# State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 3, Port Hawkesbury-Canso Strait, Nova Scotia

Scott A. Ryan[1], Gary Wohlgeschaffen[1], Nusrat Jahan[1], Haibo Niu[2], Alice C. Ortmann[1], Trevor N. Brown[1], Thomas L. King[1], and Jason Clyburne[3]

[1]Centre for Offshore Oil, Gas and Energy Research, Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, NS B2Y 4A2

[2]Department of Engineering, Dalhousie University, Truro, NS B2N 5E3

[3]Department of Chemistry, Saint Mary's University, Halifax, NS B3H 3C3

2019

**Canadian Manuscript Report of Fisheries and Aquatic Sciences 3176**

Fisheries and Oceans Canada Pêches et Océans Canada

Canada

**Canadian Manuscript Report of Fisheries and Aquatic Sciences**

Manuscript reports contain scientific and technical information that contributes to existing knowledge but which deals with national or regional problems. Distribution is restricted to institutions or individuals located in particular regions of Canada. However, no restriction is placed on subject matter, and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Manuscript reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Manuscript reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-900 in this series were issued as Manuscript Reports (Biological Series) of the Biological Board of Canada, and subsequent to 1937 when the name of the Board was changed by Act of Parliament, as Manuscript Reports (Biological Series) of the Fisheries Research Board of Canada. Numbers 1426 - 1550 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Manuscript Reports. The current series name was changed with report number 1551.

**Rapport manuscrit canadien des sciences halieutiques et aquatiques**

Les rapports manuscrits contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui traitent de problèmes nationaux ou régionaux. La distribution en est limitée aux organismes et aux personnes de régions particulières du Canada. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports manuscrits peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports manuscrits sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques.*

Les rapports manuscrits sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 900 de cette série ont été publiés à titre de Manuscrits (série biologique) de l'Office de biologie du Canada, et après le changement de la désignation de cet organisme par décret du Parlement, en 1937, ont été classés comme Manuscrits (série biologique) de l'Office des recherches sur les pêcheries du Canada. Les numéros 901 à 1425 ont été publiés à titre de Rapports manuscrits de l'Office des recherches sur les pêcheries du Canada. Les numéros 1426 à 1550 sont parus à titre de Rapports manuscrits du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 1551.

Canadian Manuscript Report of
Fisheries and Aquatic Sciences 3176

2019

# State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 3, Port Hawkesbury-Canso Strait, Nova Scotia

by

Scott A. Ryan[1], Gary Wohlgeschaffen[1], Nusrat Jahan[1], Haibo Niu[2], Alice C. Ortmann[1], Trevor N. Brown[1], Thomas L. King[1], and Jason Clyburne[3]

1. Centre for Offshore Oil, Gas and Energy Research, Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, NS B2Y 4A2
2. Department of Engineering, Dalhousie University, Truro, NS B2N 5E3
3. Department of Chemistry, Saint Mary’s University, Halifax, NS B3H 3C3

Cat. No. Fs97-4/3176E-PDF ISBN 978-0-660-30896-8 ISSN 1488-5387

Correct citation for this publication:

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 3, Port Hawkesbury-Canso Strait, Nova Scotia. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: viii + 41 p.

# CONTENTS

## FIGURES

## TABLES

## 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 3, Port Hawkesbury-Canso Strait, Nova Scotia. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: viii + 41 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 third volume of a five volume report and contains information relevant to developing an area response plan for Port Hawkesbury-Canso Strait, NS. 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 3, Port Hawkesbury-Canso Strait, Nova Scotia. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: viii + 41 p.

L'augmentation de la production canadienne de pétrole et du trafic de navires-citernes augmente 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 par les navires. À l'aide des 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 (N.-B.), Port Hawkesbury et le détroit de Canso (N.-É.), la Voie maritime du Saint-Laurent (Qc) et la partie sud de la Colombie-Britannique.

Il s'agit du troisième volume d'un rapport en cinq volumes contenant de l'information pertinente à l'élaboration d'un plan d'intervention régional pour la région de Port Hawkesbury et du détroit de Canso, en Nouvelle-Écosse. 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 et al. 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 area surrounding the Port Hawkesbury and the southern Strait of Canso, Nova Scotia (Figure 1). Port Hawkesbury and Point Tupper to the south (Figure 2) are an industrial and shipping centre for the Strait of Canso (Prouse 1994). In 1993, the refinery at Point Tupper became a terminal for supertankers, with facilities to store, blend, and transfer crude and refined oils to smaller vessels. With depths greater than 60 m, the Strait of Canso can accommodate vessels of up to 500,000 deadweight tonnes (DWT) and provides the deepest harbour on the North American east coast (Gardner Pinfold 2010). In addition to the two public harbours, Port Hawkesbury and Mulgrave, there are also five private terminals (Invest Cape Breton 2018). The whole area is known as the Strait of Canso Superport, and has handled over 30 million tonnes of cargo annually from 2005 to 2010 (Strait of Canso Superport 2018a). Of the 31.6 million metric tonnes of cargo in 2006, 21.6 million tonnes were crude petroleum (Statistics Canada 2011). In 2009, two-thirds of all cargo in Nova Scotia was handled by Port Hawkesbury, although in 2010 tonnage decreased 10.5% to 26.3 million tonnes, largely as a result of a 12.1% decline in the tonnage of crude petroleum (Government of Nova Scotia 2010).

Port Hawkesbury handles both crude oil and refined products (Gardner Pinfold 2010). Increasing amounts of foreign oil are being trans-shipped to the northeastern United States, bringing in crude oil from Europe in tankers of 250,000 DWT (20 shipments from Norway in 1998) and transferring it to smaller tankers in the 80,000 DWT range, because many foreign tankers are too large to be accommodated by the U.S. ports (SL

Ross Environmental Research 1999). This trans-shipment activity has more than doubled since 1994, amounting to about 11 million tonnes in 1998, which is 14% of all oil moved by ocean vessel in Canada, representing a large spill risk (SL Ross Environmental Research 1999).

## 2 GEOGRAPHY

Port Hawkesbury is located near the south western tip of Cape Breton Island, on the north side of the Strait of Canso, in the province of Nova Scotia, Canada. The Port Hawkesbury study area extends northeast along the Cape Breton shore line and southwest along the Eastern Shore of Nova Scotia (Figure 1).

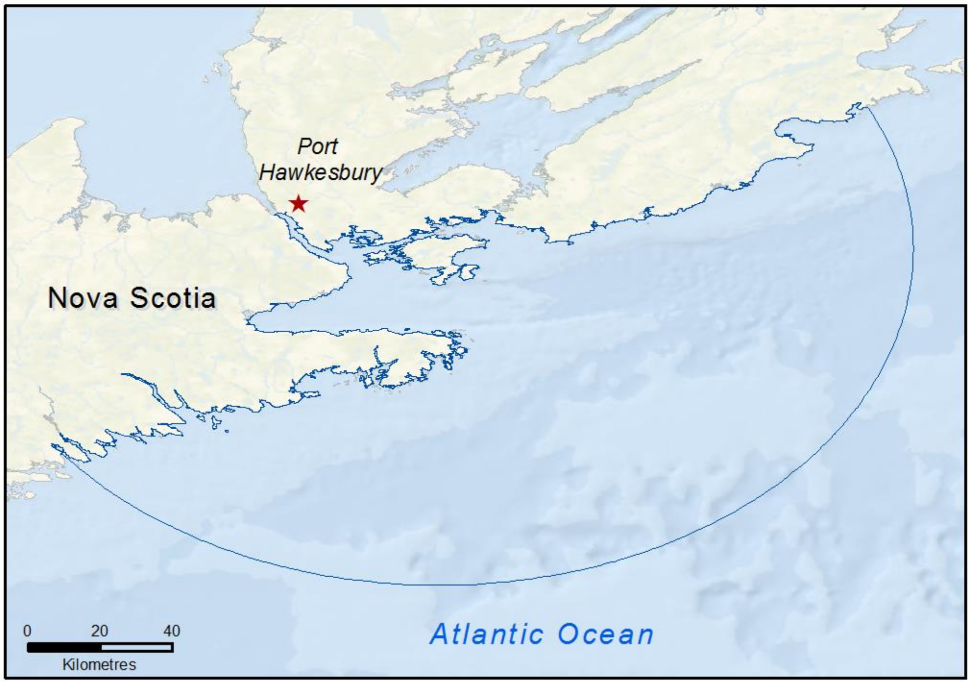


**Figure 1. Port Hawkesbury and the Strait of Canso study area**

The Strait of Canso is about 20 km long, 1 km wide at the narrowest point, and separates mainland Nova Scotia and Cape Breton Island (Figure 2). Formerly, the strait was a major open passage between the Atlantic and St Georges Bay in the Gulf of St Lawrence. It was artificially closed in 1954 at the northern end by the construction of the rock-filled Canso Causeway and locks (Figure 3) which forms a permanent link between Cape Breton and mainland Nova Scotia. The causeway blocks water flow and divides the Strait into two oceanographically distinct bodies to the north and south. The causeway has a single Seaway-max lock that can handle vessels transiting the St. Lawrence Seaway (Strait of Canso Superport 2018b).

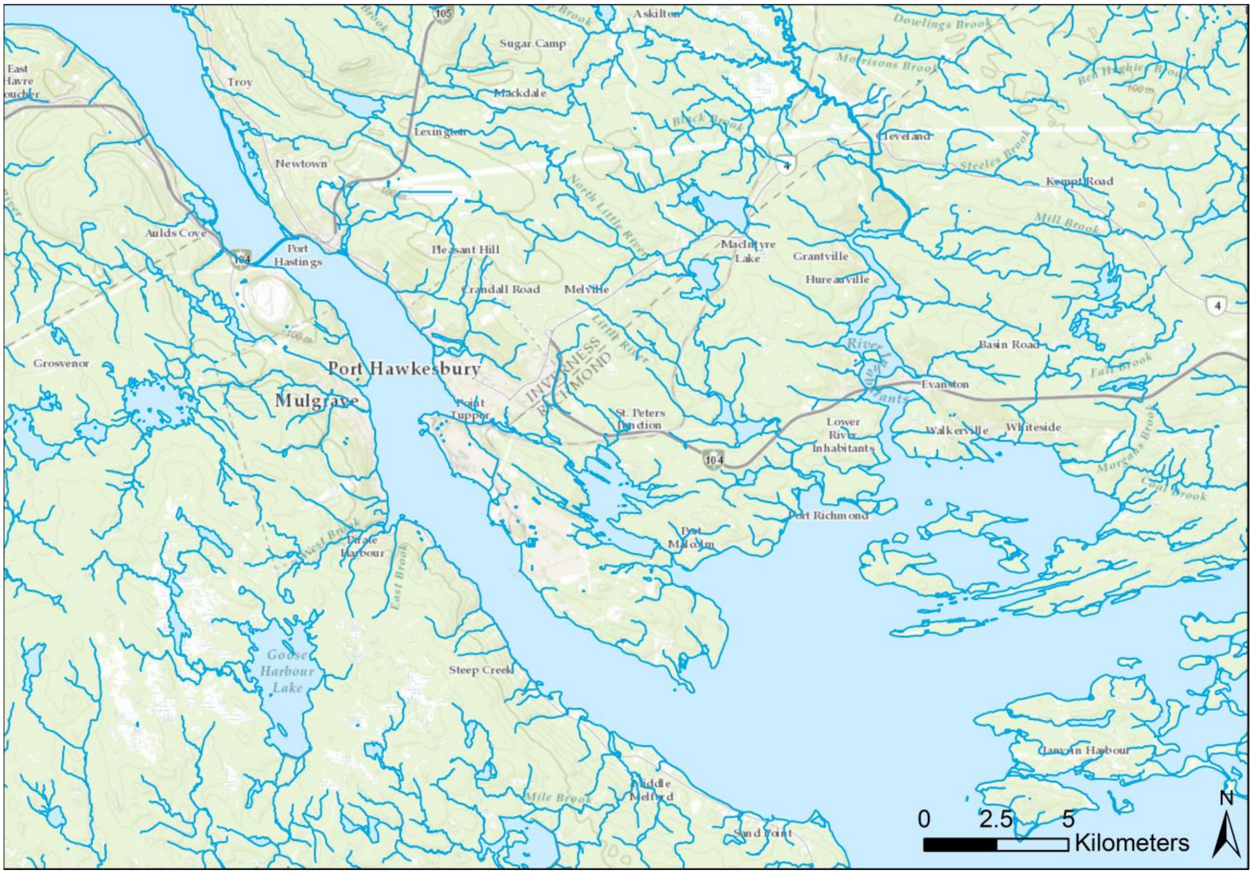


**Figure 2. Map of the Strait of Canso. River data (blue lines) from Nova Scotia Geographic Data Directory (Government of Nova Scotia 2019).**

**Figure 3. Photo of the Canso Causeway**

The southern portion of the Strait connects with Chedabucto Bay through a relatively deep, sheltered, ice-free channel. This location is highly significant to global shipping since it is roughly half the distance from Europe to the Canso Strait in comparison to ports in the Gulf of Mexico.

The Strait of Canso area includes the surrounding communities of Guysborough County, Richmond County, Inverness County, Port Hawkesbury, Port Hastings, and Mulgrave (Pinfold, 2010). The chief towns on the strait are Port Hawkesbury and Mulgrave. Adjacent to the town of Port Hawkesbury is the smaller community of Point Tupper which has an industrial park and is the location of the Bear Head LNG terminal. In addition to the LNG plant, there is a pulp and paper mill, a crude oil trans-shipment centre, oil refinery, Nova Scotia Power coal-fired electric power station with coal terminal, US Gypsum with docks handling outbound crushed rock, and Stora Forest Industries (AMEC Earth and Environmental 2008; JWEL 2004). Over the past 55 years this man-made ice-free harbour has evolved into the fastest growing cargo port in Canada, and the largest in Nova Scotia. It is vital to local businesses that export finished product to domestic and international markets and import raw materials, supplies, and equipment for local manufacturing (Strait of Canso Superport 2018c).

# 3 HYDROGRAPHY

## 3.1 BATHYMETRY

Before the causeway was built, the Atlantic Ocean communicated directly with the Strait of Canso. The tidal interaction in the strait, caused by the slightly higher tidal range of the Atlantic Ocean (Fothergill 1955), created a gentle downward slope of the mean sea-level surface from St. Georges Bay to the Atlantic Ocean and ice from the Gulf of St. Lawrence filled the strait all winter long (Pemberton 1976).

The 18 km long Strait of Canso is narrow (0.8 to 2.0 km) generally has a U-shaped cross section, with a depth in the center of the Strait of 38 to 65 m, and an average depth of approximately 45 m (Parrott et al. 2005). North of the Causeway, the minimum depth in the Strait is 35 metres at the entrance to St. Georges Bay, while depth reaches 51 metres adjacent to the Causeway (Buckley et al. 1974; Stewart and White 2001).

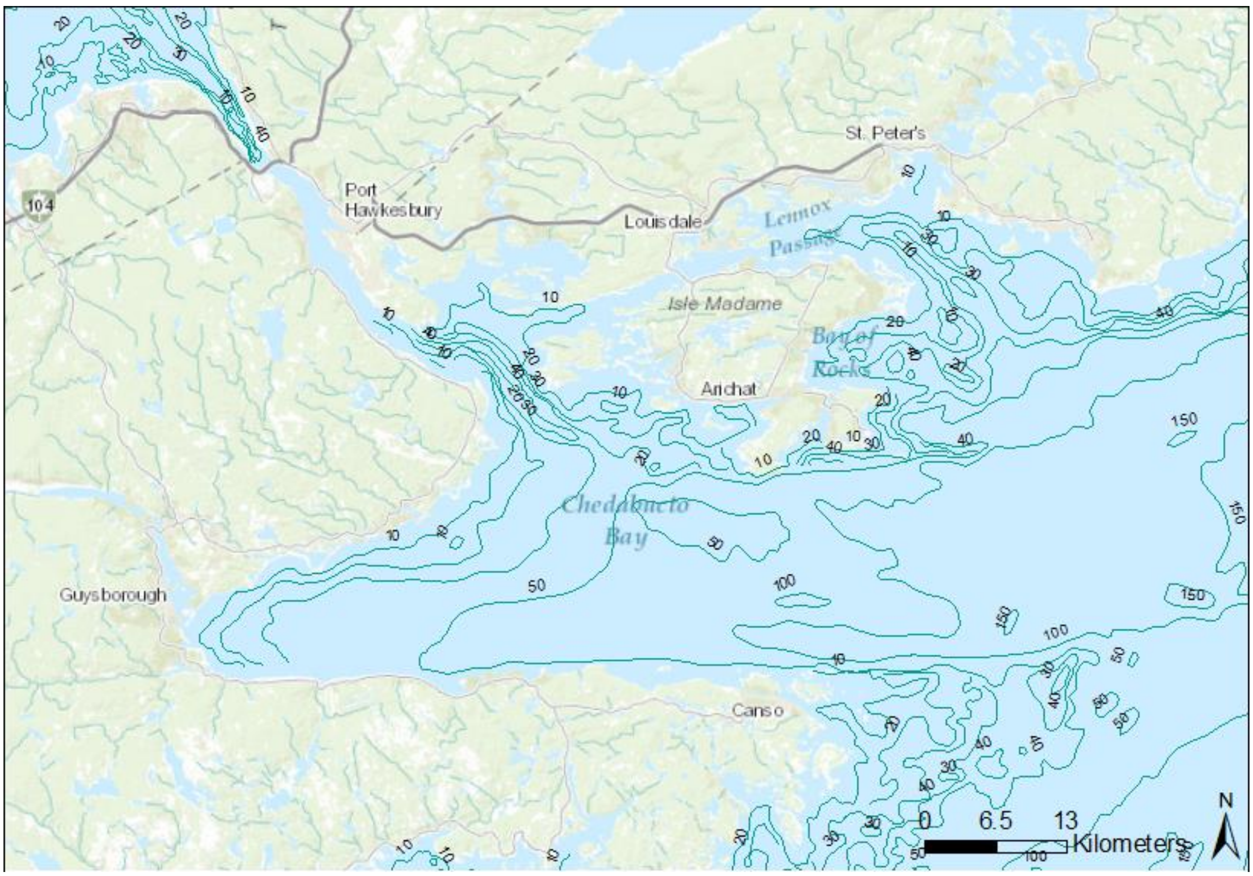


**Figure 4. Bathymetry of the Strait of Canso and Chedabucto Bay, depth values in metres.**

Water depth is about 44 m in the channel near the Melford area, gradually decreasing southward, and ending at a 35 m deep sill in Chedabucto Bay; however, the sill is below the depth of the summer thermocline, so currents in the Strait are expected to be directly affected by coastal upwelling, downwelling and internal waves from the shelf (AMEC Earth and Environmental 2008).

## 3.2 CURRENTS

Water currents in the Strait of Canso are largely influenced by its length, narrow width, U-shaped cross section, relatively deep bathymetry, and dominant westerly and northwesterly winds (Buckley et al. 1974; Lawrence et al. 1973). Construction of the Canso Causeway has resulted in the southern end of the strait, as far as Melford and Bear Head, assuming the characteristics of a tidal inlet with little exchange of water between the northern and southern portions of the strait. A relatively weak 1.85 km/h bottom current exists within the strait (Buckley et al. 1974), but wind-generated currents can be significant year round since there is no ice cover (JWEL 2004; Lawrence et al. 1973; Pemberton 1976). The causeway acts as a barrier to the flow of ice allowing the southern portion of the strait and Chedabucto Bay to remain ice-free year round (Buckley et al. 1974; McCracken 1979; Messieh and El-Sabh 1988; Stewart and White 2001).

Lawrence et al. (1973) found that currents approximately half way between the causeway and Melford had a magnitude of about 0.02 m/s. Maximum tidal currents in the vicinity of Sand Point as modelled with DFO's Web Tide (Dupond et al. 2002) are predicted to be of the order of 0.10 m/s.

In contrast, surface currents of 2.5-3% of the wind speed (0.5 m/s for a 40 knot wind) measured 10 m above the water surface can occur (Canada-Nova Scotia Strait of Canso Environment Committee 1975; CBCL 2015). The tide accounts for only 10 to 20% (maximum = 0.2 m/s) of the total current, and the rest is from winds and coastal circulation (Buckley et al. 1974; MacLaren Marex Inc. 1978).

Local data has been collected by DFO in the 1970's and early 1980's at sites including in Chedabucto Bay, in the strait entrance between Bear Head and Melford Point, and up the strait past Wright Point. Directional statistics for a site in the strait entrance showed that current direction is generally aligned with the Strait, and peak values of 0.3 to 0.6 m/s occur at 8 m depth, with typical values from 0.1 to 0.2 m/s decreasing with depth. Near surface currents of 0.2 m/s drop to less than 0.1 m/s below mid depth. A weak estuarine circulation pattern at about 0.01 to 0.08 m/s has also been suggested, with flow at the surface and bottom moving seaward, and flow at mid-depth moving toward the causeway (CBCL 2015; Lawrence et al. 1973; Parrott et al. 2005).

Current data for the Melford area from the Bedford Institute of Oceanography (BIO) Ocean Data Inventory (ODI) database (Bedford Institute of Oceanography 2007) showed low mean values, confirming previous observations for the strait (Table 1). Mean values of recorded current speeds across all seasons were fairly constant (0.01-0.11 m/s), and currents in the upper water column tended to be slightly faster.

**Table 1. ODI current speeds near Melford (AMEC Earth and Environmental 2008)**

| Season | Depth | Mean current speed range (m/s) | Max current speed range (m/s) |
|---|---|---|---|
| Fall | Upper water column (7-8m) | 0.01-0.07 | 0.18-0.50 |
| | Lower water column (23m) | 0.01-0.05 | 0.22-0.29 |
| Winter | Upper water column (8m) | 0.01-0.11 | 0.13-0.55 |
| | Lower water column (23m) | 0.01-0.05 | 0.09-0.34 |
| Summer | Upper water column (8m) | 0.02-0.08 | 0.14-0.58 |
| | Lower water column (11-12m) | 0.01-0.04 | 0.15-0.31 |

Oceanographic conditions at the Bear Head LNG site are influenced by weak 0.04 m/s tidal currents, reduced offshore swell and short-fetch local waves (CBCL 2015; JWEL 2004). Lawrence et al. (1973) reported a mean tidal current of about 0.02 m/s halfway between the causeway and Bear Head, with flow occurring in a surface and bottom layer advecting water toward the sea, while a mid-depth layer moved landward. Currents at this site are usually 0.15 m/s, but can reach 0.35 m/s on occasion (Lawrence et al. 1973).

## 3.3 TIDES

Tides in the Strait of Canso are semi-diurnal (two highs and two lows daily). Tides as reported by the Canadian Hydrographic Services (2007) tables (CHS), for Station 0576 to the northwest at Point Tupper and Station 0563 southeast at Sand Point, are summarized in Table 2. The most thorough analysis of currents in the strait was conducted by Lawrence et al (Lawrence et al. 1973), whose reported mean tidal range of 1.4 m matches CHS data.

**Table 2. Summary of tidal range from CHS tide tables**

| Station | Mean Water Level (m) | Range (m) | |
|---|---|---|---|
| | | Mean Tide | Large Tide |
| 0576 Point Tupper | 0.9 | 1.4 | 2.0 |
| 0563 Sand Point | 0.9 | 1.4 | 2.0 |

Mean spring tides rise 2.4 m and mean neaps tides rise 2 m (Pub 145 2014).

Prior to a tidal survey of Port Hawkesbury from April to May 2004 (Parrott 2010), tides were predicted, using the Tides and Currents Pro by Nautical Software Inc., and high tide ranged from about 1.5 to 2 m. Values from the survey tide gauge (Figure 5) ranged from 0 to 2 m. According to the Canada-Nova Scotia Strait of Canso Environment Committee (1975), the range in the region was 0.7 m above the mean water level, and 0.6 m below it.

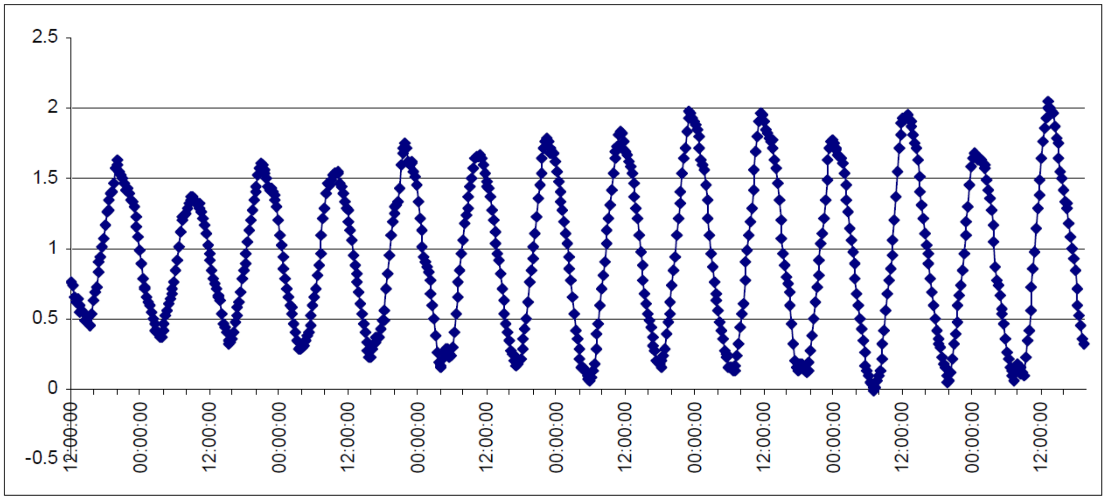


**Figure 5. Measured tides in Port Hawkesbury, 30 April - 7 May 2004, time in GMT, height in meters (Parrott 2010)**

### 3.4 WATERSHED

The Inhabitants River and Little River (Figure 2) flow into Inhabitants Bay. The watersheds in the Strait of Canso region are small (Canada-Nova Scotia Strait of Canso Environment Committee 1975), and there are no major rivers along the strait. Freshwater sources along the strait include brooks and runoff; however, the combined outflows of industries in the area divert significant quantities of freshwater to the Strait which likely causes a slight decrease in the salinity of the surface layer (Buckley et al. 1974). Freshwater discharge into Canso Strait peaks at 9-13 $m^3/s$ in March-May and November-December (Figure 6), and falls to a minimum of 2-4 m3/s in June-Sept (Gregory et al. 1993).

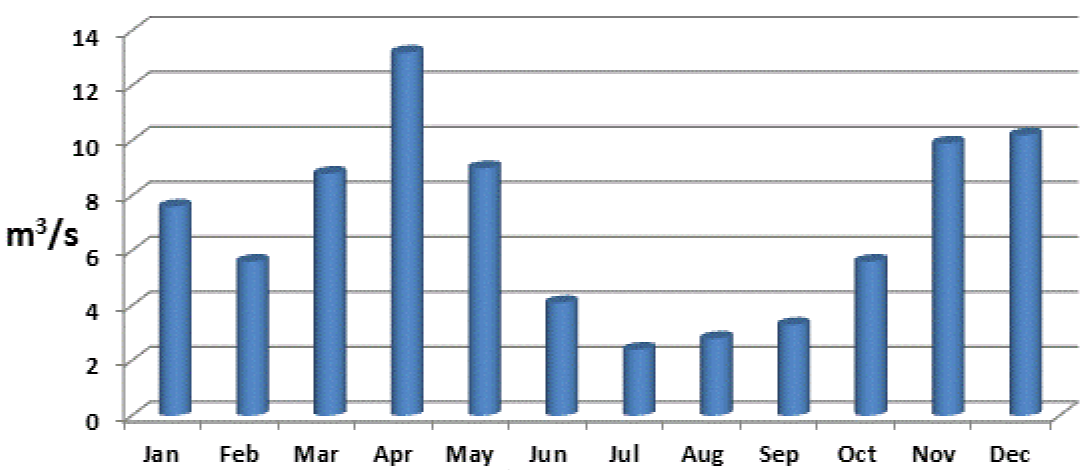


**Figure 6. Freshwater discharge ($m^3/s$) in the Strait of Canso (Gregory et al. 1993)**

## 3.5 SALINITY AND WATER TEMPERATURE

Similar to surrounding waters of the Atlantic Ocean, the southern side of the Strait of Canso is typically highly stratified in summer with a layer of relatively warm, low salinity water overlaying colder more saline water (Buckley et al. 1974; Vilks et al. 1975). The upper 20 m of the water column is generally greater than 15˚C, with a salinity of less than 29‰ (Stewart and White 2001) while depths below 35 m have temperatures of 3 to 7˚C and a salinity of 31‰. Deep waters in the strait can be affected by coastal upwelling, downwelling and shelf-generated internal waves (JWEL 2004; SNC-Lavalin 2015). An assessment of this area suggested high variability in water properties throughout the year as a result of meteorological circulation in waters stratified by local warming and freshwater input (Cranston et al. 1974; Lawrence 1972; Vilks et al. 1975).

Strong wind-generated currents near Chedabucto Bay can cause significant upwelling of cold (~3˚C) salt water creating estuarine-like circulation, flushing out the warm, fresh surface water at the Canso Causeway and replenishing the bottom water (Buckley et al. 1974; JWEL 2004; Stewart and White 2001) The passage of weather systems can result in rapid flushing of the surface layers as it does elsewhere along the Atlantic coast (Heath 1973; Platt et al. 1972).

Vilks et al. (1975) investigated the seasonal variation in temperature and salinity at ten localities in the Strait of Canso and Inhabitants Bay from the beginning of May to the middle of August, 1973. In early May, the water column is mixed with salinity 27-31‰ and temperature is close to the freezing point throughout the water column (Figure 8a). In early June, a pycnocline forms in the upper 10 m during spring warming and freshwater runoff. By summertime, surface waters trapped by the pycnocline warm up to about 20°C and salinities range from 28 to 32‰ while deeper water remains close to 2°C (Figure 8b).

On the Gulf of St Lawrence side of the Canso Causeway, the waters are less stratified, and water temperatures are higher in summer (Stewart and White 2001).

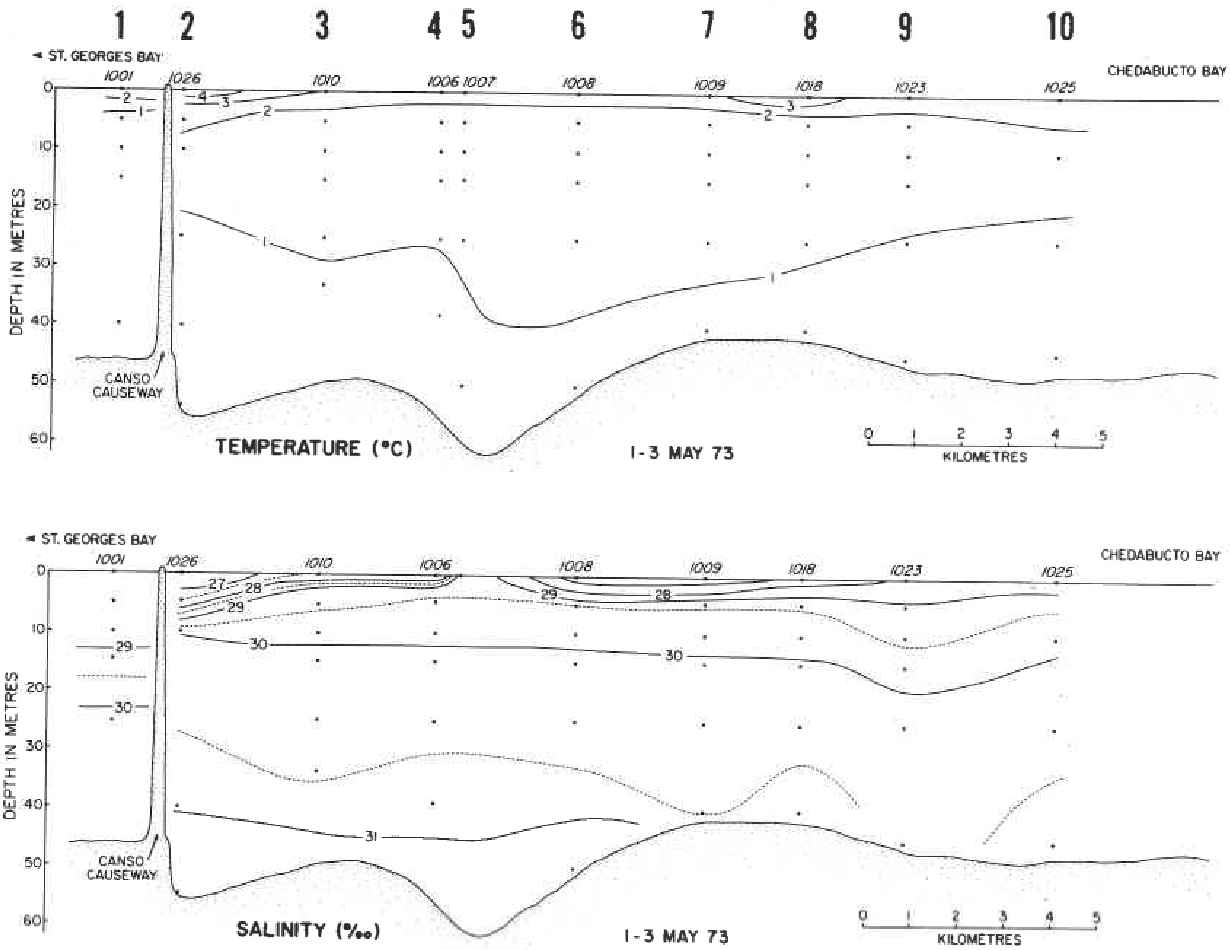


**Figure 7. Temperature and salinity along the Strait of Canso from May 1-3, 1973 (Vilks et al. 1975).**

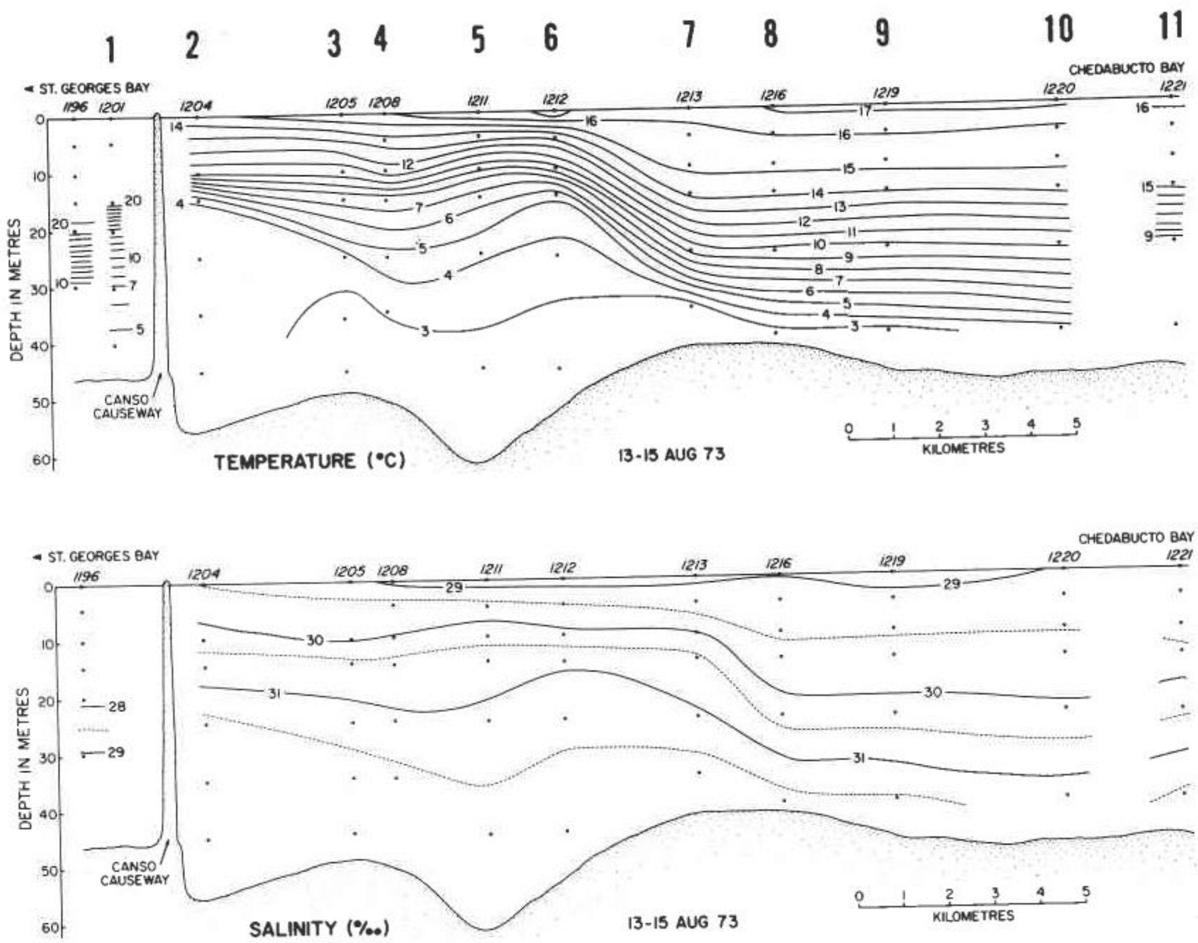


**Figure 8. Temperature and salinity along the Strait of Canso from August 13-15, 1973 (Vilks et al. 1975).**

# 4 CLIMATE

## 4.1 TEMPERATURE AND PRECIPITATION

The climate at Port Hawkesbury and the Canso Strait are much the same, situated in the northern temperate zone and having a humid, continental climate, with warm summers and no dry season. Based on records from 2010 to 2013, temperature averages -5.7°C in February and 18°C in August and is rarely below -13°C or above 27°C.

Precipitation in this region averages 1417 mm per year, with the minimum average of 91 mm occurring in July and the maximum average of 163 mm in December (Climate-Data.org 2018). Precipitation is highest from December to February as light snow, heavy snow and light rain. Precipitation in the summer falls as light rain.

The presence of the causeway prevents ice floes from reaching the southern stretch of the Strait of Canso which, generally speaking, means that Port Hawkesbury remains ice-free throughout the year. Exceptions to this statement include calm weather in the winter of 1957 resulting in a 15 cm thick sheet of ice cover across the strait, and the relatively rare occasion where drifting offshore ice makes its way to the southern entrance to the Strait of Canso (Canada-Nova Scotia Strait of Canso Environment Committee 1975).

## 4.2 WIND AND WAVES

Average monthly wind speed at Port Hawkesbury ranges from 1 to 10 m/s, with a maximum of 6 m/s in December and an average daily maximum of 9 m/s at this time of year. A 3 m/s minimum average occurs in August, when the average daily maximum is 6 m/s (WeatherSpark.com 2016).

Prevailing winds near Port Hawkesbury tend to be from the west through northwest in winter, while winds prevail from the northwest, southwest, and to a lesser extent, the southeast during the summer months (WeatherSpark.com 2016). Due to the funneling action of the Strait of Canso, the most probable wind direction throughout the year is from the southwest, leading to particularly high winds when the dominant direction is northwesterly and southeasterly. Generally speaking, the strongest winds in this area tend to come from the northwest and can at times exceed 10.7 m/s, but southerly ~14 m/s winds were also recorded in this area during a study by the NSCC Applied Geomatics Group in September of 2014 (Canada-Nova Scotia Strait of Canso Environment Committee 1975; Pub 145 2014; Webster et al. 2014). The Canadian National Building Code lists extreme hourly wind speed at Port Hawkesbury as 35.2 m/s with a 30-second gust speed of 46.6 m/s on a 100-year return period; and approximately 30 m/s (gust speed of 39.3 m/s) on a 10-year return period (CBCL 2015). At the Statia Terminals, located about 3.5 km north of Bear Head, a maximum wind speed of 25 m/s was observed on one occasion between December 2005 to March 2016 (CBCL 2015).

The strongest winds in the area around Port Hawkesbury and the Canso Strait occur near Eddy Point at the southern entrance of the Strait of Canso. In this area west and northwesterly winds were strongest, up to ~28 m/s from November through February, becoming south and southwesterly rarely exceeding 15 m/s from June through August (AMEC Earth and Environmental 2008; JWEL 2004).

The entrance to the Strait of Canso and Chedabucto Bay is relatively protected, but storm waves from the Atlantic can enter the strait. Attenuation and refraction of offshore swells moving into the Strait of Canso are expected to result in loss of energy and therefore reduced sea state (AMEC Earth and Environmental 2008). Between May 31, 1972 and February 15, 1973, significant wave height reached 1.5-1.8 m (5-6 s periods), while maximum wave height was about 2.4 m (Canada-Nova Scotia Strait of Canso Environment Committee 1975). The maximum significant wave height west of the proposed Bear Head terminal in Point Tupper is 1.8 m which is considered to be insignificant for large ocean going vessels (Strait of Canso Natural Environment Inventory, 1975). These findings were supported by a wave modelling effort which estimated significant wave heights lower than 1 m (CBCL 2015). Estimated significant wave heights for Chedabucto Bay were determined by Neu (1972) to be as high as 6 m (Table 3).

**Table 3. Estimated wave height exceedance in central Chedabucto Bay (Canada-Nova Scotia Strait of Canso Environment Committee 1975)**

| Significant wave height (m) as mean of highest 33% | Maximum wave height (m) | Number of 6-hour periods per year |
|---|---|---|
| 3 | 5.5 | 48 |
| 4 | 7 | 16.5 |
| 5 | 9 | 5.5 |
| 6 | 11 | 1 |

Internal waves, possibly from storm activity, have also been detected in the strait but are relatively weak with a maximum velocity of 0.08 m/s and a period of three to four days (Buckley et al. 1974; Lawrence et al. 1973; MacLaren Marex Inc. 1978).

Wave direction was calculated using MSC50, a hindcast of hourly data provided by Meteorological Services Canada using data from 1954-2005, including iced-over periods (Swail et al. 2006). The predominant wave direction was from the southeast 32% of the time, which is also where the highest waves originate from offshore (AMEC Earth and Environmental 2008). Corresponding to wind patterns, waves tend to be higher in winter than during the summer.

Offshore from the Strait of Canso, waves are most likely to originate from the south and southwest, with large amplitude waves likely to come from the east, south or west. From

October to March, waves tend to come from the west, southwest and south while the remainder of the year is dominated by waves from the south which are generally less than 3 m in height (JWEL 2004).

## 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 Port Hawkesbury were compiled by filtering for occurrences in the province of Nova Scotia or international waters, within the latitudinal range of 45°N to 46°N, and within the longitudinal range of 59.7°W to 61.9°W. The area of the Bras d’Or Lake, roughly north of 45.65°N and between 60.4°W and 61.2°W was excluded. This corresponds to the Strait of Canso, Chedabucto Bay, and the surrounding waters up the coast of Cape Breton Island and down the coast of the Nova Scotia mainland. It also includes St. George’s Bay to the west, which would not be affected by a spill in Port Hawkesbury because of the Canso Causeway, but does see shipping traffic transiting the Canso Canal. See Table 4 for statistics.

**Table 4. Transportation Safety Board incident and accident occurrences in the Port Hawkesbury shipping lane**

| Occurrences involving… | All years (1975-2018) | Annual Average (2015-2017) |
|---|---|---|
| All occurrences | 141 | 16.3 |
| Petroleum cargo vessels | 2 | 0 |
| Pollution or cargo lost overboard | 5 | 0 |
| Petroleum spills onboard or overboard | 0 | 0 |
| Vessels sunk, capsized or destroyed | 7 | 0 |

There are very few marine occurrences for the Port Hawkesbury area between 1975 and 2018. All of the occurrences involving pollution or vessels lost were fishing vessels, with four occurrences included in both categories. One of the occurrences involving cargo vessels carrying petroleum products was serious, in which the tanker Thalassa

Desgagnes collided with the side of the approach to the Canso Canal and the hull was damaged, but no release of petroleum product was reported. News reports of this occurrence could not be located.

Despite the fact that relatively few accidents have occurred in the area in recent years, the Canso Strait is home to one of the largest oil spills in Canadian history, the *Arrow* spill in 1970 (~10,000 metric tonnes or ~12 million litres) (Office of the Auditor General of Canada 2010).

## 5.1 ARROW SPILL

The *Arrow* was one of the oldest tankers in the fleet of Aristotle Onassis, and was chartered to Imperial Oil Limited when it came from Aruba on 4 February 1970 carrying 10 million litres of bunker C oil bound for a paper company near Point Tupper (Maritime Museum of the Atlantic 2018). Gale force winds in Chedabucto Bay (Figure 2) forced her aground on Cerberus Rock, a well-known, submerged hazard. A slick formed the following day. On the 8th the ship split in two, with the stern sinking in deeper water (Crowley 1970).

About 2000 $m^3$ of Bunker C was spilled. Corexit chemical dispersant was applied at first, but this countermeasure was disbanded as fear of its potential toxicity arose (Crowley 1970). Booming and skimming were ineffective due to inclement weather and the prevailing winds forced surface slicks to cover 300 km of shoreline. Some of the oil that was left in the tanker was transferred to the *Irving Whale* barge. The least invasive machinery was used on shorelines, such as rakes, peat moss, and shovels, without dispersant application (Owens 1972). Despite the efforts, less than 50 km were cleaned up (Lee et al. 2003), and oil persisted for several years on the shores of Chedabucto Bay (Keizer et al. 1978).

Thirty years after the spill, sediments and interstitial waters were collected from a sheltered lagoon in Black Duck Cove that had been heavily oiled and left to recover naturally. Chemical analysis of the sediments confirmed that the remaining oil had undergone significant weathering including photo-oxidation, abrasion by ice scour, dissolution, dispersion with mineral fines, evaporation of volatile components, and biodegradation (Lee et al. 2003). In the fall of 2015, 33,000 litres of oil and oily water were suctioned from the *Arrow* wreck by divers contracted by Canadian Coast Guard (CBC News 2015).

# 6 MODELLING

Predictive models of spill scenarios have been developed to illustrate the expected transport and behaviour of the oils most common to Port Hawkesbury. Port Hawkesbury is second in Canada only to Vancouver, British Columbia, in annual tonnage, due to large volumes of crushed rock and gravel shipments and oil trans-shipments. The Port handled 21.6 million tonnes of oil, including about 94% crude oil and 6% refined products (Canadian Coast Guard, 1999; Statistics Canada, 2006); therefore, modelling focused on: 1) refined products (diesel fuel oil); 2) crude oil (Arabian Light); 3) intermediate fuel oil (IFO180); and 4) the non-conventional oil products, Cold Lake Blend (CLB) and Access Western Blend (AWB) diluted bitumens that are most likely to be spilled in quantities requiring spill response. In order to demonstrate the transport and risk caused by spills in this area, a case of oil transport simulation for IFO 180 was also conducted based on the oil spill contingency and response (OSCAR) model. It is recognized that other oils such as lube oil and hydraulic oil can also be spilled, but in quantities that would be minimal and therefore not require any specific response other than monitoring.

## 6.1 OIL BEHAVIOUR

The potential behaviour of different spills in Port Hawkesbury 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 (http://response.restoration.noaa.gov/adios). The ADIOS2 database includes estimates of the physical properties of oils and products compiled from different sources, including industry, Environment 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 et al. 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.

### *6.1.1 <u>Environmental Conditions</u>*

Temperature data for Port Hawkesbury was obtained (Environment Canada 2015), but wind data was missing. Sea surface temperature and current data were also unavailable from Environment Canada; therefore, the corresponding wind (Figure 9) and current data (Figure 10) were generated based on the output from the Finite-Volume Coastal Ocean Model (FVCOM). Sea surface temperature (Figure 11) was obtained from the closest available buoy in Herring Cove (SmartAtlantic 2015).

Accordingly, the environmental parameters for the ADIOS2 were determined (Table 5). Based on the available data, the simulation period was January 1 - 31, 2003.

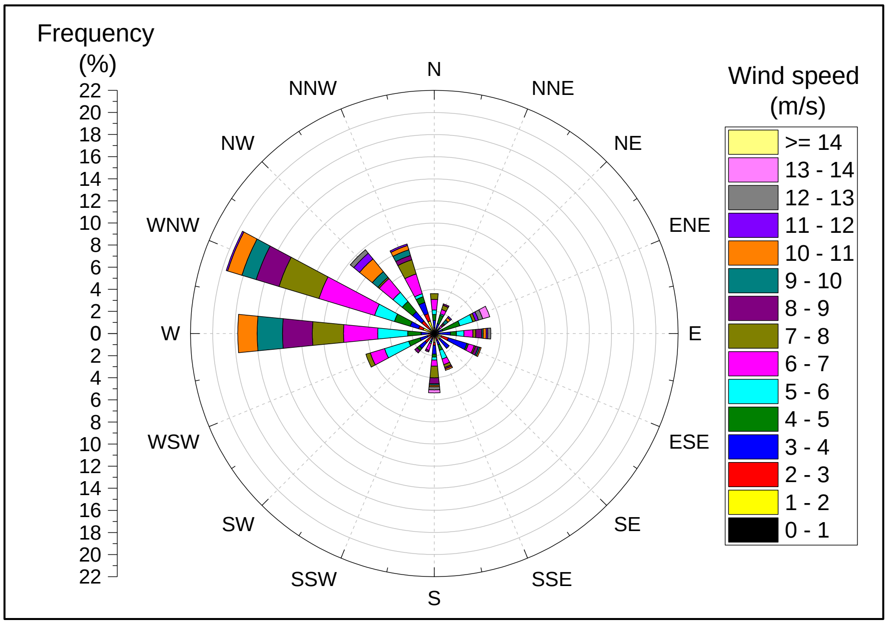


**Figure 9. Wind rose for Port Hawkesbury January 2003**

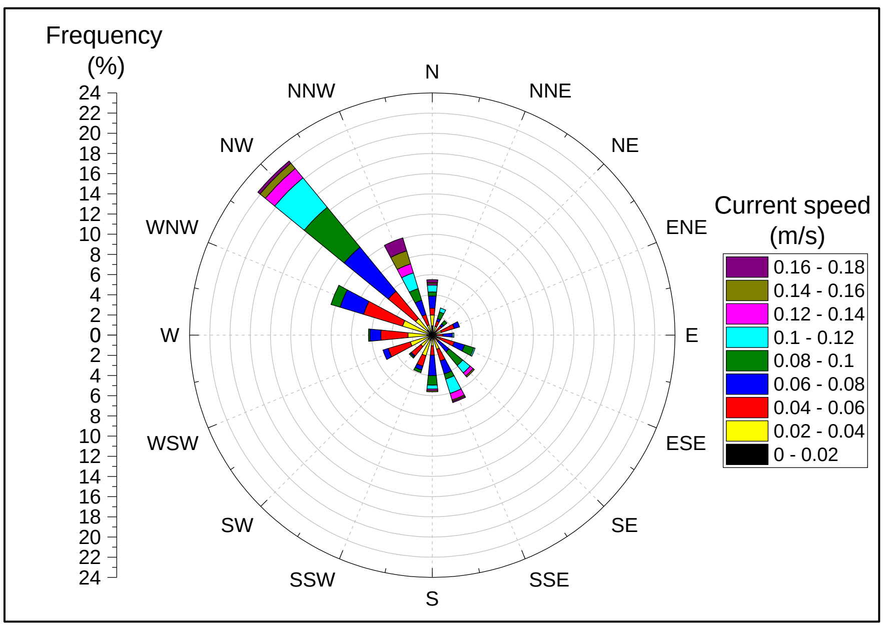


**Figure 10. Current rose for Port Hawkesbury January 2003**

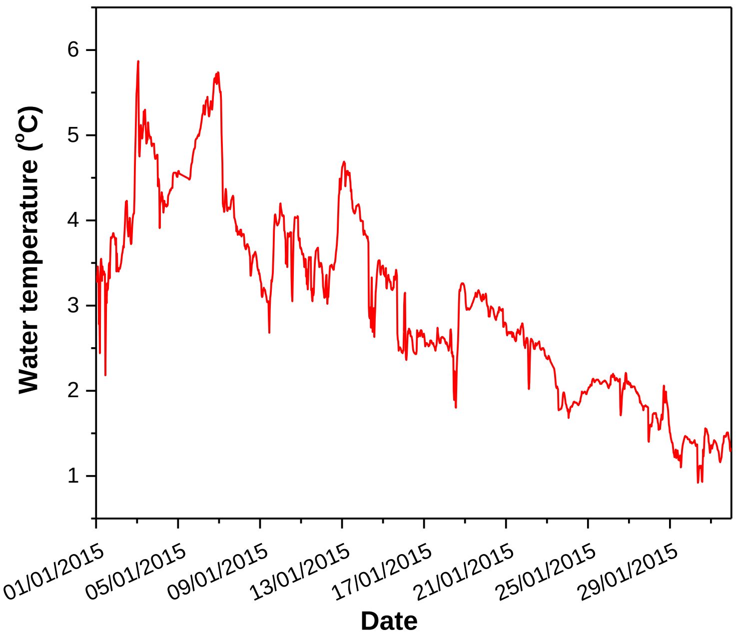


**Figure 11. Sea water temperature**

**Table 5. Environmental inputs for ADIOS2 modelling**

| Parameter | Unit | Model inputs |
|---|---|---|
| Water temperature | °C | 3 |
| Wind speed | m/s | 7 |
| Wind direction | Degree | 290 |
| Current speed | m/s | 0.06 |
| Current direction | Degree | 315 |
| Salinity | ppt | 35 |
| Sediment Load | $g/m^3$ | 5 |

### *6.1.2 Scenarios of Oil Behaviour*

Detailed properties of the oil products are listed (Table 6). To look at potential behaviour of oil from a tanker collision, the model considered a spill of 1,000 $m^3$ over a one-hour period. This quantity is representative of the loss of one tank from a typical tanker currently operating in the Canadian Atlantic.

**Table 6. Properties of oil products used in modelling**

| Oil | API (°) | Pour Point (°C) | Flash Point (°C) | Density at 12°C ($kg/m^3$) | Viscosity at 12°C (cSt) | Aromatics (%) |
|---|---|---|---|---|---|---|
| Diesel | 39.4 | -30 | 40 | 872 | 2.9 | - |
| IFO180 | 14.7 | -10 | 91 | 969 | 2848.3 | 51 |
| Arabian Light Crude | 33.4 | -53 | -20 | 872 | 15.2 | 39 |
| Cold Lake Blend | 21.0 | -25 | -2 | 947 | 361.2 | 29 |
| Access Western Blend | 20.9 | -25 | -5 | 949 | 438.8 | 21 |

### *6.1.3 Scenarios for Spills of Crude Oil*

The behaviour of a spill of ALC was analyzed using ADIOS2. Approximately 25% of the ALC would evaporate and disperse within the first 36 hours leaving most of the spilled oil to be recovered during the response (Figure 12). The dispersion rate is less than 2%. During the same period the viscosity (Figure 13) and the density (Figure 14) of the spill also increase significantly 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 after 15 hours it is possible that this oil would be slightly submerged and non-dispersible, in which case, the only cleanup options might be mechanical skimmers and pumps. Once response equipment arrives on location, it is possible that response efforts could become more 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 very difficult to overcome.

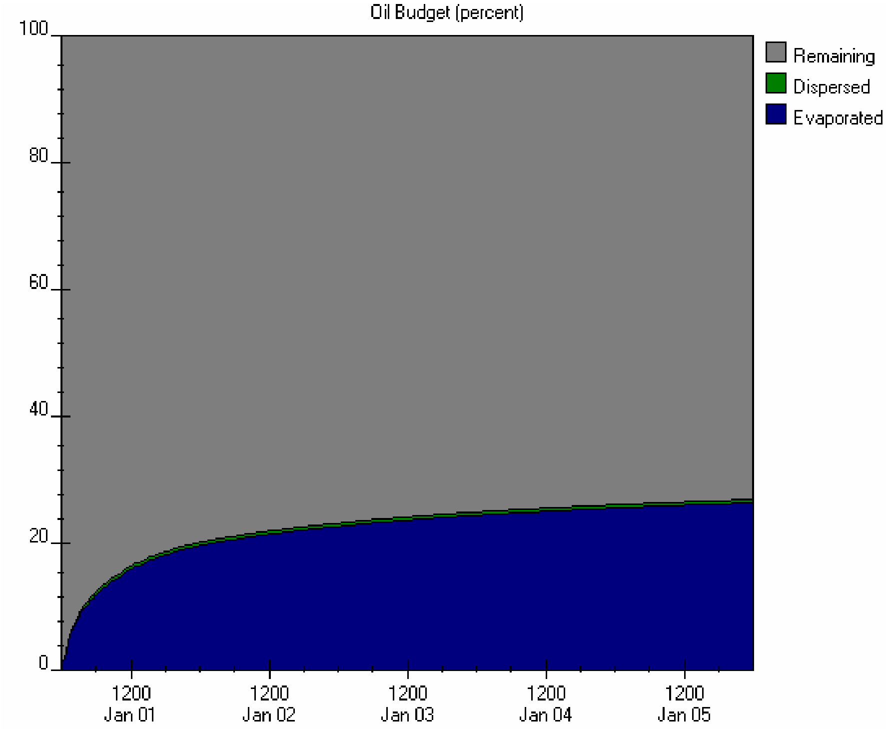


**Figure 12. Oil budget for a spill of ALC**

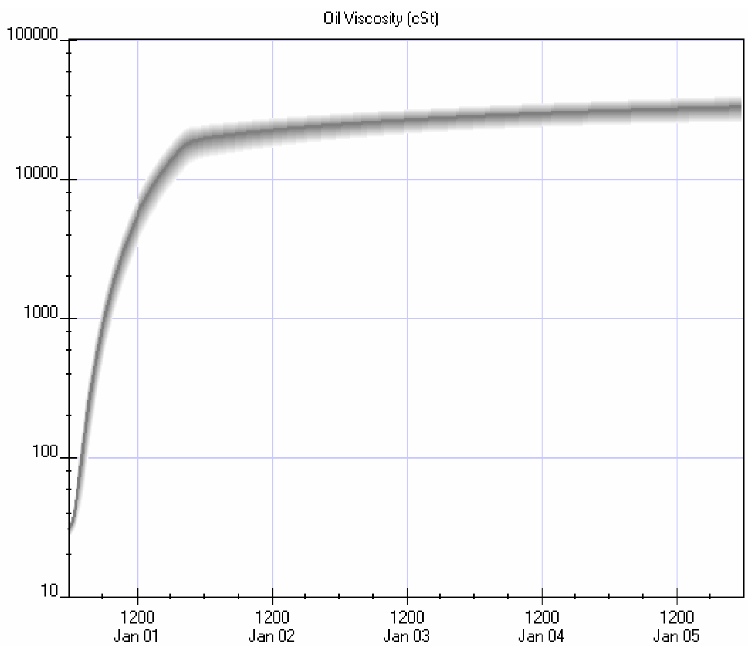


**Figure 13. Predicted change in viscosity for a spill of ALC**

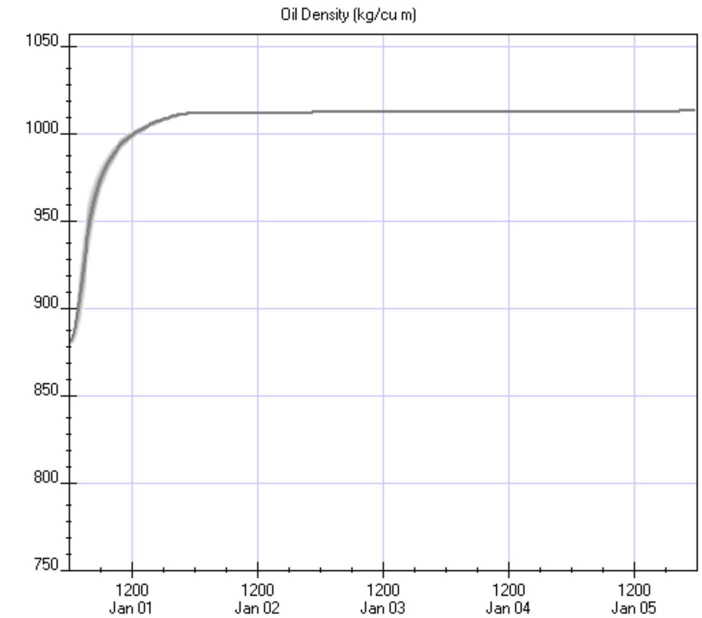

**Figure 14. Predicted change in density for a spill of ALC**

### *6.1.4 Scenarios for Spills of Refined Products*

Diesel fuel oil is a type of light refined product with an API of 39.4°. Offshore spills from this oil are likely to be caused by collision between a tankers or vessels. If this light product were spilled, ADIOS2 modelling predicts that it would be significantly dispersed and evaporated within the first 30 hours after release into the sea (Figure 15). Because of this, spills of light refined products do not represent a significant environmental issue due to their low persistence. It is unlikely that significant recovery efforts would be required other than perhaps using absorbents in the vicinity of specific sensitive environments. Monitoring natural attenuation (natural recovery) would be the response strategy of choice.

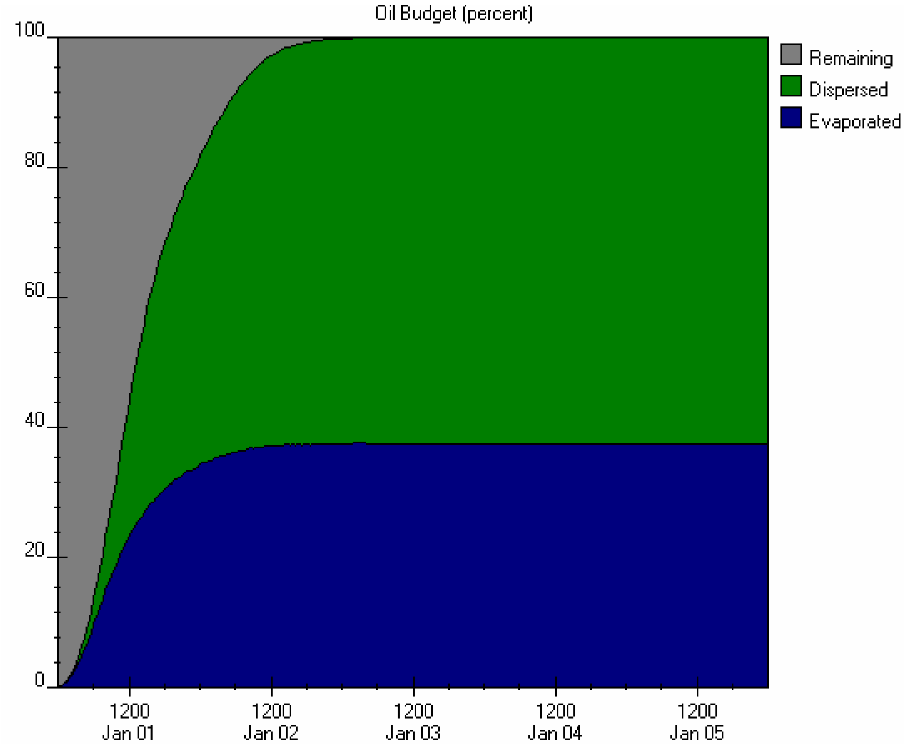

**Figure 15. Oil budget for a spill of diesel**

### *6.1.5 <u>Scenarios for Spills of Intermediate Fuel Oil</u>*

Tankers and cargo ships, among others currently operating in the Atlantic, use IFO180 as their propulsion fuel. IFO180 is a heavier oil with a pour point of -10°C, which suggests it could become semi solid at temperatures commonly observed in winter. IFO could be released into the environment through hull damage in a collision. Based on the ADIOS2 weathering modelling, most of the oil (about 87%) would remain in the environment and weathering processes would have little effect on it (Figure 16). Natural dispersion and evaporation are marginal weathering processes with this type of oil. Recovery of the oil would necessitate using mechanical techniques, as dispersants would not be efficient given the high kinematic viscosity that is well above 10,000 cSt at the time of the spill, and reaching more than 50,000 cSt after 1 day (Figure 17). High viscosity and density (Figure 18) coupled with low temperatures would make any recovery efforts using pumps and skimmers very difficult, due to freeze up of water intakes and flow rate issues with the equipment. Similar to a spill of crude oil, most of the IFO180 would likely drift with sea currents and eventually reach the shoreline where further recovery could be attempted. More details will be discussed in the oil transport section.

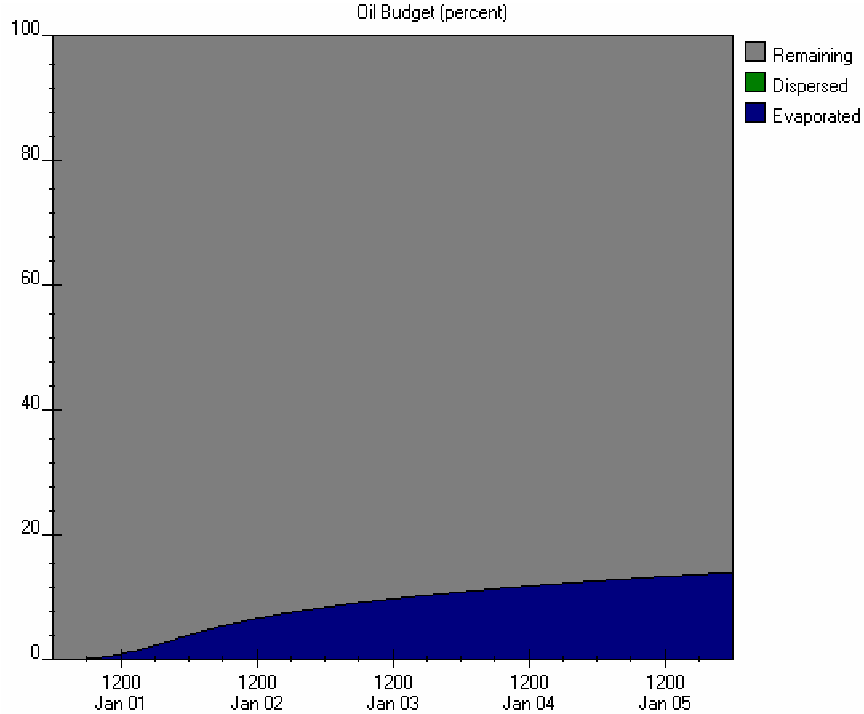


**Figure 16. Oil budget for a spill of IFO180**

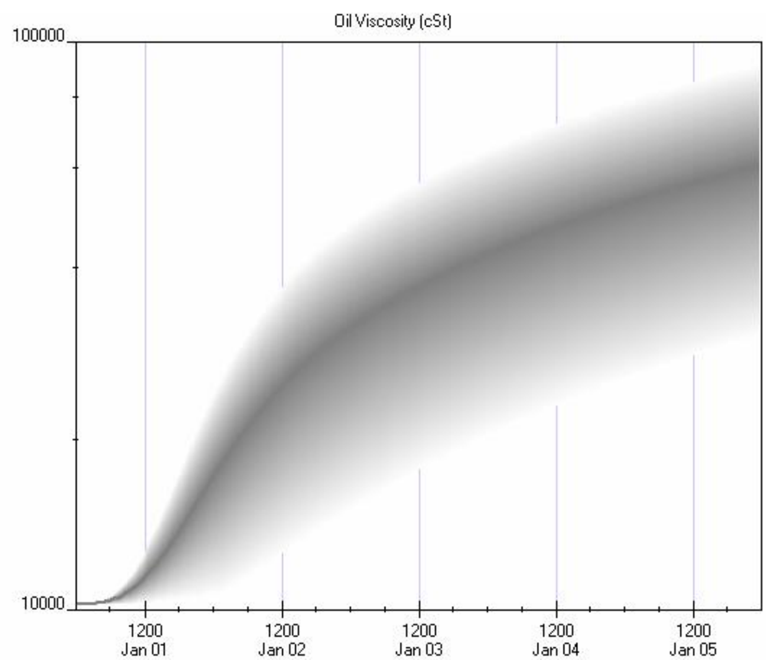


**Figure 17. Predicted change in viscosity for a spill of IFO180**

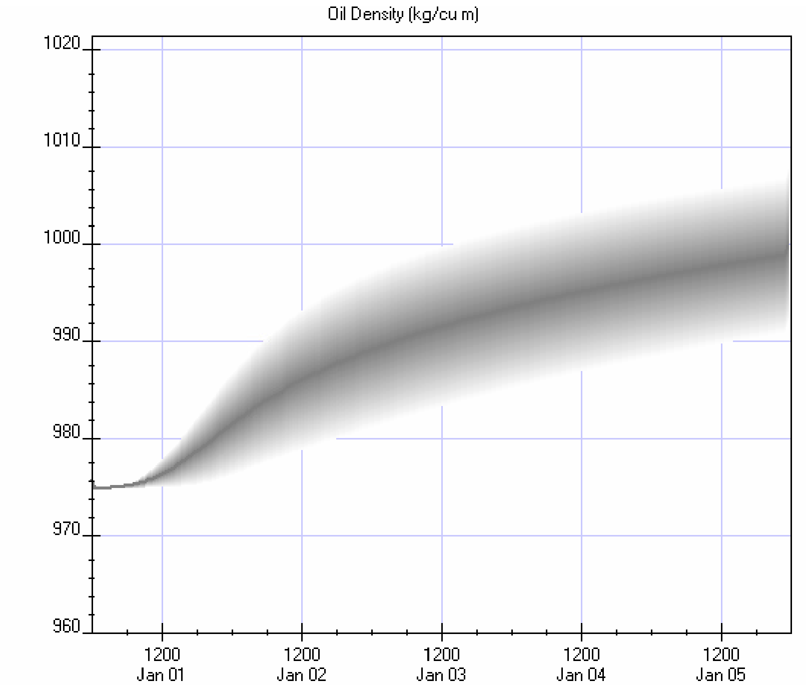

**Figure 18. Predicted change in density of IFO180**

### *6.1.6 Scenarios for Spills of Non-conventional Oils*

The ADIOS2 simulation indicates that the about 20% of both dilbits will disperse or evaporate in the first 15-18 hours, and the spills become stable thereafter (Figure 19). Dispersion is detectable in the simulation of CLB, but undetectable for AWB. During the same period the viscosity (Figure 20) and density (Figure 21) of both increase significantly, reducing the window of opportunity available for certain response techniques like dispersant application. As the kinematic viscosity rises above 10,000 cSt and density exceeds 1.00, there is the possibility that these dilbits would be slightly submerged and non-dispersible. As such, mechanical skimmers and pumps might be available as cleanup options. The key to bitumen cleanup in this area is a quick response within a short time window.

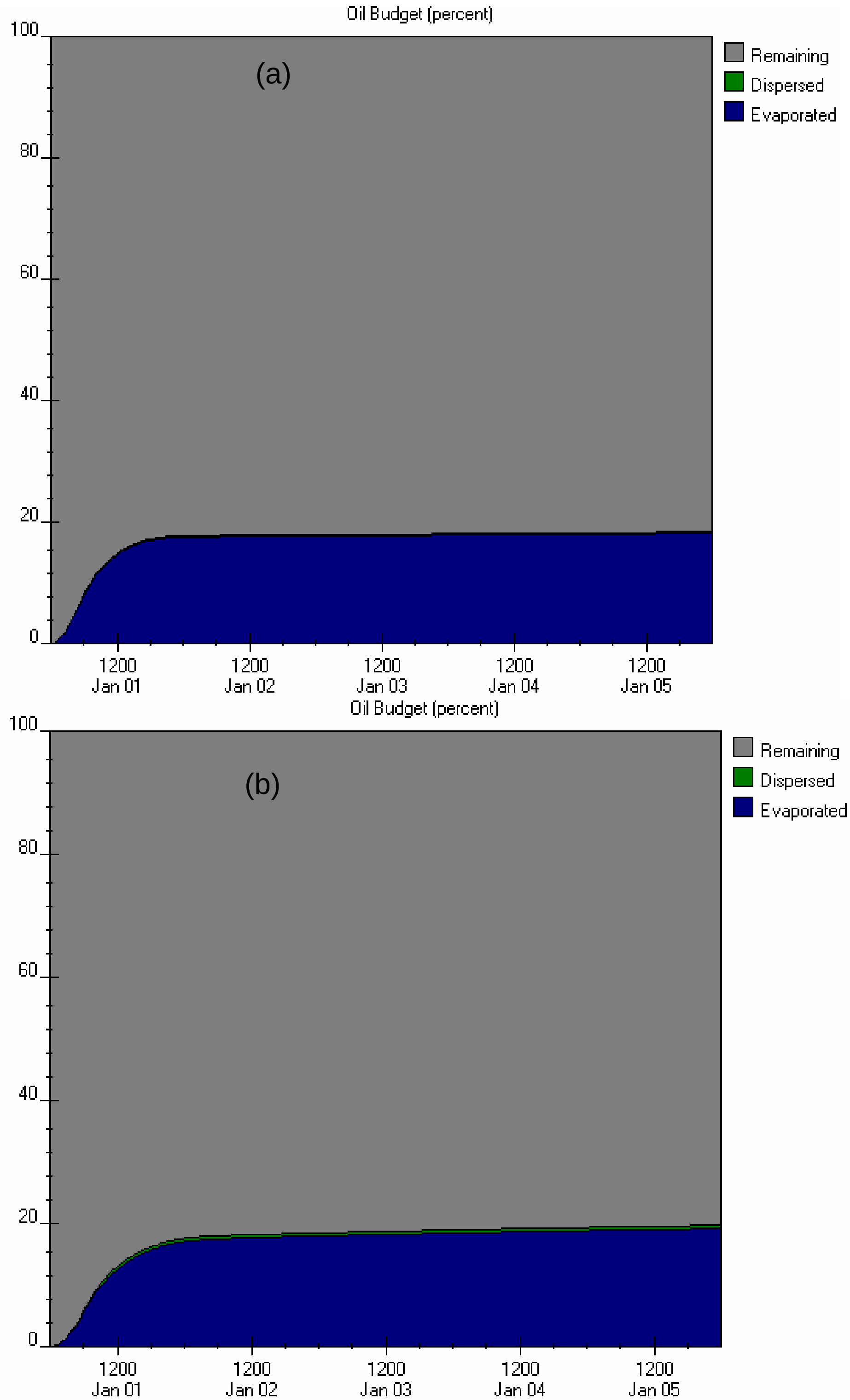


**Figure 19. Oil budget for a spill of (a) AWB and (b) CLB**

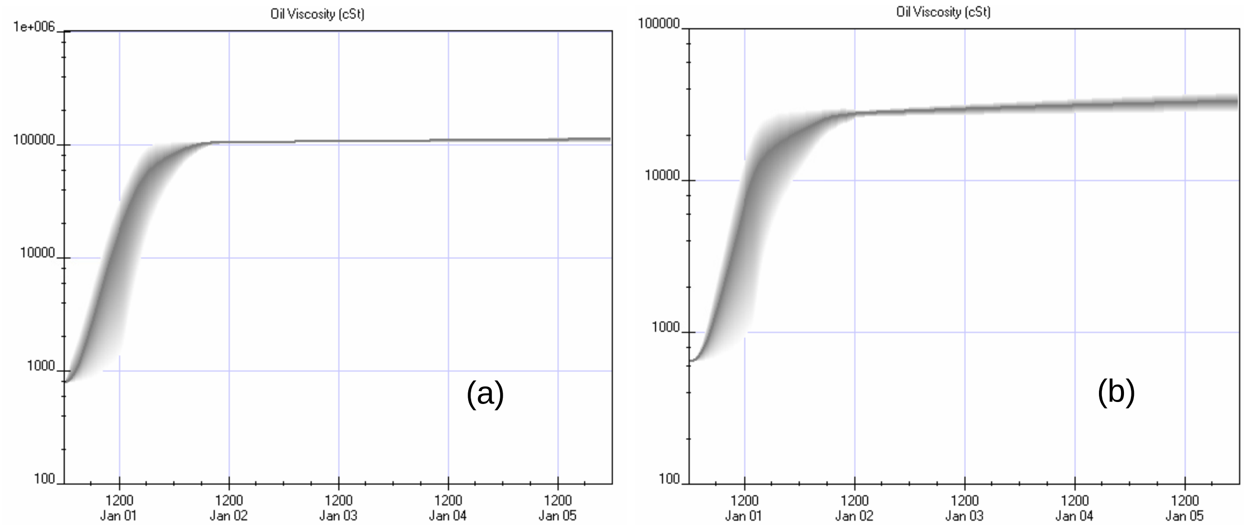

**Figure 20. Predicted change in viscosity for a spill of (a) AWB and (b) CLB**

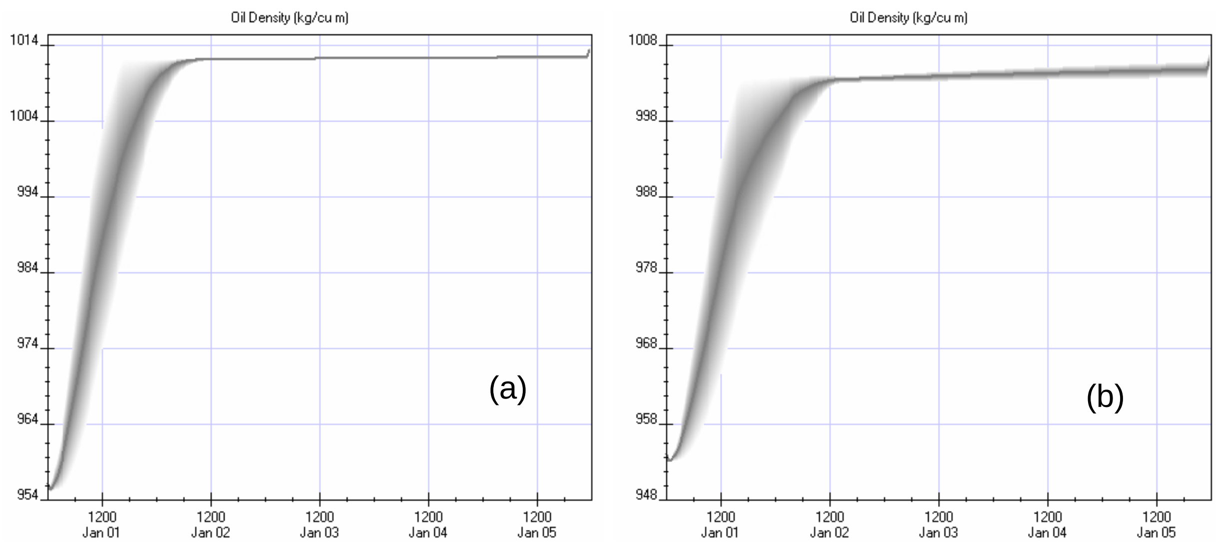

**Figure 21. Predicted change in density for a spill of (a) AWB and (b) CLB**

## 6.2 OIL TRANSPORT

To investigate the transport of oil during a spill in Port Hawkesbury with and without the application of dispersant, an oil transport simulation was conducted. It was based on a spill of 1,000 $m^3$ of IFO180 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 et al. 1997; Reed et al. 1995; Reed et al. 1999; Reed et al. 2004). 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/combat model. The OSCAR model has been validated in considerable detail (Reed et al. 1996; Reed et al. 2000).

### ***6.2.1 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), 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 (Figure 22) was divided into 640 by 450 grid cells. Depths in the simulation were taken from the high-resolution, 1-arc minute global bathymetry database, ETOPO1 (Amante and Eakins 2009). Climate data, such as wind and air temperature are the same as those used for the oil behaviour analyses (Figure 9, Figure 10, and Figure 11). 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 55 m. Furthermore, 10 layers were set for the vertical grids with resolution of 1 m. The temporal resolution was one hour.

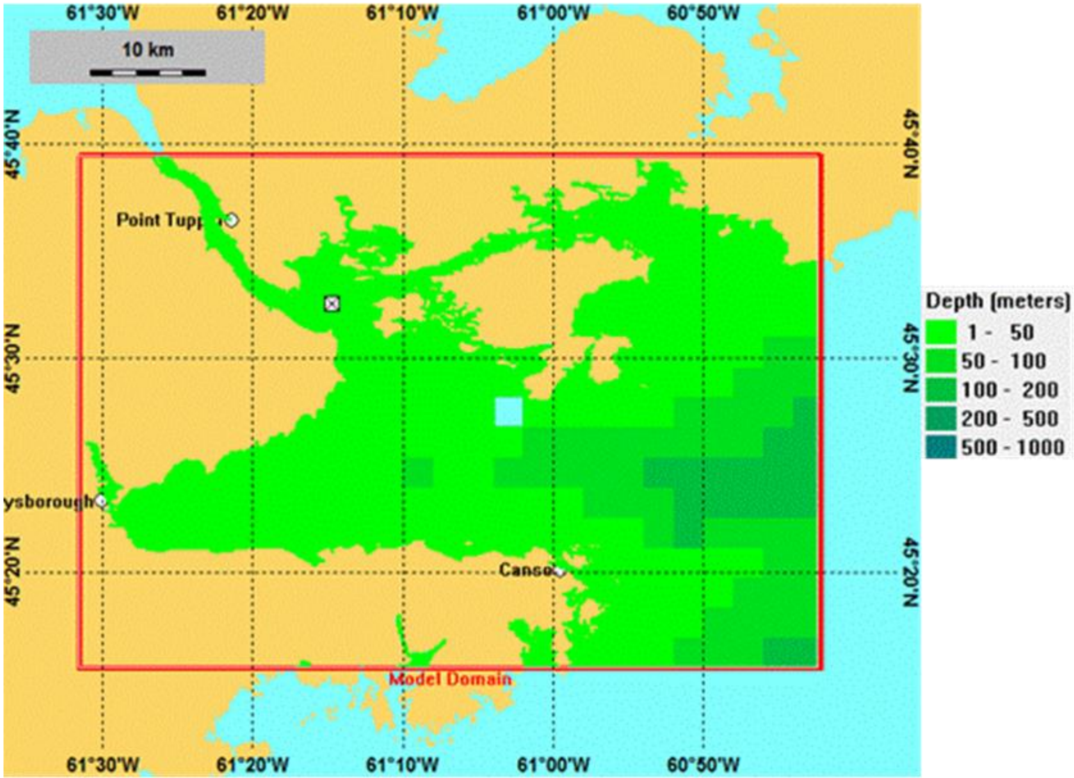

**Figure 22. Study area and model domain with bathymetric information**

### *6.2.2 Model Results*

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. Due to the availability of data, simulations ran within the period from January 2 to 31, 2003. Usually, dispersion of the oil happens in the first couple of days after the spill, and becomes undetectable thereafter. Therefore, the simulation period was set to 4 days.

The stochastic simulation incorporates a random spill date, which occurs within the first 27 days (January 2 - 28). The same approach can be applied using environmental inputs for other seasons. The dominant wind and current for the study period (Figure 9 and Figure 10) indicate that the prevailing wind direction is from the west-northwest with some variability, and the prevailing current is from the northwest. 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.

Mass balances for the 27 stochastic runs were computed. As an example, the mass balances (Figure 23) from Run No.1 (January 2), No.6 (January 7), No.15 (January 16), and No.27 (January 28) indicate diverse proportions of oil fractions due to dominant wind and current direction. For example, if the spill occurs on January 16 when the dominant drift is to the northeast, a significant amount of spilled oil would strand onshore (Figure 23c, Figure 25a). If the spill occurs on January 2 or 28, the dominant drift is to the south-southeast, so most of the oil would still be on the surface and suffer a relatively high dispersion rate (Figure 23a, d; Figure 24a, and Figure 25b). If the dominant drift direction is south-southeast, a high proportion (about 35%) of spilled oil would move out of the domain after 4 days (Figure 23b, Figure 24b). This is because the model domain has been restricted by the limited available data. More data and information for an extended study area will be needed in future.

A visual comparison of the mass balances for all 27 runs (Figure 26) indicated that a high percentage of oil reached the shore or floated on the surface, and very little remained in the water column after 4 days. Evaporation was not significant in any of them, varying from 5% to 10%, and sedimentation was not apparent in any.

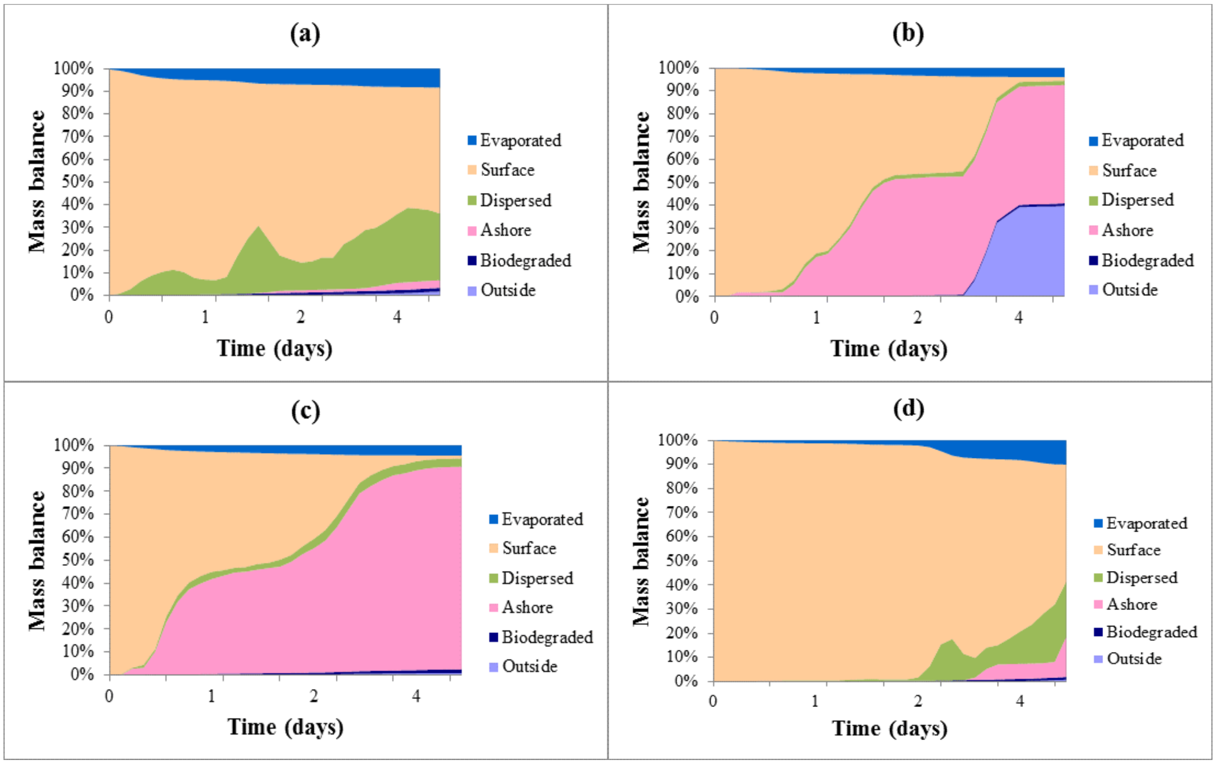


**Figure 23. Mass balance for stochastic simulation (a) No.1, (b) No. 6, (c) No.15, and (d) No. 27**

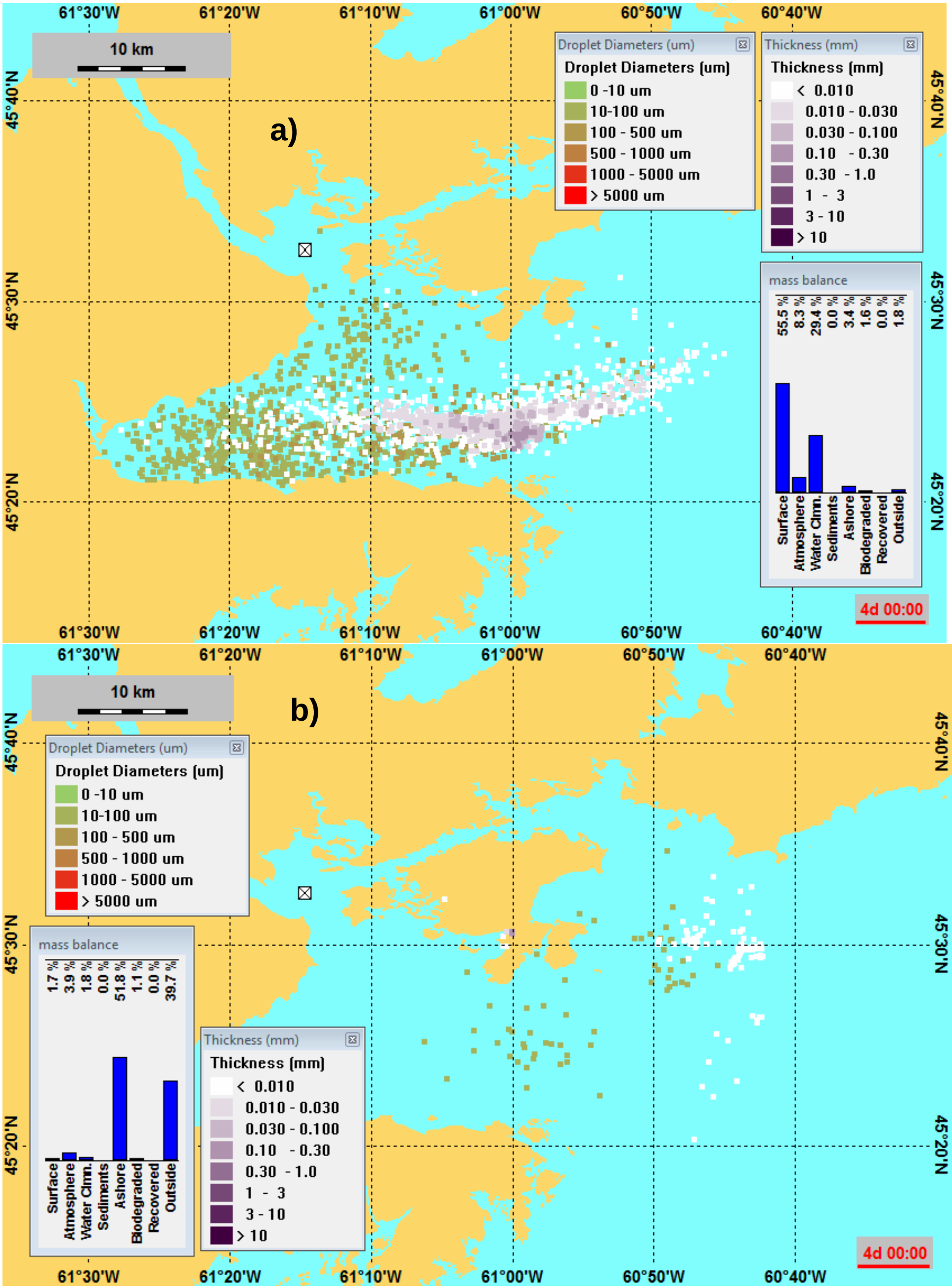


**Figure 24. Extent of oil coverage for stochastic simulation a) No.1, and b) No. 6**

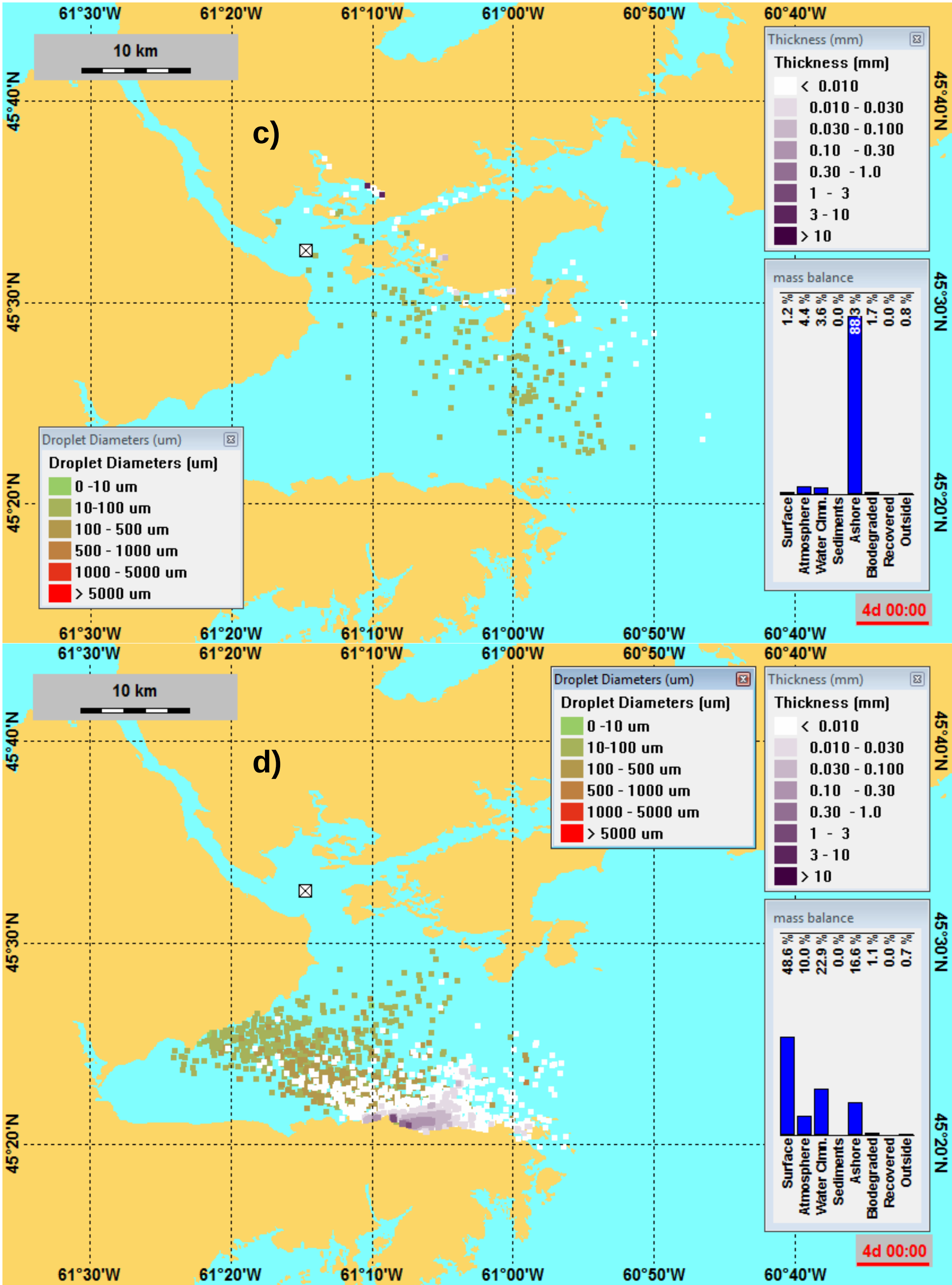


**Figure 25. Extent of oil coverage for stochastic simulation a) No.15, and b) No. 27**

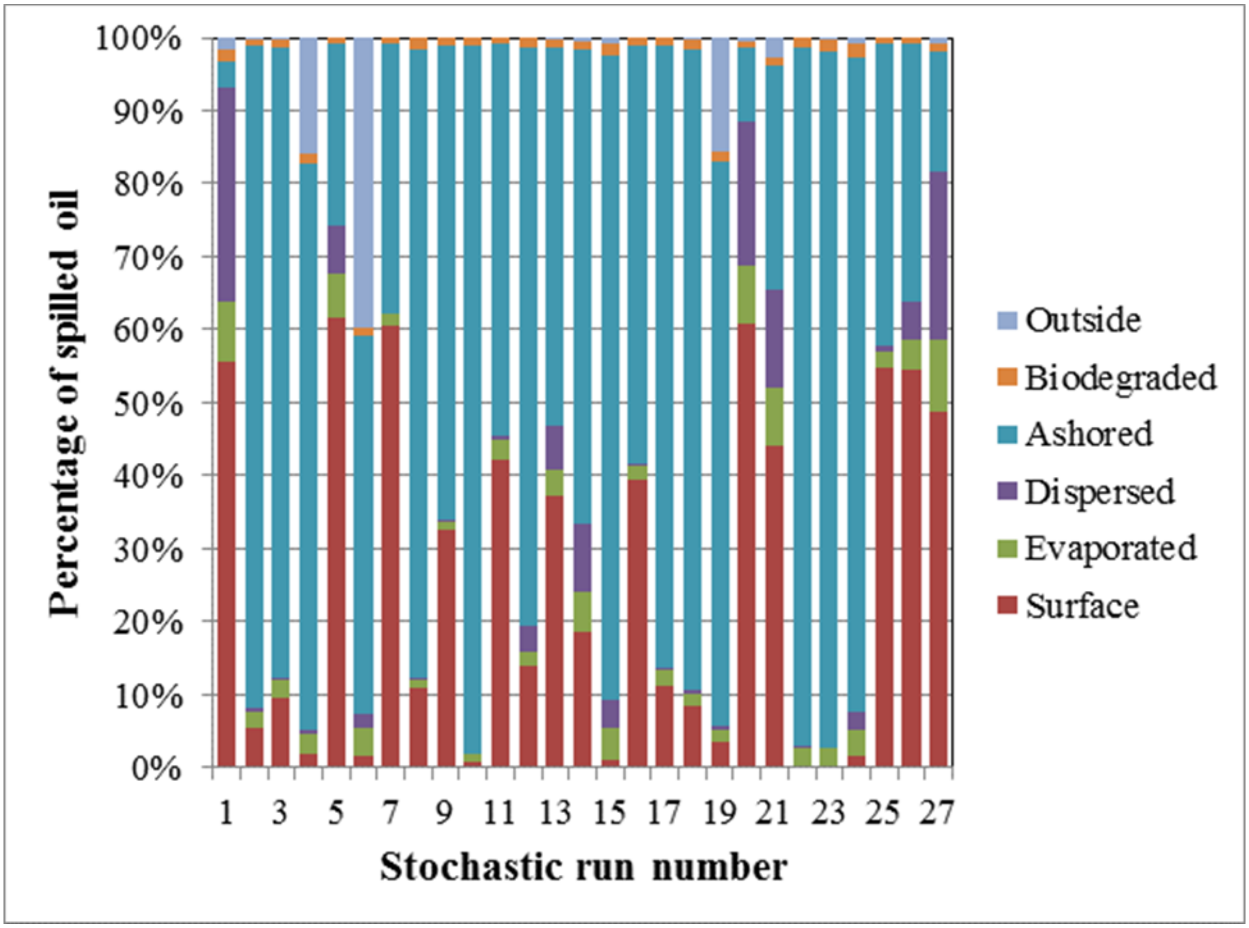


**Figure 26. Mass balance at the end of each 4-day simulation**

Finally, the individual trajectories of the 20 runs were combined to produce a probability of contamination chart showing the likelihood of surface and shoreline oiling (Figure 27 and Figure 28). Almost all the areas and shorelines within the model domain would likely become contaminated with oil. The highest risk lies in the central area of the model domain (the south coast of Isle Madame). Figure 27 also indicates that areas beyond the east boundary of the model domain would also be contaminated on the surface; however, for details on the situation beyond the present domain, further data support is needed.

The environmental impact factor (EIF) was used to represent the risk to different areas (water column, surface, and shoreline) and the total area. The water column is defined as the area of the horizontal cross section of the spill plume in water column. The impact areas with risk greater than 5% are calculated. The results show that the total impacted area was 1,123 $km^2$, the impacted sea surface area was 751 $km^2$, the impacted water column area was 864 $km^2$, and the impacted shoreline was 34 $km^2$.

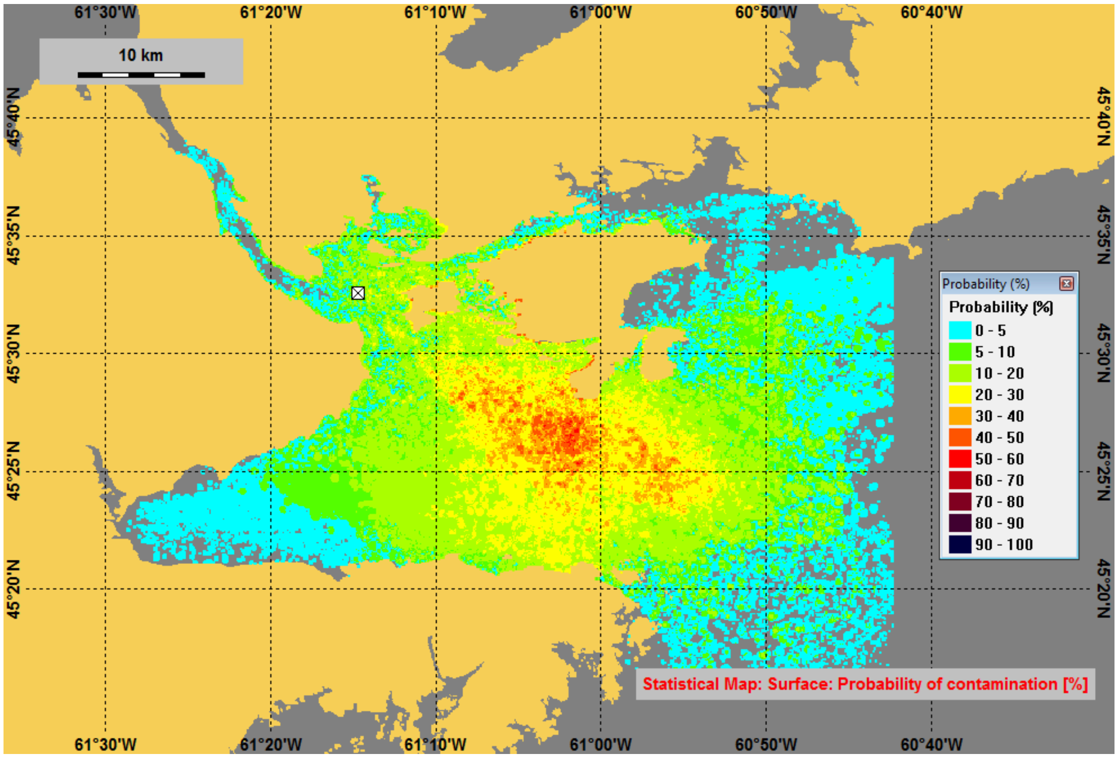


**Figure 27. Probability of surface contamination**

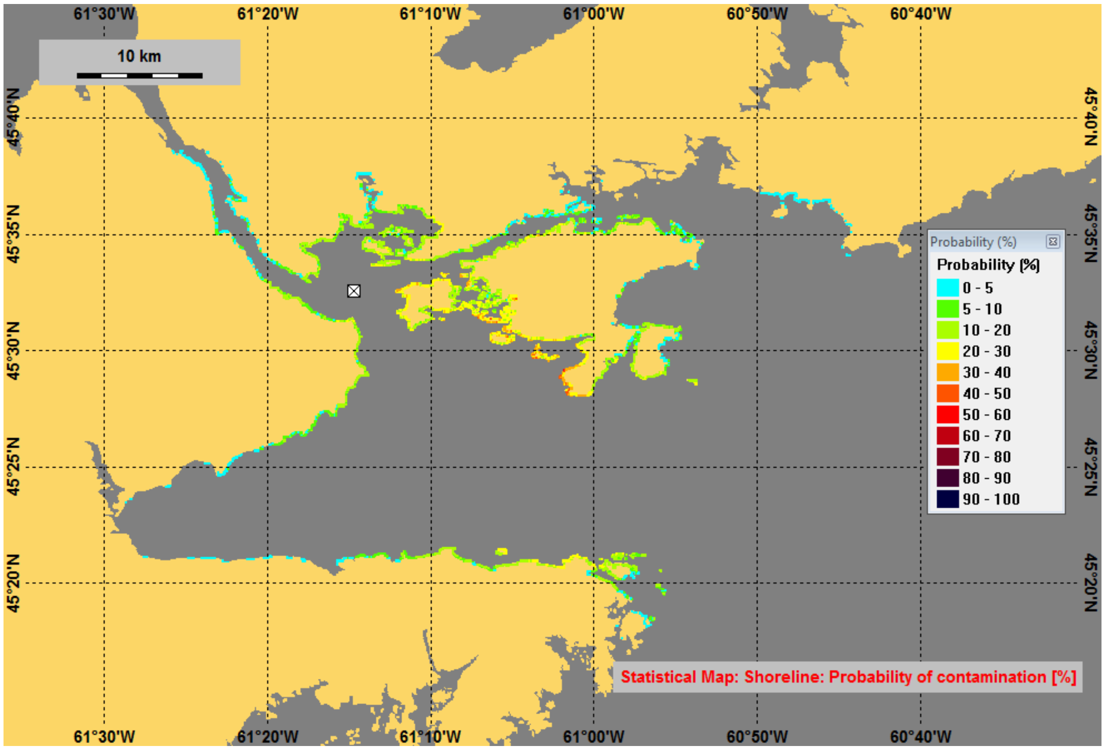


**Figure 28. Probability of shoreline contamination**

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 et al. 2010), then the results suggest that dispersant application would be beneficial in reducing the overall impacted area. 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 4-day simulation period. For some runs, especially those with a higher percentage of oil outside the model domain, oil might continue to transfer to other areas, and the final mass balance may be different from which shown above. Data acquisition for an extended area is needed for future study. In addition, a study of the efficacy of chemical dispersion (e.g., Corexit 9500) should be done. Seasonal effects on oil transport and fate should also be considered in future work.

# 7 CONCLUSIONS

Port Hawkesbury and the Canso Strait experience a mid-temperate climate with warm humid summers but snow and ice in winter. The area surrounding Port Hawkesbury and the Canso Strait is minimally developed with the exception of a few small towns and industrial areas. Oceanographic forces near Port Hawkesbury are heavily impacted by the presence of the Canso Causeway which blocks the flow of water through the strait. Some mixing on either side of the causeway does occur, but at levels which are greatly reduced from what would otherwise occur if the causeway were not present. Beyond the Canso Strait, the waters around Chedabucto Bay and south-eastern Cape Breton are highly exposed and experience heavy ocean swell along with wind and waves from the North Atlantic Ocean.

The Port Hawkesbury area, dubbed the Strait of Canso Superport, is a major shipping port in 2009 handled two-thirds of all cargo in Nova Scotia. The Strait of Canso is considered to be one of the deepest harbours on the east coast of North America and can welcome vessels too large to dock at many other ports. The refinery in nearby Point Tupper acts as a terminal for supertankers (some tankers reaching 250,000 DWT) with the capacity to store, blend and transfer oil products to smaller vessels. The Canso Superport handled over 30 million tonnes of cargo annually from 2005 to 2008. Of the 31.6 million tonnes of cargo that passed through the port in 2006, 21.6 million tonnes was crude petroleum.

ADIOS 2 oil spill modelling was conducted for this area based on a 1-hour spill of 4000 $m^3$ under winter (March) and summer (July) conditions. After 5 days, refined products would be 80% evaporated in the warmth of summer. Gasoline would only persist from 12 to 24 hours. These products are completely weathered after 2.5 days under winter conditions. Only about 1/5 of Arabian Light crude and Hibernia Light crude would evaporate and disperse within the first 36 hours, leaving most to be recovered. Increased viscosity and density of both oils in winter reduces the window of opportunity for dispersant application. Most of IFO 180 would remain in the environment and strand onshore, where extensive cleanup would be required. Very little Bunker C would be dispersed or evaporated in winter or summer, and after 2 days under winter conditions, it would likely be slightly submerged and non-dispersible, so cleanup procedures would be limited. Approximately 1/5 of dilbit would disperse or evaporate in the first 20 hours in winter or summer, before the spill stabilizes. Only Cold Lake Blend showed detectable dispersion, in winter. Dilbit viscosity and density increase within 12 to 15 hours, reducing the window of opportunity for dispersant application. These products require rapid response, and might be slightly submerged and non-dispersible in winter. In summer conditions, cleanup options are still limited to mechanical recovery.

## 8 REFERENCES


Aamo, O.M., Reed, M., and Downing, K. Oil spill contingency and response (OSCAR) model system: Sensitivity studies. *In* Proceedings of the 1997 International Oil Spill Conference, April 7-10, 1997. Fort Lauderdale, Florida 1997. American Petroleum Institute. pp. 429-438.

Amante, C., and Eakins, B.W. 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, data sources and analysis. National Geophysical Data Center, Marine Geology and Geophysics Division NESDIS NGDC-24, Boulder, Colorado.

AMEC Earth and Environmental. 2008. Environmental Impact Statement (EIS) for the Proposed Melford International Terminal.

Bedford Institute of Oceanography. 2007. Hydrographic Database and Ocean Data Inventory Database. Available from http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data_query_f.html.

Buckley, D.E., Owens, E.H., Schafer, C.T., Vilks, G., Cranston, R.E., Rashid, M.A., Wagner, F.J.E., and Walker, D.A. 1974. Canso Strait and Chedabucto Bay: a multidisciplinary study of the impact of man on the marine environment. Geol. Surv. Can. **74-30**: 133-159.

Canada-Nova Scotia Strait of Canso Environment Committee. 1975. Water resources. Halifax, NS.

Canadian Hydrographic Services. 2007. Atlantic Coast and Bay of Fundy. Canadian Tide and Current Tables.

CBC News. 2015. SS Arrow cleanup removes 30,000 litres of oil from Chedabucto Bay wreck.

CBCL. 2015. Bear Head LNG Terminal Metocean Study, draft report 140672.00 prepared for Bear Head LNG.

Chen, C., Huang, H., Beardsley, R.C., Liu, H., Xu, Q., and Cowles, G. 2007. A finite volume numerical approach for coastal ocean circulation studies: comparisons with finite difference models. J Geophys Res **112**: C03018. doi:doi:10.1029/2006JC003485.

Climate-Data.org. 2018. Climate Port Hawkesbury. Available from https://en.climate-data.org/north-america/canada/nova-scotia/port-hawkesbury-762130/2018].

Cranston, R.E., Fitzgerald, R.A., and Winters, G.V. 1974. Geochemical data from the Strait of Canso and Chedabucto Bay, Nova Scotia. BIO Data Series **BI-D-74-3**: 56.

Crowley, R.W. 1970. Arrow. Potomac Research Inc. for Department of the Navy, Naval Ship Systems Command 0994-008-1010, Washington, DC.

Dupond, F., Hannah, C.G., Greenberg, D.A., Cherniawsky, J.Y., and Naimie, C.E. 2002. Modelling System for Tides for the Northwest Atlantic Coastal Ocean. Canadian Technical Report of Hydrograph and Ocean Sciences **221**(70).

Environment Canada. 2015. Climate. Available from http://climate.weather.gc.ca/2015].

Fothergill, N.O. 1955. Tidal changes in the Strait of Canso. *In* Report of tidal and current survey, Canadian Hydrographic Service. p. 9.

Fuller, C., Bonner, J., Page, C., Ernest, A., McDonald, T., and McDonald, S. 2004. Comparative toxicity of oil, dispersant, and oil plus dispersant to several marine

species. Environmental Toxicology and Chemistry **23**(12): 2941-2949. Available from http://onlinelibrary.wiley.com/doi/10.1897/03-548.1/pdf [accessed.
Gardner Pinfold. 2010. Economic impact study of independent marine ports in Atlantic Canada. Gardner Pinfold Consulting Economics, Halifax, NS.
Government of Nova Scotia. 2010. Selected Daily Stats. Available from https://www.novascotia.ca/finance/statistics/news.asp?id=75042018].
Government of Nova Scotia. 2019. Geographic Data Directory.
Gregory, D., Petrie, B., Jordan, F., and Langille, P. 1993. Oceanographic, geographic and hydrological parameters of Scotia-Fundy and southern Gulf of St. Lawrence inlets. Can. Tech. Rep. Hydrogr. Ocean Sci. **143**: 248.
Heath, R.A. 1973. Flushing of coastal embayments by changes in atmospheric conditions. Limnology and Oceanography **18**: 849-862.
Hemmer, M.J., Barron, M.G., and Greene, R.M. 2010. Comparative toxicity of Louisiana Sweet crude oil (LSC) and chemically dispersed LSC to two Gulf of Mexico aquatic test species. U.S. Environmental Protection Agency, Office of Research and Development.
Houston, G., Gaudreau, R., and Sinclair, M. 2013. A Review of Canada's Ship-source Oil Spill Preparedness and Response Regime: Setting the course for the future. Tanker Safety Panel Secretariat 978-1-100-54627-8, Ottawa, ON.
Invest Cape Breton. 2018. Transportation Infrastructure.
JWEL. 2004. Environmental Assessment for the Proposed Bear Head LNG Terminal, Bear Head, Nova Scotia. N.E. Inc.
Keizer, P., Ahern, T., Dale, J., and Vandermeulen, J. 1978. Residues of bunker C oil in Chedabucto Bay, Nova Scotia, 6 years after the *Arrow* spill. Journal of the Fisheries Board of Canada **35**(5): 528-535. Available from http://www.google.ca/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCoQFjAB&url=http%3A%2F%2Fwww.nrcresearchpress.com%2Fdoi%2Fpdf%2F10.1139%2Ff78-097&ei=P8wVU9LNIYrH0wG564CwCA&usg=AFQjCNEYvBCA8X4Om6nqEhpreKVHQdXT5Q&bvm=bv.62286460,d.dmQ [accessed.
Lawrence, D.J. 1972. Oceanographic and Water Quality Parameters in the Strait of Canso 1968-1970. Bedford Institute of Oceanography, Data Series **BI-D-72 10**.
Lawrence, D.J., L.A., F., and R.H., L. 1973. Statistics of currents for navigation and dispersion in Canso Strait and Come by Chance Bay. Bedford Inst.of Oceanogr. Rept. **BI-73-6**.
Lee, K., Prince, R.C., Greer, C.W., Doe, K.G., Wilson, J.E.H., Cobanli, S.E., Wohlgeschaffen, G.D., Alroumi, D., King, T., and Tremblay, G.H. 2003. Composition and toxicity of residual Bunker C fuel oil in intertidal sediments after 30 years. Spill Science and Technology Bulletin **8**(2): 187-199. doi:http://dx.doi.org/10.1016/S1353-2561(03)00014-8.
MacLaren Marex Inc. 1978. Report on cavern oil storage project preliminary impact study of brining operations for province of Nova Scotia. N.S.D.o. Development.
Maritime Museum of the Atlantic. 2018. Arrow - 1970. Available from https://novascotia.ca/museum/wrecks/wrecks/shipwrecks.asp?ID=4682018].
McCracken, F.D. 1979. Canso Marine Environment Workshop. Fisheries and Marine Service Technical Report **834**.

Messieh, S.N., and El-Sabh, M.I. 1988. Man-made environmental changes in the southern Gulf of St. Lawrence, and their possible impact on inshore fisheries. Natural and Man-Made Hazards: 499-523.

Neu, H.A. 1972. Extreme Wave Height Distribution along the Canadian Atlantic Coast. Ocean Industry: 45-49.

Office of the Auditor General of Canada. 2010. Chapter 1 Oil Spills from Ships. *In* Report of the Commissioner of the Environment and Sustainable Development to the House of Commons - Fall 2010. Office of the Auditor General of Canada, Ottawa, ON. pp. 1-37.

Owens, E.H. The cleaning of gravel beaches polluted by oil. *In* 13th International Coastal and Engineering Conference. Vancouver, BC, July 10-14, 1972 1972. American Society of Civil Engineers. pp. 2549-2556.

Parrott, D.R. 2010. Cruise Hart 2004010 Geophysical and Photographic Surveys in the Strait of Canso, NS, 27 April – 14 May 2004. *Edited by* G.S.o. Canada.

Parrott, D.R., Parsons, M.B., Kostylev, V., Shaw, J., and Tay, K.-L. 2005. Seafloor Character of Canso Strait, Nova Scotia-50 years after completion of the Canso Causeway. *In* Canadian Coastal Conference.

Pemberton, S.G. 1976. Deep Bioturbation By axius serratus in the Strait of Canso, NS. McMaster University.

Platt, T., Prakash, A., and Irwin, B. 1972. Phytoplankton nutrients and flushing of inlets on the coast of Nova Scotia. Naturaliste Canadien **99**: 253-261.

Prouse, N.J. 1994. Ranking harbours in the Maritime Provinces of Canada for Potential to contaminate American Lobster (Homarus americanus) with polycyclic aromatic hydrocarbons. Can. Tech. Rep. Fish. Aquat. Sci. **1960**.

Pub 145. 2014. Nova Scotia and the St. Lawrence, Seventeenth Edition. Sailing Directions (Enroute) National Geospatial Intelligence Agency.

Reed, M., Aamo, O.M., and Daling, P.S. OSCAR: a model system for quantitative analysis of oil spill response strategies. *In* Proceedings of the 18th Arctic and Marine Oilspill Program (AMOP) Technical Seminar. Edmonton, Alberta, June 14-16 1995. Environment Canada. pp. 815-835.

Reed, M., Aamo, O.M., and Downing, K. Calibration and testing of IKU's oil spill contingency and response (OSCAR) model system. *In* Proceedings 19th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar. Calgary, Alberta 1996. Environment Canada. pp. 689-726.

Reed, M., Ekrol, N., Rye, H., and Turner, L. 1999. Oil spill contingency and response (OSCAR) analysis in support environmental impact assessment offshore Namibia. Spill Science and Technology Bulletin **5**(1): 29-38. doi:doi:10.1016/S1353-2561(98)00050-4.

Reed, M., Daling, P.S., Brakstad, O.G., Singsaas, I., Faksness, L.-G., Hetland, B., and Ekrol, N. OSCAR 2000: a multi-component 3-dimensional oil spill contingency and response model. *In* Proceedings of the 23rd AMOP Technical Seminar on Environmental Contamination and Response. Vancouver, British Columbia, June 14-16 2000. Environment Canada. pp. 663-680.

Reed, M., Daling, P., Lewis, A., Ditlevsen, M.K., Brors, B., Clark, J., and Aurand, D. 2004. Modelling of dispersant application to oil spills in shallow coastal waters.

Environmental Modelling and Software **19**(7-8): 681-690. Available from http://www.sciencedirect.com/science/article/pii/S1364815203001920 [accessed.
Samuels, W.B., Amstutz, D.E., Bahadur, R., and Ziemniak, C. 2013. Development of a global oil spill modeling system. Earth Science Research **2**(2): 52-61.
SL Ross Environmental Research. 1999. Probability of Oil Spills from Tankers in Canadian Waters. SL Ross Environmental Research Ltd, Ottawa, ON.
SmartAtlantic. 2015. Halifax (Herring Cove) Buoy. Available from http://www.smartatlantic.ca/Halifax/buoy.php2015].
SNC-Lavalin. 2015. Bear Head LNG Section 4 Overview the Environment. https://www.novascotia.ca/nse/ea/bear-head-lng/section-4a.pdf.
Statistics Canada. 2011. Shipping in Canada. Statistics Canada, Ottawa, ON.
Stewart, P.L., and White, L. 2001. A review of contaminants on the Scotian Shelf and in adjacent coastal waters: 1970 to 1995. Fisheries and Oceans Canada 2351, Dartmouth, NS.
Strait of Canso Superport. 2018a. Statistics. Available from http://www.straitsuperport.com/port/statistics/.
Strait of Canso Superport. 2018b. Strait of Canso Superport Overview. Available from http://www.straitsuperport.com/uploads/documents/fact_sheet.pdf2018].
Strait of Canso Superport. 2018c. Strait of Canso Port. Available from http://www.straitsuperport.com/port/2018].
Swail, V.R., Cardone, V.J., and Cox, A.T. 2006. 50-year (1954 to 2005) wind and wave hindcast of the North Atlantic A Long Term North Atlantic Wave Hindcast. *Edited by* M.S.o. Canada.
Transportation Safety Board of Canada. 2014. Canadian Transportation Accident Investigation and Safety Board Act. *In* Transportation Safety Board Regulations. *Edited by* G.o. Canada, http://laws-lois.justice.gc.ca/eng/regulations/SOR-2014-37/FullText.html.
Transportation Safety Board of Canada. 2018. TSB Accident Statistics. http://www.tsb.gc.ca/eng/stats/.
Vilks, G., Schafer, C.T., and Walker, D.A. 1975. The influence of a causeway on oceanography and Foraminifera in the Strait of Canso, Nova Scotia. Can. J. Earth Sci. **12**: 2086-2102.
WeatherSpark.com. 2016.
Webster, T., McGuigan, K., Crowell, N., Collins, K., and MacDonald, C. 2014. Acquisition and processing of topo-bathymetric lidar for Isle Madame in support of the World Class Tanker Safety Initiative. Applied Geomatics Research Group, NSCC Middleton, NS.
Wu, Y., Chaffey, J., Greenberg, D.A., Colbo, K., and Smith, P.C. 2011. Tidally-induced sediment transport patterns in the upper Bay of Fundy: a numerical study. Cont Shelf Res **31**(19-20): 2041-2053. doi:doi:10.1016/j.csr.2011.10.009.