State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 4, St. Lawrence Seaway, Montreal to Anticosti, Québec

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 4, St. Lawrence Seaway, Montreal to Anticosti, Québec

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 4, St. Lawrence Seaway, Montreal to Anticosti, Québec. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: viii + 42 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 4, St. Lawrence Seaway, Montreal to Anticosti, Québec. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: viii + 42 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 fourth volume of a five volume report and contains information relevant to developing an area response plan for the St. Lawrence Seaway, Québec. 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 4, St. Lawrence Seaway, Montreal to Anticosti, Québec. Can. Manuscr. Rep. Fish. Aquat. Sci. 3176: viii + 42 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 réaction à ces changements, 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 afin d'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-Jean (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.

Le présent rapport est le quatrième volume de cinq et contient de l'information pertinente relativement à l'élaboration d'un plan d'intervention régional pour la Voie maritime du Saint-Laurent, au Québec. 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 St. Lawrence Seaway, Quebec (Figure 1). The St. Lawrence is among the world's most important commercial waterways and is a significant socio-economic asset to Canada and the industrial heartland of the United States, linking the Atlantic Ocean with the Great Lakes (Government of Canada 2017). One of the three largest rivers on the North American continent, the St. Lawrence extends from the Laurentian Great Lakes to the Gulf of St. Lawrence, and is fed by two major watersheds: the Great Lakes regulated at Cornwall station, and the Ottawa River regulated at the Carillon generating station west of Montreal. Encompassing 1,610,000 km^2, it is the thirteenth largest drainage basin in the world. At any given time the St. Lawrence River contains up to 25% of the earth's freshwater, and influences environmental processes of the entire North American continent. Total freshwater runoff from the St. Lawrence River, the Saguenay River, rivers along the north shore, and smaller contributions from the south shore govern the estuarine circulation in the Gulf of St. Lawrence (Dufour and Ouellet 2007).

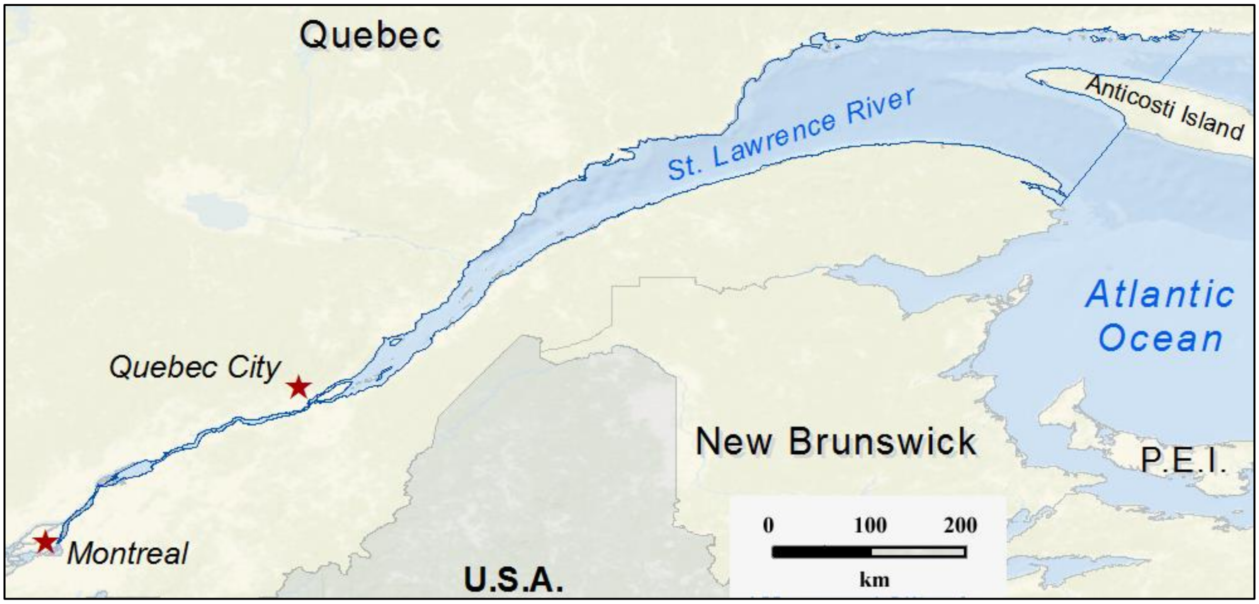

Figure 1. Saint Lawrence River study area

From Lake Ontario seaward, the river and estuary can be viewed in sections on the basis of its physical properties, with boundaries that vary according to quoted authority or intended use (Dunbar et al. 1980), but we will use the boundaries illustrated in Figure 2 (St. Lawrence Centre 1993): 1. Mille-Isles, 2. International Rapids, 3. river (fluvial section), 4. Fluvial estuary, 5. Upper estuary, 6. Lower estuary, and 7. Gulf. The study area does not include sections 1 or 2 and only extends to the western tip of Anticosti Island in the Gulf.

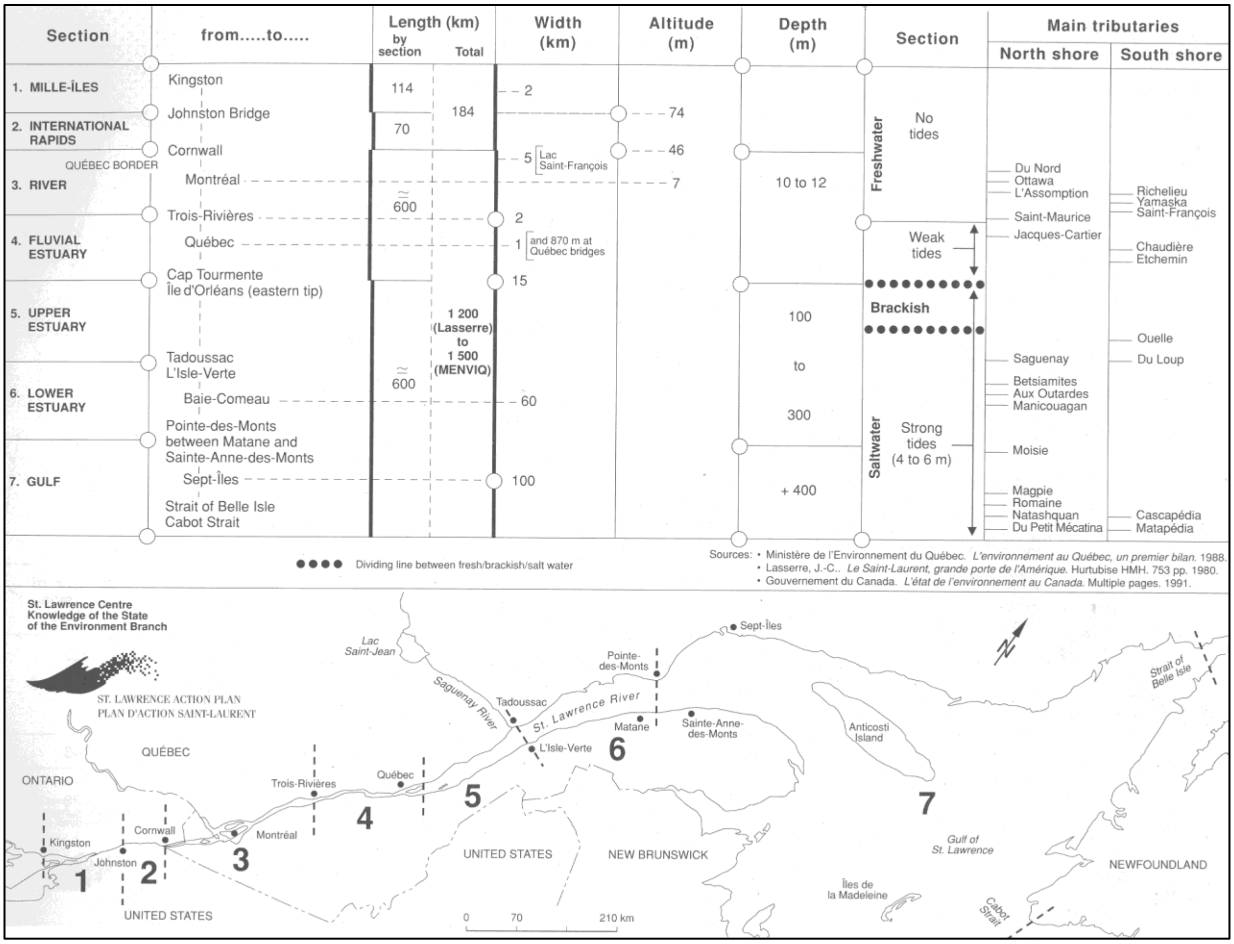

Figure 2. Sections of the St. Lawrence (St. Lawrence Centre 1993)

The estuary and Gulf are joined to the Atlantic Ocean by the Laurentian Channel. The northern end of the Channel splits into two secondary troughs diverting water to the north and south of Anticosti Island. Some of this water travels further northeast to Belle Isle Strait. Near Cabot Strait, depths can exceed 500 m (Figure 3), while elsewhere in the Gulf, they range from 100 to 400 m.

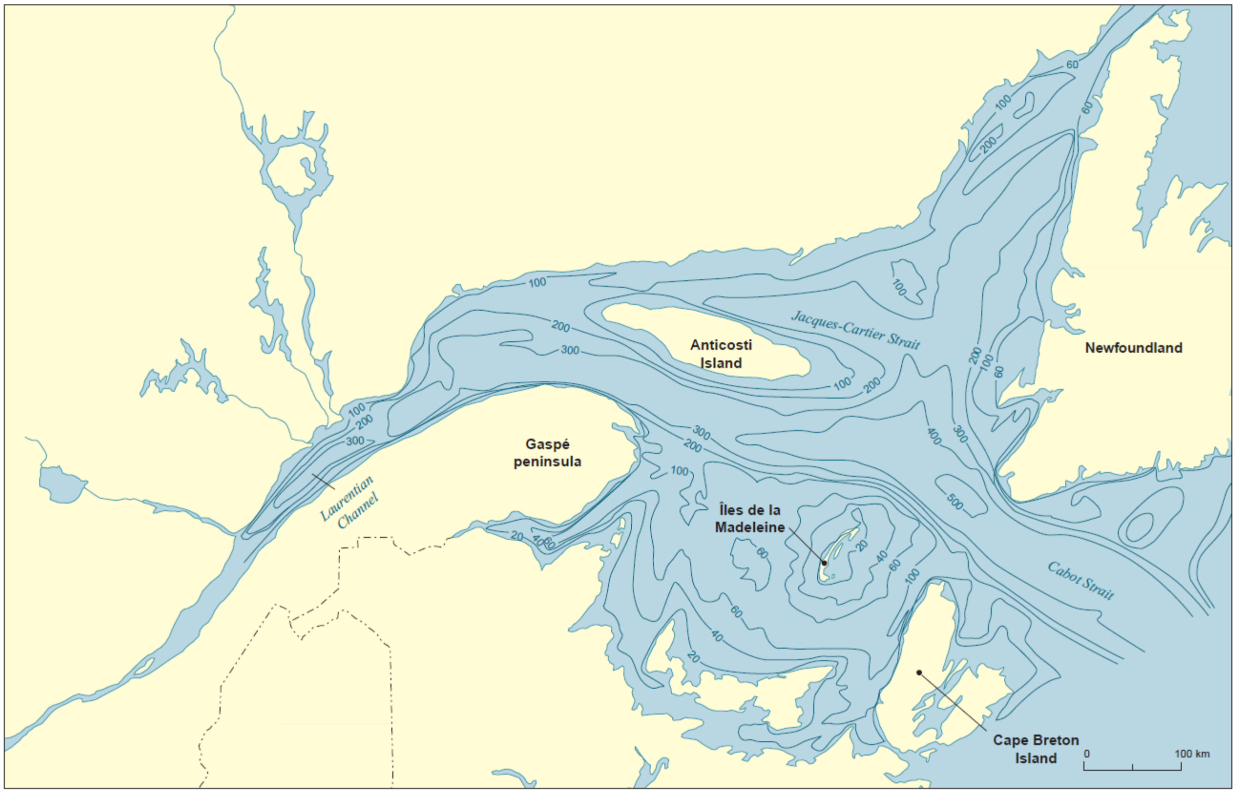

Figure 3. Bathymetry of the Gulf of St. Lawrence (Dunbar et al. 1980)

A recent report (Houston et al. 2013) considers the Gulf of St. Lawrence and the southern coast of British Columbia to be the most vulnerable regions of Canada to an oil spill. There would be severe environmental and socioeconomic impacts, taking into account the coastal characteristics (e.g. tides and sand bars), the fauna (mollusks, fish, birds, etc.) and human activities based on these resources.

In addition, the Great Lakes-St. Lawrence Seaway is a deep draft waterway of geographic, hydrologic, and economic importance that stretches 4,000 km from the Cabot Strait to the head of the Great Lakes as far as North River, Minnesota. The St. Lawrence Seaway portion extends from Montreal through Quebec and Ontario to Lake Erie, contiguous with a section of the Canada-US border. It supports 15 major ports and 50 regional ones, all connected to 40 provincial and interstate highways and about 30 rail lines – a vital, international, transportation route (New World Encyclopedia 2015).

The Port of Montreal is an international transshipment point, a hub for major petroleum pipelines, and the only container port on the St. Lawrence River. More than 100 berths handle cargo from over 200 international ports, including grain and other dry bulk goods, petroleum products, other bulk liquid consumer goods, machinery and sugar. The port handled 28,422,003 tons of cargo in 2012, and has moved an annual average of 20 million tons in the past 10 years.

The capacity to respond to an oil spill in the St. Lawrence is limited to 15,000 tons of oil (about 105,000 barrels). Under ideal conditions, maximum physical recovery of spilled oil can be expected to be 30% (Environment Canada et al. 2013), and this likely would be much lower in cold water and icy environments (Engelhardt 1994; Lee et al. 2011). The major risks would be spills from tanker and pipeline accidents.

For the study area (Figure 1), which extends from the St. Lawrence River to the western tip of Anticosti Island in the Gulf of St. Lawrence, environmental sensitivity indices (Figure 4) indicated that the zones of highest potential impact are in the estuary and the Gulf of St. Lawrence, especially near the shore (WSP Canada 2014).

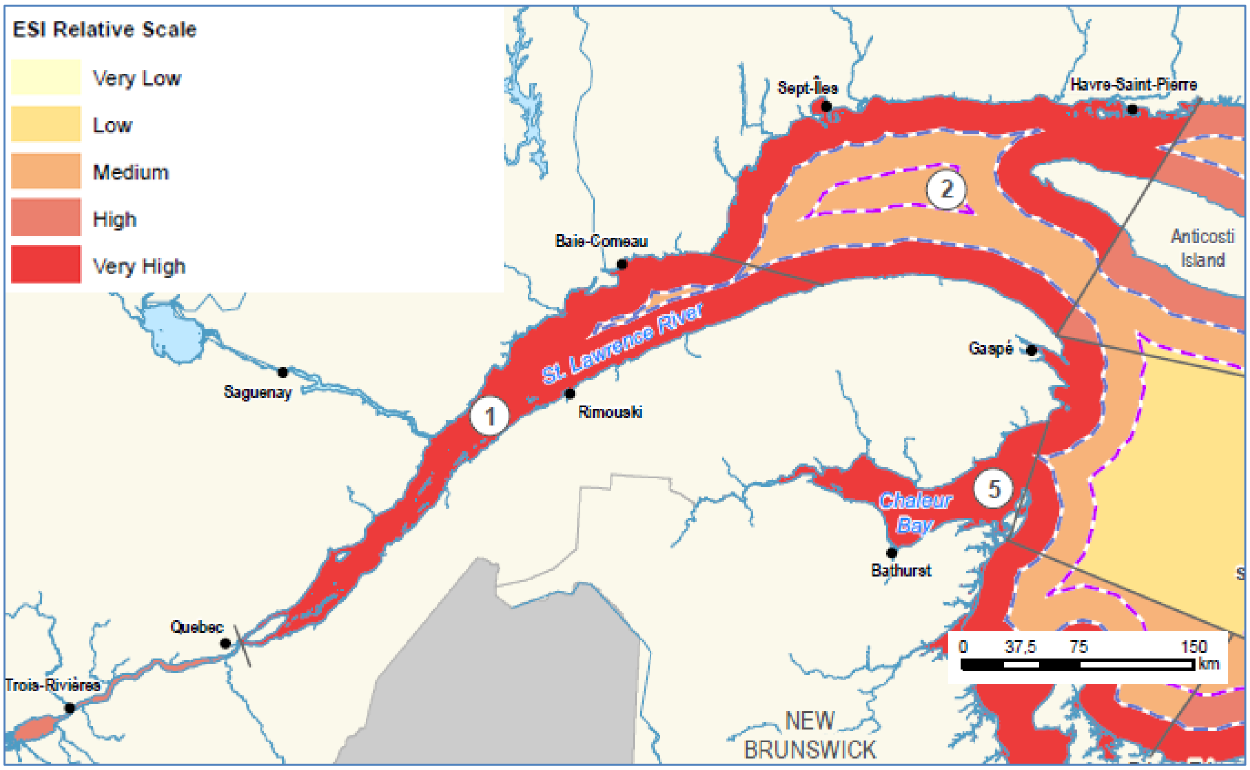

Figure 4. Environmental sensitivity indices in regions of the St. Lawrence River (Houston et al. 2013)

2 HYDROGRAPHY

2.1 BATHYMETRY

2.1.1 St. Lawrence River

The river section is 240 km long, passing through a highly industrialized region between Cornwall, Ontario, to Pointe du Lac on Lac Saint-Pierre (in Trois-Rivières), Quebec, and contains wetlands, rapids, lakes and over 100 islands (St. Lawrence Centre 1991, 1993, 1996b). There is no tidal influence in this section. Water entering the fluvial section from tributaries sometimes does not mix, but brown, humic-stained water from the Ottawa River flows alongside green, relatively clear water from the Great Lakes (Vincent and Dodson 1999), creating striking ecological contrasts (St. Lawrence Centre 1996b).

The fluvial estuary from Trois-Rivières to the eastern tip of Île d'Orléans is about 160 km long, 2 to 5 km wide (Figure 5; but only 870 m wide at the Quebec City bridges), and has fewer wetlands and more rock flats subject to tidal action (St. Lawrence Centre 1991, 1996b). The river and fluvial estuary support the highest biodiversity in terms of plant and animal life (St. Lawrence Centre 1996b). The mean tidal amplitude near the end of this reach at Quebec City is 4.1 m, rising to 5.8 m during spring tides. Current reversal and strong mixing occur on the flood tide, so this part of the river lacks the distinct cross-channel gradients in water masses which are characteristic of the fluvial section; the combined ebb plus river currents can generate an instantaneous flow of 75,000 m^3/s (Vincent and Dodson 1999).

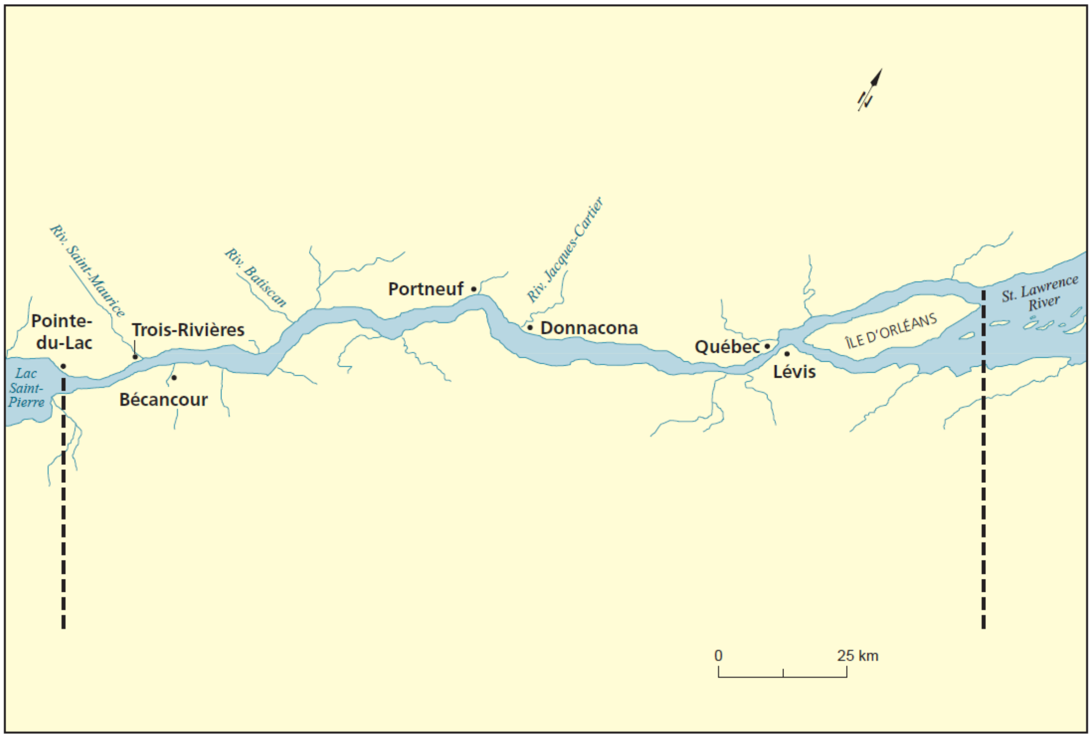

Figure 5. The fluvial estuary (St. Lawrence Centre 1996b)

2.1.2 Upper St. Lawrence Estuary

The upper estuary (Figure 6) extends 180 km from the landward limit of salt intrusion at the eastern tip of Île d'Orléans (Neu 1970), down to the head of the deep glacial valley called the Laurentian Channel, near Tadoussac. It is about 2 km wide in the river section and widens to about 25 km near Tadoussac (average = 17 km wide), and covers some 3277 km^2 (St. Lawrence Centre 1991). High-intensity currents and tides mix this transition zone of fresh and saltwater, and turbidity tends to be high between Île d'Orléans and Île aux Coudres (St. Lawrence Centre 1991). The average depth is less than 10 m, and turbulence decreases from Île -aux-Coudres to Tadoussac, so the water column becomes partially stratified (Bourgault 2001; Neu 1970), with salinity ranging from 0.5 to 25 ppt (Vincent and Dodson 1999).

In the upper estuary, more than 90% of the total kinetic energy of flow is due to the action of tides alone (Muir 1982). As the estuary becomes narrower and shallower, the tidal range increases. The maximum tidal range, near 5 m, is observed at Saint-François-de-l'île-d'Orléans (Godin 1979). The tidal range and currents then rapidly decrease in the river section landward from Quebec City owing to increased bottom friction. At Trois-Rivières, the tidal range is reduced to less than 0.2 m (Bourgault 2001; Godin 1979).

Figure 6. Upper estuary and Saguenay River (St. Lawrence Centre 1996a)

The bathymetry of the upper estuary is complicated by three flow channels of more than 10 m deep, one of which crosses the river north-south between l'Isle-aux-Coudres and the Isle-aux-Grues Archipelago (Figure 7). At Saint-Siméon depths of more than 100 m have been recorded in a trough about 50 km long. There are many islands, deep troughs, shallow banks and sills, of which the most dramatic is the Saguenay sill near Tadoussac that drops 250 m over a stretch of 20 km eastward. Included as part of the upper estuary, the Saguenay fjord (maximum depth = 320 m) is over 100 km long, and the sill at its mouth restricts flow between its water masses from the St. Lawrence, although some exchange does still occur (Belzile et al. 2016; St. Lawrence Centre 1991, 1996b). The Saguenay sill marks the start of the lower estuary (Figure 8).

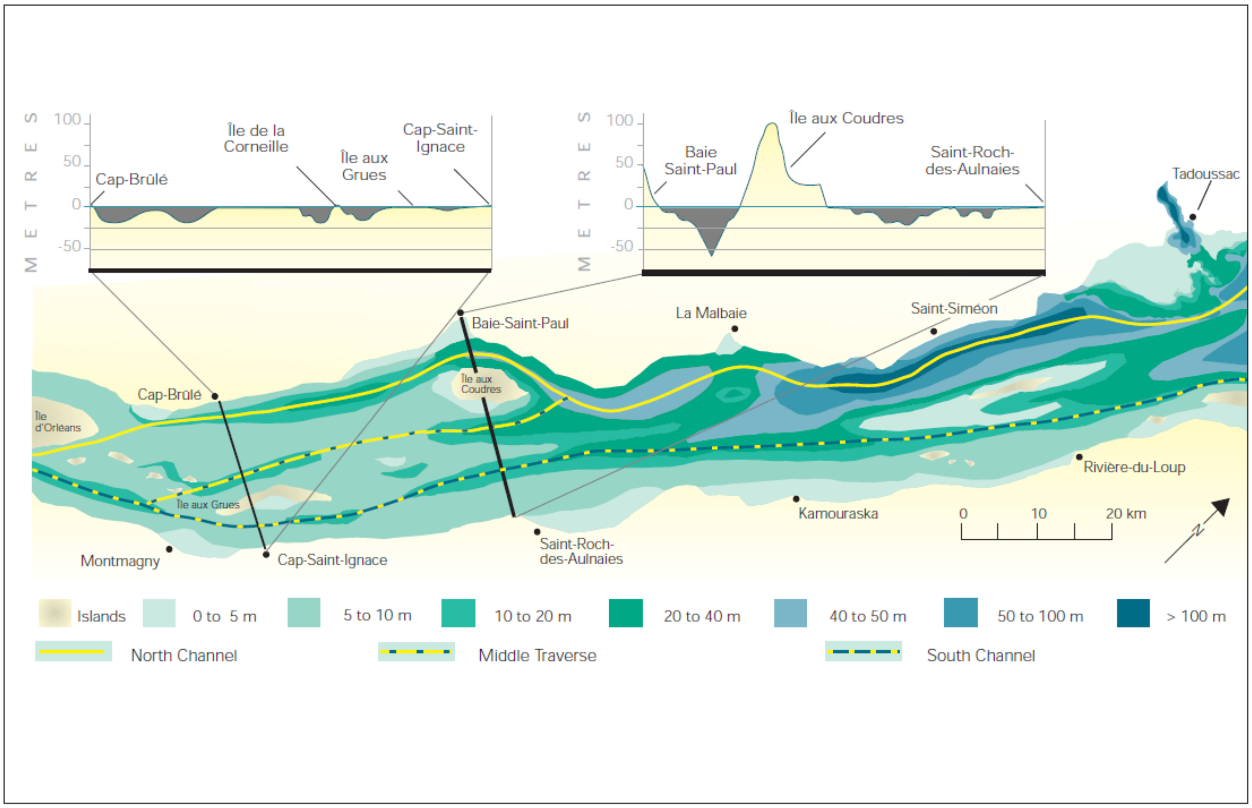

Figure 7. Bathymetry of the upper estuary (St. Lawrence Centre 1991)

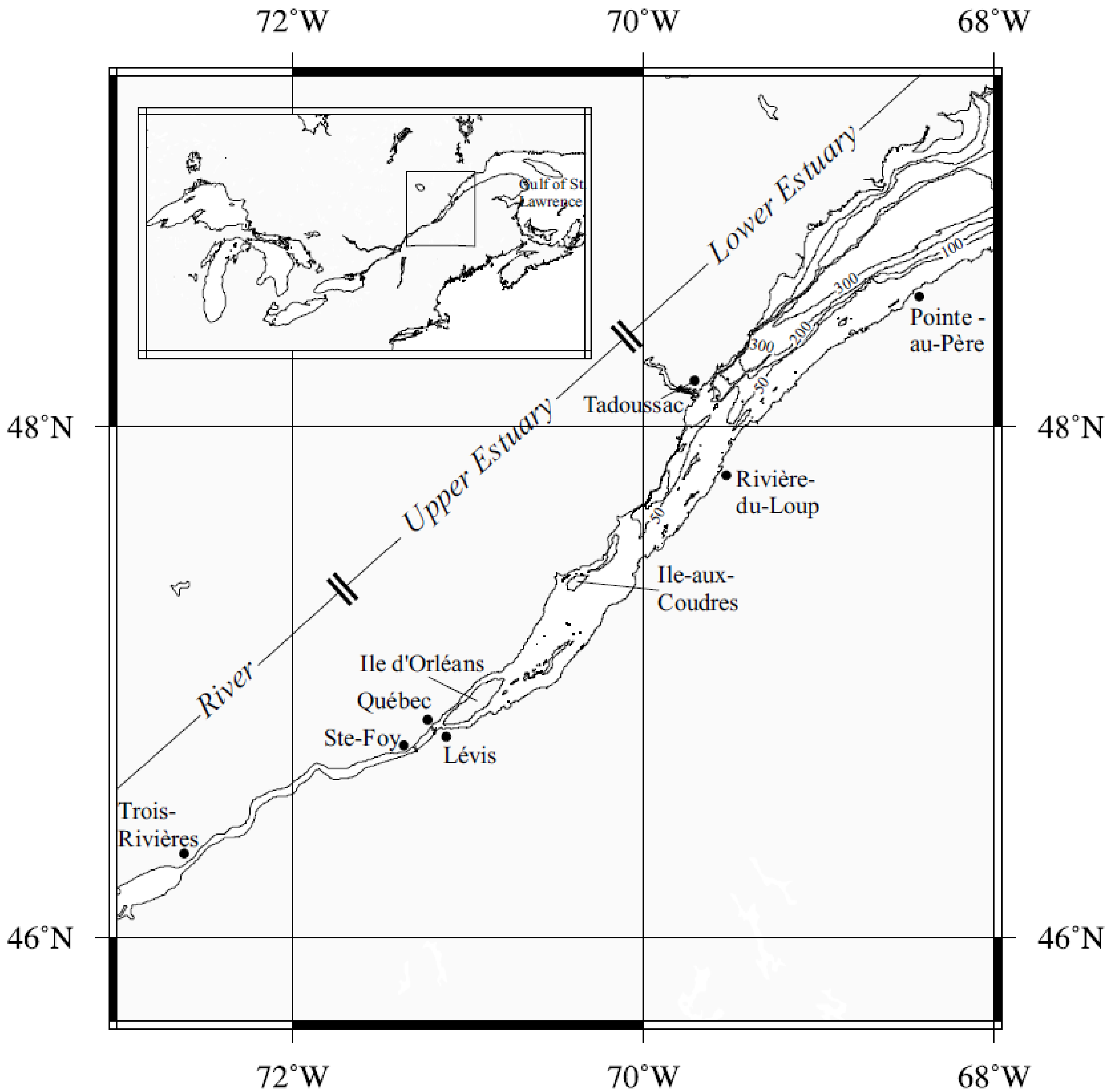

Figure 8. Upper and lower estuaries (Bourgault 2001)

2.1.3 <u>Lower St. Lawrence Estuary</u>

The last 300 km stretch of the river is the 12,600 km^2 lower estuary (Figure 9), beginning with the head of the Laurentian Channel and averaging 37 km across between Tadoussac and Pointe-des-Monts, with a maximum width of about 60 km at Baie-Comeau (St. Lawrence Centre 1991) and the sudden enlargement near Pointe-des-Monts where the Gulf of St. Lawrence begins (Bourgault 2001). Geometry and physics differ markedly between upper and lower estuaries (El-Sabh 1988).

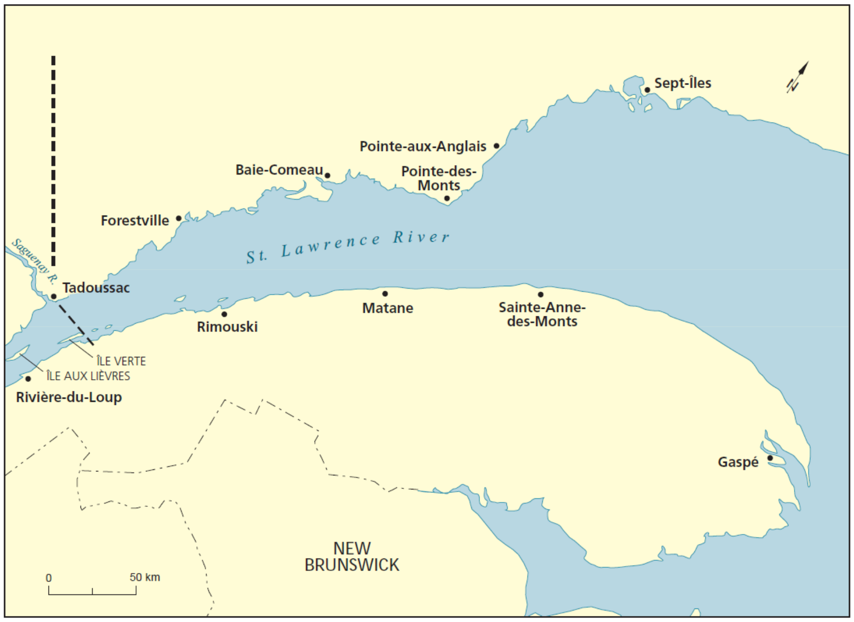

Figure 9. The lower estuary and Gulf (St. Lawrence Centre 1996b)

Circulation and mixing within the lower estuary are heavily influenced by tides, barometric pressure, air temperature, wind, local freshwater inputs, coastal relief, bathymetry, and the earth's rotation. The lower St. Lawrence estuary receives on average 12,000 m^3/s of freshwater annually with 40% higher discharge during spring freshets, creating buoyancy-driven circulation (Neu 1970), in addition to tidal mixing. The estuary shows a variable density structure, from well-mixed near the head to stratified near the mouth (Bourgault 2001; El-Sabh 1988; Neu 1970). The freshwater-saltwater transition is a dynamic front characterized by salinities in the range of 0.2-5 psu, with sharp gradients in biological properties and food-web structure (Vincent and Dodson 1999). In summer, three water masses of different temperatures and salinities are superposed, while in the winter, only two such water masses are superposed (Devine 2015; Dunbar et al. 1980; St. Lawrence Centre 1996b).

Numerical modelling has shown that mixing in the estuary is most intense near the Saguenay sill (Tadoussac) at the head of the Laurentian Channel, near English Bank, and near Ile-aux-Coudres (Bourgault 2001), especially during the spring freshet, which pushes salt intrusion seaward about 12 km and increases residual circulation and turbulent vertical mass flux. High volumes of fresh water increased water column stability in the upper estuary, but decreased it in the lower estuary.

The lower estuary empties into the Gulf (Figure 3), a semi-enclosed, 195,000 km^2 sea (St. Lawrence Centre 1996b) containing about 3,553 km^3 of water, almost seven times smaller than the Gulf of Mexico, and bordered by Quebec, New Brunswick, Prince Edward Island, Nova Scotia and Newfoundland-Labrador. de Vernal et al. (2011) briefly describe the oceanographic features of the Estuary and Gulf of St. Lawrence as an epicontinental sea, characterized by a vast watershed supplying a mean freshwater discharge of 10,900 m^3/s (Bourgault and Koutitonsky 1999).

2.2 CIRCULATION

2.2.1 Saint Laurence Estuary and River

In addition to vertical fluctuation, astronomic tides generate horizontal currents up to 0.50 m/s in channels and straits and up to 3 m/s in the region around Quebec City (St. Lawrence Centre 1996b). Mathematical simulations yielded values of 0.25 m/s or less for the lower estuary, and 1.0 m/s around Tadoussac (El-Sabh and Murty 1990; St. Lawrence Centre 1996b). In the winter, these tides move the ice back and forth, especially in the upper estuary, which limits the formation of fast ice (Environment and Climate Change Canada 2017).

The density difference between the freshwater input (about 10^4 m^3/s) to the estuary near Quebec City, and oceanic water, combined with strong tidal currents and turbulent mixing drive an estuarine like circulation. On average, the surface brackish layer (from the surface to about 30 m depth) flows seaward while a cold and salty compensating bottom flow takes place at depth to renew the waters in the deeper channels of the upper estuary (Neu 1970). This dense water comes mainly from the cold (-1 to 1 ^{0}C) intermediate layer (50-150 m depth) found throughout the lower estuary and the Gulf of St. Lawrence (Dickie and Trites 1983; El-Sabh 1988; Galbraith 2017; Koutitonsky et al. 1991). This layer is continuously advected landward into the estuary by the persistent residual circulation described above by Bourgault (2001).

Measurements of current velocity in the north channel of the upper estuary (Figure 10) near Île aux Lièvres (about 20 km upstream of Tadoussac and 125 km downstream of Île d'Orléans) during tidal phases, suggest the existence of a bi-layer current in all tidal phases except for 1 hour before high water and 2 hours before low water (Bourgault et al. 2001).

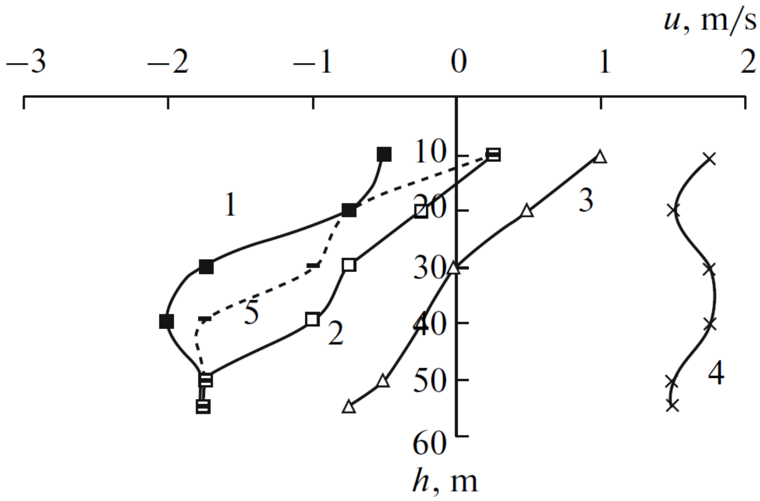

Figure 10. Current profiles in the Northern Passage at Ile-aux-Lièvres (1) 1 h before high water, (2) 2 h after high water, (3) 3 h after high water, (4) 2 h before low water, (5) 3 h after lower water (Bourgault et al. 2001)

Depending on the phase of the moon and the amount of fresh water outflow, deep, cold water from the Gulf can fill up the estuary (Koutitonsky 1979). The net transport (averaged over the tidal cycle) was found to be upriver; however, the residual flow of the Gaspé current was always directed toward the Gulf.

2.2.2 Lower Estuary

Much of the water entering the Gulf from the Saint Lawrence estuary through Honguedo Strait (between Gaspésie and Anticosti Island) moves along the southern coast (Dolgopolova and Isupova 2011) due to the Gaspé current (Figure 11). It originates at the head of the Lower Estuary, runs along the south coast to Cape Gaspé, where it is 15-20 km wide in the top 40-50 m of the water column, and dissipating on the shelf off the Magdalen Islands (Tang and Bennett 1981). Eighty percent of the water transported in the upper 50 m of the Gaspé current is upwelled from the 50-100 m layer, 71% from the northwestern Gulf and 9% from the Lower Estuary (Bugden 1981). Of the remaining 20%, 17% is due to surface recirculation from adjacent regions of the Gulf and 3% to fresh water discharged by the St. Lawrence.

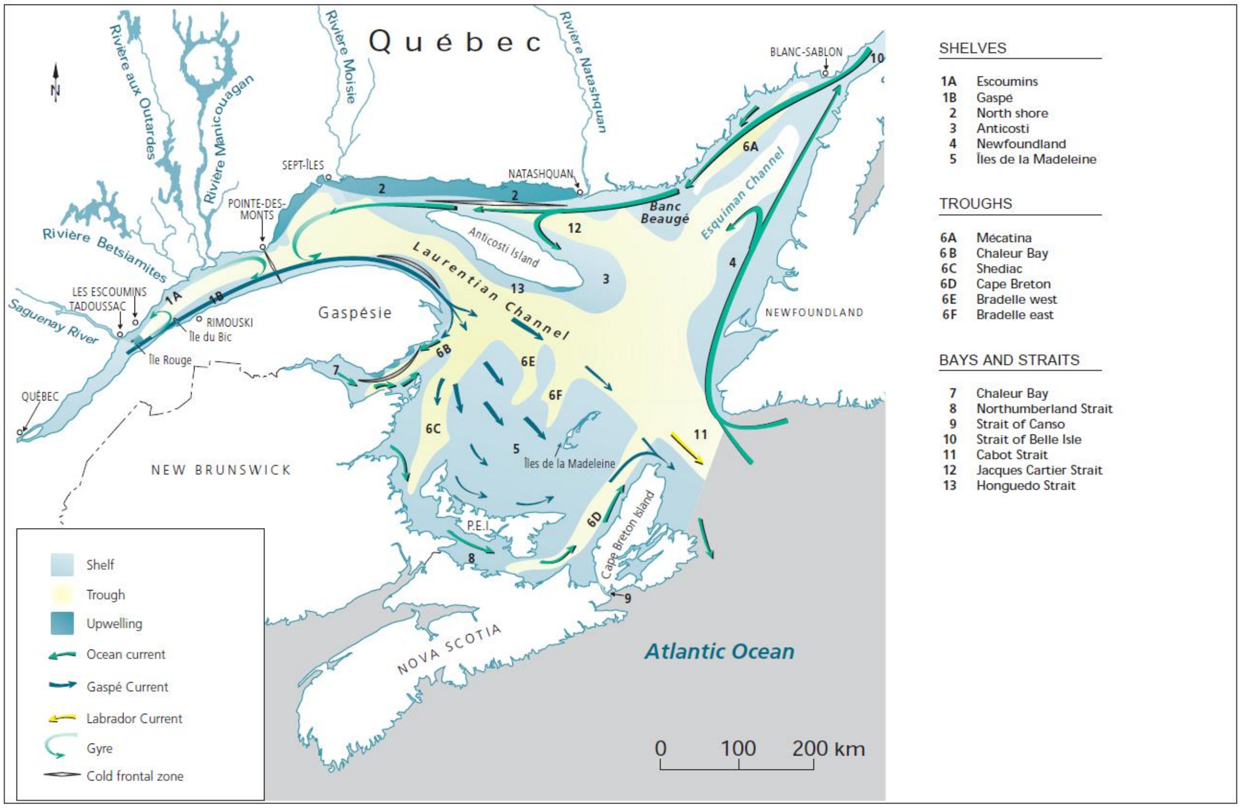

Figure 11. Currents in the lower estuary and Gulf (St. Lawrence Centre 1991)

2.3 TIDES

Mixed, semi-diurnal, barotropic tides from the Atlantic Ocean propagate through the Gulf of St. Lawrence and estuary, over the sill at the head of the Laurentian Channel, producing turbulent tidal currents and renewing the cold water basins of the north and south channels, and the Saguenay Fjord (Belzile et al. 2016; Bourgault et al. 2001; Dolgopolova and Isupova 2011; Drapeau et al. 2003; Dufour and Ouellet 2007; El-Sabh and Murty 1990; Farquharson 1962; Saucier and Chasse 2000; Saucier et al. 2003). A tide wave generated near Cabot Strait takes close to one day to reach Lake Saint-Pierre, upstream of Trois-Rivières (St. Lawrence Centre 1996b). The semidiurnal wave from tidal action amplifies (Figure 12) as it moves up the estuary (Godin 1979).

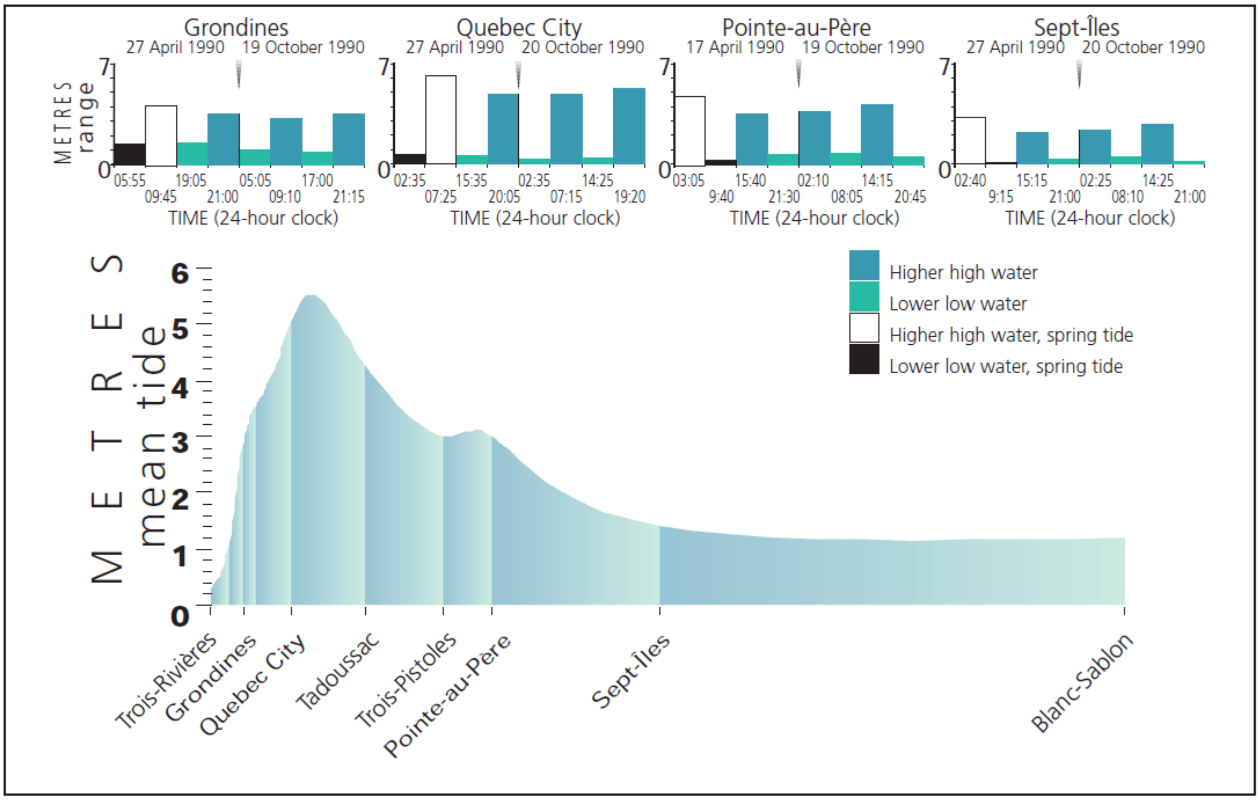

Figure 12. Variations in the tide range in the St. Lawrence (St. Lawrence Centre 1996b)

At Anticosti Island, neap tide magnitude is 1 m and spring tide is 2 m. Mean ranges are 2.3 m at Sept-Îles, 2.5 m in the Pointe-des-Monts to Mont-Joli area, 3.0 m at Pointe-au-Pére, and 4.1 m near Quebec City (Fisheries and Oceans Canada 1992). A maximum height of 4.9 m during spring tide and 2.8 m during neap tide was observed at the estuary head near Quebec City (de Borne de Grandpré and El-Sabh 1980), and a range of 5.0-7.5 m was recorded at Saint-François gauging station on the southeastern extremity of Île d'Orléan, where tidal range is known to be greatest (Godin 1979).

The mean tidal range at Quebec City is 4.1 m (St. Lawrence Centre 1993), increasing to 5.8 m for spring tides (Robitaille 1998). At Quebec City, tidal flow is 65,000 m^3/s (Robitaille 1998), which is 4.5 times the mean river flow of 12,100 m^3/s (St. Lawrence Centre 1993). At ebb tide, the sum of tidal and river flow can be up to 75,000 m^3/s off Île d'Orléans (Robitaille 1998). At Montmagny (Upper Estuary), total mean flow (river and tidal) is estimated at 90,000 m^3/s (St. Lawrence Centre 1991, 1996b). Flow velocity in the Richelieu Rapids can reach 10 m/s at ebb tide, compared with 4.6-7.4 m/s between the rapids and Quebec City (Robitaille 1998).

Upstream of Quebec City, the semidiurnal tides rise quickly and ebb slowly (El-Sabh and Murty 1990), and their influence extends as far upstream as Lake Saint-Pierre (Godin 1979). Beyond Lake Saint-Pierre, daily fluctuations in water level give way to biweekly fluctuations of about 0.20 m (Figure 13). Near Trois-Rivières, the tidal maximum never exceeds 0.2 m (Dolgopolova and Isupova 2011). The fluctuating river levels at Montreal (0.05 to 0.15 m) are superimposed on the 0.20 m biweekly astronomic tides from the estuary (Godin 1979).

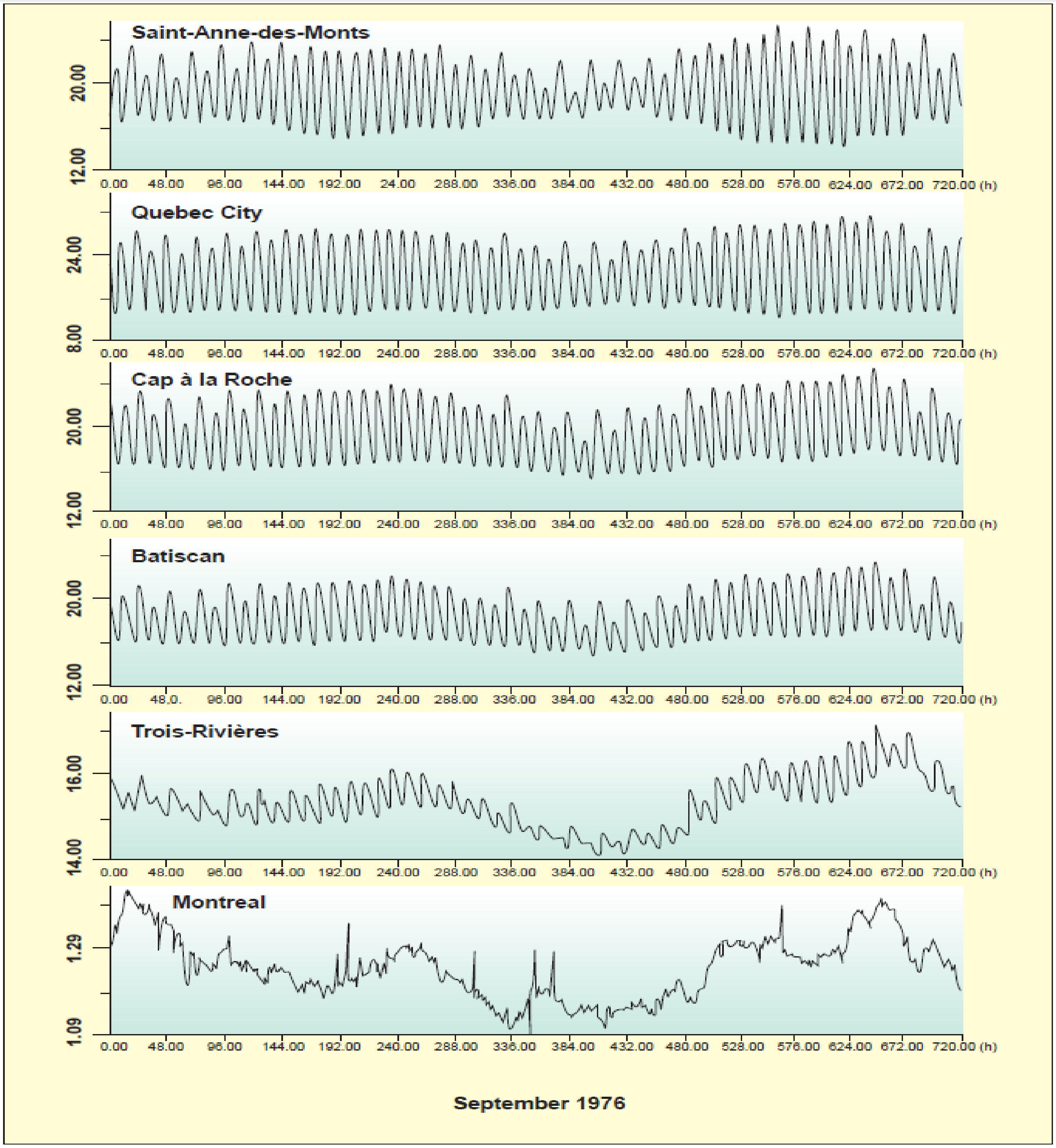

Figure 13. Modification of the tide wave between Sainte-Anne des-Monts and Montreal (Godin 1979)

2.4 WATERSHED

2.4.1 River Discharge

Freshwater inputs to the St. Lawrence River, estuary and Gulf come from the numerous tributaries within the watershed which includes the Great Lakes (Dufour and Ouellet 2007). Near the Cornwall gauging station, mean water flow is 7,350 m^3/s (232 km^3/year), maximum flow averages 10,000 m^3/s, and the minimum averages 4,500 m^3/s (Dolgopolova and Isupova 2011). Mean annual flow at Sorel is 9,868 m^3/s. For Québec City at the head of the estuary, the mean is 11,300-12,000 m^3/s or 357-379 km^3/year (Bourgault and Koutitonsky 1999; Couillard 1987; Koutitonsky 1979). Toward the mouth of the estuary, it increases to 14,400-16,800 m^3/s (454-530 km^3/year) (El-Sabh 1988). The mean long-term water flow (Table 1) at Quebec City from 1955 to 1999 was 12,000 m^3/s or 379 km^3/year (Bourgault and Koutitonsky 1999).

Table 1. Monthly average flow for the Saint Lawrence River near Québec City, 1955–1999 (Bourgault and Koutitonsky 1999)

	River Flow (m^3/s)	% of yearly total
January	10700	7.4
February	10700	7.4
March	12000	8.3
April	16800	11.7
May	15800	11.0
June	12400	8.6
July	11300	7.8
August	10600	7.4
September	10400	7.2
October	10900	7.6
November	11400	7.9
December	11100	7.7
Average for the year	12000	8.3

The monthly flow is relatively uniform (Table 1). An increase up to about 17,000 m^3/s with a maximum of 23,700 m^3/s (1976) from April to May was due to snowmelt, and variations in river water flow within each month can be even wider, depending on synoptic conditions and level variations in the Great Lakes (Dolgopolova and Isupova 2011).

The annual mean contribution, from 1964 to 2017, by the Ottawa River, the largest tributary of the St. Lawrence, is 1,942 m^3/s, with a mean daily minimum of 744 and maximum of 5,356 at Carillon generating station, west of Montreal (Ottawa River Regulation Planning Board 2018).

Freshwater runoff data for the St. Lawrence River updated monthly (Figure 14) are available from the St. Lawrence Global Observatory. Galbraith et al. (2015) used

RIVSUM (river sum) II, a hydrological watershed model, to estimate monthly runoff for other major rivers flowing into the estuary, and found that they contribute about 5,000 m^3/s, the equivalent of 40% of the St. Lawrence River (Figure 15). River regulation was found to exert a significant influence on runoff.

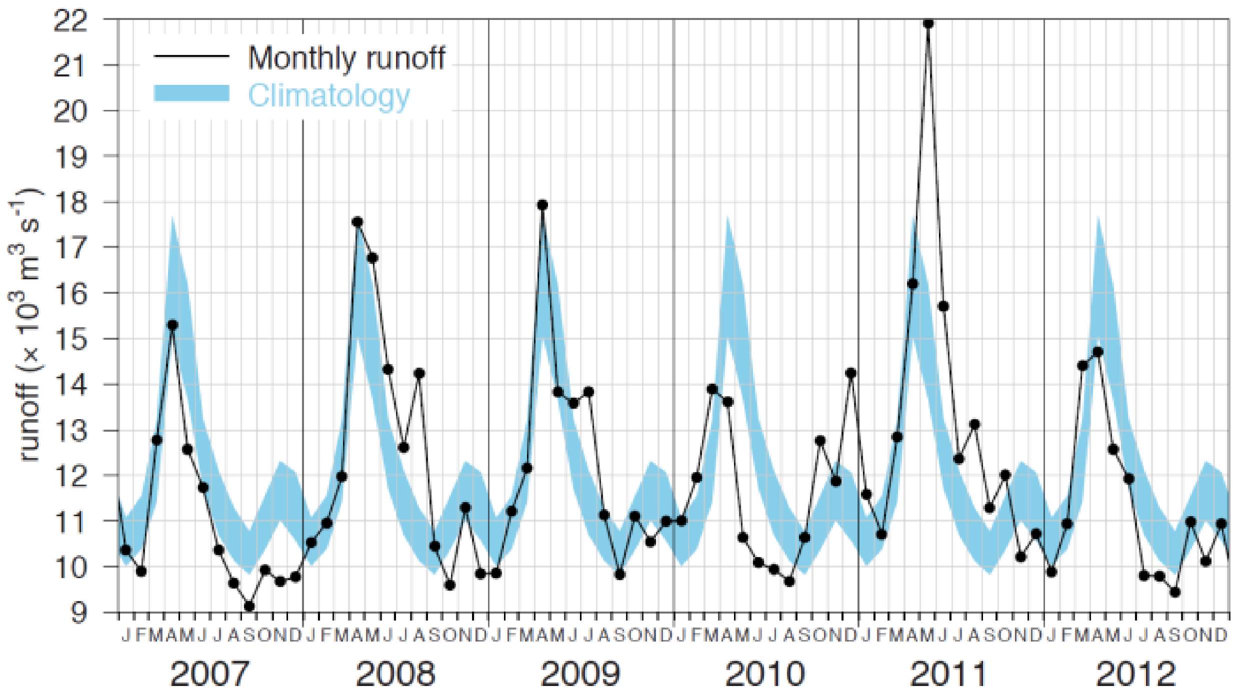

Figure 14. Mean monthly flow of the St. Lawrence at Québec City in black, and 1981-2010 monthly climatologies plus and minus one-half standard deviation in blue (Galbraith et al. 2014a)

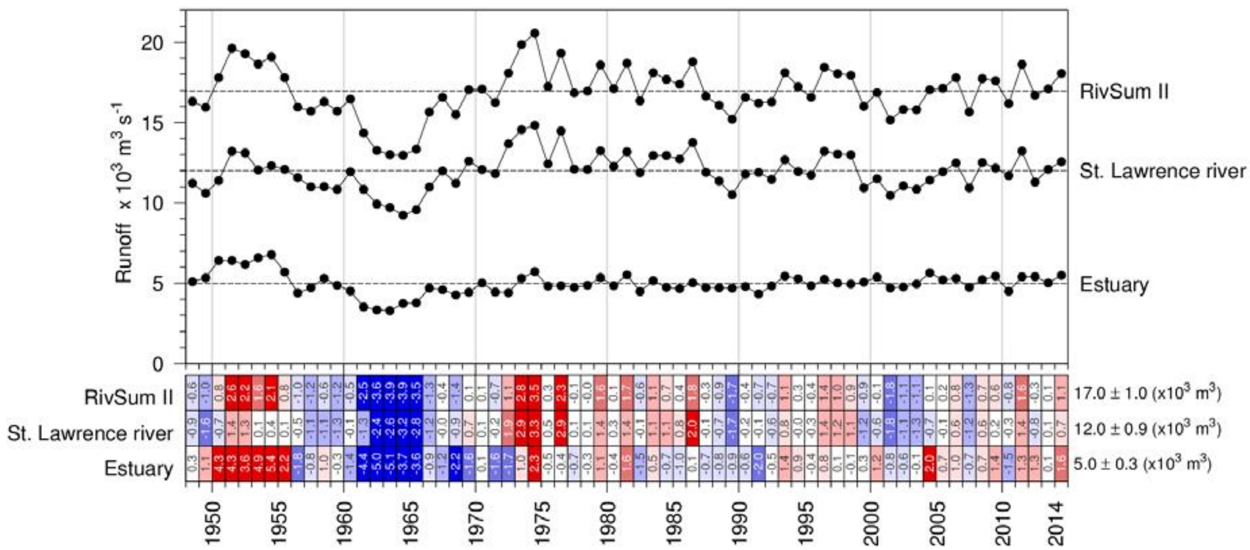

Figure 15. Annual mean flow of the St. Lawrence River at Québec City and of the sum of all rivers flowing into the estuary with the 1981-2010 climatological means as horizontal lines and on the right side of the scorecards. Scorecards are normalized anomalies with red, blue and white representing positive, negative, and not significant, respectively, and intensity represented with shading (Galbraith et al. 2015)

2.4.2 Industrial Wastewater

There are numerous petroleum product depots in addition to three oil refineries on the St. Lawrence (Figure 16). Suncor and Shell are in east-end Montreal, and Valero is in Saint-Romuald. Wastewater discharge in 1992 from these refineries contributed 74.5 kg of ammonia nitrogen, 160 kg of oil and grease, 743 kg of suspended solids, 4.4 kg of phenols and 1.3 kg of sulfides to the river daily (St. Lawrence Centre 1996b). More detailed information on refinery discharge in 2011 and 2012 can be found Table 2 (Pineault 2014).

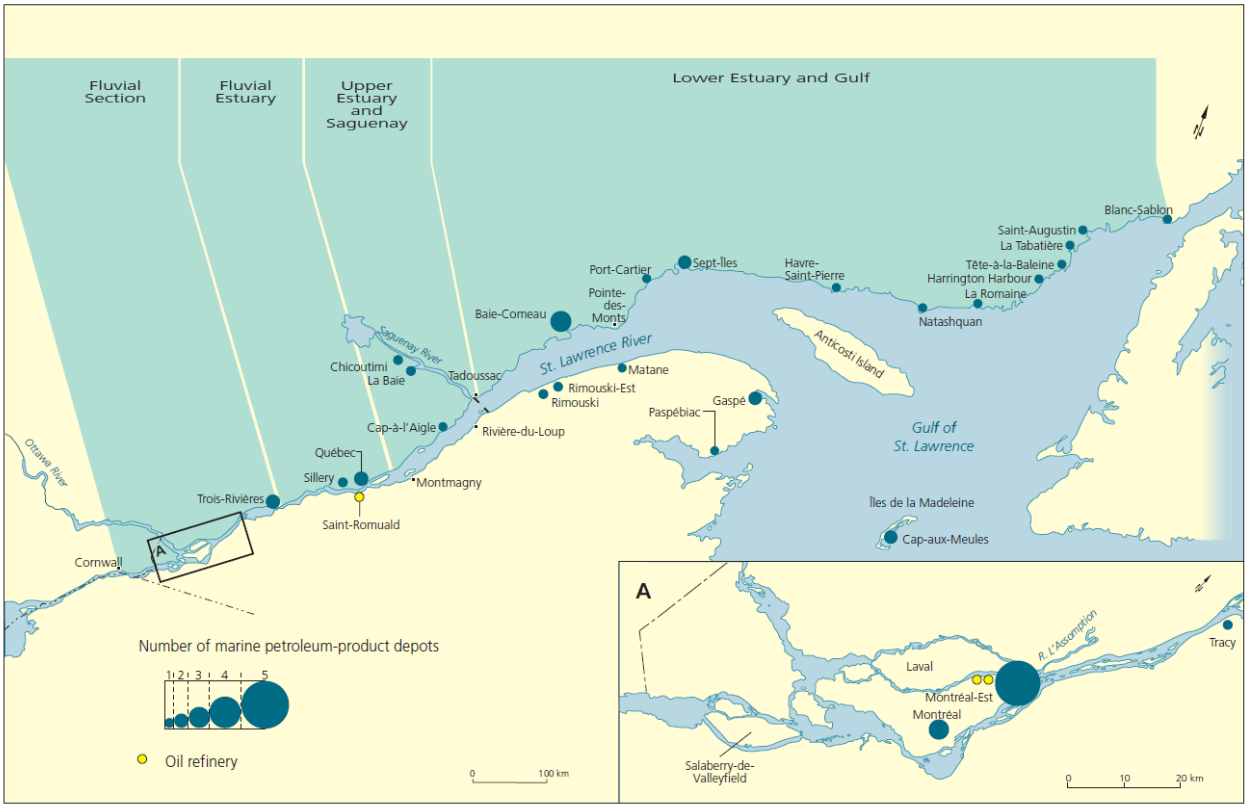

Figure 16. Oil industry along the Saint Lawrence (St. Lawrence Centre 1996b)

Table 2. Discharge from oil refineries along the Saint Lawrence River in 2011 and 2012 (Pineault 2014)

		Shell		Suncor		Valero		**Total**	
Parameter	Unit	2011	2012	2011	2012	2011	2012	**2011**	**2012**
Volume	m^3 (x1000)	2,855	1,254	4,395	4,911	4,190	3,822	**11,440**	**9,988**
Oil & Grease	kg	1,832	603	4,587	4,537	961	1,061	**7,380**	**6,201**
Phenols	kg	49	17	29	24	13	23	**91**	**64**
Sulfides	kg	56	24	191	244	258	280	**505**	**547**
Ammonia Nitrogen	kg	306	35	4,836	4,682	9,995	13,241	**15,137**	**17,958**

2.4.3 <u>Sediments and Dissolved Solids</u>

Compared with other rivers of the world, the St. Lawrence River has a low sediment load (Dolgopolova and Isupova 2011). The amount of sediment entering the estuary from the river is 1.1-6.5 million t/year (Couillard 1987; Environment and Climate Change Canada 2016; Kranck 1979). Lake Ontario contributes <3% of the suspended sediments, tributaries contribute 32% and erosion of the bed and banks of the St. Lawrence River contributes about 65% (Rondeau et al. 2000). The spring contribution is

60-70% of the total annual load, summer is 15%, fall is 15-25%, and winter is 5% (Frenette et al. 1989). Total runoff of dissolved solids into the Gulf of St. Lawrence is 92.5 thousand t/km^2 per year (Dolgopolova and Isupova 2011).

Upstream of Lake Saint-Pierre (between Montreal and Trois-Rivières) the suspended sediment concentration ranges from 4 to 10 mg/L, increasing to 30–50 mg/L downstream to Québec City, and 50-200 mg/L immediately upstream of Île d'Orléans (Couillard 1987). Downstream from Île d'Orléans, suspended sediment concentration decreases to 40-80 mg/L, dropping to < 5 mg/L at Rivière-du-Loup and < 2 mg/L at the Saguenay River.

Turbidity in the upper estuary is controlled by exchange of sediments from mudflats and marshes, due to circulation, ice, wind-induced turbulence and tide, and shows a maximum between Île d'Orléans and Île aux Coudres of 50-200 mg/L (Table 3), and peaks have exceeded 400 mg/L (d'Anglejan 1990). This region constitutes a zone of maximum turbidity from floc formation (d'Anglejan 1990; Kranck 1979), which would be important in the formation of oil-mineral aggregates during an oil spill. The zone migrates 30-40 km up and down the estuary depending on tide and river flow. Ebb tide discharges 15‰ (50% mixed with sea water) turbid water along the southern shore through the Southern Passage and forms a front, separating estuarine waters by their salinity, temperature, and turbidity, which also migrates according to changes in river flow (Dolgopolova and Isupova 2011).

Table 3. Suspended solid concentration from Kingston, Ontario to Île d'Orléans

Location	Concentration (mg/L)
Kingston	1-2
Lake Saint-Francois	4-5
Lake Saint-Louis	7-8
Lake Saint-Pierre	9-13
Quebec City	16-20
East end of Île d'Orléans	25-70
Maximum turbidity zone	200-400

Sediment dynamics are dominated by tidal action at the head of the upper estuary around Île d'Orléans where tidal marshes abound, but moving downstream to Pointe-des-Monts, this changes to wave-dominated, especially at the mouth of the lower estuary, where sandy beaches are common (Drapeau 1990; Drapeau 1992; St. Lawrence Centre 1996b). The main tributaries downstream of Quebec City (Saguenay, Betsiamites, aux Outardes and Manicouagan rivers) are responsible for sediment loading in the lower estuary (St. Lawrence Centre 1996b). Sediment accumulation occurs during winter in the marshes and tidal flats of three main inner lakes beyond the navigation canal, where flow velocity is less than 0.3 m/s and depth does not exceed 4.5 m (Dolgopolova and Isupova 2011). Erosion of these occurring during the spring freshet adds sediment to the river (d'Anglejan 1990) along with major erosion zones in canals of the middle reach of the river (Couillard 1987).

Bottom sediments of the upper estuary consist mostly of coarse sand (0.06–2 mm) and gravel (2-80 mm) with some fine silty-clays ≤60 μm (Dolgopolova and Isupova 2011), whereas the deep, lower estuary is a region of settling for these fine sediments, at a rate of 1.5-4 mm/year (d'Anglejan 1990). The silt/clay ratio averages 2.3:1, being 20-30% clay less than 0.002 mm diameter, and 5-70% fine sand of 0.063-0.125 mm diameter (d'Anglejan 1990). The organic content of suspended particulate matter in the upper estuary appears to originate from land erosion, while that of the lower estuary appears to come from marine production (d'Anglejan 1990).

2.5 SALINITY, WATER TEMPERATURE, AND DISSOLVED OXYGEN

The St. Lawrence has a classical estuary: water runoff and precipitation exceed evaporation, fresh and salt water mix, and salinity steadily decreases going upstream. The upper boundary of saline water intrusion shifts depending on river flow, tidal magnitude and phase, and spring-neap cycle (Bourgault et al. 2001; Dolgopolova and Isupova 2011). In the warm season, the boundary lies near the eastern extremity of Île d'Orléans and shifts within 20 km (Dolgopolova and Isupova 2011; Gagnon 1998). Mean surface water salinity increases from 0.1 at the head of the estuary to 18–26 at the Saguenay river mouth (Gagnon 1998), while salinity at the bed can reach 20–30‰ (Neu 1976). In the middle and lower estuary, surface salinity varies from 28 to 32‰, depending on season, and increases with depth to 33–35‰, equivalent to the Gulf (Dolgopolova and Isupova 2011; Neu 1976).

Surface and bottom waters form a salinity gradient between Île d'Orléans and Île aux Coudres (Figure 17). Between Île d'Orléans and Montmagny Archipelago, salinity in summer does not exceed 2-3‰ on the surface and 4-6‰ at the bottom. Decreased river flow in winter allows the salinity in the bottom layer to rise to 6-10‰. Seaward from Île aux Coudres changes in salinity from fresh water input is only noticeable near tributaries (Couillard 1987; Dolgopolova and Isupova 2011).

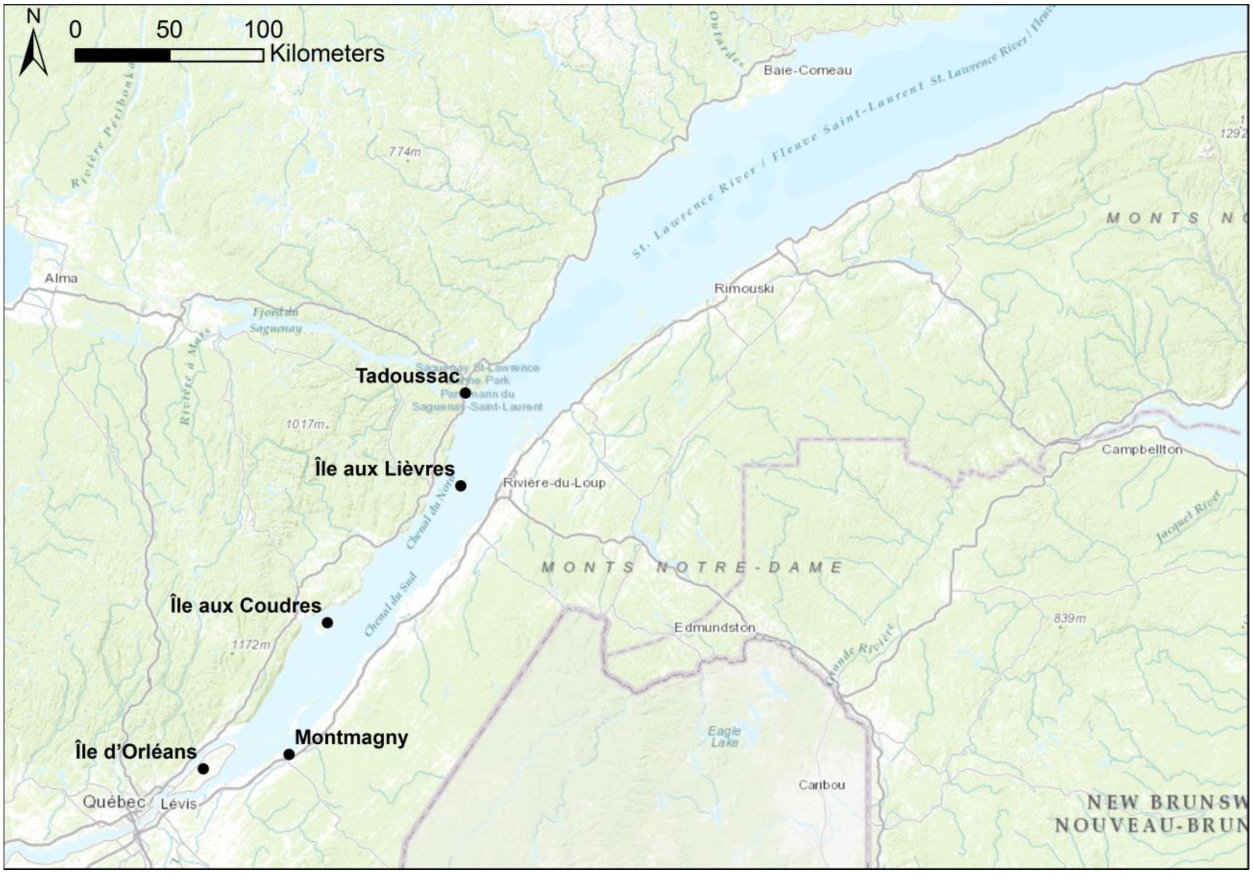

Figure 17. Geographic Locations in the upper Saint Lawrence Estuary

Near the inflow of the Saguenay River, vertical migration of the 32.5‰ isohaline with the tide has been described (de Borne de Grandpré and El-Sabh 1980). At high water, this 32.5‰ isohaline is at a depth of 20-25 m. During ebb tide, the depth of the isohaline decreases to its maximum of 75 m, and vertical flow velocities, directed toward the bed (positive) gradually increase and reach their maxima at 2.2 mm/s 4 h after high water. The reverse occurs during flood tide as the isohaline moves upward with a mean velocity of 2.3 mm/s, 2-3 h before high water. The vertical velocity gradient on a spring tide is twice that of a neap tide (de Borne de Grandpré and El-Sabh 1980; Dolgopolova and Isupova 2011).

The mean monthly water temperature on the Gulf surface ranges from 0 (January–April) to +13°C (August). From May to October, air temperature averages 2°C higher than water temperature in the Gulf surface layer. Fresh water from the St. Lawrence River tends to flow along the south shore of the lower estuary, while cold Atlantic water moves upstream at depth through the Strait of Belle Isle and the Laurentian Channel (Figure 18) resulting in three layers (Dickie and Trites 1983): (1) a seaward, mixed, 27-32 ppt, surface layer from river discharge that extends down 25 to 75 m, (2) a landward, intermediate, −1 to 2°C layer of saline (31.5–33 ppt) water from winter cooling of the Gulf surface (Banks 1966; Galbraith 2017; Gilbert and Pettigrew 1997), and (3) a slow, landward (Bourgault et al. 2001), deep, 34-34.6 ppt, warmer (4 to 6°C) layer from the Atlantic (Koutitonsky 1979).

The surface layer displays large seasonal variations in temperature and salinity due to atmospheric and buoyancy forcing. It is relatively thin (Craig and Gilbert, 2008), freezes in winter for 3 to 4 months, and warms to 18°C in summer. Seasonal gradients of temperature and productivity are extremely high (Le Fouest et al. 2006). Maximum surface temperatures occur between mid-July and mid-August, with a climatological mean (1985–2010) that ranges from about 7°C at the head of the lower estuary at Tadoussac, to over 17°C on the Magdalena Shallows. Summer surface waters are getting warmer because of rising air temperatures by 0.9°C every 100 years since 1873, and faster in recent years (Galbraith et al. 2014b). From autumn into winter, surface cooling, wind-driven mixing, decreased tributary flow and ice formation cause the surface and intermediate layer to merge down to a depth of 75 m (Galbraith 2006; Gilbert and Pettigrew 1997; Saucier et al. 2003). In spring, the cold layer that was formed in the northern Gulf of St. Lawrence and in the Laurentian Channel becomes a subsurface water mass that flows into the Estuary (Dufour and Ouellet 2007). During spring, surface warming, sea-ice melt waters, and continental runoff produce a lower-salinity and higher-temperature surface layer, beneath which the cold waters from the previous winter are partly isolated and form the summer cold intermediate layer which gradually warms, deepens, and persists until the following winter (Cyr et al. 2011; Galbraith et al. 2015; Gilbert and Pettigrew 1997). The extent of ice formation, volume of sea ice and duration of the ice season have declined since 1990. The years 1969, 2010 and 2011 were practically ice-free winters with air temperatures 2-3°C higher than normal (Galbraith et al. 2014b; Galbraith et al. 2015).

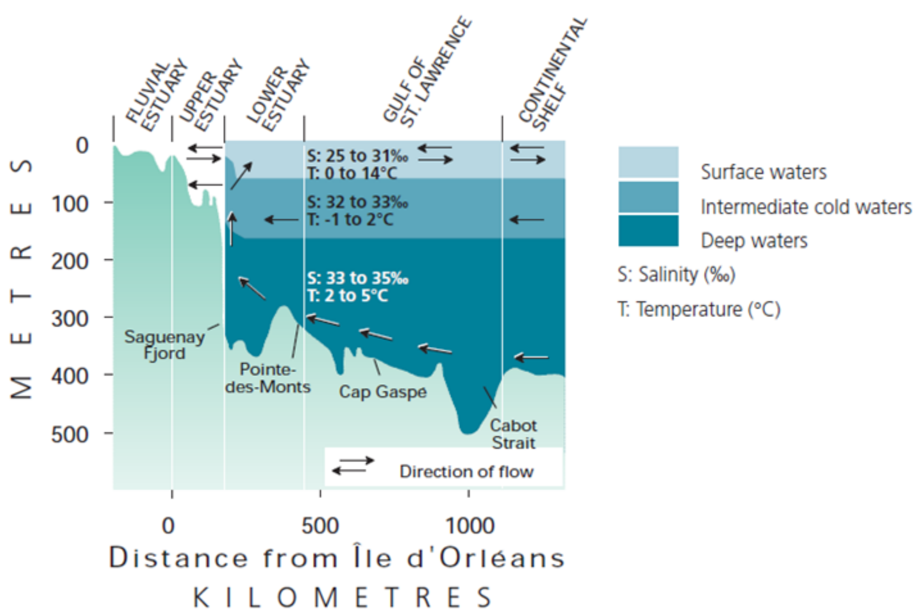

Figure 18. Water stratification in the St. Lawrence system (St. Lawrence Centre 1991)

The characteristics of the cold intermediate layer (<1°C, Figure 20) are closely related to climatic conditions: winter cooling (to -1°C down to 75 m depth, Galbraith et al. 2014a), increased density, and brine release during sea-ice formation (Craig and Gilbert 2008; Gilbert and Pettigrew 1997). Mean summer temperature in the cold intermediate layer fluctuates yearly. It was very cold for the period 1986-1998 (Figure 19), but since then, temperatures have generally been on the rise and summer 2012 was the warmest since 1980 (Galbraith et al. 2014b).

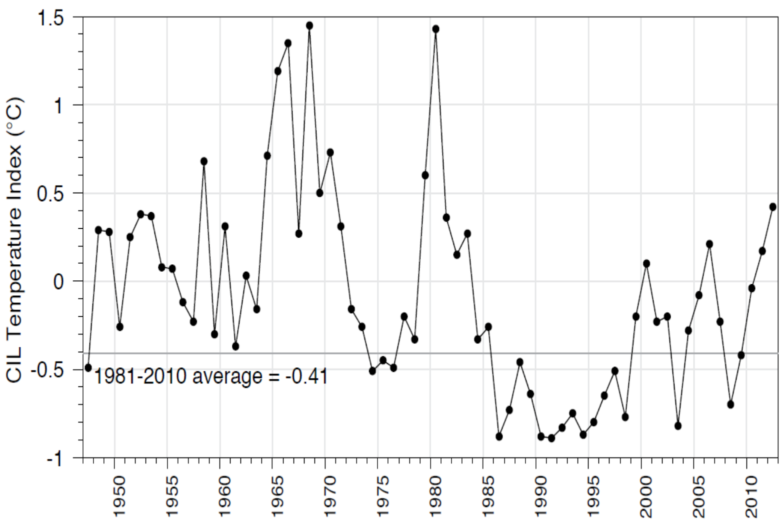

Figure 19. Mean annual mid-July cold intermediate layer (CIL) temperature (Galbraith et al. 2014b)

Currents in the cold intermediate layer are predominantly landward on the northern side of the Laurentian Channel and seaward, but weaker, on the southern side of the Channel, so that the net transport in the layer is landward (Mucci et al. 2011).

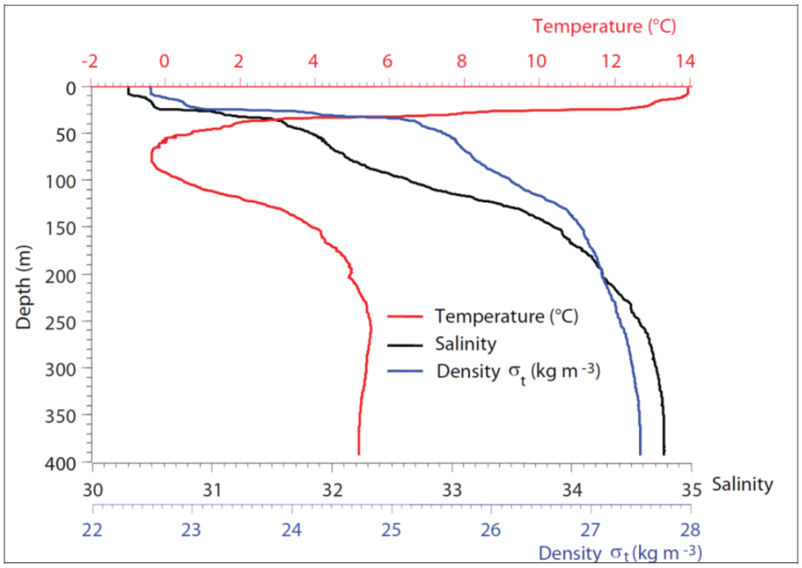

Figure 20. Summer salinity, temperature, and density profile in the Lower St. Lawrence Estuary (de Vernal et al. 2011)

The deep bottom waters are a mixture of Labrador Current and North Atlantic central waters whose proportions vary over a very long term (Bugden 1991; Gilbert et al. 2005). This water flows landward, to Tadoussac at the mouth of the Saguenay Fjord and is characterized by upwelling, which results in extremely high productivity that maintains large whale populations (de Vernal et al. 2011). Vertical mixing (Neu 1970) or the interaction of stratified, intense, tidal currents with rapid shoaling near Tadoussac (Bourgault 2001; Reid 1977) appears to be responsible for the upwelling of large amounts of nutrients from below 50 m into the photic zone. Around Tadoussac the surface water tends to be always cold due to variable, but strong, tidal mixing of the upwelled water with water from the St. Lawrence and Saguenay Rivers (Koutitonsky and Bugden 1991; St. Lawrence Centre 1996b).

Giant cyclonic and anticyclonic eddies generated by regional winds are common between Les Escoumins and the western tip of Anticosti Island (Figure 11), producing cross-currents running north at île du Bic and south at Pointe-des-Monts (St. Lawrence Centre 1991, 1996b).

Water that forms the deep layer below 150 m moves upstream from Cabot Strait and the Strait of Belle Isle, mixes little with shallower water, and takes three to four years to reach the head of the lower estuary (Gilbert 2004). Respiration of organisms and oxidation of organic material reduce the dissolved oxygen concentration (Figure 21), such that the deep waters of the lower estuary became briefly hypoxic in the early 1960s, and have been consistently hypoxic at 19 to 22% saturation since 1984 (Galbraith et al. 2014b).

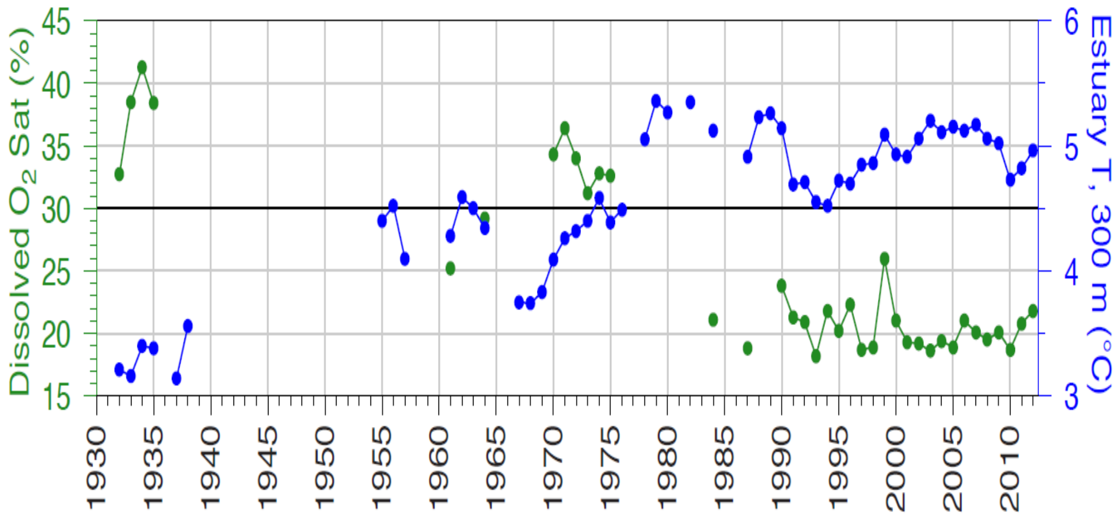

Figure 21. Temperature (blue) and dissolved oxygen (green) at 300 m in the lower estuary (Galbraith et al. 2014b)

3 CLIMATE

For the Atlantic region, it is anticipated that in the next 50 years there will be an increase in air temperature by 2-3.5ºC, >10% increase in precipitation, increased run-off, reduced sea ice (including icebergs), a rise in ocean temperature, a decrease in salinity, a decrease in the thickness of the surface mixed layer, decreased nutrient exchange from deep water to the photic zone (due to stronger stratification), decreased dissolved oxygen, and increased acidification by pH >0.1 (Fisheries and Oceans Canada 2013). The warm Gulf Stream and the cold Labrador Current are the two major ocean currents that have the greatest effect on weather in the region (Robichaud and Mullock 2001a). Circulation from the northwest causes strong southwest winds on the south shore of the lower St. Lawrence up to Île Bîcquette, near Rimouski, and fog is common over the water in the summer. Low ceilings and decreased visibility frequently occur along the coast during east and northeast winds (Robichaud and Mullock 2001b).

3.1 TEMPERATURE AND PRECIPITATION

The St. Lawrence River has a temperate climate with cold winters. Monthly average temperatures for Mont-Joli, which is centrally located along the southern shore of the St. Lawrence Estuary, shows average temperatures between -12.3°C (January) and 17.5°C (July) (Figure 22) (The Weather Network 2019). Precipitation statistics for Mont-Joli show an average annual rainfall of 606 mm and average annual snowfall of 350 cm with relatively consistent levels of precipitation throughout the year.

The St. Lawrence River is typically covered with ice from mid-December to mid-April and ice floes are also common in the greater estuary during this time (Dolgopolova and Isupova 2011).

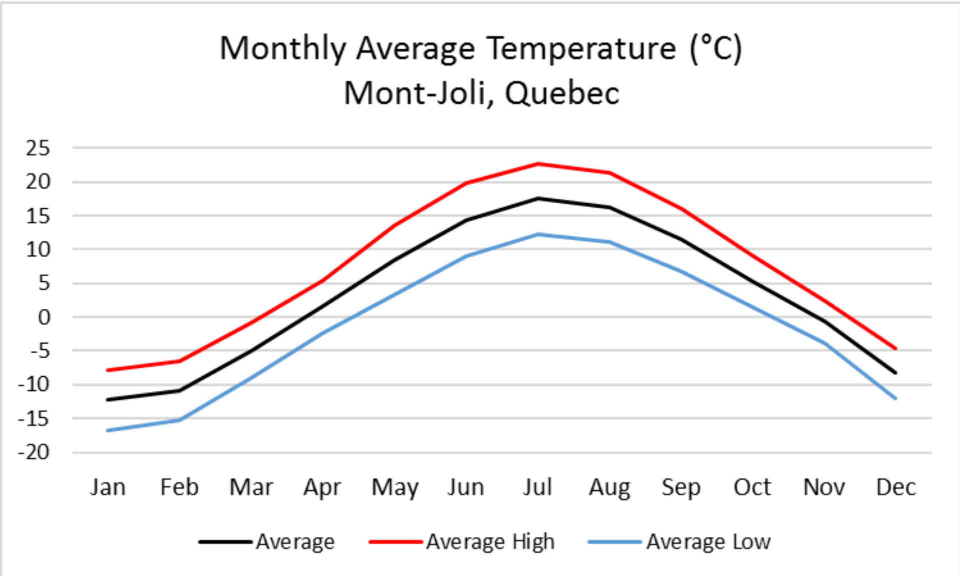

Figure 22. Monthly Average Temperature at Mont-Joli, QC (The Weather Network 2019)

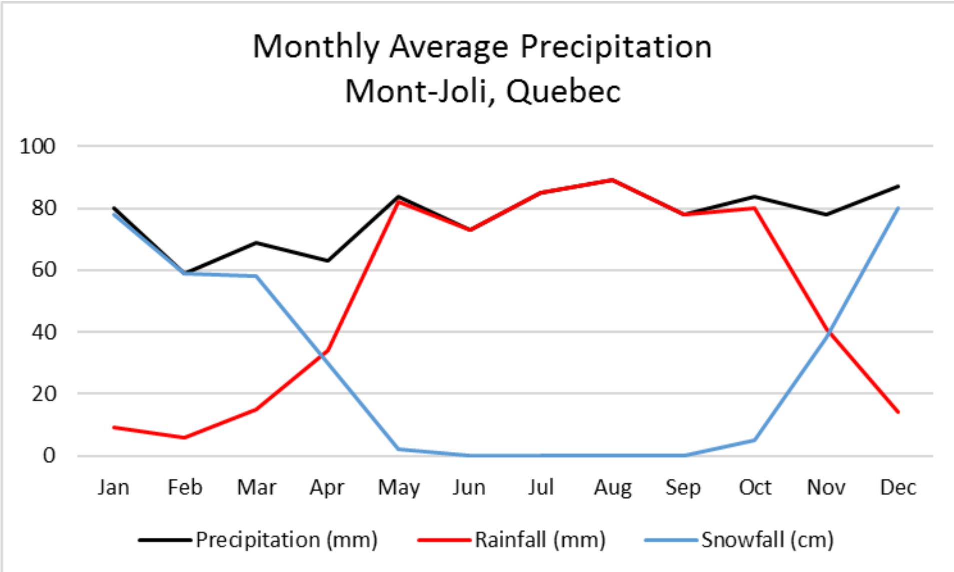

Figure 23. Monthly Average Precipitation at Mont-Joli, QC (The Weather Network 2019)

3.2 WIND AND WAVES

From June to November winds blow from the southwest and west (Figure 24), whereas in the winter they are northwesterly (Dufour and Ouellet 2007; Koutitonsky and Bugden 1991), but storm tracks can force wind direction (Dolgopolova and Isupova 2011). Wind speed is generally under 20 km/h, and the recurrence of winter winds >57 km/h is always less than 10% (Dolgopolova and Isupova 2011).

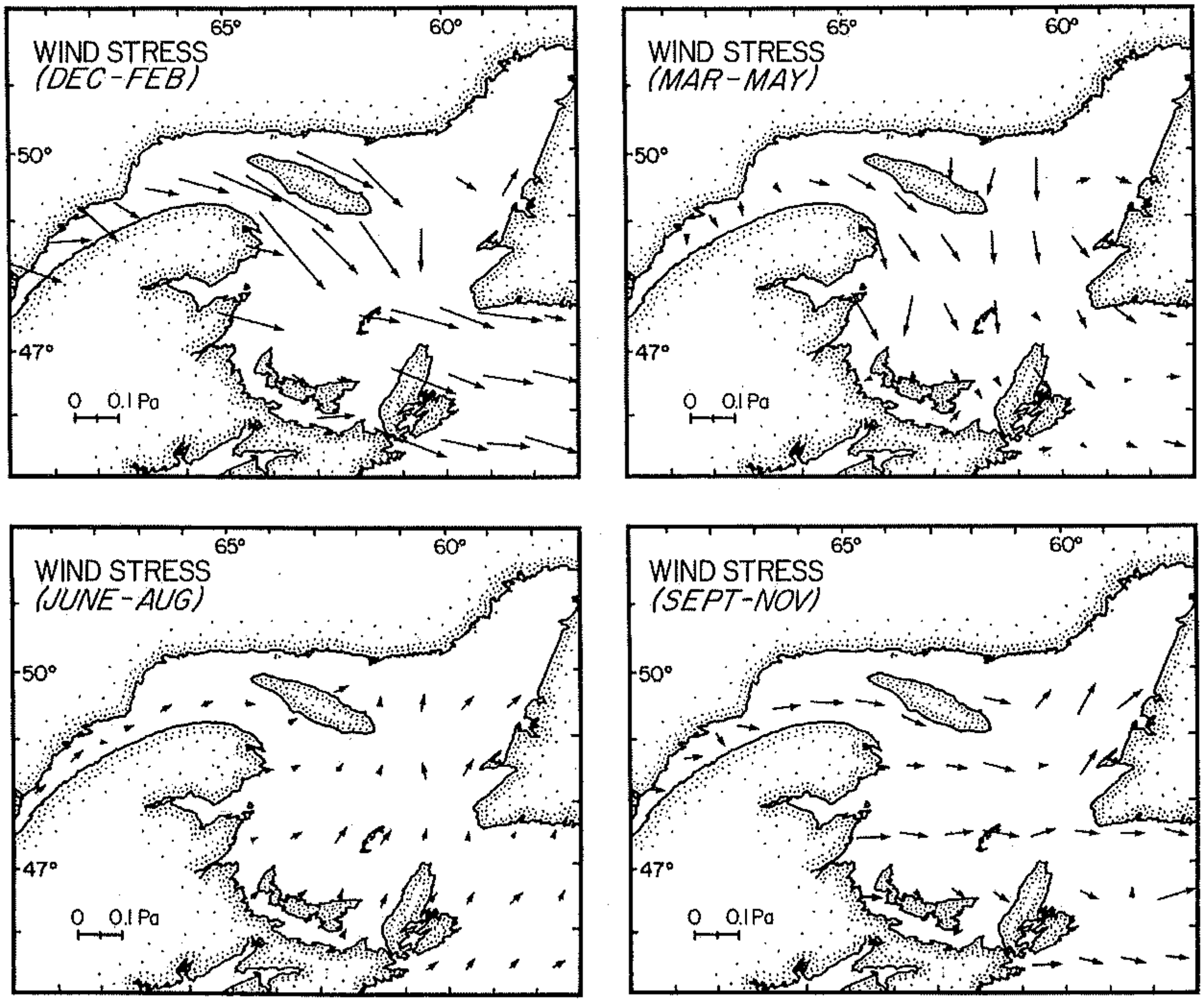

Figure 24. Wind direction in the St. Lawrence Estuary and Gulf; arrow size is proportional to wind speed (Koutitonsky and Bugden 1991)

At Mont-Joli on the southern shore of the lower estuary, the winter winds are predominantly westerly or southwesterly. Wind direction is a direct result of channeling in the St. Lawrence River Valley. Summer winds show a similar pattern, but tend to be lighter. The main wind axes are southwest and northeast, although southwesterlies in summer are almost twice as frequent as in winter (Robichaud and Mullock 2001a).

A model to evaluate the effect of ice cover on wave climate has been developed for the Gulf of St. Lawrence (Ruest et al. 2015). The study area was limited to deep water areas (>50 m), which excludes the western tip of Anticosti Island, but still encompasses the lower estuary. Average cumulative ice concentration determined by the regional ocean model with wind forcing from the Canadian Regional Climate Model (CRCM-1 and CRCM-2) generally increased from east to west for the 1981–2010 period, and extreme wave height was reduced by ice cover. In the estuary, 99% Significant wave height (Hs) was 1–2 m and the 50-yr Hs was 2.5–4 m, compared to 2–4 m and 4.5–8 m in the rest of the Gulf. The presence of ice reduced the wave height. The impact of sea ice was statistically significant within the whole study area. The ice-free condition increased the 99% Hs by 8–16% and the 50-yr Hs by 10% (Ruest et al. 2015).

4 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 Montreal were compiled by filtering for occurrences in the province of Quebec or international waters, within the latitudinal range of 45.3°N to 50.3°N, and within the longitudinal range of 64.0°W to 74.6°W. Chaleur Bay and surrounding areas of the Gulf of St. Lawrence, and parts of the Bay of Fundy located in this box are excluded. The area encompasses the St. Lawrence Seaway. See Table 4 for statistics.

Table 4. Transportation Safety Board incident and accident occurrences in the Port of Montreal and Saint Lawrence Seaway

Occurrences involving…	All years (1975-2018)	Annual Average (2015-2017)
All occurrences	2105	116.7
Petroleum cargo vessels	128	6.0
Pollution or cargo lost overboard	100	1.3
Petroleum spills onboard or overboard	3	0.7
Vessels sunk, capsized or destroyed	17	1.0

Eight occurrences involving cargo vessels carrying petroleum products were also flagged as occurrences involving pollution or lost cargo. In most cases the nature of the pollution was not stated in the occurrence summary and the occurrences were not flagged as petroleum spills in the database. One of these cases is the tanker Irving Nordic in 1991. The Marine Investigation Report (Transportation Safety Board of Canada 1991) states that the Irving Nordic, carrying 11,000 tons of crude oil, left the navigation channel of the St. Lawrence River downstream from Trois-Rivières due to a navigational error and struck bottom causing considerable damage to the ship and puncturing one cargo tank. The report indicates minor pollution and estimates one barrel of oil was lost, but this is not recorded in the TSBC database. Traces of oil were found in a nearby marina but could not be conclusively linked to the Irving Nordic.

The Irving Nordic was one of seven reported occurrences where a cargo vessel carrying petroleum product was seriously damaged. Another relevant occurrence is the collision between the oil tanker Hyde Park and the container vessel Cast Prosperity in 2005. The Hyde Park was carrying 30,000 tons of gasoline. Both vessels were travelling upstream in the dredged channel of Lac Saint-Pierre Southwest of Trois-Rivières when the Cast Prosperity attempted to overtake the Hyde Park. Due to the shape of the narrow and shallow channel strong hydrodynamic forces drew the vessels together into a collision. Both vessels suffered considerable damage, including damage to hull plating on the Hyde Park adjacent to three cargo tanks. Gasoline was smelled on deck but the tanks were not reported to be breached. The Marine Investigation Report (Transportation Safety Board of Canada 2005) goes into considerable detail about the difficulties of navigating in narrow channels such as some sections of the St. Lawrence Seaway.

Most of the vessels reported sunk or otherwise lost in the St. Lawrence Seaway are fishing vessels (10 out of 17) which are typically small vessels with median length of 12.85m. The rest are pleasure craft or small work boats.

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.

4.1 IRVING WHALE

The *Irving Whale* oil barge was carrying a cargo of 4500 tons of Bunker C crude oil when it sank in 67 meters of water in the Gulf of St. Lawrence, between Prince Edward Island and the Magdalen Islands on September 7, 1970 (Gagnon et al. 2010; Latremouille 1974), causing a large initial oil spill and subsequent leaks for the next 26 years. Approximately 80 km of shoreline were affected by the spill. During beach clean-up operations under the auspices of Transport Canada, oil residues and PCB-contaminated sediment were gathered in plastic bags. The bags were buried in holes, trenches or natural cavities at the base of the fore dune or behind the first row of dunes, and no record of the burial sites for the bags of contaminated sediment is available (Gagnon et al. 2010). Major changes that the dunes have undergone since 1970 are such, that it is impossible to determine the current locations of the bags within the beach profile (between the foreshore and back dune). The sunken barge was finally salvaged by the federal government on July 30, 1996.

4.2 NEPCO 140

On June 23, 1976, the *Eileen C.* was moving the *NEPCO 140* barge up the St. Lawrence River, from Montreal to the Niagara Mohawk Power Plant at Oswego, New

York (Foley and Tresidder 1977). The barge went aground on a shoal northeast of Wellesley Island, spilling oil in the American Narrows, a restricted channel in the Thousand Islands region surrounded by ledges and low cliffs, where the depth is greater than 46 m, and the current exceeds 6.5 km/h. The tug and barge proceeded 8 km upstream through the Narrows to Mason Point. Over 4 days 1,140,000 L of spilled No. 6 oil were pushed 137 km downstream by 3.5-13 km/h currents and westerly winds in spite of the deployment of booms and skimmers, impacting more than 483 km of island and mainland shore, including almost all the American side of the river (Foley and Tresidder 1977).

About 1,000 wildfowl and an unknown number of mammals and reptiles suffered impacts (Foley and Tresidder 1977). Shorelines were power-washed by hand, and contaminated aquatic and marsh vegetation was manually cut and hauled. Cleanup lasted 122 days, but many areas were left to recover naturally. The cost exceeded $8 million (Foley and Tresidder 1977).

4.3 RICHELIEU

On July 13, 2010 near the Côte Ste-Catherine lock, Quebec (south shore of Montreal), 50-200 tons of diesel fuel from the punctured fuel tank of the Canada Steamship Lines (CSL) freighter, *Richelieu*, washed on shore after it ran aground, covering 11 birds with oil (five of which subsequently died), affecting about 3 km of shoreline, and delaying 17 ships (CTV News 2010a, 2010b; Hamilton Spectator 2010; The Toronto Star 2010). All CSL ships keep emergency booms onboard, and these were immediately deployed and contained the slick (CBC News 2010). Cleanup of the 500 m^2 area took about 3 days and required thirty to fifty people.

4.4 TANKER TRUCK

On Tuesday, 2 September 2014, a tanker truck travelling on Route 132 near Saint-Lambert on Montreal's south Shore swerved to avoid an earlier accident involving a motorhome and car, between the Victoria and Champlain bridges (Global News 2014). The truck driver lost control, crashed into the two vehicles, and rolled into the St. Lawrence River. An estimated 400 L of diesel fuel spilled into the river from the truck's punctured tank. An environmental team was sent to the site to clean up the spill. The truck was also carrying around 40 tons of dry cement.

4.5 TUGBOAT

On Dec.18, 2014, a tugboat sank near Trois-Rivières, Quebec, spilling diesel fuel into the St. Lawrence River, of which 10,000 L were recovered. It remains unknown how much of the 22,000 L of diesel that were on the ship went into the water (CBC News 2008).

4.6 LONGUEUIL DIESEL SPILL

A fuel reservoir of a water filtration plant in Longueuil, Quebec, leaked 28,000 L of diesel into the St. Lawrence River, which led to a municipal drinking water non-consumption advisory lasting several days (CBC News 2015).

5 CONCLUSIONS

The Montreal and Gulf of St. Lawrence region experiences a mid-temperate climate with warm, humid summers, and snow and ice during the winter months. In summer, strong southwest winds on the south shore of the lower St. Lawrence up to Île Bîcquette, fog on the water, low ceilings and decreased visibility along the coast during east and northeast winds.

Montreal is an international transshipment port, a hub for major petroleum pipelines, and the only container port on the St. Lawrence River. It has moved an annual average of 20 million tons in the past 10 years. There are numerous petroleum product depots in addition to three oil refineries along the St. Lawrence River.

The Great Lakes-St. Lawrence Seaway is a deep draft, vital international transportation route of geographic, hydrologic, and economic significance. The study region extends from Montreal to the western tip of Anticosti Island in the Gulf of St. Lawrence, and can be viewed in sections: the river or fluvial section, the fluvial estuary, the upper estuary, and the lower estuary. The major factors affecting estuarine circulation in the region are freshwater runoff from the St. Lawrence River, Saguenay River, rivers along the north shore, and smaller contributions from the south shore, and tides from the Gulf of St. Lawrence.

The upper estuary, from the limit of salt intrusion at the eastern tip of Île d'Orléans to the head of the Laurentian Channel at Tadoussac, expands from 2 to 25 km wide, and is dominated by high intensity currents, tides, strong mixing and high turbidity. In winter, tides move ice back and forth, preventing fast ice formation.

The last 300 km is termed the lower estuary, averaging 37 km across between Tadoussac and Pointe-des-Monts, with a maximum width of 60 km at Baie-Comeau. Higher freshwater discharge during spring freshets creates buoyancy-driven circulation in addition to tidal mixing. In summer, three water masses of different temperatures and salinities are superposed, but only two occur in winter. Mixing is most intense near the Saguenay sill (Tadoussac), near English Bank, and near Ile-aux-Coudres, especially when the spring freshet pushes salt intrusion seaward about 12 km and increases turbulent vertical mixing. Giant cyclonic and anticyclonic eddies generated by regional winds are common between Les Escoumins and the western tip of Anticosti Island. From mid-December to mid-April, ice cover is prevalent in the river and fast ice and ice floes in the estuary.

6 REFERENCES

Banks, R.E. 1966. Cold Layer in Gulf of St Lawrence. J Geophys Res **71**(6): 1603-&. doi:DOI 10.1029/JZ071i006p01603.

Belzile, M., Galbraith, P.S., and Bourgault, D. 2016. Water renewals in the Saguenay Fjord. Journal of Geophysical Research: Oceans **121**(1): 638-657. doi:doi:10.1002/2015JC011085.

Bourgault, D. 2001. Circulation and mixing in the St. Lawrence Estuary. Department of Atmospheric and Oceanic Sciences and Centre for Climate and Global
Change Research, McGill University, Montreal.

Bourgault, D., and Koutitonsky, V.G. 1999. Real-time monitoring of the freshwater discharge at the head of the St. Lawrence Estuary. Atmosphere-Ocean **37**(2): 201-218. Available from <Go to ISI>://WOS:000081532600004 [accessed.

Bourgault, D., Saucier, F.J., and Lin, C.A. 2001. Shear instability in the St. Lawrence Estuary, Canada: A comparison of fine-scale observations and estuarine circulation model results. J Geophys Res-Oceans **106**(C5): 9393-9409. doi:Doi 10.1029/2000jc900165.

Bugden, G.L. 1981. Salt and Heat Budgets for the Gulf of St-Lawrence. Can J Fish Aquat Sci **38**(9): 1153-1167. doi:DOI 10.1139/f81-155.

Bugden, G.L. 1991. Changes in the temperature-salinity characteristics of the deeper waters of the Gulf of St. Lawrence over the past several decades. Can. Spec. Publ. Fish. Aquat. Sci. **113**: 139-147.

CBC News. 2008. 3 small oil spills spotted in Bay of Fundy. CBC.ca, https://www.cbc.ca/news/canada/new-brunswick/3-small-oil-spills-spotted-in-bay-of-fundy-1.750404.

CBC News. 2010. St. Lawrence Seaway fuel spill contained. Available from https://www.cbc.ca/news/canada/montreal/st-lawrence-seaway-fuel-spill-contained-1.8682782018].

CBC News. 2015. Damaged infrastructure, poor design caused Longueuil diesel leak: Environment Quebec. Available from https://www.cbc.ca/news/canada/montreal/damaged-infrastructure-poor-design-caused-longueuil-diesel-leak-environment-quebec-1.29166202018].

Couillard, D. 1987. Quality of Suspended and Bottom Sediments of the St-Lawrence System (Canada). Hydrolog Sci J **32**(4): 445-467. doi:Doi 10.1080/02626668709491205.

Craig, J., and Gilbert, D. 2008. Estimation of mixed layer depth at the AZMP fixed stations. AZMP Bulletin **7**: 37–42.

CTV News. 2010a. St. Lawrence Seaway reopens after fuel spill. Available from https://www.ctvnews.ca/st-lawrence-seaway-reopens-after-fuel-spill-1.5327422018].

CTV News. 2010b. Five mallards die in St. Lawrence Seaway oil slick. Available from https://www.ctvnews.ca/five-mallards-die-in-st-lawrence-seaway-oil-slick-1.5337032018].

Cyr, F., Bourgault, D., and Galbraith, P.S. 2011. Interior versus boundary mixing of a cold intermediate layer. J Geophys Res-Oceans **116**. doi:Artn C12029
10.1029/2011jc007359.

d'Anglejan, B. 1990. Chapter 6: Recent sediments and sediment transport processes in the St. Lawrence estuary. *In* Oceanography of a Large-Scale Estuarine System. *Edited by* M.I. El-Sabh and N. Silverberg. Springer-Verlag, New York. pp. 109-129.
de Borne de Grandpré, C., and El-Sabh, M.I. 1980. Étude de la circulation verticale dans l'estuaire du Saint-Laurent au moyen de la modélisation mathématique. Atmosphere-Ocean **18**(4): 304-321. doi:10.1080/07055900.1980.9649094.
de Vernal, A., Guillaume, S.-O., and Denis, G. 2011. Oceanography and Quaternary geology of the St. Lawrence Estuary and the Saguenay Fjord. IOP Conference Series: Earth and Environmental Science **14**(1): 012004. Available from http://stacks.iop.org/1755-1315/14/i=1/a=012004 [accessed.
Devine, L., ;Plourde, S.; Starr M.; St-Pierre, J.-F.; St-Amand, L.; Joly, P.; Galbraith, P.S. 2015. Chemical and Biological Oceanographic Conditions in the Estuary and Gulf of St. Lawrence during 2014.
Dickie, L., and Trites, L.M. 1983. The Gulf of St. Lawrence. *In* Estuaries and Enclosed Seas. *Edited by* B.H. Ketchum. Elsevier, New York. pp. 403–425.
Dolgopolova, E.N., and Isupova, M.V. 2011. Water and Sediment Dynamics at Saint Lawrence River Mouth. Water Resour+ **38**(4): 453-469. doi:10.1134/S009780781104004x.
Drapeau, G. 1990. Chapter 7: Nearshore sediment dynamics in the St. Lawrence estuary. *In* Oceanography of a Large-Scale Estuarine System. *Edited by* M.I. El-Sabh and N. Silverberg. Springer-Verlag, New York. pp. 130-154.
Drapeau, G. 1992. Sediment Dynamics in the St-Lawrence Estuary. Geogr Phys Quatern **46**(2): 233-242. doi:DOI 10.7202/032907ar.
Drapeau, G., Munro, J., and Nellis, P. Long term fate of dredged sediments at Ile Madame dumping site (St. Lawrence Estuary): A basic assessment. *In* Proceedings of the 2nd International Symposium on Contaminated Sediments. Quebec City, Quebec 2003. *Edited by* H. Tremblay and J. Locat and R. Galvez-Cloutier. pp. 36–40.
Dufour, R., and Ouellet, P. 2007. Estuary and Gulf of St. Lawrence marine ecosystem overview and assessment report. Can. Tech. Rep. Fish. Aquat. Sci. **2744**: 112. Available from www.dfo-mpo.gc.ca/Library/329836.pdf [accessed.
Dunbar, M.J., Maclellan, D.C., Filion, A., and Moore, D. 1980. The biogeographic structure of the Gulf of St. Lawrence. McGill University 32, Montreal.
El-Sabh, M.I. 1988. Physical oceanography of the St. Lawrence estuary. Hydrodynamics of Estuaries. CRC Press, Boca Raton, FL. pp. 61-78.
El-Sabh, M.I., and Murty, T.S. 1990. Mathematical modelling of tides in the St. Lawrence estuary. *In* Oceanography of a Large-Scale Estuarine System. *Edited by* M.I. El-Sabh and N. Silverberg. Springer-Verlag, New York. pp. 10-50.
Engelhardt, F.R. 1994. Limitations and innovations in the control of environmental impacts from petroleum industry activities in the Arctic. *Marine Pollution Bulletin* **29**(6-12): 334-341. Available from http://www.sciencedirect.com/science/article/B6V6N-487DM3F-N/2/a1d0f91030a0b3d037f3acaea5135c5b [accessed.
Environment and Climate Change Canada. 2016. Water pollution: erosion and sedimentation. Available from https://www.canada.ca/en/environment-climate-

change/services/water-overview/pollution-causes-effects/erosion-sedimentation.html.
Environment and Climate Change Canada. 2017. Sea Ice Climatic Atlas for the East Coast 1981-2010. Available from https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/publications/sea-climatic-atlas-east-coast-1981-2010.html2018].
Environment Canada, Fisheries and Oceans Canada, and Natural Resources Canada. 2013. Federal Government Technical Report: Properties, Composition and Marine Spill Behaviour, Fate and Transport of Two Diluted Bitumen Products from the Canadian Oil Sands. Government of Canada (Environment Canada, Fisheries and Oceans Canada, and Natural Resources Canada) ISBN 978-1-100-23004-7.
Farquharson, W.I. 1962. Tides, tidal streams and currents in the Gulf of St. Lawrence. Canadian Hydrographic Service, Ottawa, ON.
Fisheries and Oceans Canada. 1992. Gulf of St. Lawrence. Fisheries and Oceans Canada, Ottawa, ON.
Fisheries and Oceans Canada. 2013. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Atlantic large aquatic basin.
Foley, J.P., and Tresidder, S.J. The St. Lawrence River oil spill of June 23, 1976 - are you ever truly ready? *In* Proceedings of the 1977 International Oil Spill Conference. New Orleans, LA, 8-10 March 1977 1977. American Petroleum Institute. pp. 81-85.
Frenette, M., Barbeau, C., and Verrette, J.-L. 1989. Aspects quantitatifs, dynamiques et qualitatifs des sédiments du Saint-Laurent. Gouvernement du Québec.
Gagnon, M. 1998. Bilan régional - Rive sud de l'estuaire moyen du Saint-Laurent: Zones d'intervention prioritaire 15, 16 et 17. Environnement Canada - région du Québec.
Gagnon, V., Camirand, R., and Blouin, M. 2010. Pollution incident following the sinking of the *Irving Whale* in 1970: Action plan to update the intervention strategy for managing bags buried in the Iles de la Madeleine dunes. Environmental Response Quebec Region, Canadian Coast Guard, Champlain, QC.
Galbraith, P., Plourde, S., and Starr, M. 2014a. Oceanographic Processes in the Estuary and Gulf. St. Lawrence Action Plan 2011-2026. Fisheries and Oceans Canada.
Galbraith, P.S. 2006. Winter water masses in the Gulf of St. Lawrence. J Geophys Res-Oceans **111**(C6). doi:Artn C06022
10.1029/2005jc003159.
Galbraith, P.S., Chassé, J., Gilbert, D., Larouche, P., Caverhill, C., Lefaivre, D., Brickman, D., Pettigrew, B., Devine, L., and Lafleur, C. 2014b. Physical Oceanographic Conditions in the Gulf of St. Lawrence in 2013. DFO Can. Sci. Advis. Sec. Res. Doc. **62**: 84.
Galbraith, P.S., Chassé, J., Nicot, P., Caverhill, C., Gilbert, D., Pettigrew, B., Lefaivre, D., Brickman, D., Devine, L., and Lafleur, C. 2015. Physical Oceanographic Conditions in the Gulf of St. Lawrence in 2014. F.a.O. Canada.

Galbraith, P.S.C., J.; Caverhill, C.; Nicot, P.; Gilbert, D.; Pettigrew, B.; Lefaivre, D.; Brickman, D.; Devine, L.; Lafleur, C. 2017. Physical Oceanographic Conditions in the Gulf of St. Lawrence in 2016.

Gilbert, D. 2004. Propagation of temperature signals from the northwest Atlantic continental shelf edge into the Laurentian Channel. *In* ICES. p. 12.

Gilbert, D., and Pettigrew, B. 1997. Interannual variability (1948-1994) of the CIL core temperature in the Gulf of St. Lawrence. Can J Fish Aquat Sci **54**: 57-67. doi:DOI 10.1139/f96-160.

Gilbert, D., Sundby, B., Gobeil, C., Mucci, A., and Tremblay, G.H. 2005. A seventy-two-year record of diminishing deep-water oxygen in the St. Lawrence estuary: The northwest Atlantic connection. Limnology and Oceanography **50**(5): 1654-1666. doi:DOI 10.4319/lo.2005.50.5.1654.

Global News. 2014. Tanker truck crashes into Saint Lawrence River. Available from https://globalnews.ca/news/1539076/tanker-truck-crashes-into-saint-lawrence-river/2018].

Godin, G. 1979. Tides in the St-Lawrence Gulf and Estuary. Naturaliste Canadien **106**(1): 105-121. Available from <Go to ISI>://WOS:A1979HL58500008 [accessed.

Government of Canada. 2017. St. Lawrence River: overview. Available from https://www.canada.ca/en/environment-climate-change/services/st-lawrence-river.html2018].

Hamilton Spectator. 2010. Oil leak closes part of Seaway. Available from https://www.thespec.com/news-story/2164105-oil-leak-closes-part-of-seaway/2018].

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.

Koutitonsky, V.G. 1979. Water Mass-Transport at the Entrance of the St-Lawrence Estuary. Naturaliste Canadien **106**(1): 75-88. Available from <Go to ISI>://WOS:A1979HL58500006 [accessed.

Koutitonsky, V.G., and Bugden, G.L. 1991. The physical oceanography of the Gulf of St. Lawrence: A review with emphasis on the synoptic variability of the motion of St. Lawrence: Small ocean or big estuary? . Canadian Special Publication of Fisheries and Aquatic Sciences **113**: 57-90.

Koutitonsky, V.G., Long, B., Lefaivre, D., and Sala, M. 1991. The Influence of Hydrodynamical Processes on Sediment Transport in the Northern Gulf of St-Lawrence. Cont Shelf Res **11**(8-10): 1209-1221. doi:Doi 10.1016/0278-4343(91)90098-Q.

Kranck, K. 1979. Dynamics and Distribution of Suspended Particulate Matter in the St-Lawrence Estuary. Naturaliste Canadien **106**(1): 163-173. Available from <Go to ISI>://WOS:A1979HL58500012 [accessed.

Latremouille, M.P. (ed). 1974. Bedford Institute of Oceanography Biennial Review 1973/74. Bedford Institute of Oceanography, Dartmouth, NS.

Le Fouest, V., Zakardjian, B., Saucier, F.J., and Cizmeli, S.A. 2006. Application of SeaWIFS- and AVHRR-derived data for mesoscale and regional validation of a

3-D high-resolution physical-biological model of the Gulf of St. Lawrence (Canada). J Marine Syst **60**(1-2): 30-50. doi:10.1016/j.jmarsys.2005.11.008.
Lee, K., Boudreau, M., Bugden, J., Burridge, L., Cobanli, S.E., Courtenay, S., Grenon, S., Hollebone, B., Kepkay, P., Li, Z., Lyons, M., Niu, H., King, T.L., MacDonald, S., McIntyre, E.C., Robinson, B., Ryan, S.A., and Wohlgeschaffen, G. 2011. State of Knowledge Review of Fate and Effect of Oil in the Arctic Marine Environment. National Energy Board of Canada, Ottawa, ON.
Mucci, A., Starr, M., Gilbert, D., and Sundby, B. 2011. Acidification of Lower St. Lawrence Estuary Bottom Waters. Atmosphere-Ocean **49**(3): 206-218. doi:10.1080/07055900.2011.599265.
Muir, L.R. 1982. Internal tides in a partially mixed estuary. Canada Centre for Inlands waters, Burlinfton, Ont.
Neu, H.J.A. 1970. A study on mixing and circulation in the St. Lawrence estuary up to 1964.
Neu, H.J.A. 1976. Runoff regulation for hydro-power and its effect on the ocean environment. Hydr. Scien. Bull. **3**(9): 433-444.
New World Encyclopedia. 2015. Saint Lawrence River. Available from http://www.newworldencyclopedia.org/entry/Saint_Lawrence_River2018].
Ottawa River Regulation Planning Board. 2018. Ottawa River at Carillon. Available from http://www.ottawariver.ca/ottawa-river-carillon.php.
Pineault, S. 2014. Les effluents liquides du secteur des raffineries de pétrole. Gouvernement du Québec.
Reid, S.J. 1977. Circulation and mixing in the St. Lawrence estuary near Ilet Rouge. Fisheries and Oceans Canada.
Robichaud, B., and Mullock, J. 2001a. The Weather of Atlantic Canada and Eastern Quebec: Chapter 5.
Robichaud, B., and Mullock, J. 2001b. The weather of Atlantic Canada and eastern Quebec graphic area forecast 34 Atlantic Region. NAV Canada.
Robitaille, J. 1998. Regional Assessment: Pointe-du-Lac–Deschambault. Environment Canada – Quebec Region.
Rondeau, B., Cossa, D., Gagnon, P., and Bilodeau, L. 2000. Budget and sources of suspended sediment transported in the St. Lawrence River, Canada. Hydrological Processes **14**(1): 21-36. doi:DOI: 10.1002/(SICI)1099-1085(200001)14:1<21::AID-HYP907>3.0.CO;2-7.
Ruest, B., Neumeier, U., Dumont, D., Bismuth, E., Senneville, S., and Caveen, J. 2015. Recent wave climate and expected future changes in the seasonally ice-infested waters of the Gulf of St. Lawrence, Canada. Climate Dynamics.
Saucier, F.J., and Chasse, J. 2000. Tidal circulation and buoyancy effects in the St. Lawrence Estuary. Atmosphere-Ocean **38**(4): 505-556. doi:Doi 10.1080/07055900.2000.9649658.
Saucier, F.J., Roy, F., Gilbert, D., Pellerin, P., and Ritchie, H. 2003. Modeling the formation and circulation processes of water masses and sea ice in the Gulf of St. Lawrence, Canada. J Geophys Res-Oceans **108**(C8). doi:Artn 3269
10.1029/2000jc000686.
St. Lawrence Centre. 1991. A river, estuaries, and a gulf, broad hydrographic divisions of the St. Lawrence. *In* The Environmental Atlas of the St. Lawrence. *Edited by* J.

Raveneau and O. Mercier and E. Saint-Pierre and N. Lavigne and E. Drueding. Environment Canada, Montreal, Quebec. p. 1 hardcopy plate.
St. Lawrence Centre. 1993. St. Lawrence Update. Environment Canada, Montreal, Quebec.
St. Lawrence Centre. 1996a. State of the Environment Report on the St. Lawrence River. Volume 2: The state of the St. Lawrence. Environment Canada - Quebec Region, Montreal, Quebec.
St. Lawrence Centre. 1996b. State of the Environment Report on the St. Lawrence River. Volume 1: The St. Lawrence ecosystem. Environment Canada - Quebec Region, Montreal, Quebec.
Tang, C.T., and Bennett, A.S. 1981. Physical oceanographic observations in the northwestern Gulf of St. Lawrence. Bedford Institute of Oceanography, F.a.O. Canada, Dartmouth, NS.
The Toronto Star. 2010. Cleanup of oil spill near Montreal ties up a dozen ships in St. Lawrence. Available from https://www.thestar.com/news/canada/2010/07/14/cleanup_of_oil_spill_near_montreal_ties_up_a_dozen_ships_in_st_lawrence.html2018].
The Weather Network. 2019. Weather Statistics: Mont-Joli, QC 2019].
Transportation Safety Board of Canada. 1991. Marine Investigation Report M91L3012. Government of Canada, http://www.tsb.gc.ca/ENG/rapports-reports/marine/1991/m91l3012/m91l3012.asp.
Transportation Safety Board of Canada. 2005. Marine Investigation Report M05L0205. Government of Canada, http://www.tsb.gc.ca/eng/rapports-reports/marine/2005/m05l0205/m05l0205.asp.
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/.
Vincent, W.F., and Dodson, J.J. 1999. The St. Lawrence River, Canada-USA: the need for an ecosystem-level understanding of large rivers. Jpn. J. Limnol. **60**: 29-50.
WSP Canada. 2014. Risk assessment for marine spills in Canadian waters Phase 1: Oil spills south of the 60th parallel. WSP Canada Inc. 131-17593-00.