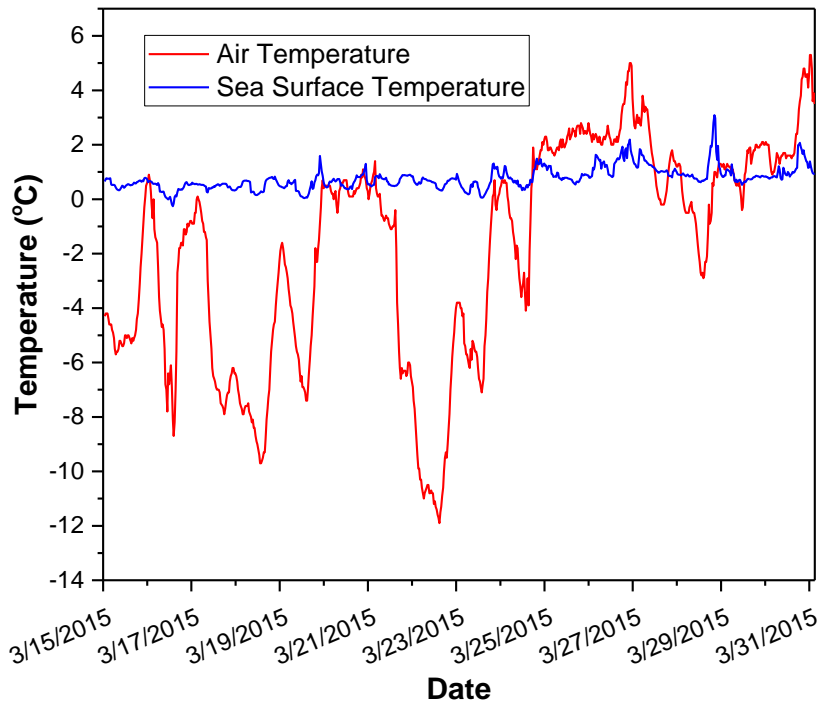
**Figure 17. Port of Saint John wind rose 1-15 July 2015**



**Figure 18. Port of Saint John current rose 15-31 March 2015**

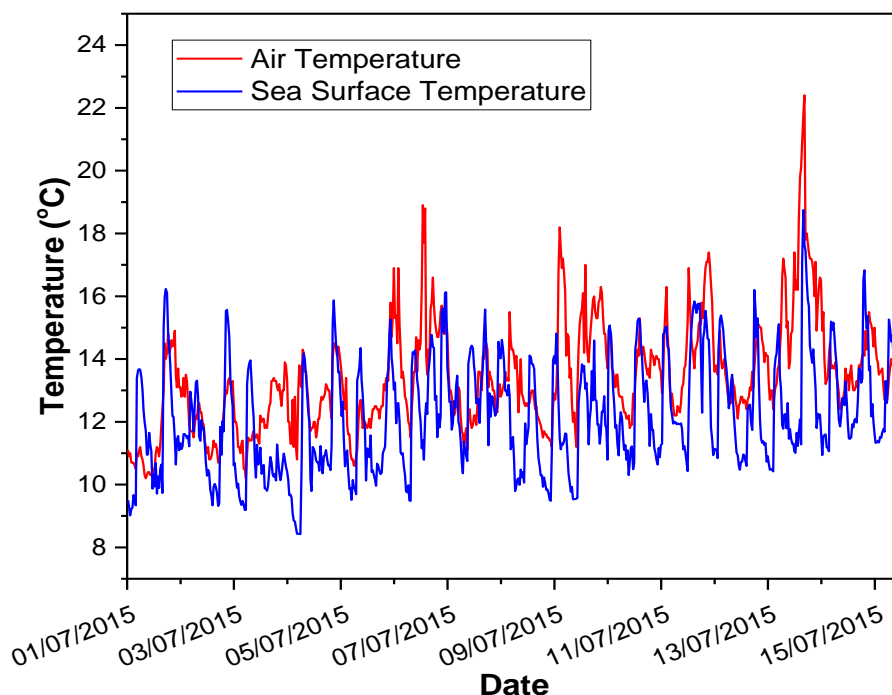


**Figure 19. Port of Saint John current rose 1-15 July 2015**



**Figure 20. Port of Saint John temperature 15-31 March 2015**





**Figure 21. Port of Saint John temperature 1-15 July 2015**

Using the March (winter) and July (summer) 2015 buoy data, the environmental parameters for ADIOS2 for winter and summer scenarios were determined (Table 4).

**Table 4. Environmental inputs for ADIOS2 modelling**

Parameter	Unit	Scenario	
		Winter (March)	Summer (July)
Water temperature	°C	1	12
Wind speed	m/s	8	4
Wind direction	degree	306	225
Current speed	m/s	0.6	0.4
Current direction	degree	70	85
Salinity	ppt	35	35
Sediment load	g/m <sup>3</sup>	5	5

### **6.3.2 Scenarios of Oil Behaviour**

According to relevant petroleum activities, oils that would most likely be involved in a spill are (Table 5)

1. refined products: unleaded gasoline, diesel fuel, jet fuel, and bunker C fuel oil;
2. intermediate fuel oil 180 (IFO180);
3. crude oils: Arabian Light Crude (ALC) and Hibernia Light Crude (HLC); and
4. non-conventional oil products: Cold Lake Blend (CLB) dilbit and Access Western Blend (AWB) dilbit.

**Table 5. Properties of petroleum products most likely to be spilled at the Port of Saint John, New Brunswick**

Oil	API (°)	Pour Point (°C)	Flash Point (°C)	Density at 12°C (kg/m <sup>3</sup> )	Viscosity at 12°C (cSt)	Aromatics (%)
Unleaded gasoline	56.7	-	-30	752	4.3	-
Diesel	39.4	-30	40	872	2.9	-
Jet fuel	43.0	-21	40	820	5.9	-
Bunker C	12.3	15	98	985	1646.8	55
IFO180	14.7	-10	91	969	2848.3	51
Arabian Light crude	33.4	-53	-20	872	15.2	39
Hibernia Light crude	37.1	6	19	543	21.4	15
Cold Lake Blend	21.0	-25	-2	947	361.2	29
Access Western Blend	20.9	-25	-5	949	438.8	21

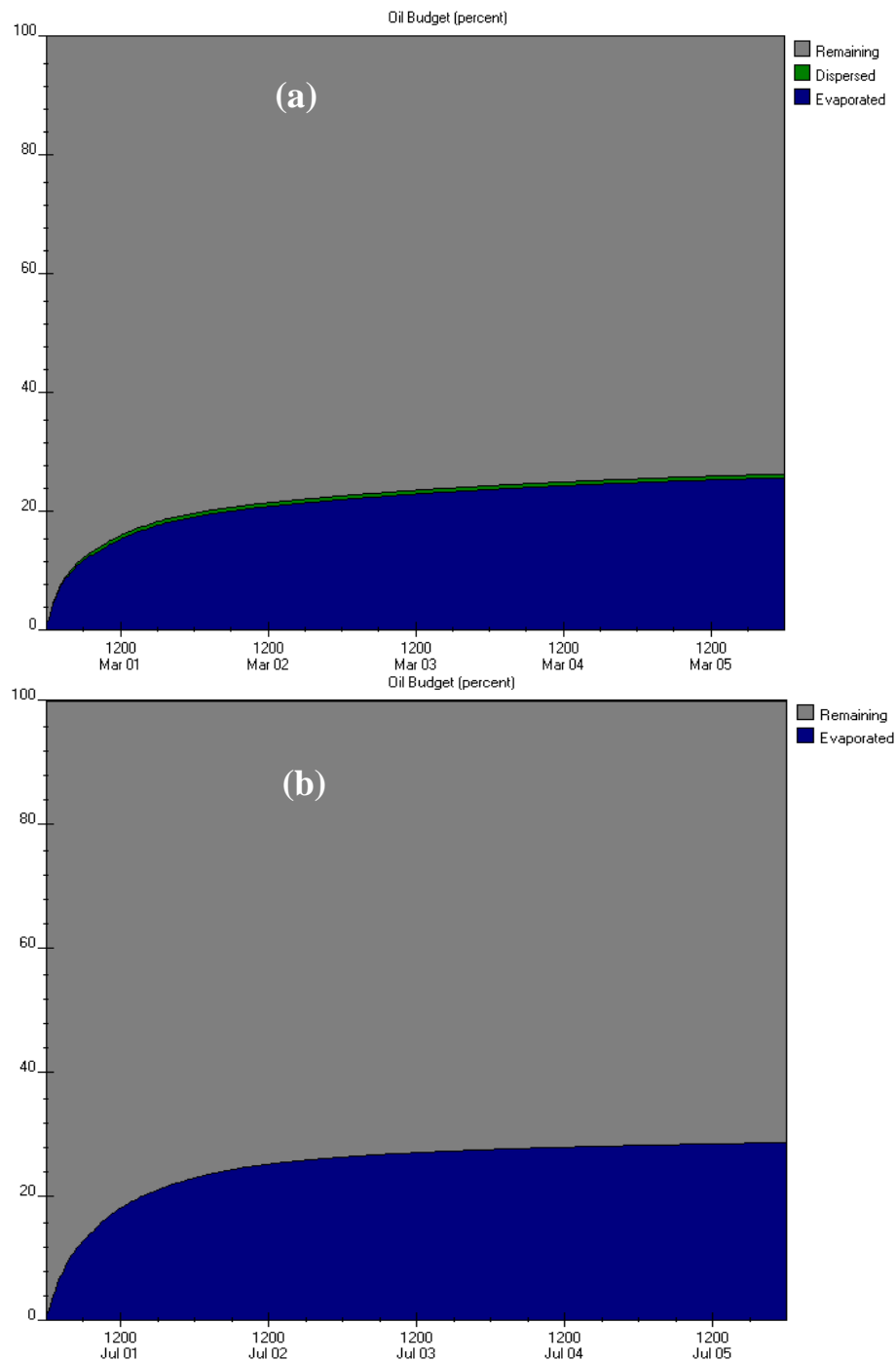
To look at potential behaviour, the model considered a spill of 4000 m<sup>3</sup> (~25,000 barrels) over a one-hour period from a tanker as a result of a collision or other accident. This quantity is representative of the loss of one tank from a typical tanker currently operating in the Canadian Atlantic.

### **6.3.3 Scenarios for Crude Oil Spills**

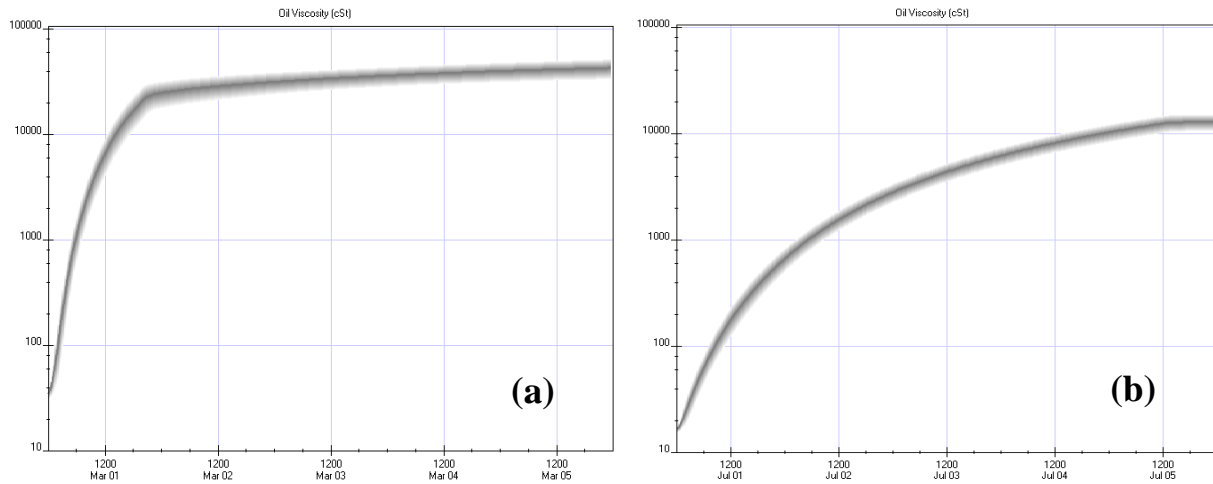
Two types of crude oil (Arabian Light, ALC and Hibernia Light, HLC) were modeled by ADIOS2 under winter (March) and summer (July) conditions. Modeling results included oil budgets, changes in viscosity and density (Figure 22 to Figure 27).

The ADIOS2 weathering model showed that a small proportion of ALC would evaporate and disperse (approximately 20%) within the first 36 hours leaving most of the spilled oil to be recovered during the cleanup response (Figure 22). Dispersion is undetectable in summer, which may be due to higher temperatures (enhanced evaporation) and lower wind speeds (lower wave energy). The oil budget of HLC is similar to ALC in both winter and summer (Figure 25) with a slightly higher proportion (approximately 30%) of the spilled oil degrading within the first 24 hours. In winter during the same period the viscosity (Figure 23a and Figure 26a) and density (Figure 24a and Figure 27a) of both oils increased significantly, reducing the window of opportunity available for some response techniques (e.g. dispersant application). With a kinematic viscosity above 10,000 cSt and a density slightly above 1.00 after 15 hours, it is possible that this oil would be slightly submerged and non-dispersible, in which case mechanical skimmers and pumps might be the only cleanup options. In summer, the kinematic viscosity above 10,000 cSt (Figure 23b and Figure 26b) and density slightly above 1.00 after 4 days for ALC and 3 days for HLC (Figure 24b and Figure 27b), are better suited for cleanup operations. Once response equipment is on location, it is possible that cleanup could indeed be efficient, as fresh oil would be constantly rising to the surface, maintaining the

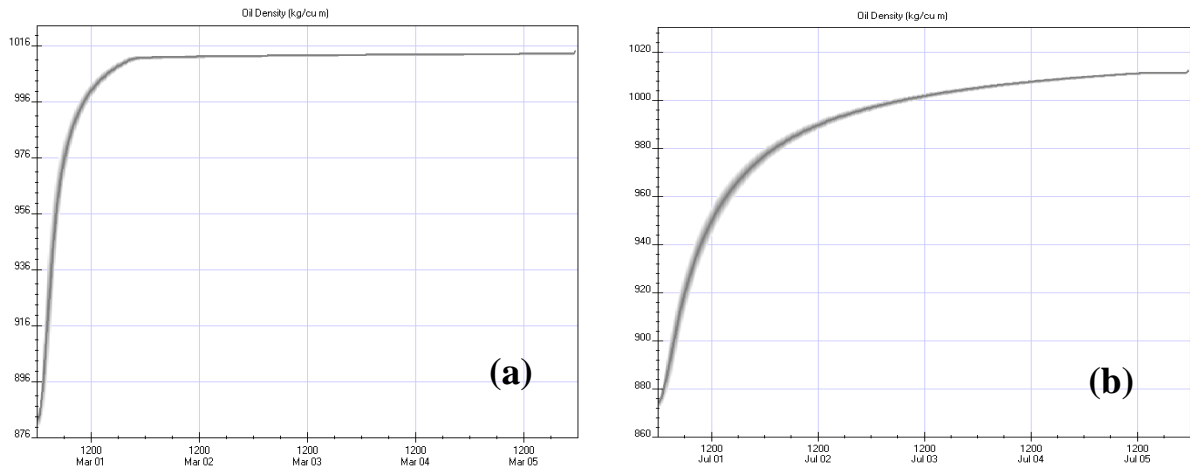
window of opportunity for successful operations. In spite of this, logistical challenges, such as waste management, and health and safety issues would be difficult to overcome.



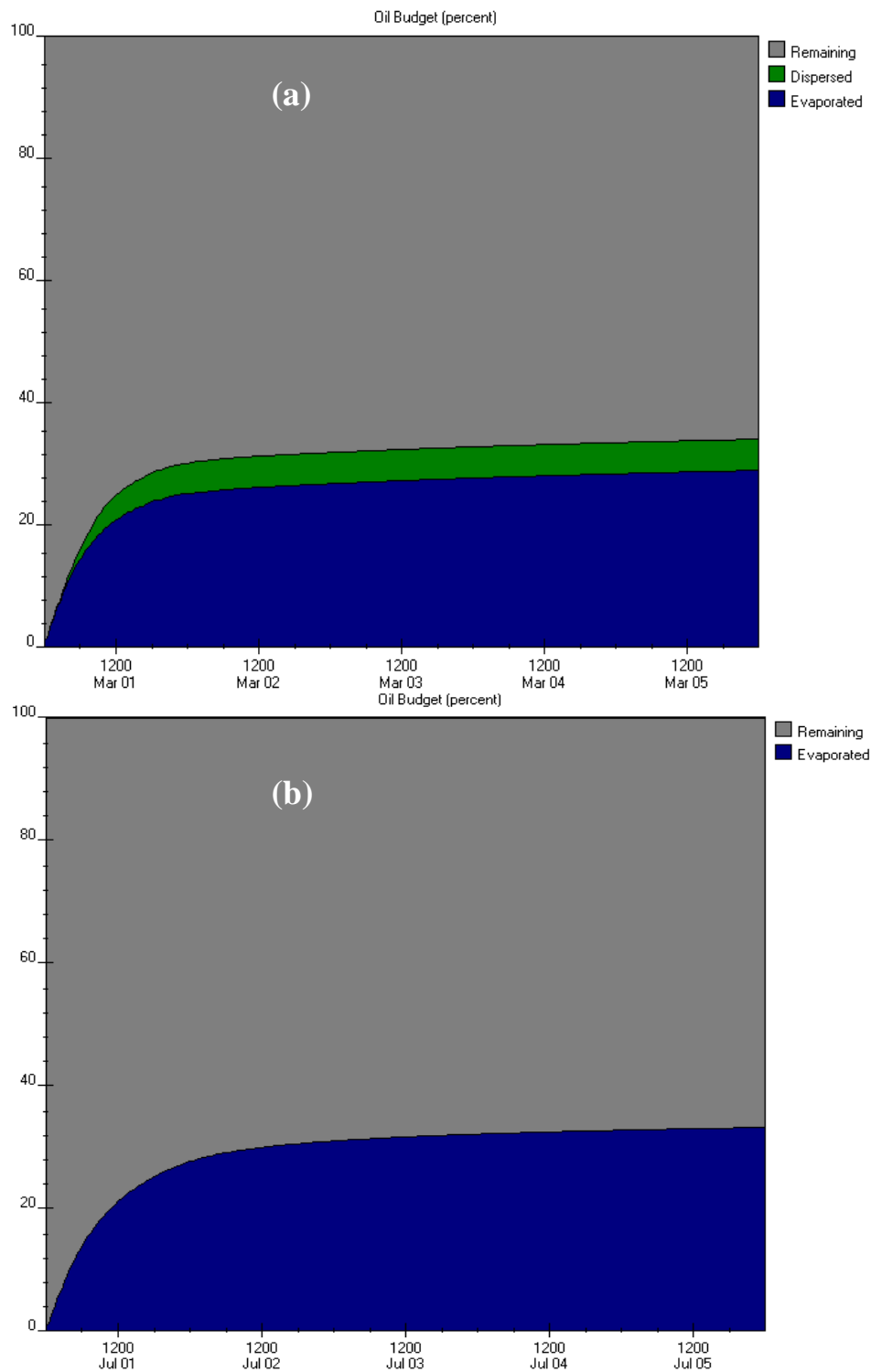
**Figure 22. ADIOS2 oil budget for a spill of ALC in (a) winter and (b) summer**



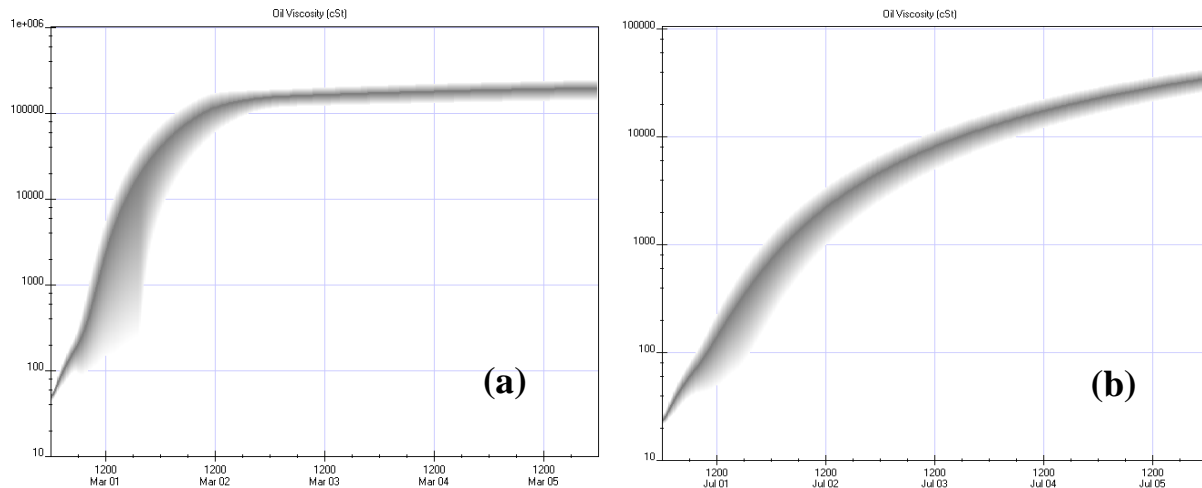
**Figure 23. ADIOS2 change in viscosity for a spill of ALC in (a) winter and (b) summer**



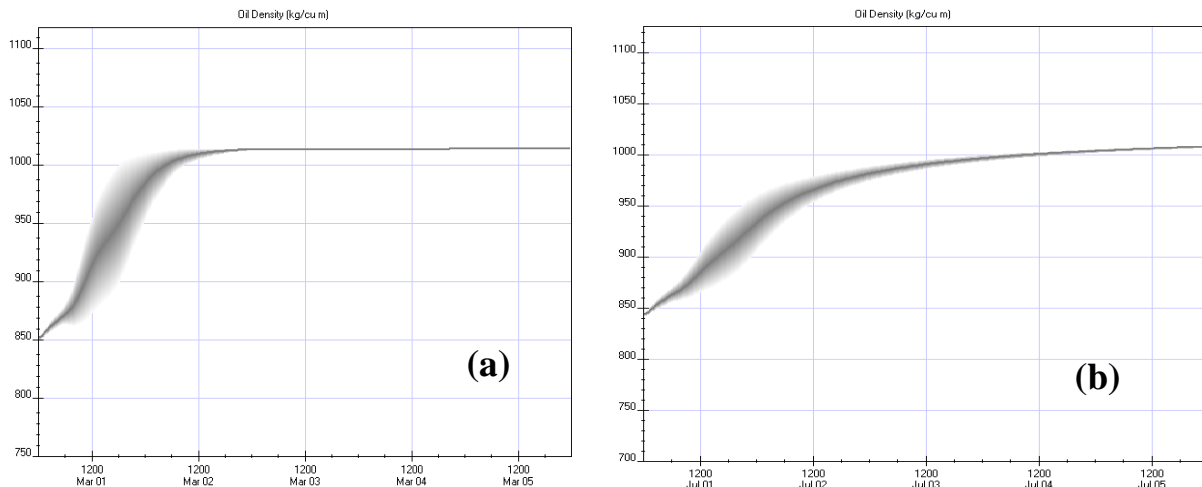
**Figure 24. ADIOS2 change in density for a spill of ALC in (a) winter and (b) summer**



**Figure 25. ADIOS2 oil budget for a spill of HLC in (a) winter and (b) summer**



**Figure 26. ADIOS2 change in viscosity for a spill of HLC in (a) winter and (b) summer**



**Figure 27. ADIOS2 change in density for a spill of HLC in (a) winter and (b) summer**

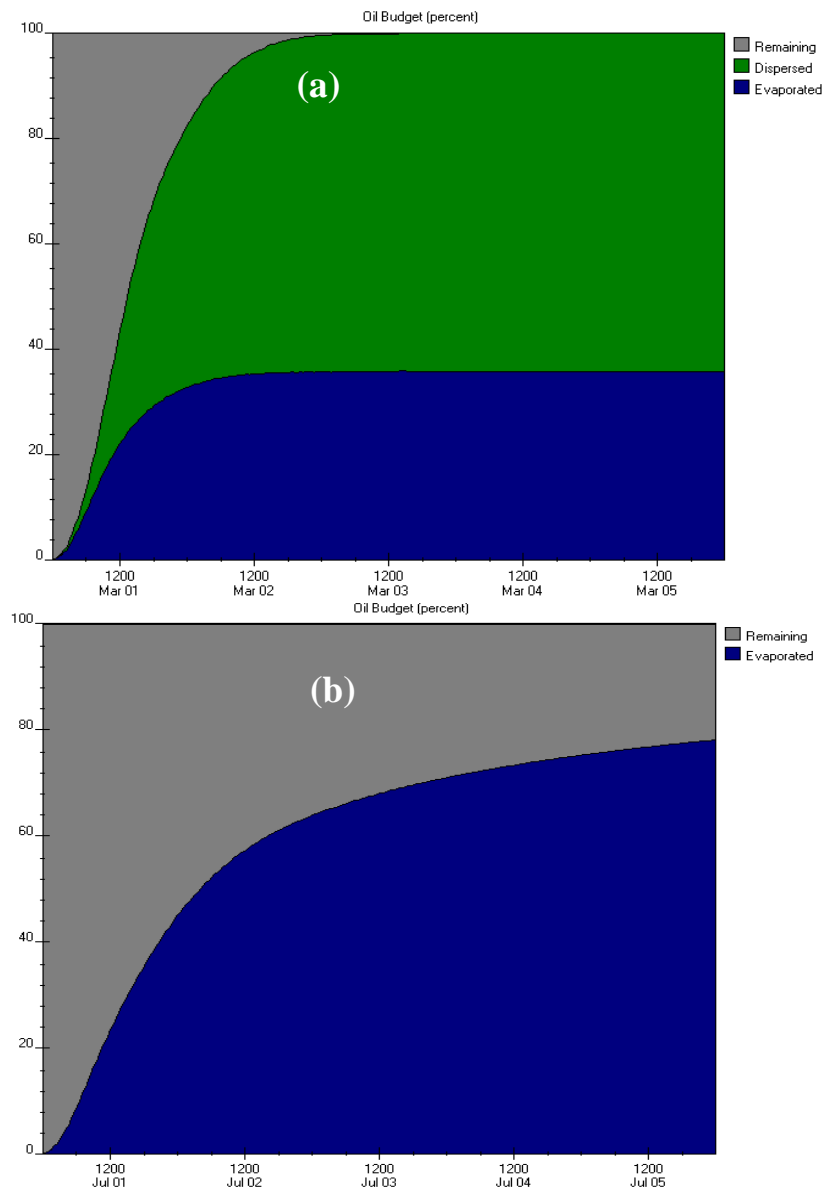
#### **6.3.4 Scenarios for Refined Product Spills**

Four types of refined products (unleaded gasoline, diesel, jet fuel, and bunker C) were modeled with ADIOS2 under both winter and summer conditions (Figure 28 to Figure 33).

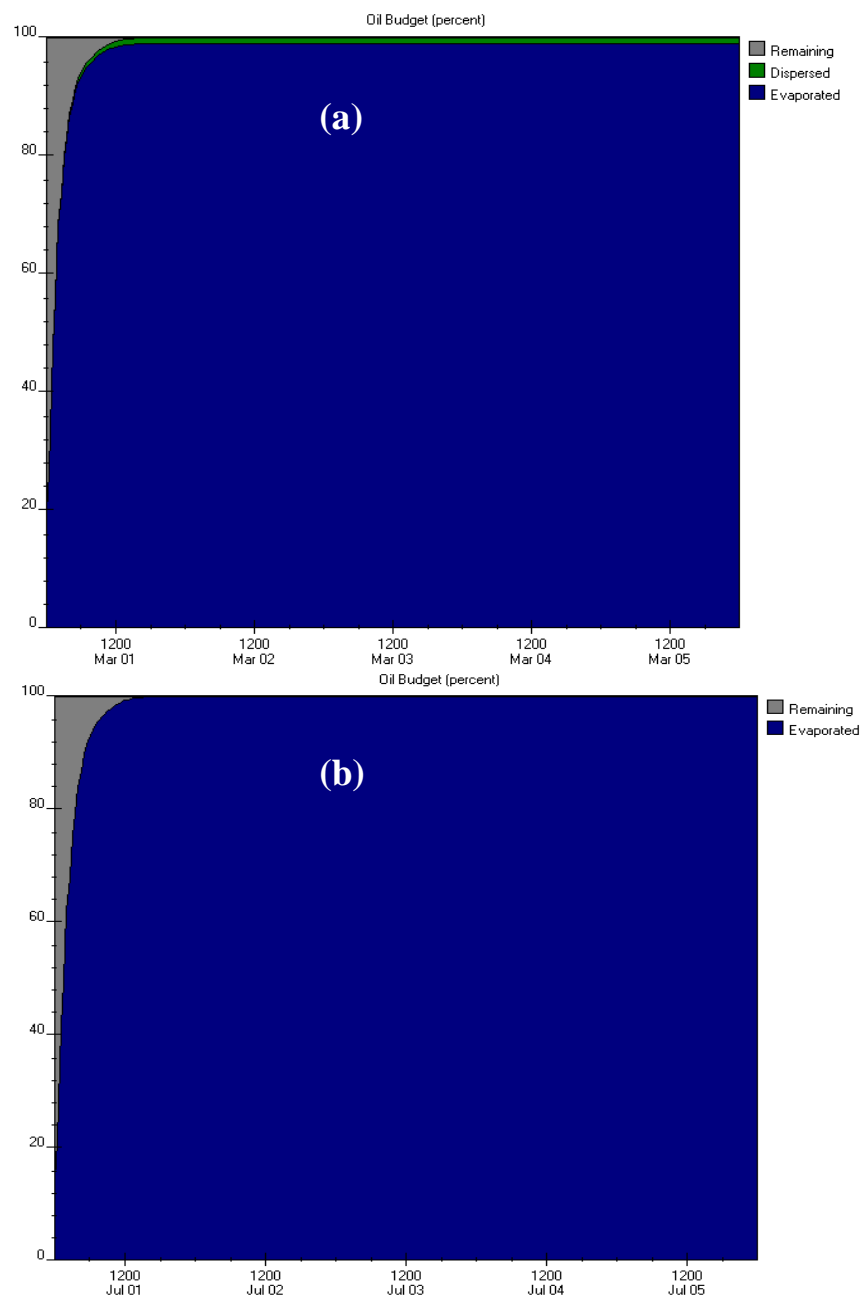
Gasoline, diesel, and jet fuel are very light fractions of crude oil (APIs ranging from 40° to 60°) from the refinery in the Port of Saint John and are transported to foreign ports by tankers. Offshore spills from these products are most likely to occur from collision between tankers, or from accidental spills at the refinery. If these products were to spill from a storage tank into the sea, ADIOS2 modelling showed that they would disperse and evaporate within the 12 hours to 3 days (Figure 28 to Figure 30). For example, in

winter, both dispersion and evaporation would entirely remove gasoline within half a day (Figure 29a), and in summer, evaporation alone would remove the entire amount (Figure 29b). Jet fuel spills would evaporate and disperse within two days under simulated winter conditions (Figure 30a), and would evaporate after five days in the summer (Figure 30b). A spill of diesel would completely disperse and evaporate in two and half days under winter conditions (Figure 28a). However, due to higher temperatures and lower wind energy, evaporation alone occurs under summer conditions and about 80% of the spill would evaporate after five days (Figure 28b). Because of rapidity of dispersion and evaporation, spills of light refined products would not represent a significant environmental issue due to their very low persistence. A response to such spills probably would not require significant recovery efforts, other than perhaps using absorbents in the vicinity of specific environmental sensitivities. Monitoring of natural attenuation (natural recovery) would be the best strategy.

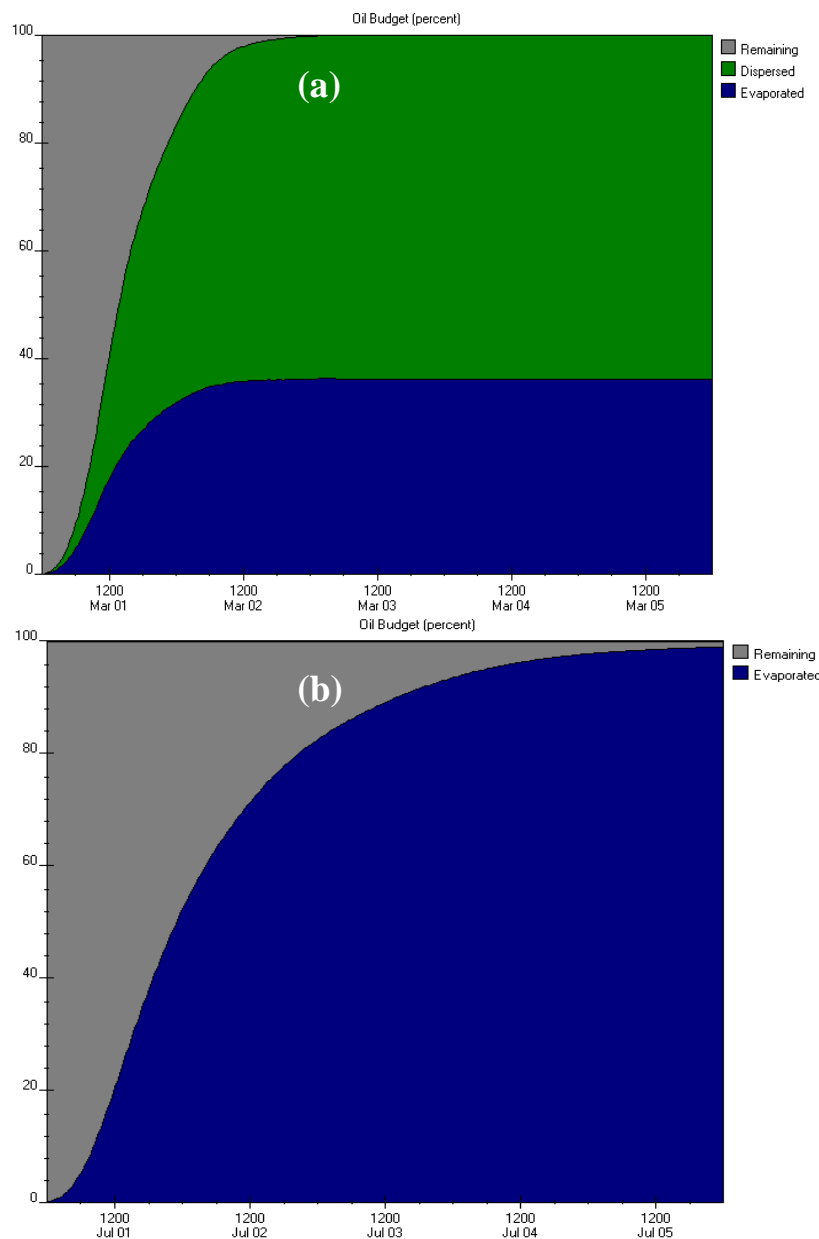




**Figure 28. ADIOS2 oil budget for a spill of diesel in (a) winter and (b) summer.**



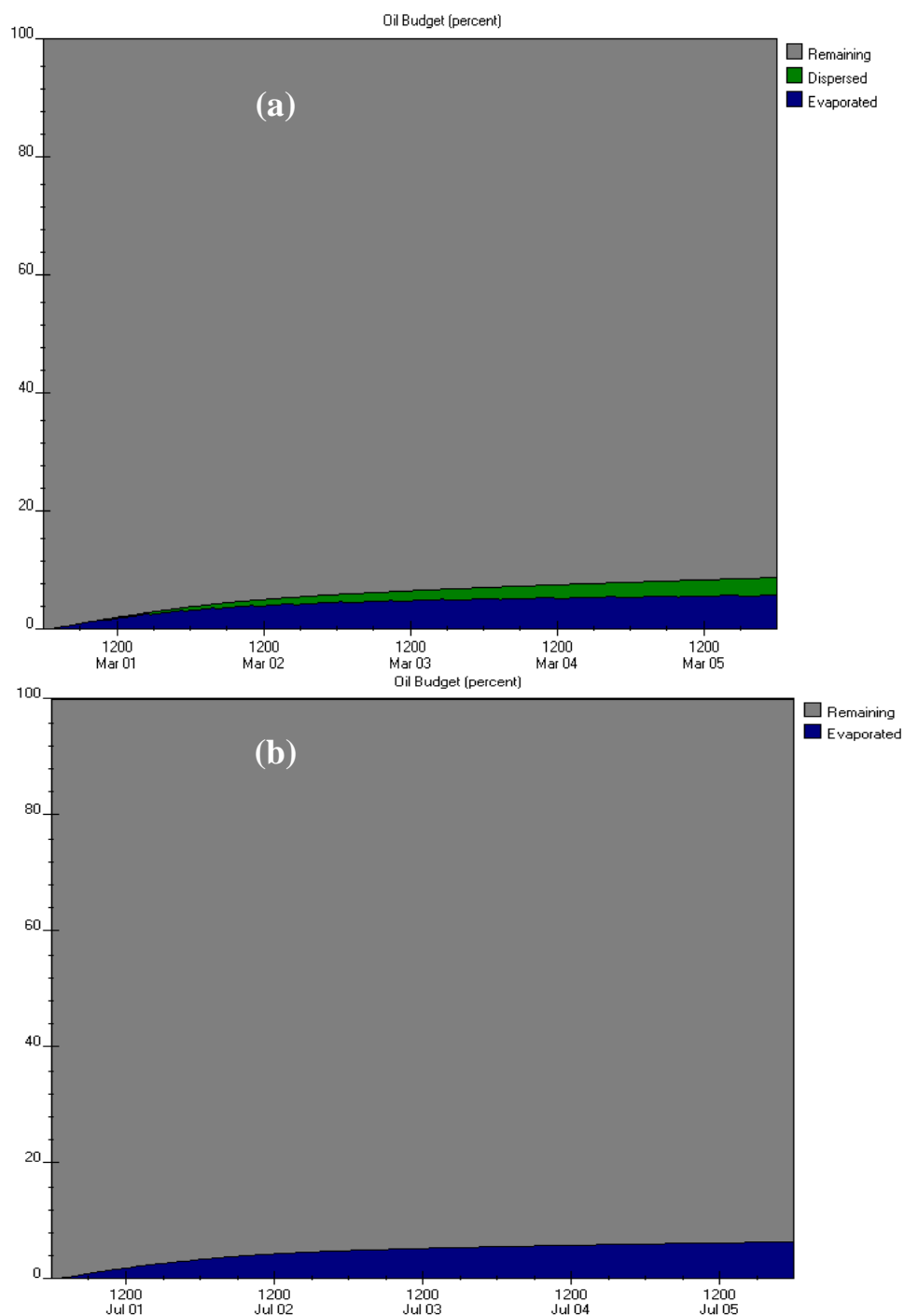
**Figure 29. ADIOS2 oil budget for a spill of gasoline in (a) winter and (b) summer.**



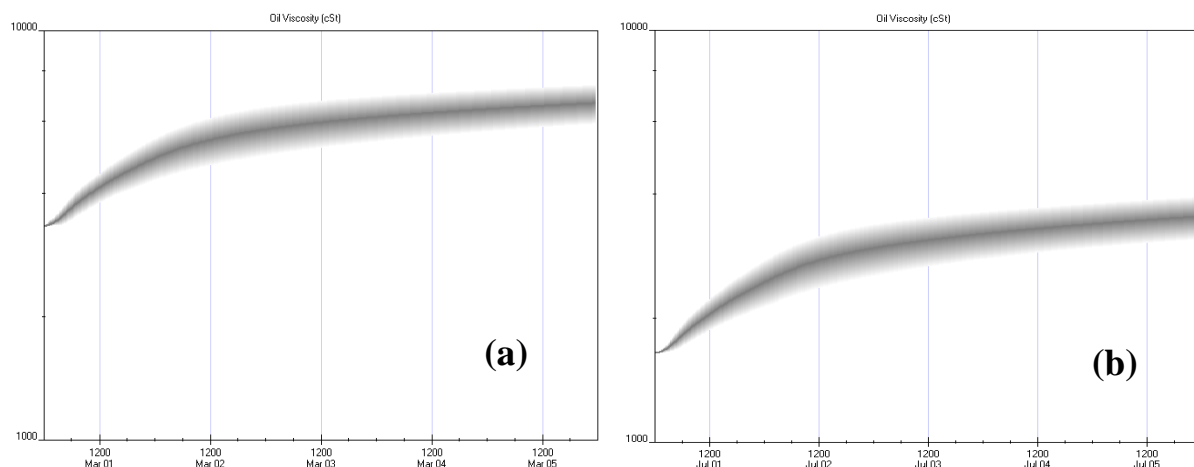
**Figure 30. ADIOS2 oil budget for a spill of jet fuel in (a) winter and (b) summer.**

Compared to light refined products, the heavy products such as bunker C oil are very difficult to evaporate or disperse (Figure 31). Based on the ADIOS2 simulation, about 10% of a bunker C spill would disperse or evaporate in winter conditions, whereas only about 8% would evaporate in summer conditions. Having a kinematic viscosity close to 10,000 cSt and a density slightly above 1.00 g/cm<sup>3</sup> (the density of freshwater at 20°C), after two days under winter conditions, it is possible that this oil would slightly submerge and not readily disperse (Figure 32a, Figure 33a). In that case, only booming with mechanical skimmers and pumps might be applicable as a recovery option. Physical factors such as viscosity and density are affected by changing temperatures, decreasing with increasing temperature. The viscosity and density of an oil spill in

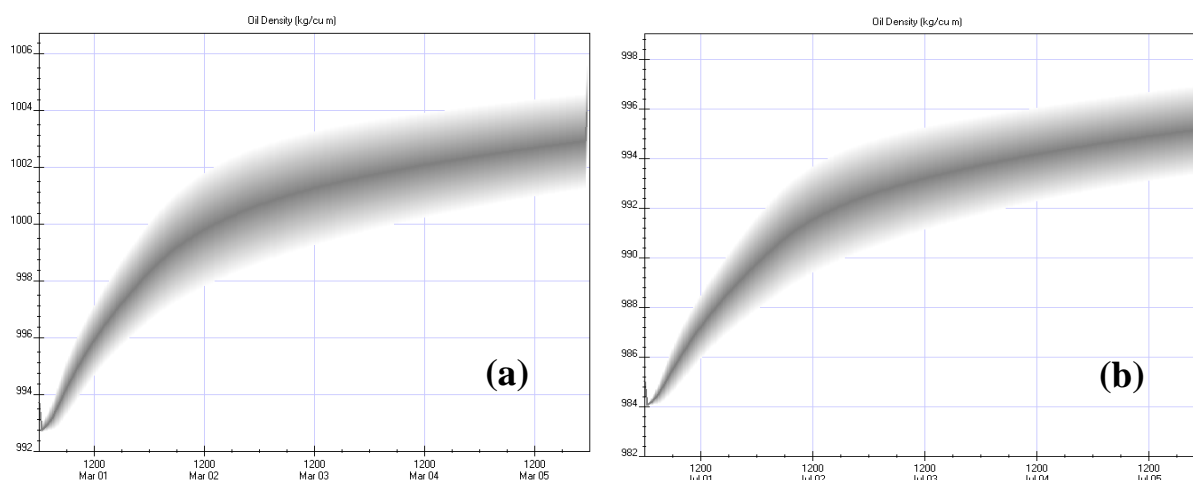
summer is lower than in winter (Figure 32b, Figure 33b), thus encouraging the rate of oil spreading, making the application of dispersant more suitable.



**Figure 31. ADIOS2 oil budget for a spill of bunker C oil in (a) winter and (b) summer.**



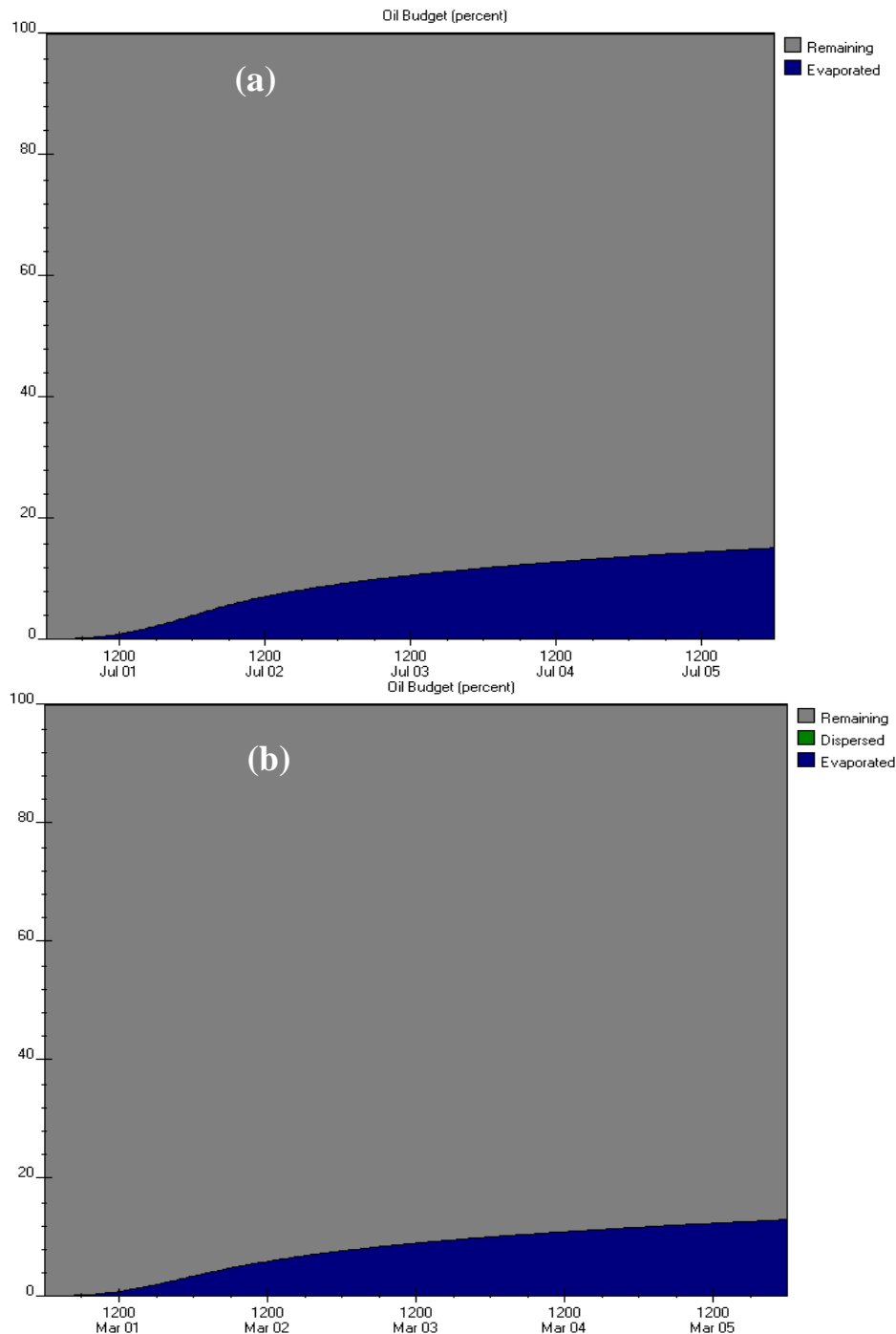
**Figure 32. Change in viscosity for a spill of bunker C oil in (a) winter and (b) summer calculated by ADIOS2.**



**Figure 33. Change in density for a spill of bunker C in (a) winter and (b) summer predicted by ADIOS2.**

### **6.3.5 Scenarios for Intermediate Fuel Oil Spills**

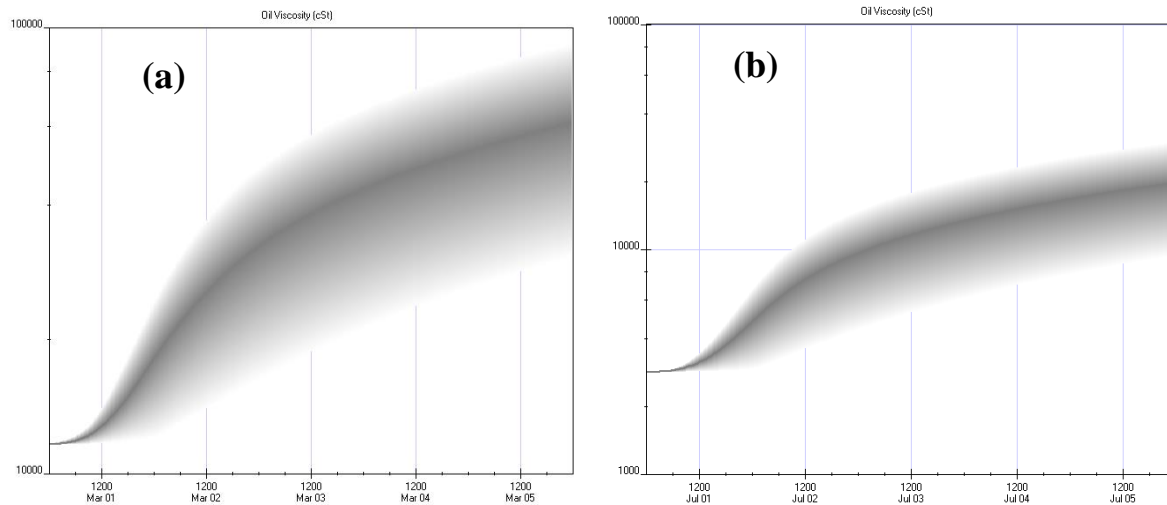
Tankers and cargo ships, among others currently operating in the Atlantic, use intermediate fuel oil (IFO), which is heavy, with a pour point of  $-10^{\circ}\text{C}$ , and is semi solid at typical winter temperatures. A spill of IFO180 could result from hull damage in a collision. Most of the oil (83% in winter and 87% in summer) would remain unchanged in the environment (Figure 34).



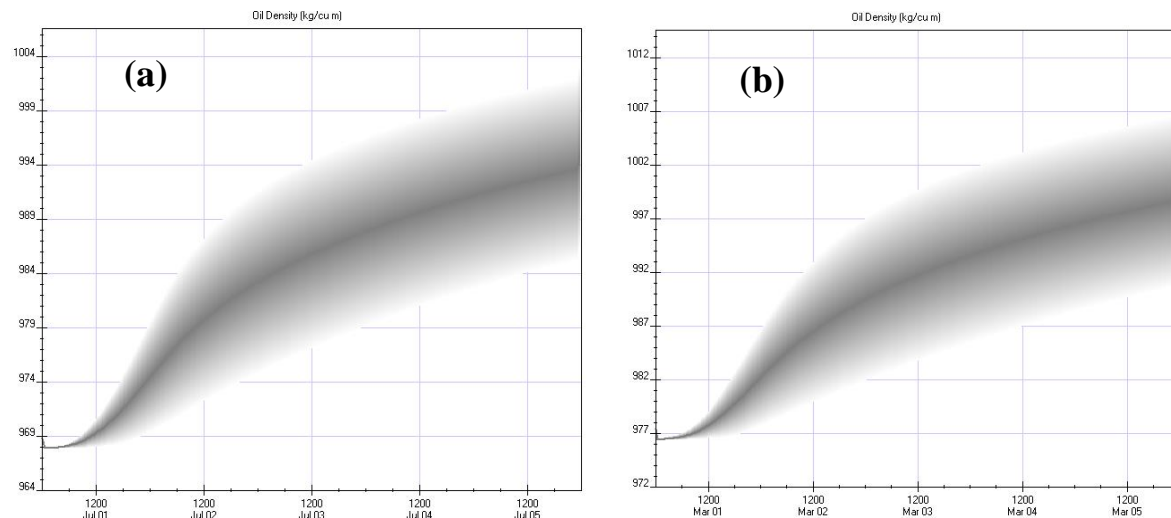
**Figure 34. ADIOS2 oil budget for a spill of IFO180 in (a) winter and (b) summer.**

Natural dispersion and evaporation are marginal weathering processes with this type of oil, especially in the cold winter waters that are typical for Atlantic Canada (Figure 35a, Figure 36a). The only feasible spill response for this oil would be mechanical means, because dispersants would not be effective, given its high kinematic viscosity ( $>10,000$  cSt) at the time of the spill, which increases to more than 50,000 cSt after a few days (Figure 35a). Even recovery efforts using booms and skimmers would be difficult due to

the high viscosity coupled with low winter temperatures that cause freezing of water intakes, and flow rate issues with the equipment. Similar to a spill of crude oil, most of the IFO would likely drift with sea currents and eventually reach the shore, where further recovery could be required. Changes in viscosity and density are less significant in summer (Figure 35a, Figure 36a). The viscosity is lower than 10,000 cSt in the first two days, making dispersant applicable during this window (Figure 35a).



**Figure 35. Change in viscosity for a spill of IFO180 in (a) winter and (b) summer as calculated by ADIOS2.**



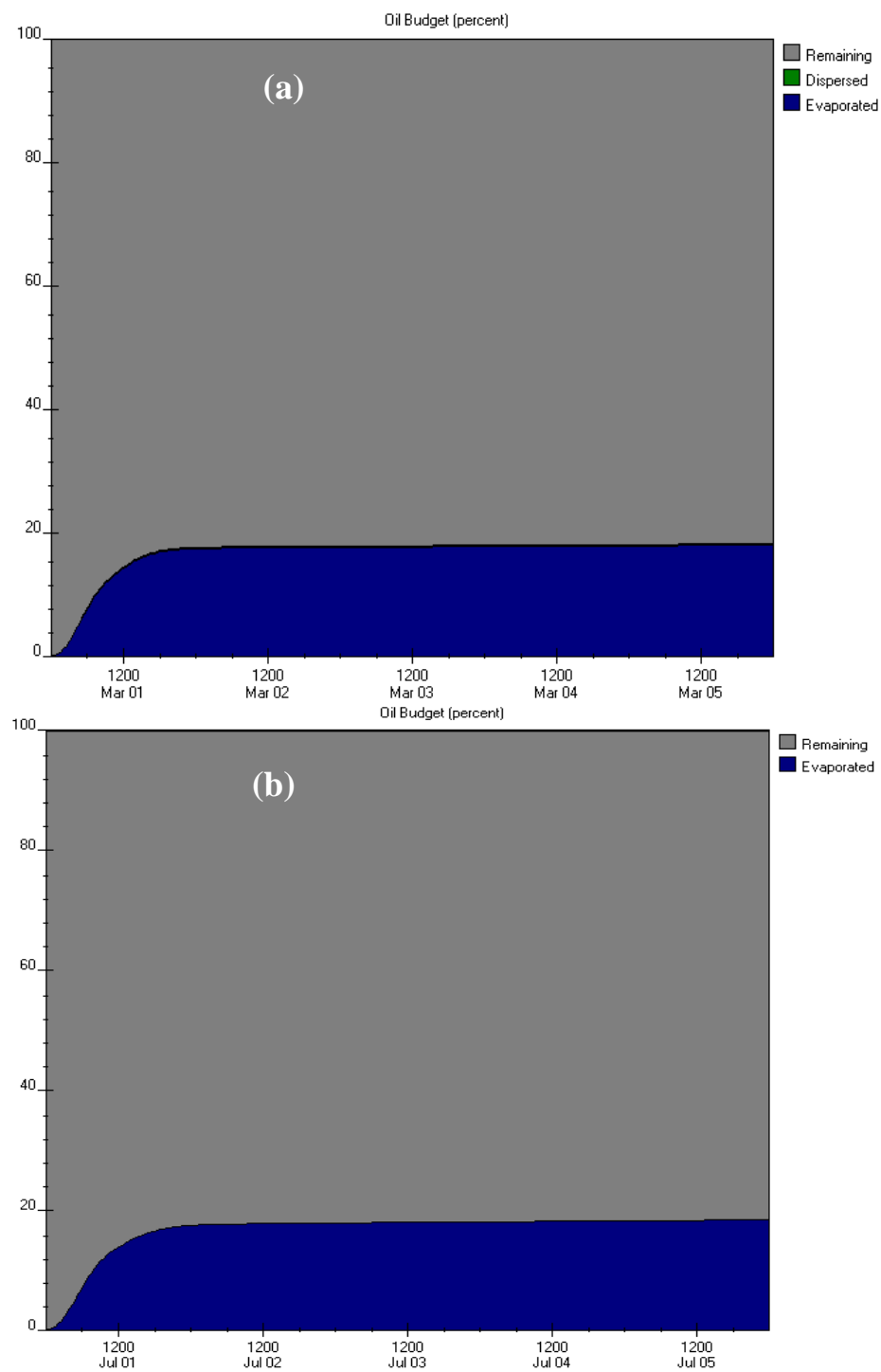
**Figure 36. Change in density for a spill of IFO180 in (a) winter and (b) summer calculated by ADIOS2.**



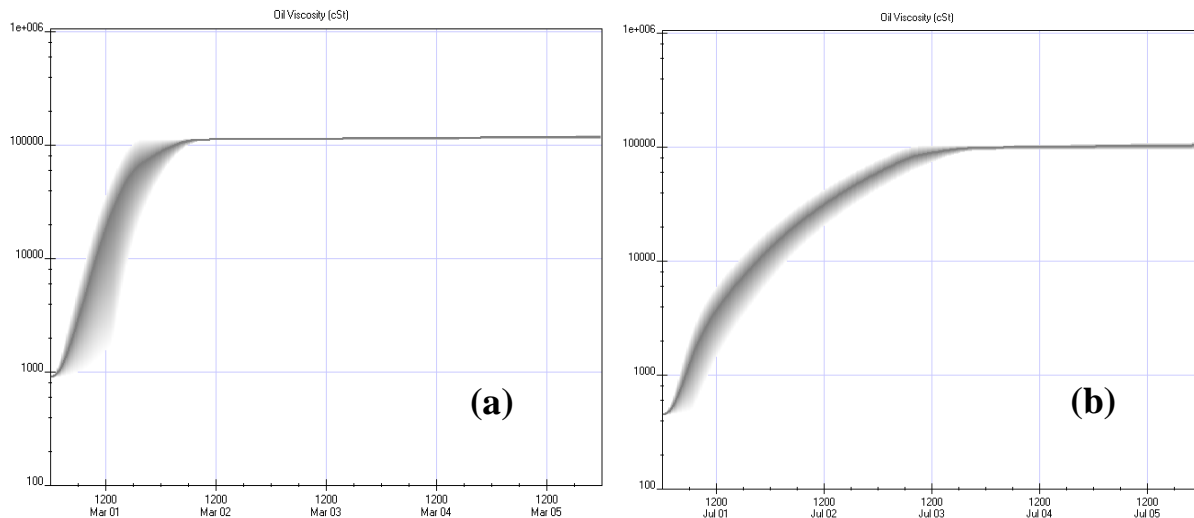
### **6.3.6 Scenarios for Spills of Non-Conventional Oils**

The recently proposed deep water marine terminal in the Port of Saint John 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. These crude oils are mainly non-conventional oils such as the Cold Lake Blend (CLB) and Access Western Blend (AWB) diluted bitumens.

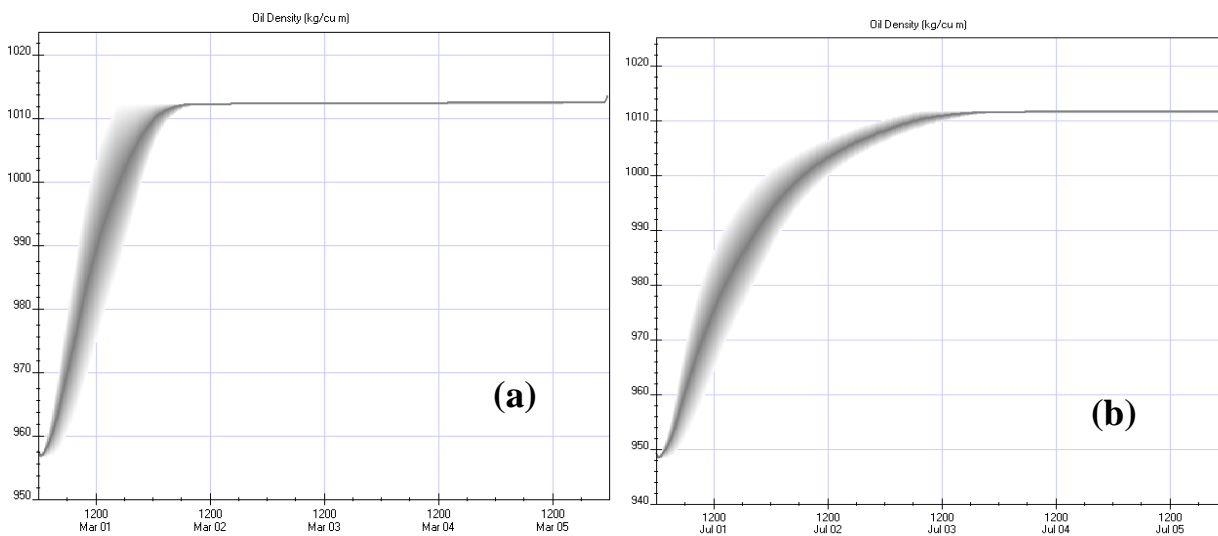
The behaviour of dilbit is similar to IFO180. ADIOS2 simulation results indicated that approximately 20% of both dilbit products would be dispersed or evaporated in the first 20 hours under both winter and summer conditions, and the spills would become stable thereafter (Figure 37, Figure 40). In addition, dispersion is only detectable in the simulation of CLB under winter conditions, and undetectable in the rest. Viscosity (Figure 38, Figure 41) and density (Figure 39, Figure 42) of both oils also increases significantly within the first 20-24 h, thus reducing the window of opportunity available for some response techniques, such as dispersant application. With a kinematic viscosity above 10,000 cSt and a density slightly above 1.00 g/cm<sup>3</sup> after 15 h for AWB and 12 h for CLB under winter conditions, it is possible that this oil would slightly submerge and not readily disperse. In that case, only mechanical skimmers and booms might be applicable as recovery options. Changes in viscosity and density are slightly better in the summer, with a kinematic viscosity above 10,000 cSt and a density slightly above 1.00 g/cm<sup>3</sup> after 24 h for AWB and 30 h for CLB, but still demanding quick response within a short time frame for any recovery option to be of use.



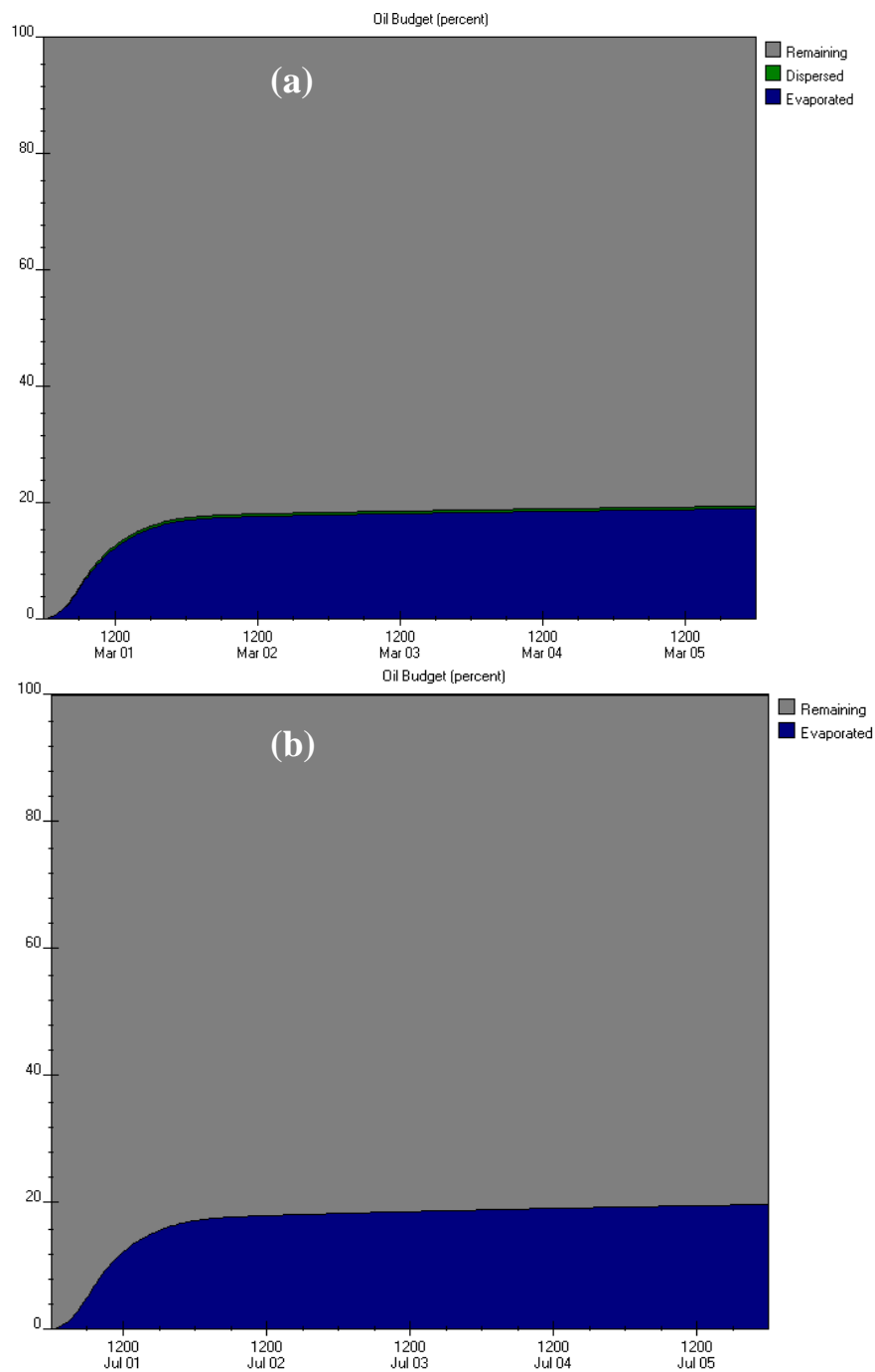
**Figure 37. ADIOS2 oil budget for a spill of Access Western Blend in (a) winter and (b) summer; note that the dispersed fraction is hardly visible**



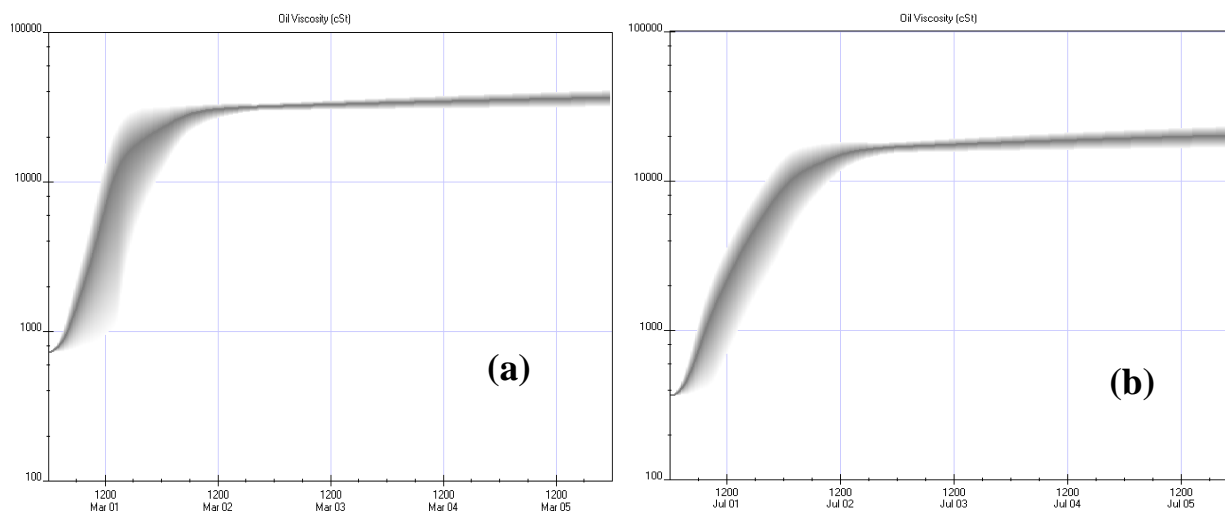
**Figure 38. Change in viscosity calculated by ADIOS2 for a spill of AWB in (a) winter and (b) summer.**



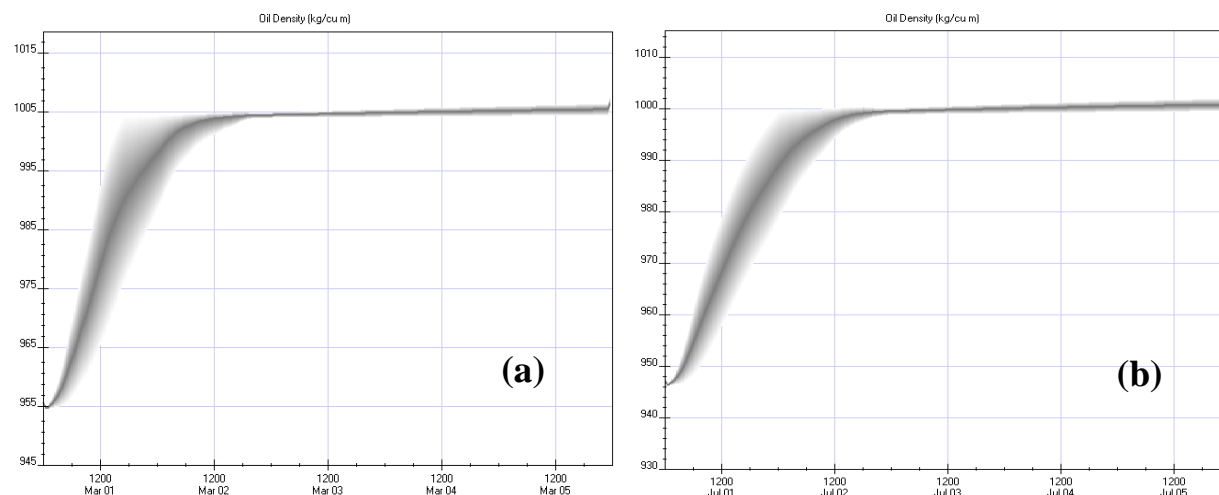
**Figure 39. Change in density calculated by ADIOS2 for a spill of AWB in (a) winter and (b) summer.**



**Figure 40. ADIOS2 oil budget for a spill of Cold Lake Blend in (a) winter and (b) summer.**



**Figure 41. Change in viscosity predicted by ADIOS2 for a spill of CLB in (a) winter and (b) summer.**



**Figure 42. Change in density predicted by ADIOS2 for a spill of CLB in (a) winter and (b) summer.**

## 6.4 OIL TRANSPORT

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 is very strong, exceeding 3 m/s through the Minas Passage (Karsten, McMillan, Lickley, & Haynes, 2008; Wu, Chaffey, Greenberg, Colbo, & Smith, 2011). 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 its effects on oil fate and behaviour for this study area (Nuka Research Planning Group, 2006). To investigate the transport of oil during a spill in the Port of Saint John with and without the application of dispersant, an oil transport simulation was conducted. It was based on a spill of 1,000 m<sup>3</sup> of Arabian Light Crude (ALC) using the

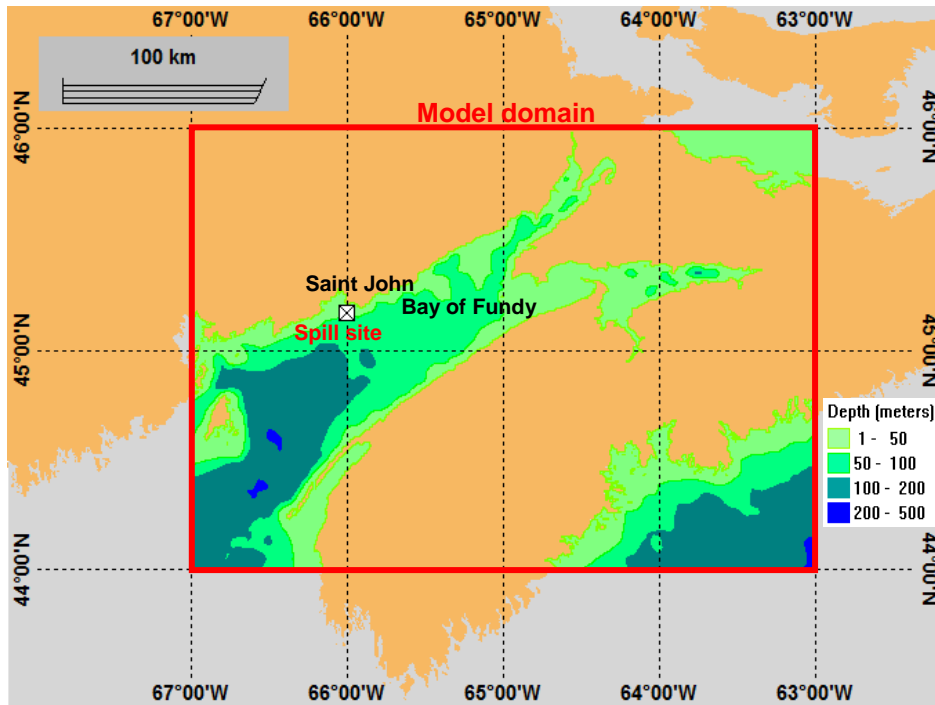
oil spill contingency and response (OSCAR) model under both winter and summer conditions.

The OSCAR is specifically designed to support oil spill contingency and response decision making (Aamo, Reed, & Downing, 1997; Reed, Aamo, & Daling, 1995; Reed et al., 2004; Reed, Ekrol, Rye, & Turner, 1999). 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 include spreading, drifting, natural dispersion, chemical dispersion, evaporation, stranding, dissolution, adsorption, settling, emulsification and biodegradation. The model has three key components: a databased oil-weathering model; a three-dimensional fate/trajectory model; and an oil spill response/combustion model. The OSCAR model has been validated in considerable detail (Reed, Aamo, & Downing, 1996; Reed et al., 2000).

#### **6.4.1 Model Inputs and Setup**

The ocean currents that were used in this oil spill modelling were from a hydrodynamic model based on the Finite-Volume Coastal Ocean Model (FVCOM), a proven three-dimensional, finite-volume, unstructured grid, ocean model (Chen et al., 2007). The outputs from the FVCOM are high-resolution data (spatial resolution up to 10 m and temporal resolution of 1 hour) in a triangular mesh, which are highly capable in characterized complex topographies (e.g. river and shoreline). The model was evaluated against independent observational data, including tidal elevation, tidal current (in the water column and bottom layer), and tidal residual current and tidal asymmetry indicators. The evaluation showed that the model was 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 (Figure 43) was 4 degrees by 2 degrees divided into 700 by 500 grid cells. Depths in the simulation were taken from the high-resolution 1-arc minute global bathymetry database, ETOPO1 (Amante & Eakins, 2009). The maximum depth was 286 m. Climate data, such as wind and air temperature for the study area were downloaded from Environment and Climate Change Canada. 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 current data from the FVCOM were interpolated based on the defined grid cells and modelling domain. After interpolation, the horizontal resolution for current was 50 m. Furthermore, ten layers were set for the vertical grids with resolution of 1 m. The temporal resolution was one hour.



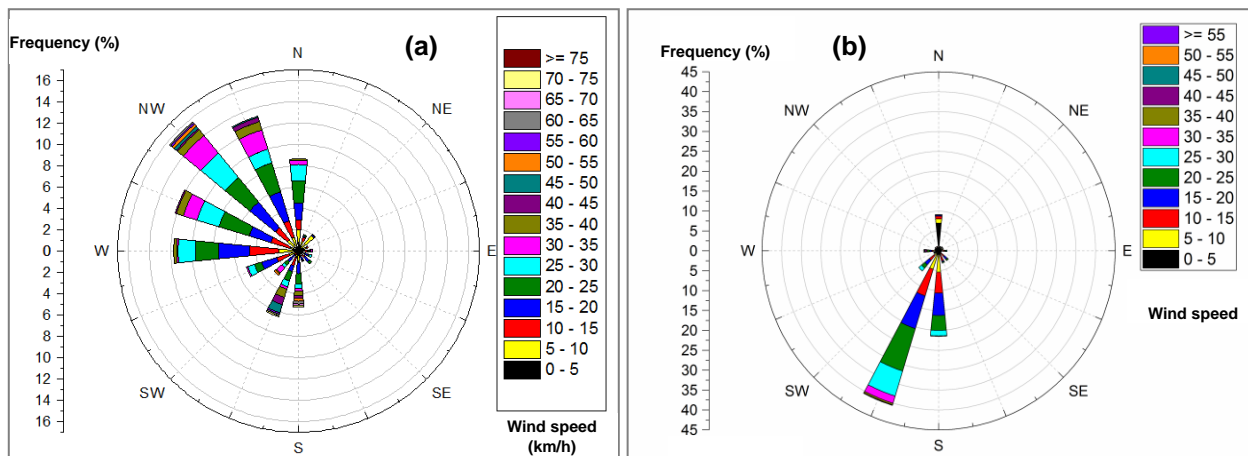
**Figure 43. Study area, model domain and bathymetry**

#### **6.4.2 Scenarios**

Environmental conditions, especially wind, play an important role in the fate and transport of spilled oil. Since the dominant wind for a particular season of the year varies significantly, winter (January 1 to 31, 2013) and summer scenarios (July 1 to 31) were chosen to study the effects of chemical dispersant application with seasonal variation. These two months can well represent the winter and summer conditions of the area, and further reflect two extreme scenarios of oil spill, either with or without dispersant. The choice of 30 day periods was based on the general nature of spill dispersion that usually occurs within the first 10 days, after which the spill becomes undetectable. Therefore, the simulation period was set to 10 days for each scenario.

The stochastic simulation incorporates a random spill date, which occurs within the first 20 days of the modelled period. The same approach can be applied using environmental inputs for other seasons. The wind roses for January and July (Figure 44) indicated that the prevailing wind direction in winter is from the northwest, but in summer is from southwest. Wind direction in winter is more diverse than in summer, and wind speed in winter is significantly higher than in summer.





**Figure 44. Wind speed, direction and frequency for (a) winter and (b) summer**

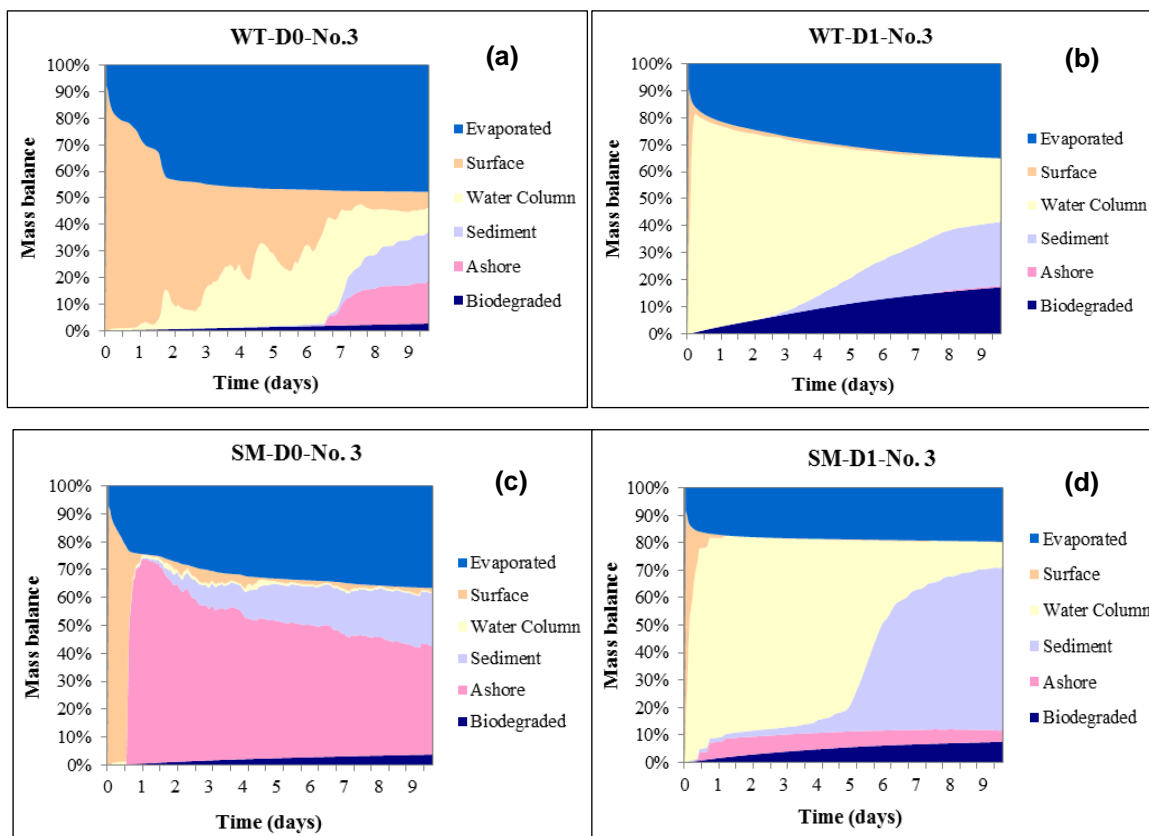
Dispersant application begins almost immediately after the spill occurs, and continues throughout the simulation period to treat the under-dosed fraction. This approach ensures the highest treatment efficiency (not limited by dispersant quantity), and enables us to study the maximum likely effects of dispersant on oil fate/behaviour. For example, if the maximum likely reduction of onshore oil is insignificant under ideal conditions, then the application of dispersant is probably not justified. The chosen dispersant was Corexit 9500 with a dispersant effectiveness of about 40% for Arabian Light (Blondina et al., 1999), since large volumes of freshwater from the Saint John River can reduce dispersant effectiveness.

Using a stochastic approach, the likelihood of particular trajectories occurring, based on historical wind speed and direction, was estimated, and the results were combined to produce an overall probability of where oil might travel. A 10-day period was selected based on preliminary simulations, to ensure that spilled oil could potentially reach the shore. For each scenario, 20 stochastic runs were performed.

Mass balances for the 20 stochastic runs were computed, as illustrated by Run No.3, (Figure 45) to show the effects of chemical dispersant application under different seasonal conditions (winter and summer). The case without dispersant application in winter (Figure 45a) indicates that a large amount of oil remained at 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. With dispersant application in winter (Figure 45b), surface oil was effectively dispersed soon after the spill occurred 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 spill) compared with the situation without dispersant (6.5 days). In summer scenarios, because the prevailing wind direction was toward the north, the spilled oil moved shoreward and became stranded onshore in a very short period (Figure 45c).

After dispersant application, most of the spilled Arabian Light Crude (ALC) oil entered the water column before reaching the shoreline (Figure 45d). The abrupt increase in percentage of chemically dispersed oil in the water column early on (Figure 45b, d) was due to the reduced and unstable oil-water interfacial tension. Later, part of the dispersed oil returned to the surface and the water column until stable. The dispersion rate gradually decreased after the initial dispersant application, and became stable as oil droplets returned to the surface from the water column (Figure 45). Before the increases of oil ashore and in the sediment, the dispersion rates were about 60% in both winter (Day 3, Figure 45b) and summer (Day 5, Figure 45d) scenarios. More sedimentation occurred in summer (about 55%, Figure 48d) than in winter (about 35%, Figure 48b). Biodegradation was significantly enhanced because more oil entered the water column.



**Figure 45. Mass balances in a single stochastic run for (a) winter without dispersant, (b) winter with dispersant, (c) summer without dispersant, and (d) summer with dispersant**

The extent of oil coverage for Run No.3 (Figure 46 & Figure 47) shows that a significant amount of ALC remained in the water column and much less remained on the surface after applying dispersant than without it. Most of the oil was transported and trapped in the northeast corner (Chignecto Bay) which is a very shallow area. Oiled particles contacted the seabed and settled to the sediment. Quantitative comparisons of the effects are presented in Figure 49.

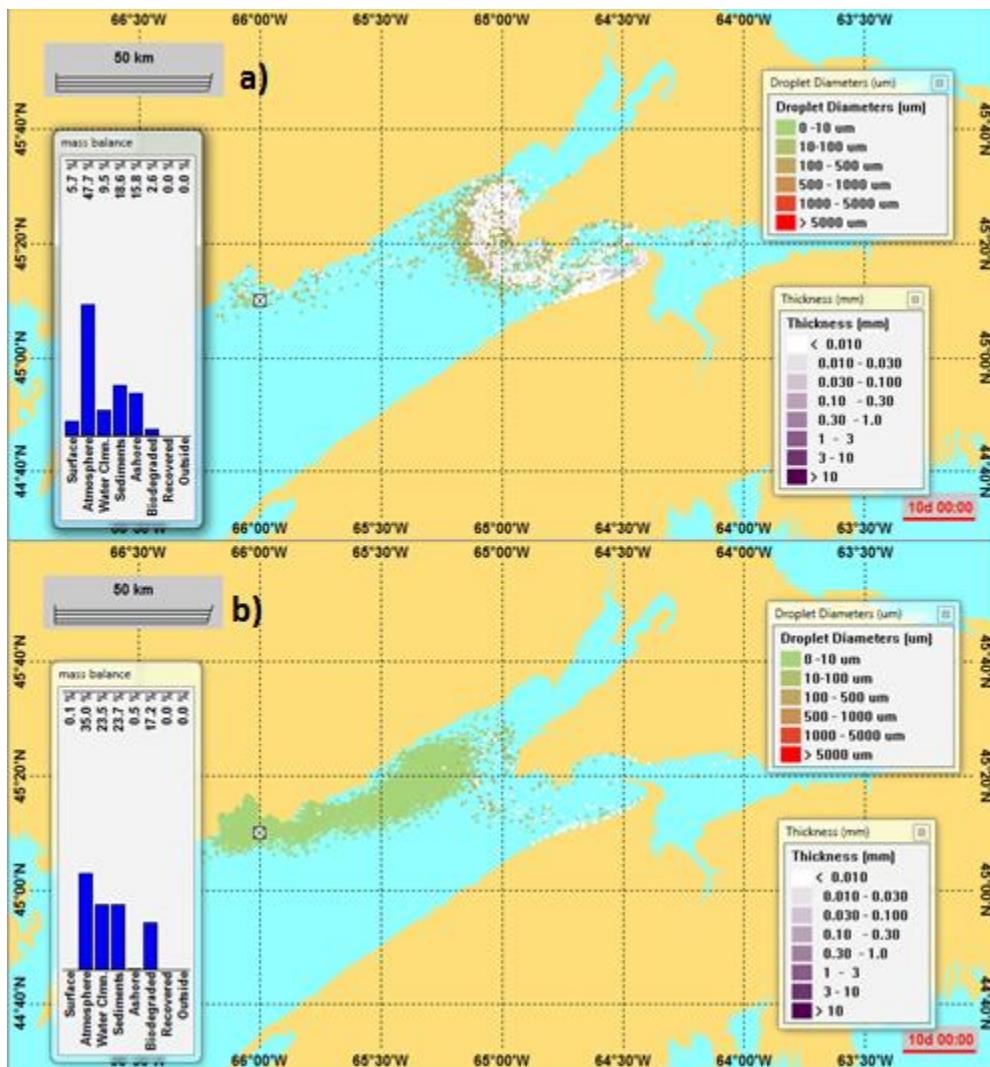
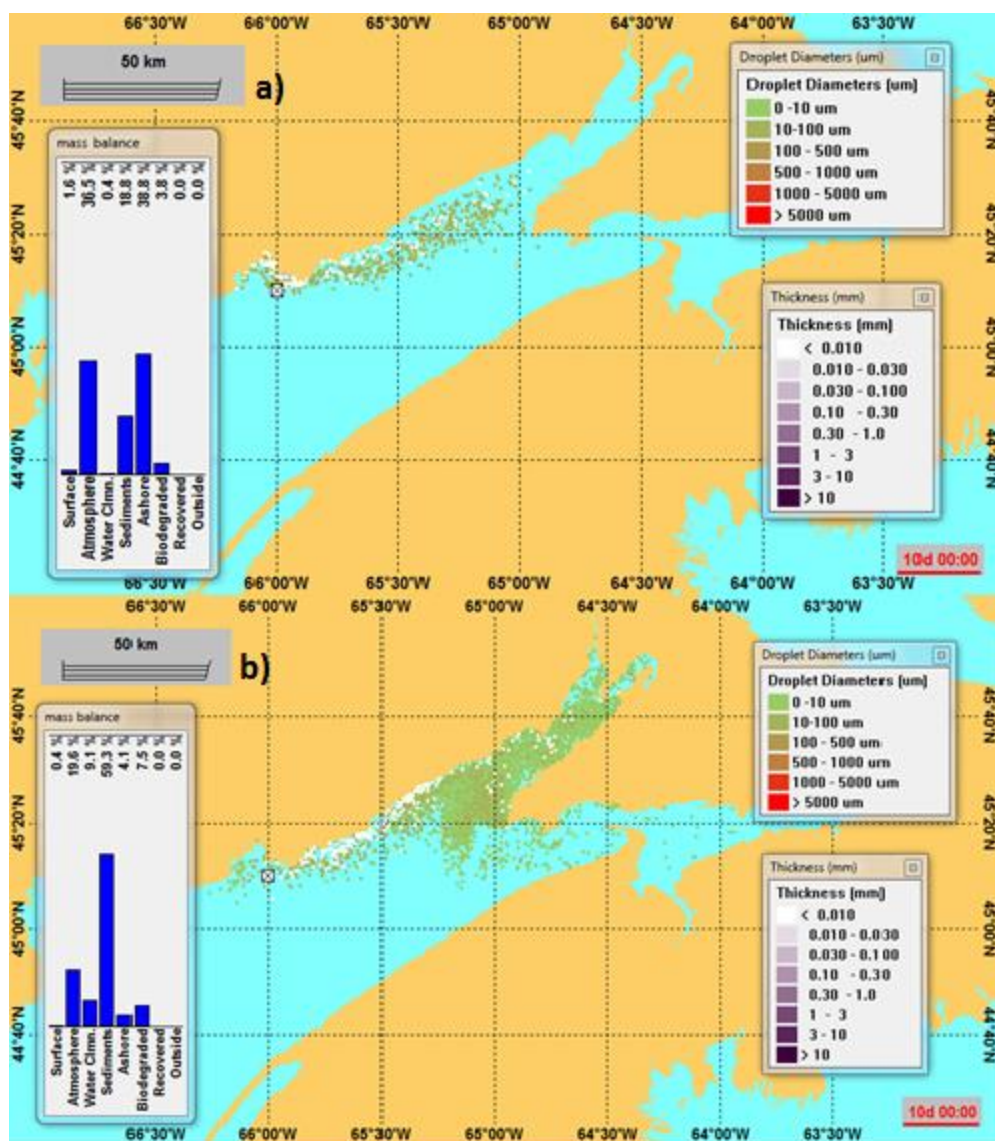


Figure 46. Extent of oil coverage for (a) summer without dispersant, and (b) summer with dispersant in a single stochastic run



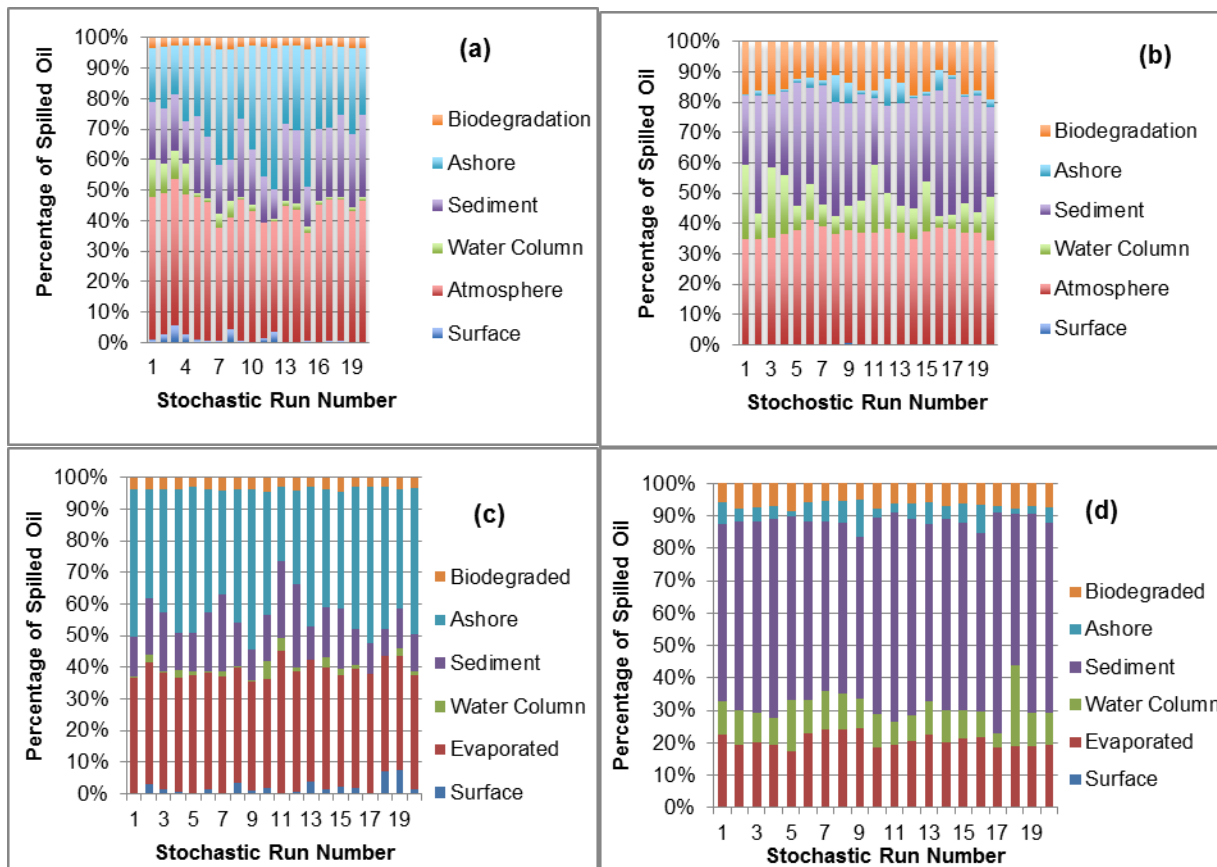
**Figure 47. Extent of oil coverage for (a) winter without dispersant, and (b) winter with dispersant in a single stochastic run**

Mass balances for the 20 runs at the end of each 10-day simulation period showed a higher percentage of oil reaching the shoreline and very little remaining in the water column for the case without dispersant application (Figure 48a, c). With dispersant application, the percentage of oil stranded onshore was reduced in all 20 runs, while the amount in the water column and sediment increased in most cases (Figure 48b, d).

On average, 25.9% and 35.6% of the total spilled ALC oil was prevented from reaching shore after 10 days due to dispersant application in winter and summer, respectively (Figure 49). This application also helped enhance biodegradation. The increase in biodegraded oil was on average 11.6% and 3.1% of the total spilled in winter and summer, respectively. This would be beneficial if shoreline protection were of high priority. Compared with the winter scenario, strong shoreline retention occurred in

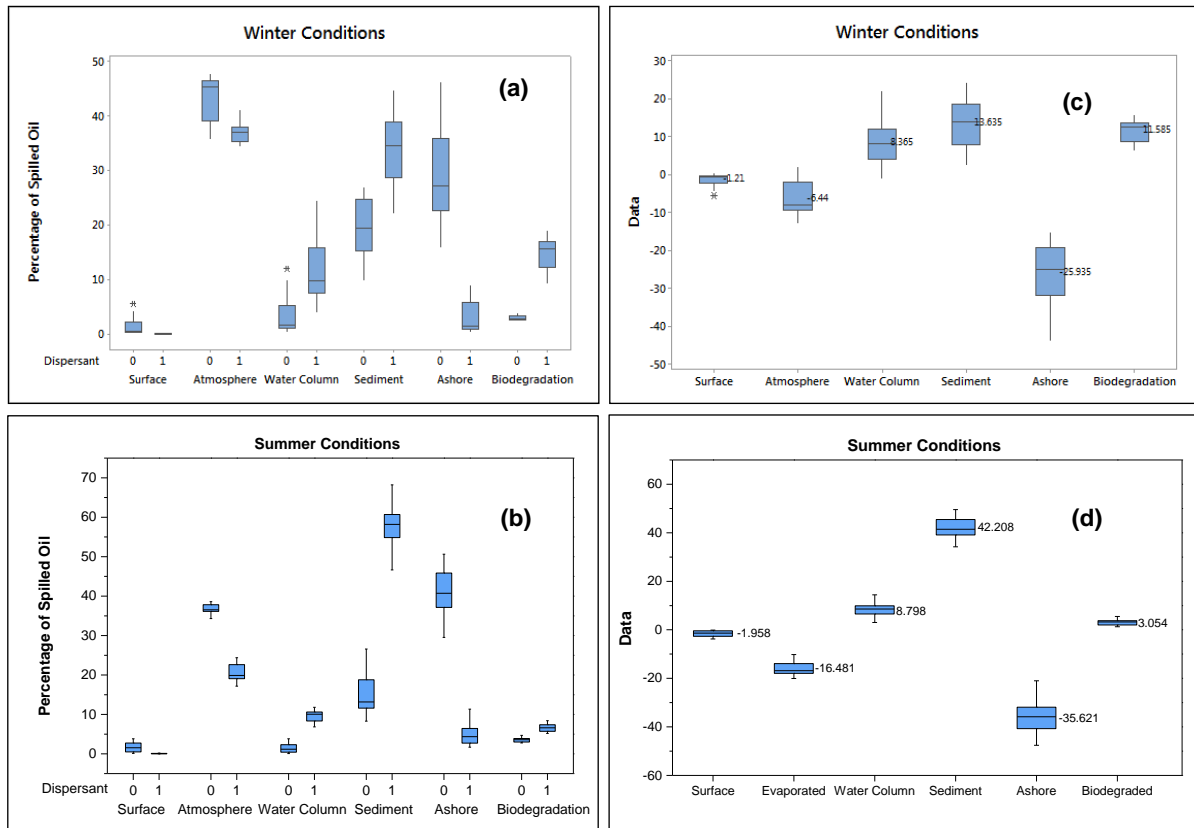


summer, which reduced the amount of oil available for biodegradation. Hence, the biodegradation rate in summer was lower than in winter.



**Figure 48. Mass balance for (a) winter without dispersant, (b) winter with dispersant, (c) summer without dispersant, and (d) summer with dispersant at the end of each 10-day simulation period for the 20 stochastic runs.**

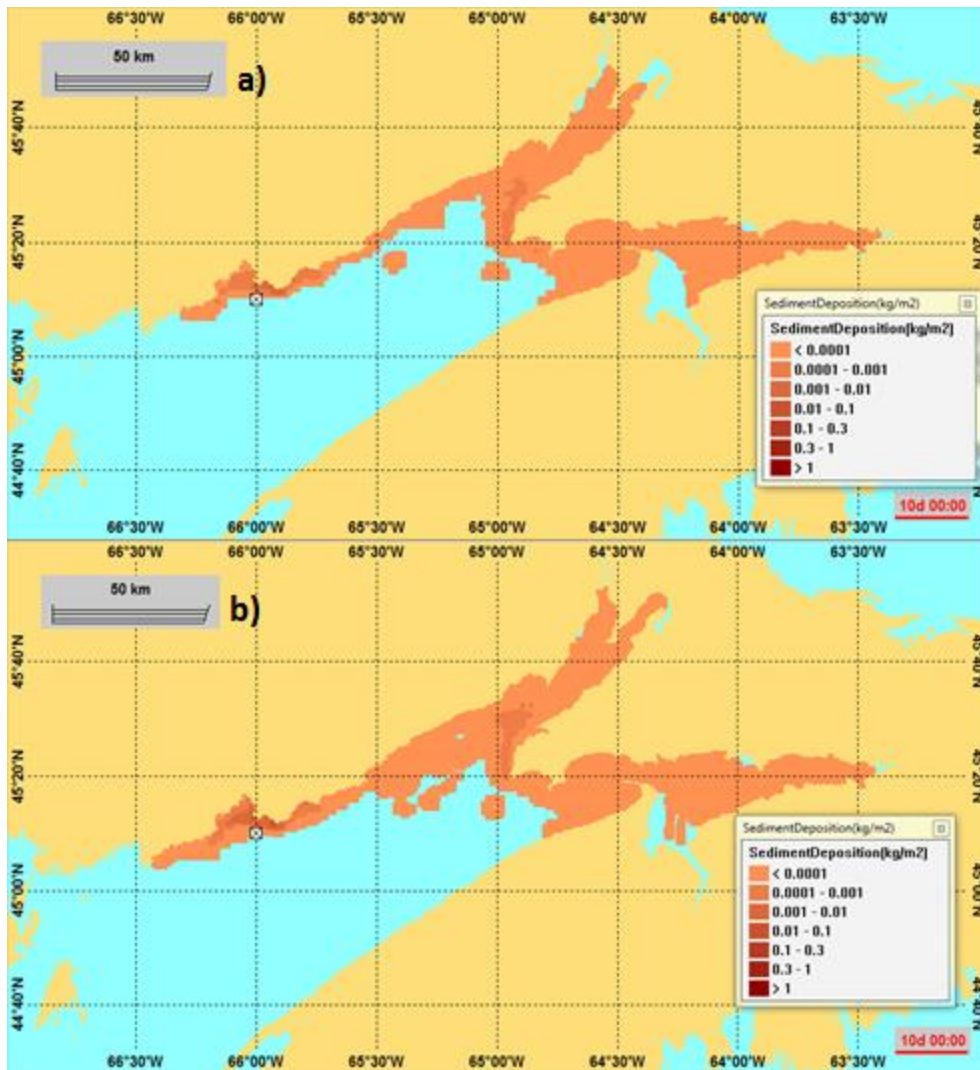
It should be noted that the application of chemical dispersant increased the amount of oil in sediment for all 20 simulations. In winter, the range of increase was from 2.7% (No.20) to 24.3% (No.8), with a mean of 13.6% (Figure 49a, c). Sedimentation was more significant in summer, ranging from 28.1% (No. 8) to 58.6% (No. 18), with a mean of 42.2% (Figure 49b, d).



**Figure 49. Effects of dispersant: (a) mass balance, with = 1, and without = 0, dispersant application in winter, (b) summer, (c) naturally dispersed versus chemically dispersed oil in winter, and (d) summer; a positive value in (c) or (d) indicates that chemically dispersed oil exceeded naturally dispersed oil, and vice versa**

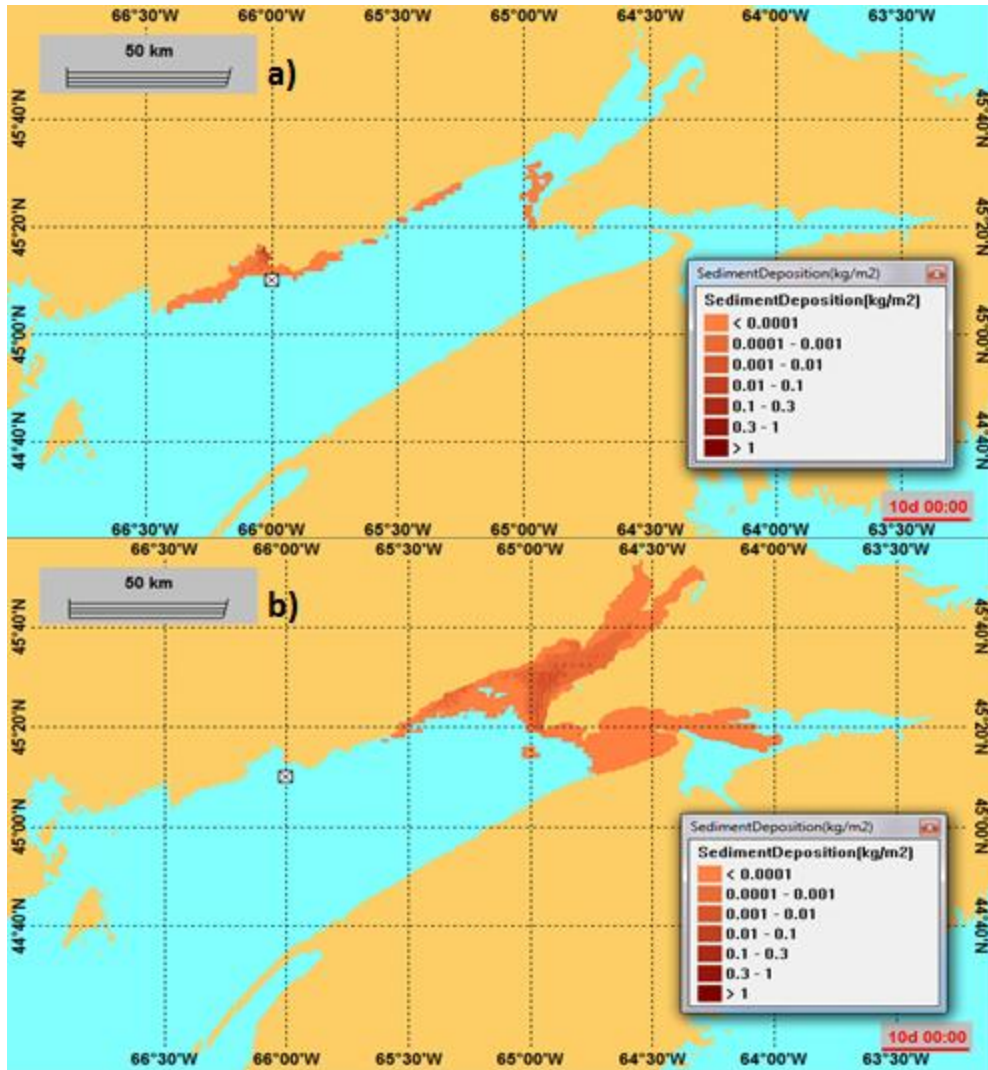
The increased sedimentation due to dispersant application was also reflected in higher sediment oil concentrations in both seasons (Figure 50 & Figure 51), as well as increases in the water column averaging 8.4% (winter) and 8.8% (summer) of the total spilled ALC. The water column increases would be of concern if fisheries are of higher priority than the 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 together to produce a probability of surface and shoreline contamination (Figure 52, Figure 53). The affected area was significantly larger in winter than in summer (Figure 52), which was mainly due to the higher wind speeds in more varied directions (Figure 44), and the Saint John River spring freshet.



**Figure 50. Mass balance of sediment oil concentration for (a) winter without dispersant, and (b) winter with dispersant in a single stochastic run (No.3)**



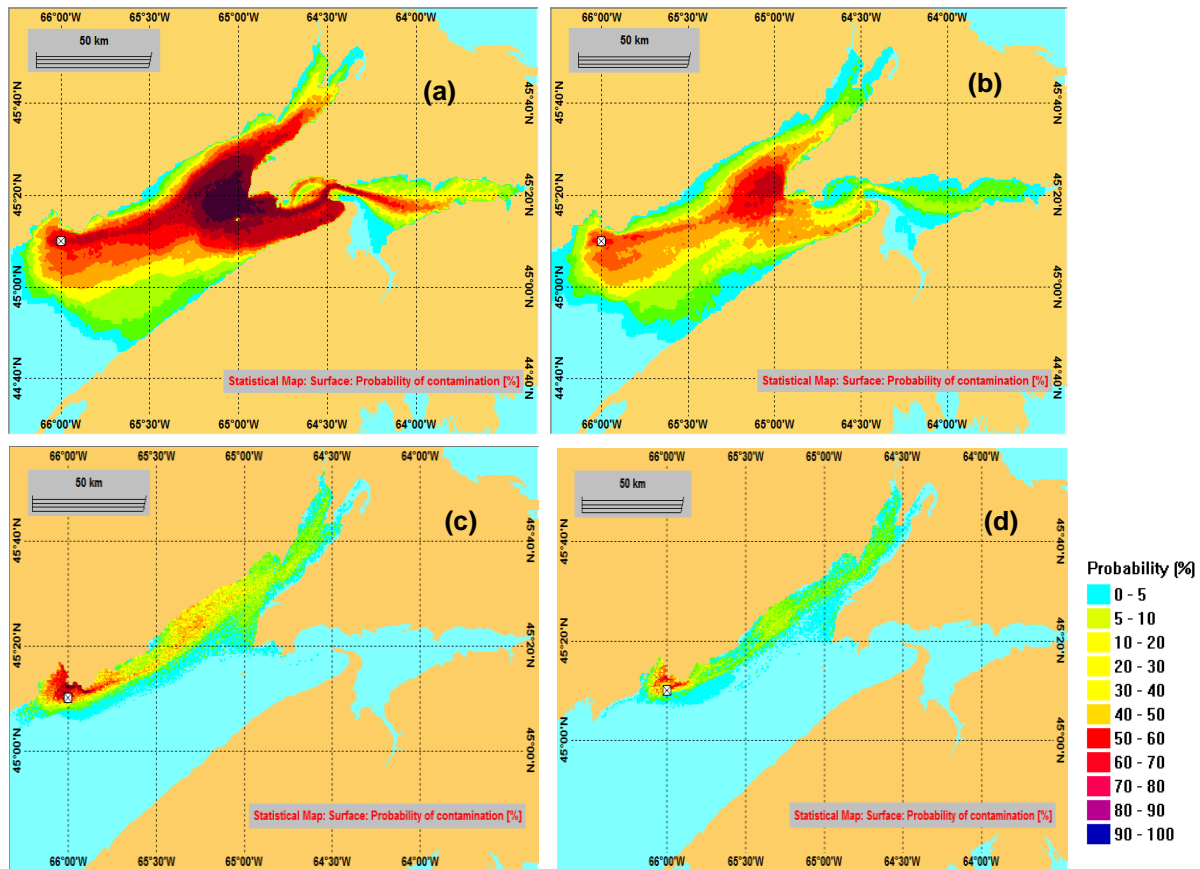


**Figure 51. Mass balance of sediment oil concentration for (a) summer without dispersant, and (b) summer with dispersant in a single stochastic run (No.3)**

The environmental impact factor (EIF) was used to represent the risk to different ecological compartments (water column, surface, and shoreline) and to the total area. The water column was defined as the horizontal cross section of the spill plume. Impacted areas with risk greater than 5% are shown in Table 6. 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 km<sup>2</sup> to 5,980 km<sup>2</sup> in winter. The impacted sea surface area was reduced from 6385 km<sup>2</sup> to 5015 km<sup>2</sup> (Figure 52a, b).

Furthermore, the impacted shoreline was reduced from 173 km<sup>2</sup> to 96 km<sup>2</sup> (Figure 53). The total impacted area in summer was significantly smaller than in winter. However, the total impacted area in summer increased from 2078 km<sup>2</sup> to 2859 km<sup>2</sup> after dispersant application, which was caused by a 121% increase in impacted water column. In contrast, the total impacted sea surface in summer decreased from 1,604

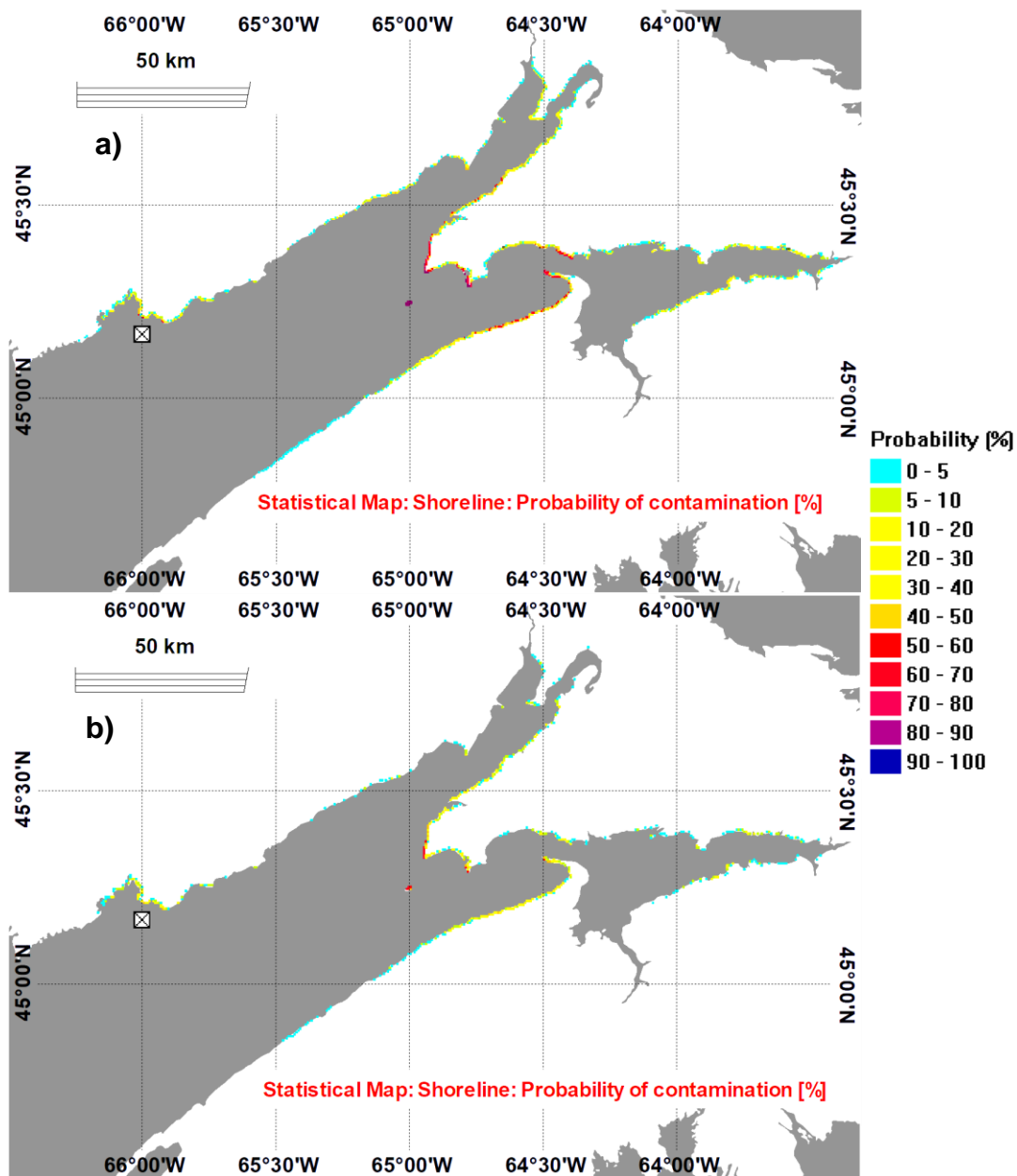
km<sup>2</sup> to 897 km<sup>2</sup> (Figure 52c, d) and impacted shoreline decreased from 61 km<sup>2</sup> to 29 km<sup>2</sup> (Figure 54).



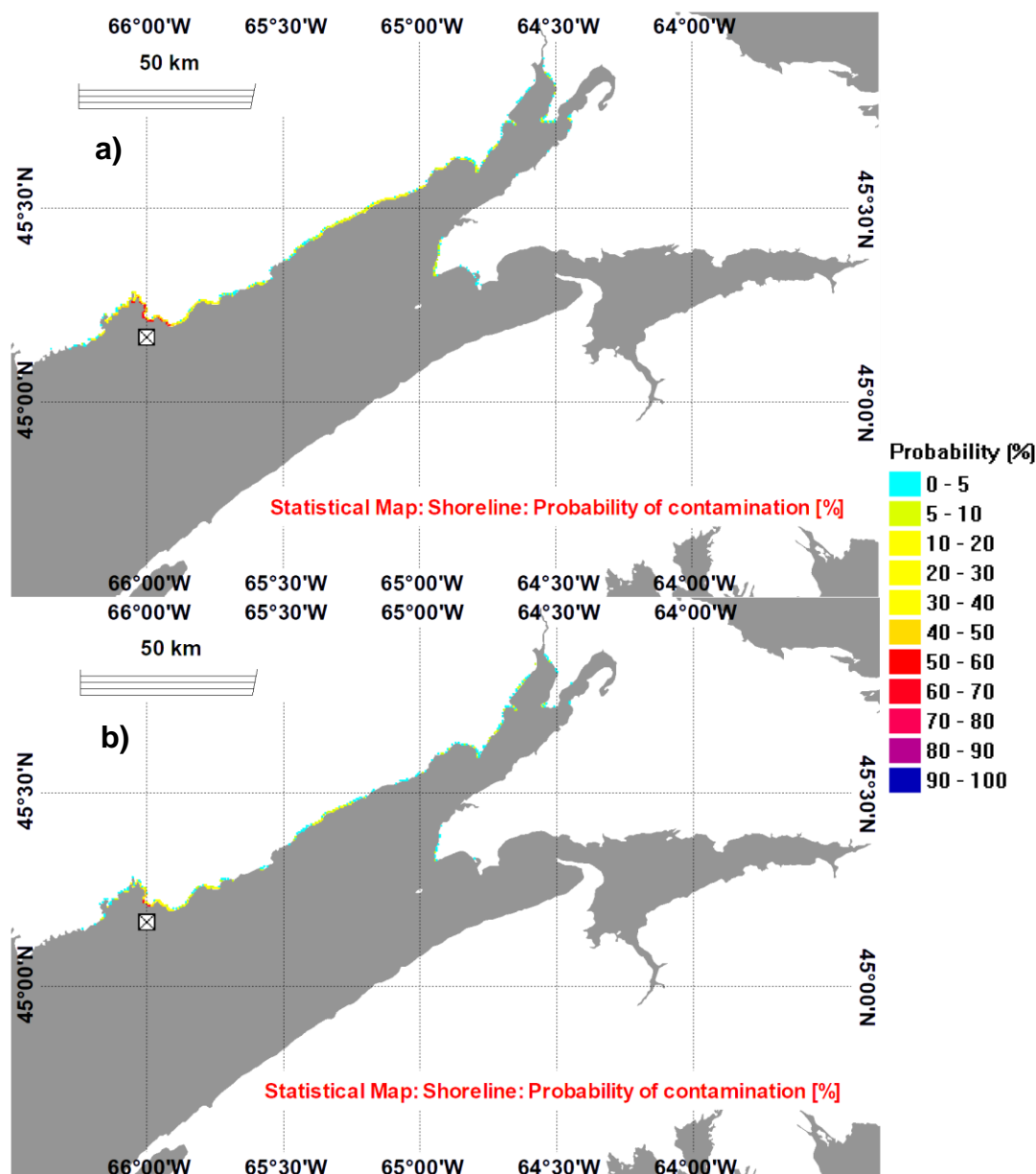
**Figure 52. Probability of surface contamination in (a) winter without dispersant, (b) winter with dispersant, (c) summer without dispersant, and (d) summer with dispersant**

**Table 6. Percent difference (Diff) of surface and shoreline contamination when using chemical dispersant in impacted areas (km<sup>2</sup>) with greater than 5% risk**

IMPACT	WINTER			SUMMER		
	No dispersant	Dispersant	Diff (%)	No dispersant	Dispersant	Diff (%)
Water column	5498	4756	-13	1250	2769	121
Surface	6385	5015	-21	1604	898	-44
Shoreline	173	96	-44	61	29	-52
Total	6996	5980	-15	2078	2859	38



**Figure 53. Probability of shoreline contamination in (a) winter without dispersant, and (b) winter with dispersant**



**Figure 54. Probability of shoreline contamination in (a) summer without dispersant, and (b) summer with dispersant**

Assuming that species of concern in the study area are of equal importance, and the toxicity of oil-dispersant mixtures are about the same or less than that of oil alone (Fuller et al., 2004; Hemmer, Barron, & Greene, 2010), then the results suggest that dispersant application would be beneficial in reducing the overall impacted area in the winter. The application of dispersant in summer would require more caution. If the sea surface and shoreline (e.g., ecological reserves, habitat for species at risk, and human residential areas) are the major areas of concern, then dispersant would be recommended. In contrast, the application of dispersant would not be recommended in summer if the concern is for the water column (i.e. fisheries).

Note 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 differ from the present simulations. A laboratory-derived dispersant effectiveness of 40% 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.

## 7 CONCLUSIONS

The Port of Saint John and surrounding areas experience a mid-temperate climate with warm humid summers but snow and ice in winter. The City of Saint John surrounds the majority of the inner harbour with development up to the shoreline, but relatively undeveloped shorelines are prevalent inland along the Saint John River estuary, the outer harbour, and the greater Bay of Fundy. Hydrography in the system is dominated by the interaction between very high tides from the Bay of Fundy, seasonally variable freshwater outputs from the Saint John River, and the presence of three geological sills within the river estuary, inland of Saint John Harbour.

The Port of Saint John sees approximately 80 cruise ships per year, over 200,000 passengers, and handles over 26 million metric tonnes of cargo annually. Tankers of 200,000 deadweight tonnage and larger carrying foreign oil travel the Bay of Fundy. The port handled approximately 12,382,874 metric tons (MT) of crude oil, 11,770,564 MT of petroleum, 656,556 MT of refined petroleum products, and 239,640 MT of natural gas in 2016, making it the busiest port in Canada with respect to hydrocarbon products. Considering the high volume of oil products being transported through the port, Saint John is considered to have the highest risk of an oil spill of any port in Canada

Modelling scenarios have been presented to predict the behaviour, fate and transport of oil products spilled en route to the Port of Saint John. The ADIOS 2 model was used to assess refined products, and conventional and non-conventional crude oil spills under winter (March) and summer (July) conditions. The results of the model are based on a specific quantity of oil products that could potentially be spilled. After five days, refined products, in particular diesel fuel, would be 80% evaporated under summer conditions, where warm water temperatures contribute to evaporation and low wind speeds reduce dispersion. Gasoline would only persist from 12 to 24 hours. These products were predicted to be completely weathered after 2.5 days under winter conditions, where higher winds play an important role in both evaporation and dispersion in spite of colder temperatures.

Two types of crude oil (Arabian Light and Hibernia Light) were modeled and approximately 1/5 of Arabian Light crude would evaporate and disperse within the first 36 hours, leaving most of the spilled oil to be recovered during the response. Similar results were found for Hibernia Light crude. In winter during the same time frame, the viscosity and the density of both oils increased significantly, reducing the window of opportunity available for some response techniques, such as dispersant application. The longer these oils remain in the environment the more difficult it becomes to manage the spill.

Based on the modelling, a large percentage of spilled IFO 180 or Bunker C would remain in the environment. Weathering processes would have little effect on it. As a result of its environmental persistence, this fuel oil would eventually reach the shoreline where more extensive clean up procedures would be required. The modelled viscosity

and density of Bunker C after 2 days under winter conditions suggest that it would be slightly submerged and non-dispersible, so clean up procedures would be limited.

ADIOS2 simulation results indicate that approximately 1/5 of diluted bitumen is dispersed or evaporated in the first 20 hours under both winter and summer conditions, and spills becomes stable thereafter. In addition, dispersion is only detectable in the simulation of Cold Lake Blend under winter conditions and undetectable for the rest. The viscosity and density of AWB and CLB increase significantly within the first 12 to 15 hours, reducing the window of opportunity available for some response techniques, such as dispersant application, and raising the possibility that these products would be slightly submerged and non-dispersible under winter conditions.

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