

## St. Lawrence UPDATE

The thematic reports published as part of the St. Lawrence UPDATE series are intended for individuals and organizations concerned with conserving and protecting the St. Lawrence River.

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# **D**YNAMICS AND CONTAMINATION OF ST. LAWRENCE RIVER SEDIMENT

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*The St. Lawrence River not only supports a great variety of animal and plant life, it contributes in many ways to the well-being of humans. People living along its banks use the river for drinking water, commercial and sport fishing, transportation, industry, tourism and recreation. Like the large rivers in other industrialized countries, albeit to a lesser extent, the St. Lawrence has been showing signs of decline in recent decades. In response, the federal and provincial governments created the St. Lawrence Vision 2000 action plan to protect, conserve and restore the river, for environmental as well as socio-economic reasons.*

*Gaining more knowledge of the St. Lawrence and understanding the links between human activities and the environment will help protect the river. Such information must then be shared; that is, made available. It may help to enlighten decision makers for whom the sound management and sustainable development of the river are a concern. This report is produced in this cooperative spirit. It is key to our success in recovering use of the river, in developing resources too often neglected, and in taking action so that future generations will, in their turn, benefit from and enjoy the priceless heritage that is the St. Lawrence River.*

*This thematic report on the dynamics and contamination of St. Lawrence sediment was prepared by the State of the Environment Section of the St. Lawrence Centre of Environment Canada, as part of its mandate to report on the condition of the river. It is intended to give interested parties basic information on the processes of sediment erosion, transport, deposition and contamination. A better understanding of these processes and their evolution over time will help to guide our intervention activities and preserve the habitats that sediment supports.*

*This report is aimed, above all, at the layperson. For their part, scientists in other fields of study will certainly also find the information contained in these pages useful and interesting.*

*The St. Lawrence, the 19th longest river in the world, drains an area equivalent to about 85 percent of the province of Quebec. Scarred by the industrial age, the river's flow regime has been profoundly altered by the construction of hydro-electric and control dams at its upstream end, and by dredging of the ship channel.*

*The sediment load of the St. Lawrence is relatively low for a river of its size. Fine-grained mineral particles and organic debris from the Great Lakes, tributaries of the St. Lawrence and the river itself are carried in suspension in the water column and settle in lakes of the Fluvial Section, on foreshores in the estuary, and in the Laurentian Channel.*

*Heavy metals in ionic and other forms, and organic molecules such as PAHs and PCBs, have the capacity to become attached to mineral particles and organic matter in the water before finally settling to the bottom. Some heavy metals such as cadmium, copper, mercury, zinc and lead as well as PAHs are naturally present in ancient sediments, and, while their concentrations can vary from place to place, levels exceeding two and one-half times natural values are considered to imply inputs from human activity. This multiple is defined as the Threshold of Significant Contamination (TSC). It serves as a basic tool for determining the spatial distribution of sediment contamination in the river.*

*In the mid-1980s, the most heavily contaminated areas of the St. Lawrence were the fluvial lakes (Saint-Louis and Saint-Pierre), the Saguenay River, Baie des Anglais, Chaleur Bay, and the harbour areas of Montreal and Quebec City. In recent years, however, a general decline in contamination has been noted, owing to a reduction in contaminant loads, and to inputs of less contaminated sediment that is gradually covering the older sediments.*

*Enlargement and maintenance of the ship channel, as well as ports and marinas, require the dredging of just over 450 000 m<sup>3</sup> of sediments every year, of which just under 400 000 m<sup>3</sup> is dumped in open water in view of its low level of contamination.*

*Le Saint-Laurent figure au 19<sup>e</sup> rang des grands fleuves pour ce qui est de la longueur, et il draine un territoire équivalent à 85 p. 100 de la superficie de la province de Québec. Marqué par l'ère industrielle, le fleuve a vu son régime d'écoulement profondément modifié par la construction de barrages hydroélectriques, incluant les barrages de retenue en amont, et le creusement du chenal de navigation.*

*La charge sédimentaire du Saint-Laurent est relativement faible pour un fleuve de cette envergure. Les particules minérales fines et les débris organiques qui proviennent des Grands Lacs, des tributaires et du fleuve lui-même voyagent en suspension dans la colonne d'eau et se déposent dans les secteurs lacustres du tronçon fluvial, sur les estrans de l'estuaire et dans le chenal Laurentien.*

*Les métaux lourds, sous forme ionique et autres, ainsi que les molécules organiques comme les HAP et les BPC, ont la capacité de voyager avec les particules minérales et la matière organique présentes dans l'eau, pour ensuite se déposer sur le fond. Certains métaux lourds comme le cadmium, le cuivre, le mercure, le zinc et le plomb ainsi que les HAP sont présents naturellement dans les sédiments anciens, et bien que les teneurs puissent varier spatialement, on considère qu'une augmentation de deux fois et demi supérieure aux teneurs naturelles découle d'apports dus aux activités humaines. Cette valeur correspond au seuil de contamination significative (SCS) qui sert d'outil de base pour établir la répartition spatiale de la contamination des sédiments du fleuve.*

*Au milieu des années 1980, les lacs fluviaux (Saint-Louis et Saint-Pierre), le Saguenay, la baie des Anglais et la baie des Chaleurs présentaient les secteurs les plus fortement contaminés du Saint-Laurent avec les zones portuaires de Montréal et Québec. On observe depuis quelques années une baisse généralisée de la contamination grâce à une réduction des charges de contaminants allié à des apports de sédiments moins contaminés qui recouvrent graduellement les sédiments anciens.*

*L'agrandissement et l'entretien du chenal de navigation, des ports et des marinas entraînent le dragage d'un peu plus de 450 000 m<sup>3</sup> de sédiments chaque année, dont un peu moins de 400 000 m<sup>3</sup> sont rejetés en eau libre en raison de leur faible contamination.*

# T ABLE OF CONTENTS

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<i>Production Team</i> .....	<b>iii</b>
<i>Contributors</i> .....	<b>v</b>
<i>Management Perspective</i> .....	<b>vii</b>
<i>Abstract</i> .....	<b>ix</b>
<i>Résumé</i> .....	<b>xi</b>
<i>List of Figures</i> .....	<b>xvii</b>
<i>List of Tables</i> .....	<b>xxi</b>
<i>List of Information Supplements</i> .....	<b>xxiii</b>
<i>Introduction</i> .....	<b>1</b>
A river of many faces .....	<b>1</b>
A river under pressure .....	<b>2</b>
Sediments: reservoirs for contaminants .....	<b>2</b>
Sediments: the memory of the St. Lawrence .....	<b>2</b>
<i>The River Bed and Banks Support Habitats</i> .....	<b>3</b>
Water depth and substrate type: crucial for many species .....	<b>3</b>
Wetlands regulate river flow and trap heavy metals .....	<b>4</b>
Urban areas and farmland contribute to sediment inputs .....	<b>4</b>
Forests: effective sediment filters .....	<b>7</b>
Islands protect shorelines and essential wildlife habitats .....	<b>8</b>
<i>A Hydrological Regime Greatly Altered by Human Activity</i> .....	<b>9</b>
A route to the heart of the continent .....	<b>9</b>
Flow regulated by upstream dams and control structures .....	<b>12</b>
Drifting shorelines .....	<b>14</b>

<i>The Slow Process of Erosion: the Origin of Sediment</i> .....	19
St. Lawrence sediment reflects the rock and soil in its drainage basin.....	19
The path to the river is fraught with traps .....	20
Sediment deposition patterns are complex in the St. Lawrence .....	21
Buried sediments are slowly consolidated.....	22
<i>Surface Sediment</i> .....	23
The fluvial lakes: sediment sinks .....	23
River corridor sections: transport zones .....	29
Brackish and saltwater sections: sediment sinks .....	29
<i>A Deficit Sediment Budget</i> .....	39
Fresh water .....	39
Salt water .....	41
Input from tributaries in the watershed.....	42
<i>Sediments: Transporters of Contaminants</i> .....	45
Exchanges between water and sediment .....	45
<i>The Role of Benthos in Contaminant Transfer</i> .....	51
Continuous mixing of sediments .....	51
Contaminant transfer to organisms .....	52
Infiltrating the food chain .....	52
Toxic effects .....	52
<i>Contaminated Areas of the St. Lawrence</i> .....	57
Sources of contamination .....	57
How to judge whether contamination is significant .....	58
How to judge whether sediments are polluted .....	59
How to assess the degree of contamination .....	60
How to determine the history of contamination .....	60
How to describe contaminated areas of the St. Lawrence .....	60
Contaminated areas of the St. Lawrence .....	61
Port areas .....	70
Marine areas .....	74

<i>The Resuspension of Sediments</i> .....	<b>83</b>
Capital and maintenance dredging .....	<b>83</b>
<i>Conclusion</i> .....	<b>93</b>
<i>References</i> .....	<b>95</b>
<i>Glossary</i> .....	<b>109</b>
<i>Appendixes</i> .....	<b>115</b>
1 Chemical reactions involved in diagenesis .....	<b>116</b>
2 Comparison of nomenclatures from studies used to map surface sediment .....	<b>117</b>
3 Interim criteria for quality assessment of St. Lawrence River sediment (April 1992) .....	<b>118</b>
4 Preindustrial levels of heavy metals and PAHs in sediment .....	<b>119</b>
5 Sediment quality characteristics and data sources used in this report .....	<b>121</b>
6 Riverbank remediation methods .....	<b>122</b>
7 Potential impacts of dredging on the river environment .....	<b>124</b>

# LIST OF FIGURES

---

<b>1</b>	<i>Pelagic and littoral zones (cross-section).....</i>	<b>4</b>
<b>2</b>	<i>Favoured habitats of certain fish and benthic invertebrate species .....</i>	<b>5</b>
<b>3</b>	<i>Zonation of wetland vegetation in the St. Lawrence River and Gulf .....</i>	<b>6</b>
<b>4</b>	<i>Intensity of corn cultivation in southern Quebec .....</i>	<b>7</b>
<b>5</b>	<i>Changes in the dimension of the ship channel since 1854 .....</i>	<b>10</b>
<b>6</b>	<i>Physical changes to fish habitat between 1945 and 1988.....</i>	<b>11</b>
<b>7</b>	<i>Hydro-electric power stations and control structures upstream of Montreal .....</i>	<b>12</b>
<b>8</b>	<i>Variations in the flow rate from 1955 to 1985 between Cornwall and Île d'Orléans.....</i>	<b>13</b>
<b>9</b>	<i>Compilation of data on the state of St. Lawrence riverbanks between Cornwall and Île d'Orléans .....</i>	<b>15</b>
<b>10</b>	<i>Map of the Contrecoeur archipelago.....</i>	<b>16</b>
<b>11</b>	<i>Riverbank stabilization at Ilet à Lacroix using willow works, slope reshaping and fascines .....</i>	<b>16</b>
<b>12</b>	<i>Riverbank stabilization on de la Cache, Pilier and Chipeau islands using cedar log cribs.....</i>	<b>17</b>
<b>13</b>	<i>Structure of a crystal.....</i>	<b>19</b>

<b>14</b>	<i>The St. Lawrence basin and its physiographic regions .....</i>	<b>20</b>
<b>15</b>	<i>The three modes of transport of sediment particles .....</i>	<b>21</b>
<b>16</b>	<i>Relationship between particle size, flow velocity and bottom deposition .....</i>	<b>21</b>
<b>17</b>	<i>Ternary diagram based on Shepard's nomenclature (1954) .....</i>	<b>24</b>
<b>18</b>	<i>Bathymetry and current velocity in the fluvial lakes.....</i>	<b>25</b>
<b>19</b>	<i>Spatial distribution of turbidity on June 17, 1987, and September 7, 1988, from LANDSAT satellite images.....</i>	<b>28</b>
<b>20</b>	<i>Spatial distribution of aquatic vegetation on June 17, 1987, and September 7, 1988, from LANDSAT satellite images.....</i>	<b>28</b>
<b>21</b>	<i>Concentrations of suspended solids between Trois-Rivières and Pointe-des-Monts .....</i>	<b>33</b>
<b>22</b>	<i>Sedimentary cycle and the relationship between vegetation and grazing by Greater snow geese (Chen caerulescens) .....</i>	<b>36</b>
<b>23</b>	<i>Inputs, transport and sedimentation of suspended solids downstream of Cornwall .....</i>	<b>44</b>
<b>24</b>	<i>Process of adsorption and desorption of sediment particles .....</i>	<b>46</b>
<b>25</b>	<i>Principal biochemical processes in organic matter decay.....</i>	<b>48</b>
<b>26</b>	<i>Transfer of sediment contaminants to higher organisms .....</i>	<b>53</b>

<b>27</b>	<i>Principal points of entry of contaminants into the St. Lawrence.....</i>	<b>58</b>
<b>28</b>	<i>Evolution of sediment contamination in lakes Saint-François and Saint-Louis.....</i>	<b>63</b>
<b>29</b>	<i>Evolution of sediment contamination in Lake Saint-Pierre .....</i>	<b>67</b>
<b>30</b>	<i>Evolution of mercury (Hg) and total PAH concentrations in sediments of the Saguenay Fjord.....</i>	<b>78</b>
<b>31</b>	<i>Evolution of sediment contamination in the Laurentian Channel.....</i>	<b>80</b>
<b>32</b>	<i>Relative volumes of dredging and disposal between 1983 and 1993.....</i>	<b>84</b>
<b>33</b>	<i>Sediment behaviour during open-water disposal.....</i>	<b>85</b>

# LIST OF TABLES

---

<b>1</b>	<i>Water level variations .....</i>	<b>14</b>
<b>2</b>	<i>Riverbank protection works between Montreal and Tracy .....</i>	<b>29</b>
<b>3</b>	<i>SS budget in the Fluvial Section (Cornwall to Quebec City) .....</i>	<b>41</b>
<b>4</b>	<i>SS budget for the estuarine and marine sections of the St. Lawrence (Quebec City to Cabot Strait).....</i>	<b>43</b>
<b>5</b>	<i>Criteria for mercury contamination vs. criteria for mercury pollution in sediments .....</i>	<b>59</b>
<b>6</b>	<i>Significant contamination, apprehended pollution and maximum contamination in Lake Saint-François in 1989 .....</i>	<b>62</b>
<b>7</b>	<i>Significant contamination, apprehended pollution and maximum contamination in Lake Saint-Louis in 1984 and 1985 .....</i>	<b>63</b>
<b>8</b>	<i>Significant contamination, apprehended pollution and maximum contamination in the Lesser La Prairie Basin in 1987 .....</i>	<b>66</b>
<b>9</b>	<i>Significant contamination, apprehended pollution and maximum contamination in Lake Saint-Pierre in 1986.....</i>	<b>67</b>
<b>10</b>	<i>Significant contamination, apprehended pollution and maximum contamination in Montreal harbour in 1990.....</i>	<b>70</b>

<b>11</b>	<i>Significant contamination, apprehended pollution and maximum contamination in Quebec City harbour in 1989.....</i>	<b>73</b>
<b>12</b>	<i>Significant contamination, apprehended pollution and maximum contamination in Trois-Rivières harbour in 1992.....</i>	<b>74</b>
<b>13</b>	<i>Significant contamination, apprehended pollution and maximum contamination in the Upper Estuary in 1989 and 1990.....</i>	<b>75</b>
<b>14</b>	<i>Significant contamination, apprehended pollution and maximum contamination in the Saguenay Fjord in 1986 (metals) and in 1983 (PAHs).....</i>	<b>78</b>
<b>15</b>	<i>Significant contamination, apprehended pollution and maximum contamination in the Baie des Anglais and Anse du Moulin in 1990 .....</i>	<b>81</b>
<b>16</b>	<i>Significant contamination, apprehended pollution and maximum contamination in Chaleur Bay in 1979 .....</i>	<b>81</b>

# LIST OF INFORMATION SUPPLEMENTS

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<i>Large-Scale Works Affecting the River Bed .....</i>	<b>10</b>
<i>Global Warming and the St. Lawrence .....</i>	<b>12</b>
<i>Bilateral Treaty Governs Water Levels .....</i>	<b>13</b>
<i>Protecting the Banks of the Contrecoeur Islands .....</i>	<b>15</b>
<i>A River Emerges from the Water .....</i>	<b>20</b>
<i>Classification of Sediments .....</i>	<b>24</b>
<i>The Role of Aquatic Plant Communities in Sedimentation .....</i>	<b>28</b>
<i>Sediment Dynamics on Cap-Tourmente Flats .....</i>	<b>36</b>
<i>Ice Action on the Foreshore .....</i>	<b>37</b>
<i>Ranking the St. Lawrence among the World's Major Rivers .....</i>	<b>40</b>
<i>Benthic Species as Indicators of St. Lawrence Water Quality .....</i>	<b>54</b>
<i>Lead Shot Contamination of Waterfowl in the St. Lawrence .....</i>	<b>55</b>
<i>Arsenic in the St. Lawrence Ecosystem .....</i>	<b>60</b>
<i>Sediment Contamination in the Lachine Canal .....</i>	<b>72</b>
<i>Refloating the Irving Whale .....</i>	<b>79</b>
<i>Mercury Mass Balance in the Lower Estuary .....</i>	<b>80</b>

# INTRODUCTION



Parks Canada – Jean Audet

**S**atellite views show the St. Lawrence River taking a simple course to the sea. From southwest to northeast, it flows straight as an arrow connecting the Great Lakes to the Atlantic Ocean. However, the river is anything but simple when seen at ground level. Its banks and bed are highly diverse, reflecting the complex succession of geological events that shaped it. The St. Lawrence is a young river on a long journey, and its story is not over yet.

## *A river of many faces*

From its source at the outlet of the Great Lakes, the St. Lawrence flows more than 1600 km to the Atlantic Ocean, making it the 19th longest river in the world. It is a river of many faces, reflecting its great variety of physical, climatic and biological

characteristics. There is not one St. Lawrence, but several. From south to north, fresh water gradually gives way to salt water, and the cultivated fields of the lowlands are succeeded by evergreen forests on the North Shore. Subtle differences are also found on opposite shores, a result of the parallel flow of water masses with very distinct physical and chemical properties.

The St. Lawrence is a paradox — a “clay-footed colossus.” The clay that forms its bed, which lies more than 30 m thick in places, plays very little part in its sedimentary regime. The bulk of its sediment load consists instead of materials from its shores and its watershed — the legacy of the last glaciations — that it has been transporting and reworking incessantly for about 10 000 years.

## *A river under pressure*

With two-thirds of Quebec's population clustered along a narrow strip on both shores of the St. Lawrence, human density inevitably puts pressure on the river environment. Other pressures take the form of structures built to produce electricity and protect riverside residents from spring floods, and roads that often destroy flats and marshes. In addition, the St. Lawrence has long been used as a convenient dump site for an impressive volume of discharges including household and industrial wastewater, runoff water and snow cleared from streets. Fortunately, public awareness has grown in recent years and action has been taken to reduce direct discharges into the river. However, erosion continues to attack riverbanks in some areas, and pesticides contained in the soils of certain drainage basins migrate towards the river through its tributaries. Other contaminants migrate towards the river in the form of airborne pollutants.

## *Sediments: reservoirs for contaminants*

Hidden from human eyes, the St. Lawrence river bottom is the setting for numerous exchanges with the water mass as well as complex biological and chemical processes. The migration of particles towards the bottom, and their melding into a more or less solid matrix, swollen to some degree with water, often produces contaminant concentrations that are greater than in the surrounding water. This is true only in principle, since the concentrations will vary depending on the solubility of the contaminant and its degree of affinity to organic matter. If these sediments are resuspended, they become efficient transporters of contaminants.

Sediments are of interest for reasons other than their recognized ability to transport contaminants. Many organisms depend on them, including bacteria, molluscs, crustaceans, worms, insects and fish, all of which may absorb a portion of the contaminants present in the sediments. These

groups of organisms then become an entry point for toxic compounds into the ecosystem through the interplay of predator-prey relationships that enable a portion of the contaminants to ultimately reach human beings.

## *Sediments: the memory of the St. Lawrence*

By accumulating in successive layers on the bottom, sediments "memorize" past and present levels of contamination. They record factors such as climate, water flow and chemical properties and vegetation with a constancy and regularity that would be the envy of advanced measurement devices. Brought to the surface, sediment beds can be "read" like archives that faithfully reflect system conditions during their deposition period. This ability of sediments to memorize environmental conditions is what makes them so interesting today for understanding broad historical trends in contamination and assessing the true impact of our actions in this area.

# CHAPTER 1

## *The River Bed and Banks Support Habitats*

**Wetlands are important transition zones that help protect shorelines from erosion. Urban and agricultural areas contribute to the sediment load, while forests retain and stabilize soil particles. In some areas, islands act as breakwaters that protect habitats on the adjacent shore.**

**L**ike air and water, sediment is a fundamental component of the ecosystem. A quick review of the principal river and estuary habitats will help us understand the various aspects associated with the subject of St. Lawrence sediment. The river and its banks can be described in terms of six habitat types: pelagic, wetland, open, forest, island and marginal. This is the classification used in the thematic report, *The St. Lawrence River: Diversified Environments* (Bouchard and Millet, 1993).

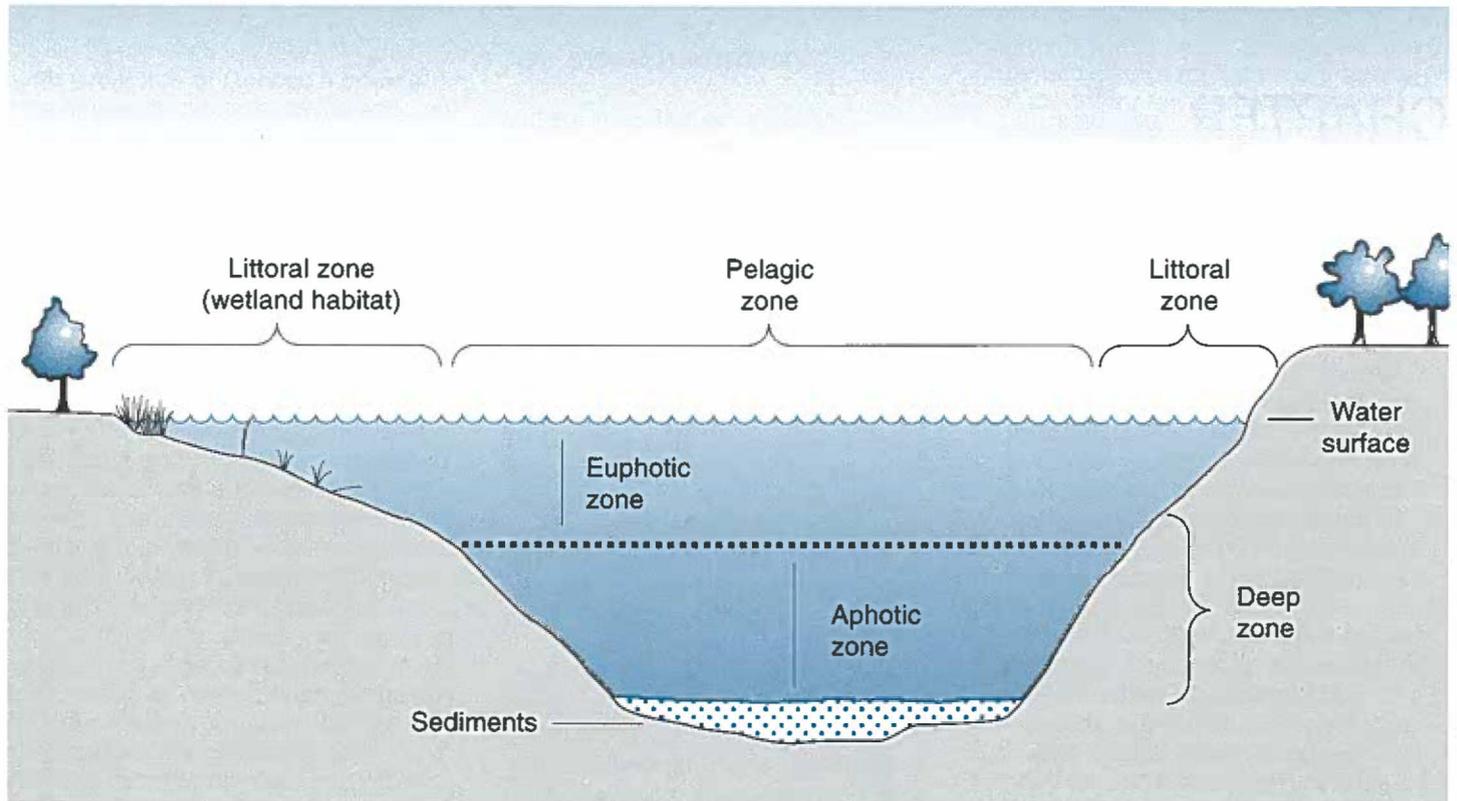
### *Water depth and substrate type: crucial for many species*

The pelagic habitat comprises the open-water zone immediately offshore from the littoral zone and permanently covered by water. It includes a deep aphotic zone and a surface euphotic zone. The *aphotic zone* is characterized by a total absence of light. Since photosynthesis is impossible, no vegetation grows here. The *euphotic zone* encompasses surface waters penetrated by sunlight. This is where the bulk of organic matter production

takes place by the action of photosynthesis (Figure 1). The dividing line between aphotic and euphotic zones is constantly shifting throughout the St. Lawrence in response to changes in turbidity, which is largely governed by seasonal weather changes.

Most fish species live in the pelagic zone except during the brief spawning period that brings many species to the littoral zone (Figure 2). When water depth does not permit water masses to stratify in summer, as is the case in shallow areas of the St. Lawrence fluvial lakes, many species (sturgeon, walleye, etc.) seek out deep troughs where they find the colder temperatures needed to regulate their metabolism.

The distribution of invertebrates on the river bed is governed by sediment type, water depth, current velocity and water quality. Typical freshwater benthic invertebrates are the *Bithynia tentaculata*, a mollusc, and the crustacean *Gammarus fasciatus*. Some insects such as the larva of *Chironomus* sp., the most widespread in fresh water, spend one or more stages of their brief existence here. The Laurentian Channel is home to *Nereis* sp., a large annelid that grows



Source: SLC, 1996.

**Figure 1 Pelagic and littoral zones (cross-section)**

up to 10 cm long and is eaten by many vertebrate species in the estuary and gulf. Many saltwater benthic invertebrates are harvested commercially (lobster, scallops, crab, oysters) (Figure 2).

In shallow bays and lake sections of the Fluvial Section, mud deposition allows aquatic plants to take root and spread under certain conditions to form large submerged aquatic plant communities. In the estuary and the gulf, only eelgrass (*Zostera marina*), a vascular plant, is able to invade bays to form such plant communities. However, they are generally much smaller than in the Fluvial Estuary.

### **Wetlands regulate river flow and trap heavy metals**

The three types of freshwater wetlands along the St. Lawrence are aquatic plant communities, marshes and swamps. Transects typical of

these environments are shown in Figure 3. *Aquatic plant communities* are composed of floating, submerged or emergent plants, while *marshes* are environments containing herbaceous vegetation that is periodically flooded to a depth of about 2 m in most freshwater areas of the St. Lawrence. Wet meadows appear mostly as riparian strips only a few metres wide between marshes and swamps. *Swamps* are inundated mainly by the spring flood and are characterized by the presence of trees and shrubs adapted to prolonged flooding. The river stretch between Cornwall and Quebec City contains 80 percent of the river's wetland habitats, mainly in the form of aquatic plant communities and swamps. (Lehoux, 1996).

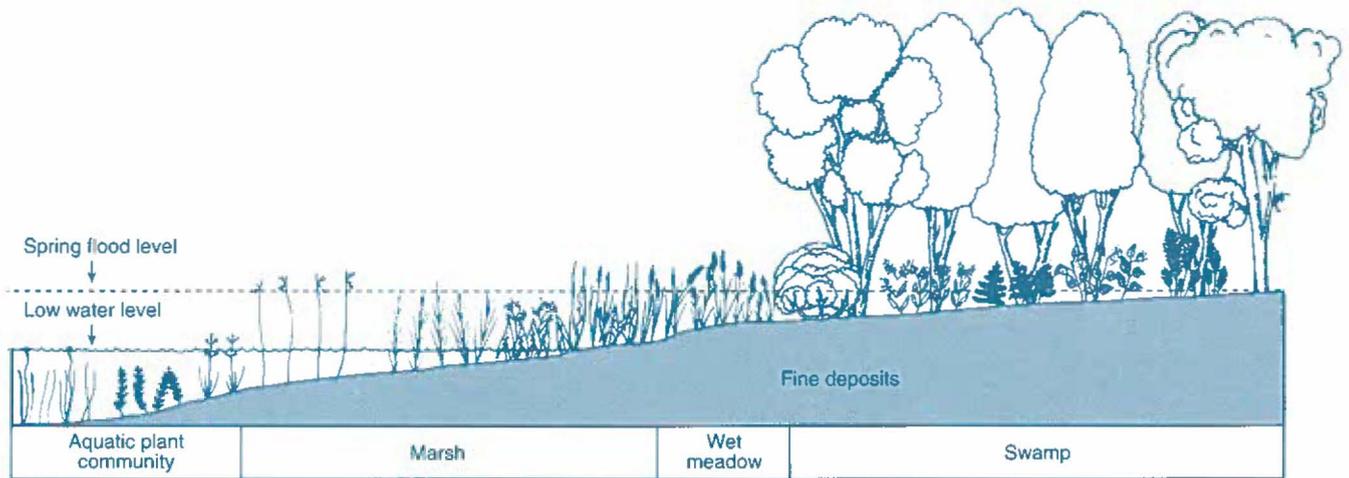
Wetlands are often compared to giant sponges, retaining water which is later released slowly during the dry season. The plant mass does indeed slow down the water flow and act as a filter that can retain the fine organic and mineral particles present in the

water. The plant roots, firmly anchored in the littoral mud, protect the banks against erosion and trap contaminants along with mineral particles. The contaminants are released into the marsh mud later in the season after the plants decompose. The American bulrush (*Scirpus americanus*) can absorb 0.9, 2.4, 6.7 and 14.5 mg/m<sup>2</sup> per year of mercury, lead, copper and zinc, respectively. Metal concentrations in marsh plants can reach 11 times their levels in sediments (Gilbert, 1990).

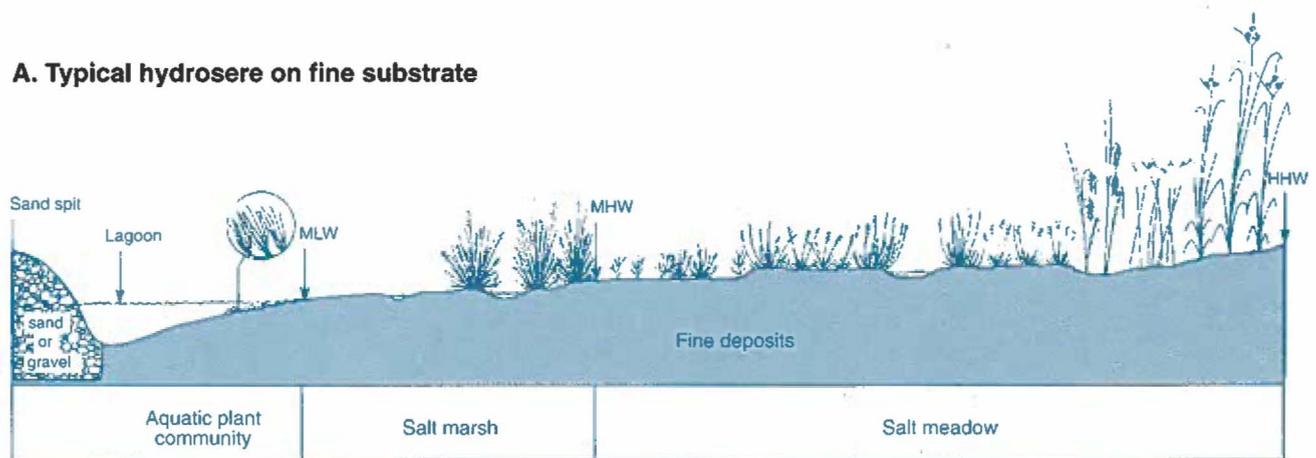
### **Urban areas and farmland contribute to sediment inputs**

The St. Lawrence shoreline in urban and agricultural zones of Quebec is generally characterized by the near-total lack of a riparian strip of trees or shrubs. A survey conducted in the summer of 1994 between Cornwall and Île d'Orléans found that 658.5 km of the total 1532 km of

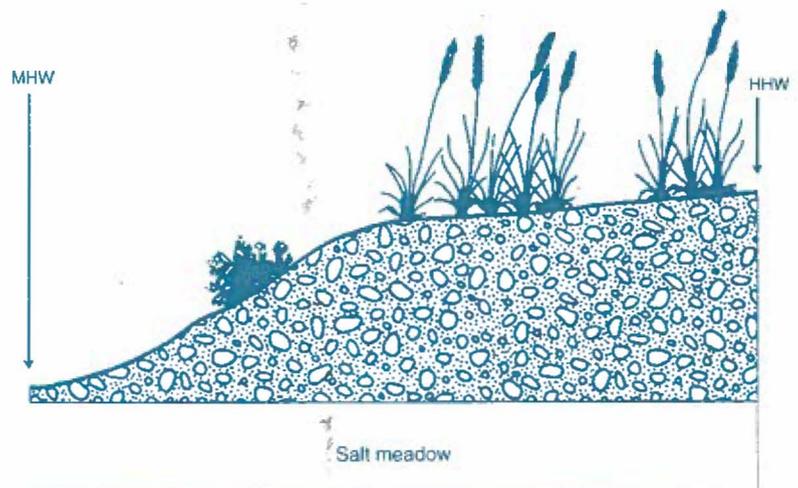




**A. Typical hydrosere on fine substrate**



**B. Typical hydrosere on coarse substrate**



MLW: mean low water  
 MHW: mean high water  
 HHW: higher high water

Source: Gratton and Dubreuil, 1990.

**Figure 3 Zonation of wetland vegetation in the St. Lawrence River and Gulf**

shoreline in this section had been altered by humans to some degree with walls, riprap or backfill (Lehoux, 1996).

Furthermore, tributaries that drain areas of the most intensive field crop production in Quebec — the Châteauguay, Richelieu, L'Assomption, Saint-François, Nicolet, Yamaska, Chaudière and Bécancour rivers — empty into the St. Lawrence between Montreal and Quebec City. The fine- and medium-grain soils of the St. Lawrence Lowlands are particularly vulnerable to erosion.

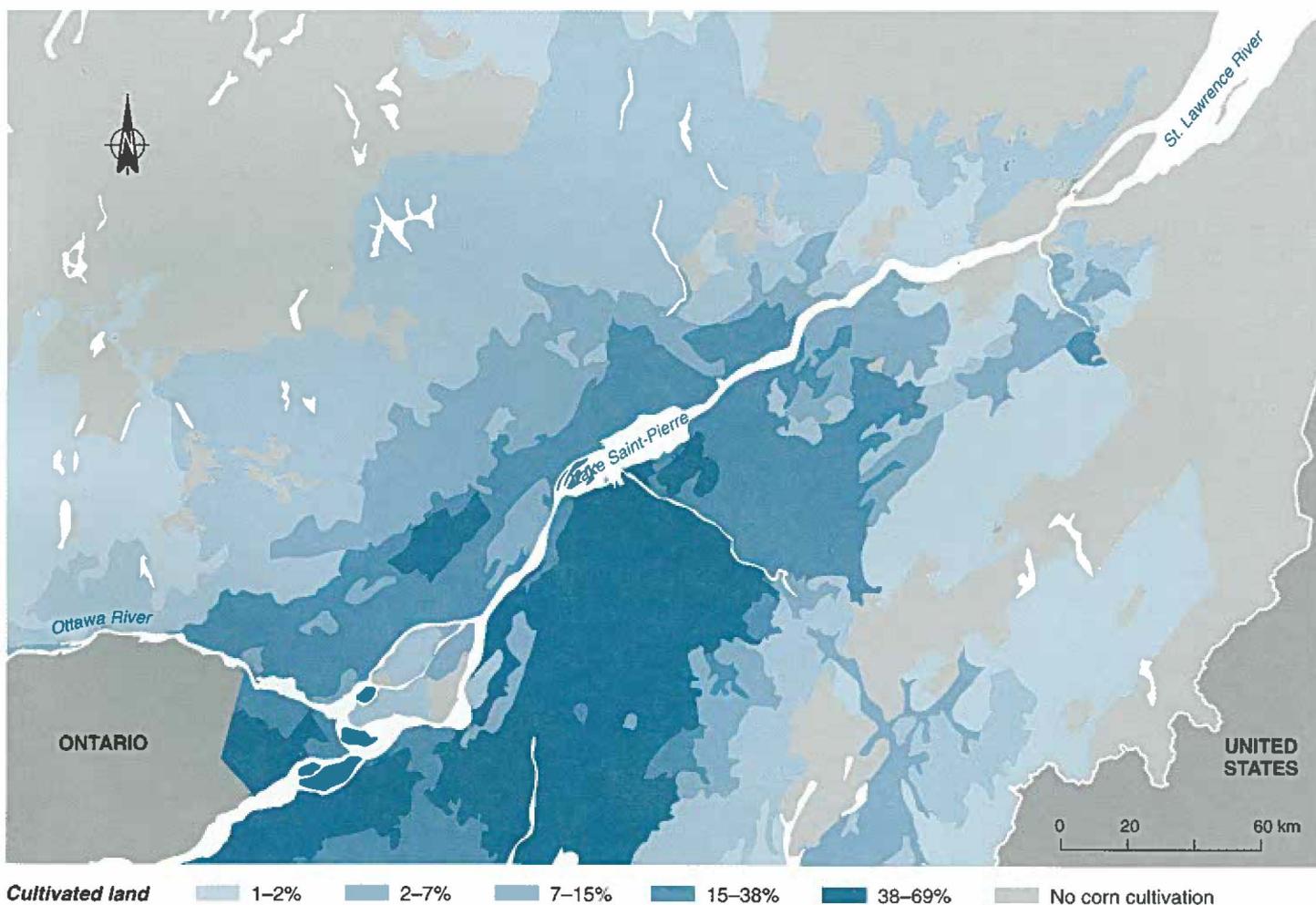
The amount of land dedicated to corn farming increased by 400 percent

between 1971 and 1991. Corn crops now occupy 350 000 hectares (ha) of land, concentrated mainly around Montreal and along the St. Lawrence between Montreal and Quebec City (Figure 4) (Government of Quebec, 1992). The volume of soil erosion associated with potato and corn growing has been estimated at 6 and 13 t/ha/yr, respectively (Government of Quebec, 1992). A study of the Bayonne, Coaticook and Ouareau rivers showed that the suspended solids (SS) component attributable to agriculture in these rivers could be as high as 90 percent (Government of Quebec, 1992). About 40 percent of this soil loss occurs in spring, when snow melts while the soil is bare of

vegetation (Environment Canada and MENVIQ, 1985).

### *Forests: effective sediment filters*

Forests transfer large amounts of water vapour into the atmosphere through evapotranspiration. Tree roots stabilize the forest soil by preventing free soil particles from escaping. When a forest is altered or disappears, the forest soil becomes vulnerable to agents of erosion, increasing the amount of sediment moving into watercourses. Logging is one of the causes cited for the gradual degradation of *barachois* (tidal ponds) in



Source: Cossette, 1995.

**Figure 4** Intensity of corn cultivation in southern Quebec

Chaleur Bay, a shallow bay bordered by high plateaus where trees are being harvested.

Trees occupy 40 percent of the riparian strip between Cornwall and Tadoussac. Hardwood forest is dominant between Cornwall and La Malbaie on the north shore and Saint-Pascal (Kamouraska) on the south shore. Mixed hardwood and evergreen forest occupies most of the land on the south shore and the nar-

row strip circling the Gaspé Peninsula. Evergreen forest covers the north shore downstream of Forestville.

### *Islands protect shorelines and essential wildlife habitats*

There are more than 1250 islands, alone or linked in archipelagos, in the St. Lawrence corridor. Island shore-

lines account for 66 percent of the total freshwater shoreline of the St. Lawrence. The shallow waters near many islands promote the development of wetlands that are usually well preserved due to their relative isolation. Because of their location, the islands are particularly exposed to currents and wake waves from passing ships, and some of them are subject to severe erosion. Other islands act as protective breakwaters for the shoreline and adjacent habitats.

# CHAPTER 2

## *A Hydrological Regime Greatly Altered by Human Activity*

**We have dredged the river bed, backfilled its shores and built ports and dams. These physical modifications have altered the flow of the water mass. Natural phenomena such as floods, ice jams and waves erode the banks and influence the sedimentary regime.**

**T**he bed and banks of the St. Lawrence River have been profoundly altered over the past 150 years. Backfilling has transformed marshes considered worthless by developers into land suitable for building. Embankments were then added to protect the property from floods and erosion. Dam construction for hydro-electricity production and flood control, and the digging of the ship channel, also significantly modified the river flow. Bridges, piers, booms and wharfs have affected flow conditions by creating zones of turbulence and eddies that upset the sedimentary balance in localized areas. See map, *Draining, backfilling and dredging in the St. Lawrence* for their locations.

### *A route to the heart of the continent*

Because of its strategic geographic position and its size, the St. Lawrence River is a natural route into the heart of North America. Very

early on, its rapids and shallows were by-passed and dredged to allow ships to reach the Great Lakes. As shipping developed, work to enlarge the channel proceeded almost without a break in the 19th and 20th centuries. The ship channel as we know it today was developed in several stages, but mainly since the 1950s. A ship sailing up the St. Lawrence River to Duluth on Lake Superior today must follow a channel that reaches almost 3700 km inland (see Information Supplement, *Large-Scale Works Affecting the River Bed*).

The navigable channel strictly speaking includes a stretch through deep water in the Lower Estuary and Gulf. However, upstream of Les Escoumins on the north shore, ships follow a buoyed channel for 500 km to Montreal. From Montreal, ships continuing on to the Great Lakes take the St. Lawrence Seaway, which begins at the Saint-Lambert locks south of Montreal and extends 388 km to the Welland Canal between lakes Ontario and Erie. For half the distance, the

## Information Supplement

## Large-Scale Works Affecting the River Bed

The configuration of the river bed, even more than the climate, has always restricted St. Lawrence navigators. Travelers in the early 18th century had to get past many rapids to reach Lake Ontario, almost 200 km west of Montreal. The construction of the first canal at Beauharnois between 1842 and 1845 marked the start of a series of major projects affecting the river bed (Figure 5).

The construction of the St. Lawrence Seaway in the 1950s turned the river into an immense work site. Although the Seaway route largely followed the fluvial lakes and the reservoirs created behind dams, an enormous volume of material had to be excavated nonetheless. In the Quebec and Ontario sections, 43 364 000 m<sup>3</sup> was removed from the river bed by dry excavation and 13 872 000 m<sup>3</sup> by dredging. The construction of seven locks for the Seaway<sup>1</sup> required the excavation of 2 294 000 to 3 440 000 m<sup>3</sup> of material. Around the same time, Ontario Hydro and the Power Authority of the State of New York (PASNYS) removed 75 448 000 m<sup>3</sup> of material from the International Rapids section between Lake Ontario and Cornwall to build the Moses Saunders hydro-electric generating station (Lasserre, 1980).

In 1959, with the official inauguration of the Seaway by the Canadian and U.S. governments, the ship channel was lengthened to 3700 km and the Atlantic Ocean was connected to the five Great Lakes. Downstream of Montreal, major works had already started in 1952 to increase the channel's minimum water depth to 10.7 m.

A second phase of major construction took place in the 1970s. About 13 000 000 m<sup>3</sup> of clay and silt was

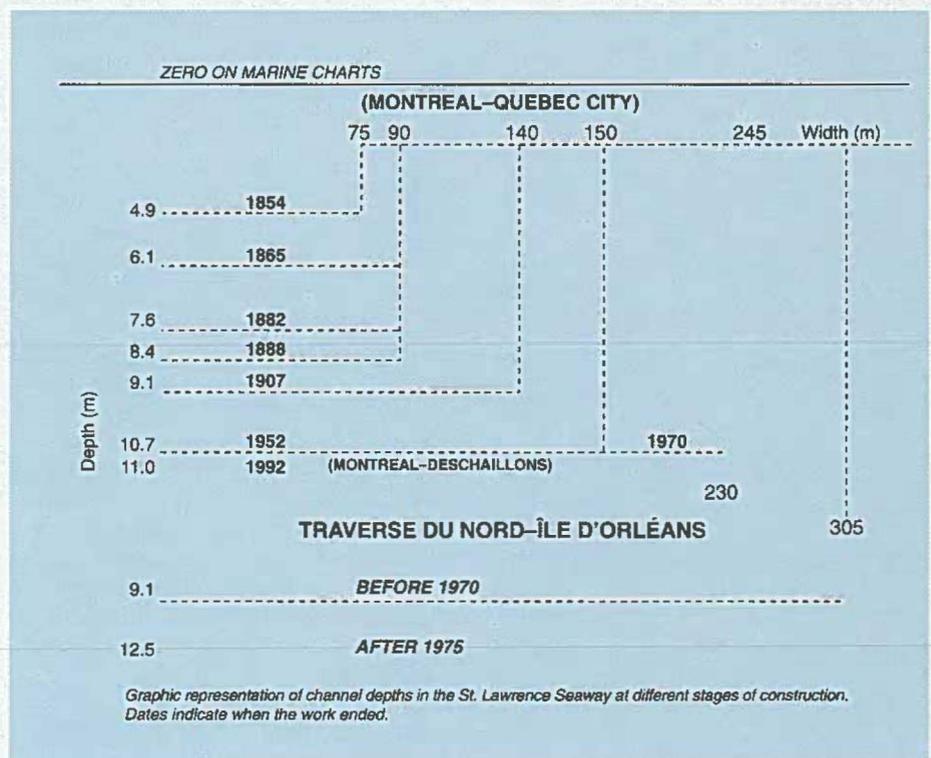
dredged from the channel in Lake Saint-Pierre, and 360 000 m<sup>3</sup> of schist was removed at Cap-à-la-Roche to correct an unsafe curve. Downstream of Quebec City, the Traverse du Nord channel was deepened from 9.1 to 12.5 m over a distance of 30 km. This required the dredging of 10 000 000 m<sup>3</sup> of sand and gravel. The latest improvements to the ship channel date from 1992 when it was deepened to 11.0 m between Montreal and Quebec City. This was not a major undertaking since most of the corridor was already this deep (SLC, 1993a).

Later phases of St. Lawrence Seaway construction and enlargement required the removal of millions of tonnes of unconsolidated material and bedrock. Most of the excavated material was used in the construction of locks, dikes and long stretches of

embankment bordering the ship channel around Montreal. Dredged material was also dumped on shoals near the dredging sites. This material created Île aux Sternes at the outlet of Lake Saint-Pierre and Île Chipeau in the Contrecoeur archipelago.

Today, shallow depths above Montreal still limit the movement of large ships towards the Great Lakes, as do climate and a winding route that demands an expert knowledge of the Seaway.

1. Saint-Lambert, Côte-Sainte-Catherine, Beauharnois (two locks), Bertrand H. Snell, Dwight D. Eisenhower and Iroquois.



Source: Canadian Coast Guard, 1994.

**Figure 5** Changes in the dimension of the ship channel since 1854

channel is contained within embankments. There are seven locks to lift ships up the 64 m difference in height between Montreal and Lake Ontario. Water levels are therefore completely regulated. The minimum guaranteed water depth in the ship channel is 12.5 m downstream of Quebec City, 10.7 m between Quebec City and Deschaillons, 11.0 m up to Montreal (Saint-Lambert) and 8.2 m in the Seaway above Montreal. The channel increases from 245 m wide between Montreal and Quebec, and 305 m wide downstream of Quebec City.

Seasonal variations in water levels and certain tidal windows allow ships drawing up to 15.2 m (over the 12.5 m minimum water depth guaranteed at low tide) to take the channel to Quebec City. The locks restrict the movement of large ships upstream of Montreal and create a busy transshipment business in the Port of Montreal.

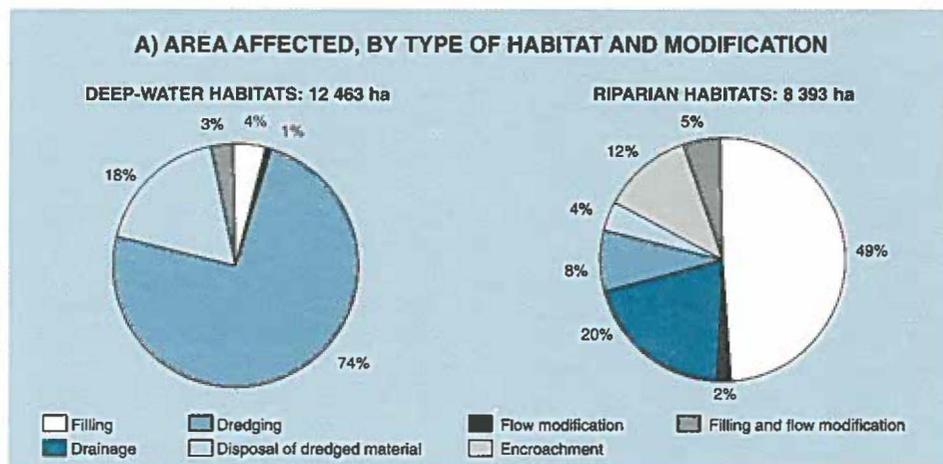
#### An underwater barrier for living creatures

The St. Lawrence Seaway was built at a time when our knowledge of ecosystems was very fragmented. Project planning often focused solely on technical and economic aspects, while environmental impact studies were not normally done. In the Montreal area, moreover, the dredging of the ship channel coincided with other large construction projects that created the Expo 67 islands, the Louis-Hippolyte-Lafontaine tunnel, and Highway 132 on the south shore. It is therefore very difficult to assess precisely the Seaway's impact on St. Lawrence ecosystems.

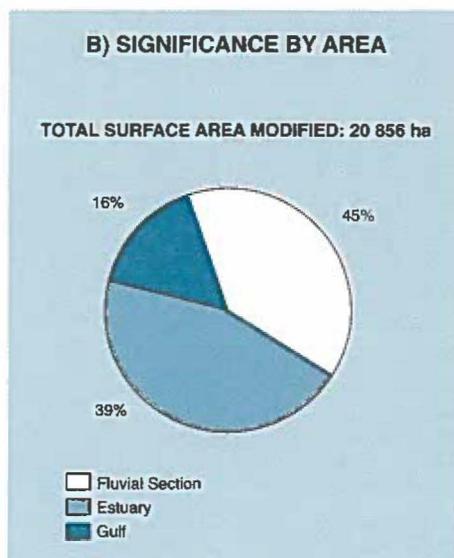
It is generally agreed that these projects, especially the dredging of the ship channel, changed the river bed's configuration significantly. Digging a channel in otherwise shallow areas of the river had the effect of "channeling" the water mass. This created a water wall that presented a physical barrier to many species of fish.

Marquis et al. (1991) and Robitaille et al. (1988) compared aerial photographs taken from 1945 to 1988 which identify a substantial loss of fish habitat. A total of 20 856 ha was lost over this period (Figure 6). Deep-water habitat loss is estimated at 12 463 ha, with 8393 ha of river-banks lost. Almost all (84 percent)

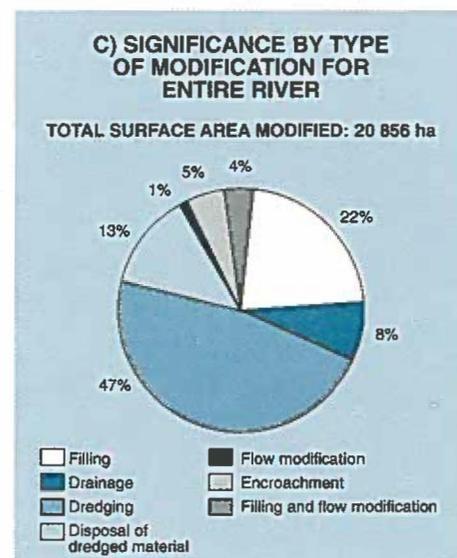
losses occurred in the Fluvial Section and Fluvial Estuary (Figure 6B), and can be traced to dredging, filling, draining of the river bed, encroachment on the banks, and changes to water flow, etc. The modifications are shown on the map, *Draining, backfilling and dredging in the St. Lawrence* in Chapter 9.



Source: Adapted from Marquis et al., 1991, and Robitaille et al., 1988.



Source: Adapted from Marquis et al., 1991, and Robitaille et al., 1988.



Source: Adapted from Marquis et al., 1991, and Robitaille et al., 1988.

**Figure 6 Physical changes to fish habitat between 1945 and 1988**

## Flow regulated by upstream dams and control structures

The natural flow regime of the Great Lakes–St. Lawrence system has been modified by numerous control structures (Figure 7). Upstream from Lake Saint-François, three major dams (Moses Saunders, Long-Sault and Iroquois) regulate the river flow between Lake Ontario and Cornwall. The Beauharnois and Les Cèdres generating stations play the same role at the outlet of Lake Saint-François.

From a hydrological point of view, the St. Lawrence cannot be separated from the Great Lakes. Together they form a system in which any change in water levels (or flow) upstream is inevitably reflected downstream. The equilibrium of the system is dictated by the amount of water entering (precipitation, runoff, groundwater inflow) and leaving (evaporation, outlet flow). This equilibrium changes from season to season (seasonal variation), year to year (inter-annual variation) and over very long periods (decades, centuries) (see Information Supplement, *Global Warming and the St. Lawrence*).

### Information Supplement Global Warming and the St. Lawrence

Average annual temperatures have risen around the world since the beginning of the 20th century.

Geological history has shown us that the earth's climate has fluctuated widely over a long time period. The Great Lakes–St. Lawrence region became 0.7°C warmer between 1895 and 1991. During this period, water in the Great Lakes fell to very low levels.

For the St. Lawrence, global warming would produce a slight drop in water levels in the Fluvial Section and Upper Estuary due to reduced flow at the outlet of the Great Lakes. Littoral areas would therefore expand, accompanied by a drying of existing wetlands and degradation in water quality. The reduced flow would also mean less dilution of pollutants. Shipping would also be adversely affected and the ship channel would need intensive dredging (Lapel Inc., 1989). Suspended solids (SS) concentrations could be expected to rise if the sediment load remains the same.

Another effect of reduced flow could be a shift in temporary and permanent sedimentation zones. In addition, higher SS concentrations would probably also affect light penetration, the main growth factor for autotrophic organisms at the base of the food chain.

In contrast to predictions for the upstream section of the St. Lawrence, water levels are expected to rise in the Upper Estuary, Lower Estuary and Gulf areas, as a consequence of faster melting of polar ice and snow and the thermal expansion of ocean masses. According to the latest forecasts, sea levels will rise from 20 to 95 cm above current levels (IPCC, 1995). Under this scenario, current patterns in the St. Lawrence would change profoundly and shore erosion would accentuate as waters encroach on beaches and the shore following the formation of temporary and permanent inundation zones. Salt water is also expected to penetrate farther upstream and enter tributary mouths and water tables, possibly putting additional pressure on drinking water resources.

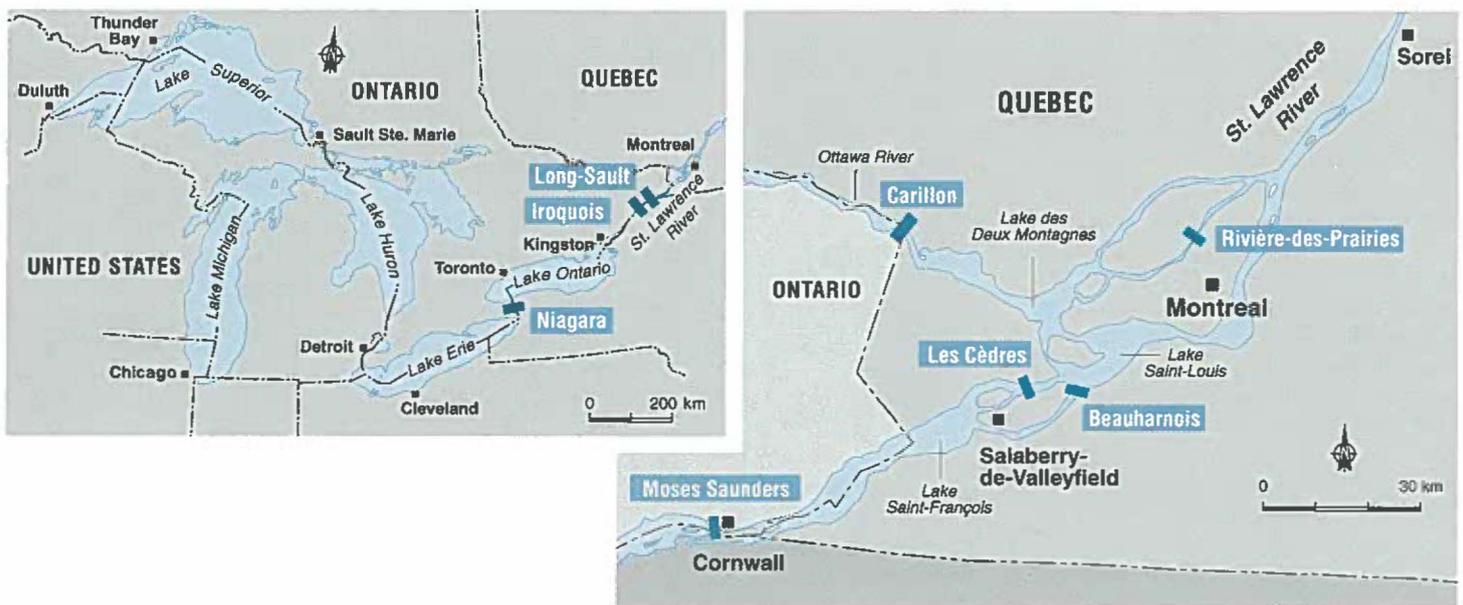


Figure 7 Hydro-electric power stations and control structures upstream of Montreal

Flow regulation upstream has reduced the range of water level variation in much of the Fluvial Section between Cornwall and Montreal. In Lake Saint-François, for example, inter-annual variations might reach as high as 50 cm before the last control facilities were built in the 1960s. They are below 15 cm today. In general, floods have been flattened out and low water levels are less pronounced (see Information Supplement, *Bilateral Treaty Governs Water Levels*).

Flow regulation at the outlet of Lake Ontario does not guarantee total control of water levels since water inputs cannot be controlled and accurately predicted over the long term. Indeed, there have been long periods of both low and high water inputs in the past (Figure 8). Moreover, water level fluctuations vary greatly in the Fluvial Section due to inputs from tributaries and the morphometric characteristics of the cross-section of the river (Table 1). For example, Lake Saint-Louis receives waters from both the Great Lakes and the Ottawa River, and its water levels and flow are

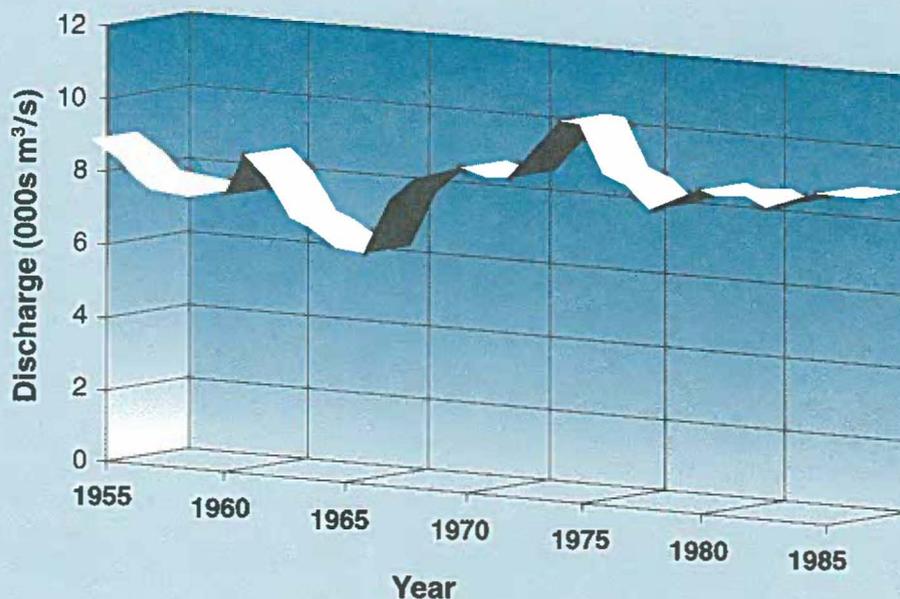
strongly influenced by the floods of the Ottawa. The discharge of the Ottawa River fluctuates between seasonal extremes of 306 m<sup>3</sup> per second in the low water period and 8190 m<sup>3</sup>/s in times of flooding (Bergeron, 1995).

Other factors that can locally influence St. Lawrence water levels and flow rate are precipitation, evaporation, runoff, ice jams, dense aquatic plant growth, tides and wind. Water level variations in the estuary and the gulf are primarily influenced by strong winds and high tides rather than by the inflow of water from upstream, from the Saguenay Fjord or from precipitation. Inter-annual water level variations are low (Table 1).

Water level variations are not bad in themselves, since plants and animals can adapt to them to a certain point. However, problems arise when water levels remain extremely low or high for prolonged periods. The disappearance of vegetation triggers shore erosion in areas where soil type and exposure to waves and currents allow

### Information Supplement Bilateral Treaty Governs Water Levels

The International Joint Commission (IJC) is a bilateral agency that applies the *Boundary Waters Treaty* between Canada and the United States. The International St. Lawrence River Board of Control implements the Lake Ontario water regulation plan (Plan 1958-D). Its role is to manage water levels in lakes Ontario and Saint-François and maintain a minimum guaranteed level at the Port of Montreal. The permissible variation is now set at 0.30 cm, but new variations are under study. Efforts are being made to improve the existing regulation plan by adding criteria designed to preserve natural ecosystems, while protecting the interests of riverside residents as well as stakeholders such as ship owners, pleasure boaters and electricity producers (IJC, 1993).



Source: Argus Inc. (1991) in Lehoux, 1996.

**Figure 8** Variations in the flow rate from 1955 to 1985 between Cornwall and Île d'Orléans

**Table 1** Water level variations

Lake Saint-François	<p><i>Water levels and flow stabilized artificially since 1960 and controlled by Moses Saunders, Beauharnois and Coteau-du-Lac dams (control structures).</i></p> <p>At Coteau-Landing:</p> <ul style="list-style-type: none"> <li>• Mean water level before 1964: 46.31 m and inter-annual variations &lt; 50 cm</li> <li>• Mean water level after 1964: 46.57 m and inter-annual variations &lt; 15 cm</li> <li>• Mean historic water level: 46.39 m</li> <li>• Mean flow rate at Cornwall inlet (1986-1990): 7720 m<sup>3</sup>/s</li> <li>• Mean flow rate at Coteau-Landing outlet: 7864 m<sup>3</sup>/s</li> </ul>
Lake Saint-Louis–Sorel	<p><i>Lake Saint-Louis: Confluence of Great Lakes and Ottawa River. Water levels and flow strongly influenced by discharge of the Ottawa River, which can vary between seasonal extremes of 306 m<sup>3</sup>/s in low water periods and 8190 m<sup>3</sup>/s in periods of flooding. Abrupt water level fluctuations and inter-annual variations as high as 1.2 m at Pointe-Claire, 5.0 m at the Port of Montreal and 2.0 m at Sorel.</i></p> <p>At Pointe-Claire:</p> <ul style="list-style-type: none"> <li>• Mean water level before 1964: 21.03 m</li> <li>• Mean water level after 1964: 21.31 m</li> <li>• Mean historic water level: 21.14 m</li> </ul> <p>Port of Montreal:</p> <ul style="list-style-type: none"> <li>• Mean water level before 1964: 7.39 m</li> <li>• Mean water level after 1964: 6.77 m</li> <li>• Mean historic water level: 7.15 m</li> </ul> <p>Sorel:</p> <ul style="list-style-type: none"> <li>• Abrupt annual fluctuations and very large annual variations.</li> <li>• Mean water level before 1964, after 1964 and historic mean: 5.04 m</li> </ul>
Estuary and Gulf	<p><i>Water level variations in the estuary and gulf are primarily influenced by strong winds and high tides rather than inflows from the river upstream, the Saguenay River or precipitation. Inter-annual variations in water levels are low.</i></p> <ul style="list-style-type: none"> <li>• Lauzon: mean historic variation: 0.60 m</li> <li>• Pointe-au-Père below Rimouski: mean historic variation: 0.00 m</li> <li>• Port of Sept-Îles: mean historic variation: 1.53 m</li> </ul>

Source: Bergeron, 1995.

it. High water levels are often blamed for the loss of several hectares of forests of great ecological value on the shores of lakes Saint-Louis and Saint-François.

### *Drifting shorelines*

A 1994 inventory of riverbanks between Cornwall and Île d'Orléans

showed that 28 percent of the 1532 km of shoreline in this section was affected to varying degrees by erosion. The proportion rises to 47 percent when only the 848 km of natural shoreline is considered (Lehoux, 1996).

No systematic inventory has been done on shore stability in the estuary and gulf. However, several local ero-

sion problems have been observed, particularly in the intertidal marsh of Cap Tourmente, Rivière-du-Loup bay, and the Manicouagan and aux Outardes river deltas.

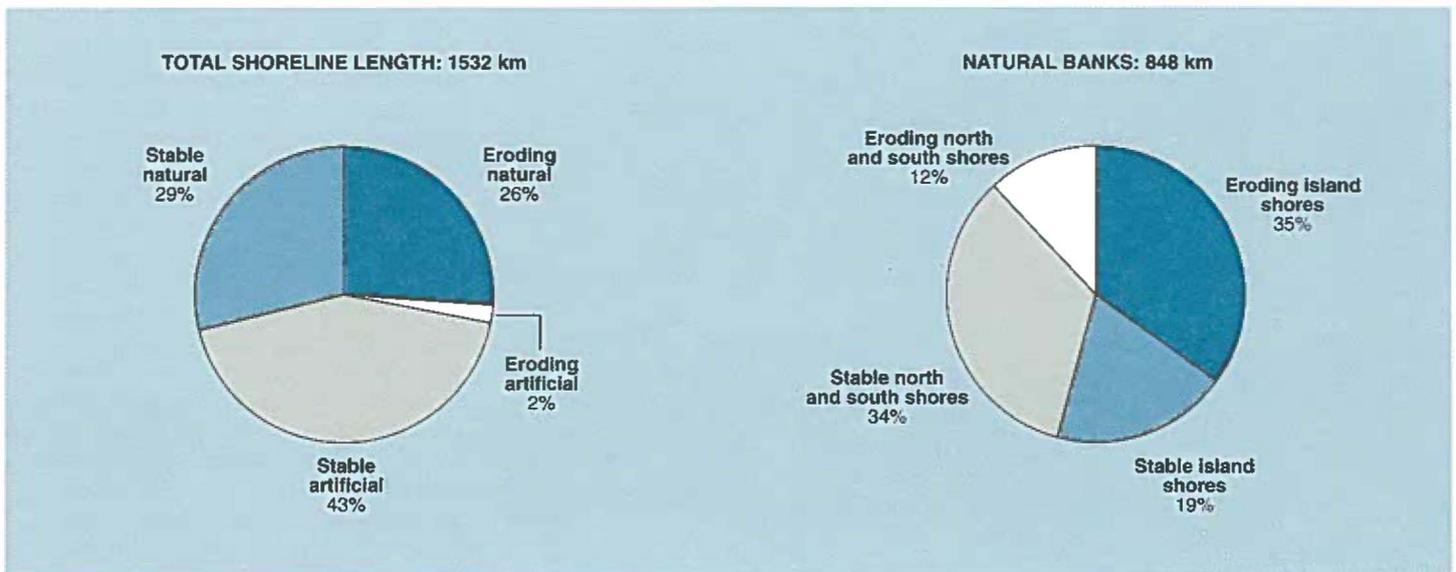
Riverside residents have a variety of defences against shore erosion, whether natural or caused by human activity. A total of 658.5 km of the 1532 km of shoreline between Cornwall and Île d'Orléans, or 45 percent, are protected by artificial structures (walls, riprap or embankments) (Figure 9).

Without adequate protection, the shoreline may recede dramatically. A comparison of aerial photographs taken at 20-year intervals shows that several shore sections on certain islands in the Fluvial Section are receding at an average rate of 3 m/yr. Along the Montreal–Trois-Rivières stretch alone, shore losses from erosion are estimated at 40 ha/yr for the past 20 years (Lehoux, 1996). This represents many tens of thousands of cubic metres of sediments (between 400 000 and 600 000) apparently contributed to the river's sediment budget every year (Lehoux, 1997).

Shore erosion increases local turbidity and makes water less attractive for drinking or swimming. An increase in sediment levels in water can also silt up septic tanks and spawning areas, while plant and animal life on the eroded riverbank disappear along with the bank that sheltered them.

Several methods have been devised to stabilize riverbanks. Some, like concrete blocks and riprapping, are effective, but have the disadvantage of being ugly and creating sterile environments from an ecological viewpoint. In recent years, interest has turned to finding effective soil stabilization methods that preserve the ecological role of the riverbank (see Information Supplement, *Protecting the Banks of the Contrecoeur Islands*).

Erosion occurs in principle when there is an imbalance between erosion forces and the input of sediments of natural or human origin. In most cases, however, it is caused by



Source: Lehoux, 1996.

**Figure 9** Compilation of data on the state of St. Lawrence riverbanks between Cornwall and Île d'Orléans

#### Information Supplement

### Protecting the Banks of the Contrecoeur Islands

The Contrecoeur archipelago is typical of an area where the forces of erosion are very active. The archipelago is formed of two strings of islands lying parallel to the shore. The outer group facing the river act as barrier islands. Most of them were reshaped by dredged material dumped during the digging of the Seaway channel. Closer to shore to the southeast, the second group of low-lying islands are flooded in spring, but protected from erosion by aquatic plant communities and marshes that absorb wake waves. The barrier islands were severely eroded when river levels rose in the 1965-1975 period and some banks are receding at a rate of 1 to 2 m every year.

Aquatic plant communities and marshes between the two island groups are endangered. Protective measures are needed to protect the

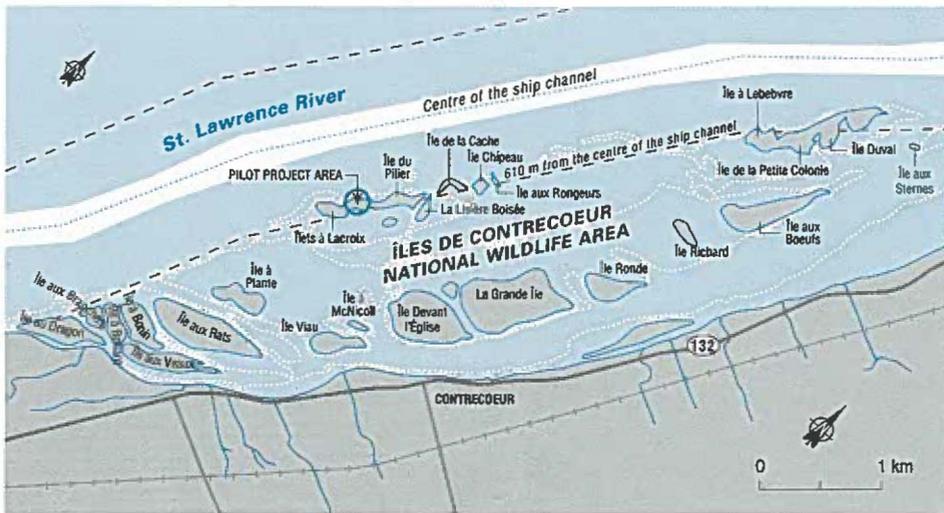
barrier islands that shield them. The aquatic plant communities and marshes of the Contrecoeur islands provide valuable spawning, nesting and nursery habitats, supporting bird communities such as the Northern pintail (*Anas acuta*) and Gadwall (*Anas strepera*), as well as abundant and diverse fish communities (Figure 10).

Pilot projects to stabilize banks have been conducted on barrier islands threatened by erosion, including the Lacroix, Pilier, de la Cache and Chipeau islands. On the Lacroix islets, bank vegetation planting was tried along with slope reshaping and fascine installation (Figure 11). Cedar log cribs were used on Île de la Cache (Figure 12).

Erect willow (*Salix eriocephala*) was the main species used in the Lacroix islets project for several reasons. It grows widely along Quebec waterways and has a well developed root system that offers strong anchorage and good resistance to erosion. The willow also responds well to propa-

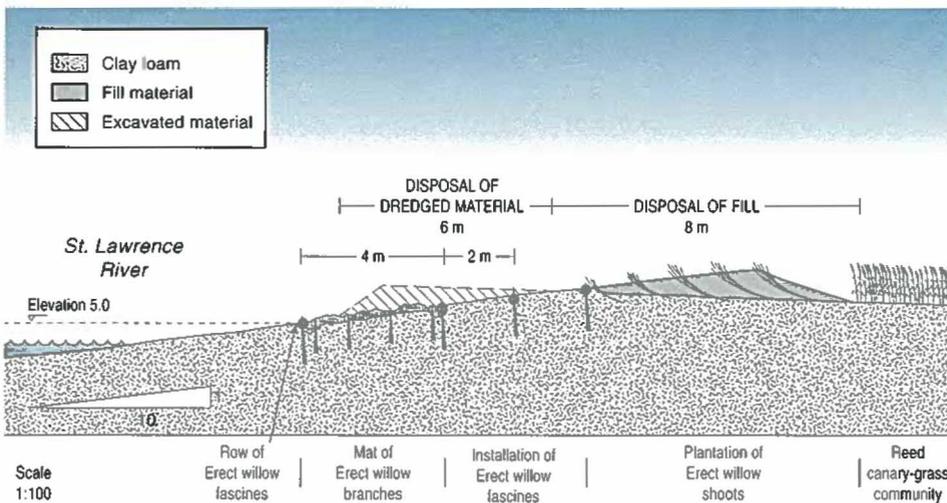
gation by cuttings and grows rapidly (Argus Inc., 1996). However, certain indigenous plants such as Sweet clover (*Melilotus* sp.) and Indian hemp (*Apocynum cannabinum*) have colonized the area. They may undermine the project by competing with the willows for nutrients, water and light. After a full annual erosion cycle, the structure has demonstrated excellent physical stability against ice and the spring flood.

At the Île de la Cache project, monitoring showed that the structure performed well, resisting the action of ice, spring flood, waves and river currents. However, because the low water level was not well understood, there was some erosion damage to the base of the cribs. This situation could be rectified by adding a few rows of cedar logs to the base (Argus Inc., 1992).



Source: Argus Inc., 1996.

**Figure 10** Map of the Contrecoeur archipelago



Source: Argus Inc., 1996.

**Figure 11** Riverbank stabilization at Ile à Lacroix using willow works, slope reshaping and fascines

interdependent processes that are often difficult to assess individually. These processes are described below.

### Water levels vary

Water level variations that persist for long periods cause an upward or downward migration of riparian vegetation. Since some time may pass before a better adapted plant community colonizes the bank, the bare soil is left particularly vulnerable to erosion. Annual or seasonal variations can reduce, cancel or amplify the impact of waves, ice and currents on shoals and on gently sloping banks.

In the estuary, daily tidal variations resuspend mud and rework the sand on the foreshore. These variations also change the level of attack of waves, currents and ice on beaches and at the foot of cliffs (Lehoux, 1996).

### Waves attack the shore

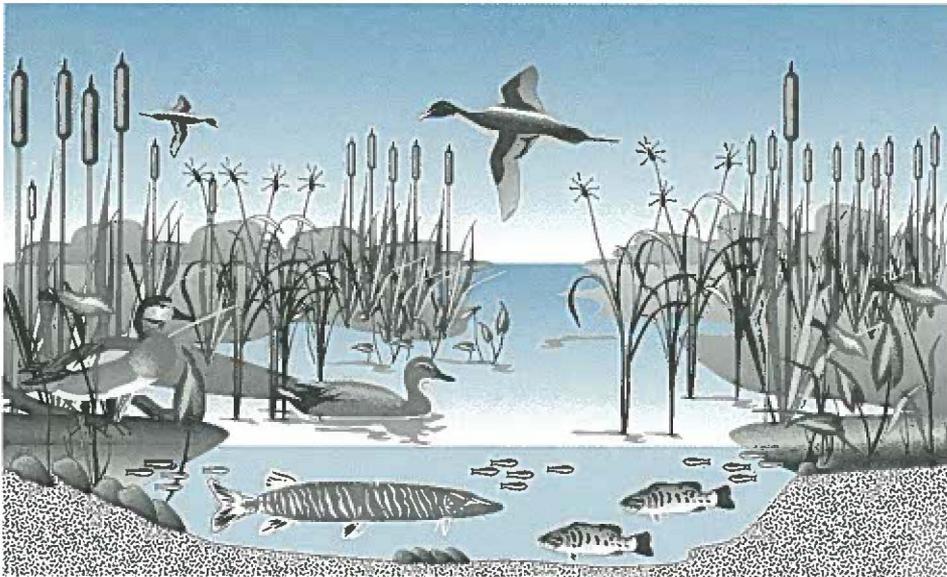
Wind waves are generated by winds acting on the water surface. Their strength depends mainly on wind speed, duration and fetch (the distance over which wind blows without encountering obstacles). The impact of wind-induced swells is greater

when the winds are strong and blow for a long time, when the fetch is long, and when shoreline materials are friable. All these conditions come together in shallow lake environments (lakes Saint-François, Saint-Pierre and Saint-Louis) and in intertidal zones downstream of Trois-Rivières (the Portneuf flats, for example), where swells play an important role in bottom sediment dynamics, especially from mid-October to mid-December when winds blow from the northeast. However, conditions are harshest in the Gulf of St. Lawrence, where waves reach heights of 4 to 5 m and occasionally up to 6 or 7 m. The force of these waves seriously erodes the littoral zone in many areas of the Gaspé coast and the North Shore.

Wake waves are generated by ships passing near the shore. Wherever the ship channel runs less than 600 m from shore, both the north and south riverbanks and island shores are threatened by erosion (Panasuk, in Lehoux, 1996). A single ship passing through the channel creates water level variations equal to 70 percent of the variation caused by spring floods. The eroding power of wake waves increases with the speed and tonnage of the ship. However, smaller pleasure craft generate equally damaging wake waves because they generally use channels that run close to shore. There is also the mass effect of pleasure boats, as some channels are heavily used. Wave erosion is most severe in early spring and fall, when natural wave-attenuating agents are absent; that is, aquatic plants have died off and ice has not yet formed on the shore.

### Ice scours the shore

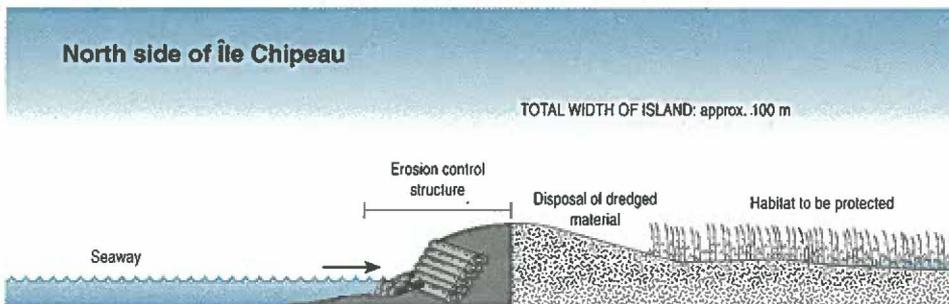
Since the opening of the St. Lawrence Seaway, ice cover in the Fluvial Section downstream from Montreal has been limited to sheltered bays for much of the winter. In the estuary and gulf, a narrow band of littoral pack ice is attached to the shoreline, while huge ice floes drift on the currents. In the river corridor and Fluvial Estuary, ice-induced erosion is caused by the ice jams that form in periods of intense cold. The ice congestion is often substantial and powerful enough to reach the banks, scour the soil and damage vegetation. Ice in the estuary is mainly associated with foreshore



#### Habitats to be protected

- Emergent deepwater marsh with cattail and arrowhead species, and River bulrush
- Waterfowl: Gadwall and Northern pintail
- Fish: Northern pike, Yellow perch, sunfish, Brown bullhead, cyprinids, Largemouth bass

#### North side of île Chipeau



Source: Modified from Argus Inc., 1992.

**Figure 12** Riverbank stabilization on de la Cache, Piller and Chipeau islands using cedar log cribs

ice that is in periodic contact with the bottom and therefore picks up an appreciable quantity of solid matter. The spring breakup lifts the fast ice attached to the bank along with large rafts of vegetation and sedimentary material held fast. The *Spartina* marshes of the estuary are subjected to this intense scouring by ice that destabilizes them and sends clumps of plant matter drifting downstream. Ice erosion of the shoreline dispatches millions of tonnes of fine sediments into the gulf every year (Dionne, 1971; 1981; 1984).

#### Currents undermine the shore

The eroding power of currents depends on riverbank morphology (shape, position and slope), shore-face profile, sediment texture, and the presence of vegetation. During floods, the current in narrow sections of the river can be strong enough to erode the banks. This occurs in the secondary channels of the Boucherville archipelago and some sections of the ship channel between Trois-Rivières and Quebec City.



# CHAPTER 3

## *The Slow Process of Erosion: the Origin of Sediment*

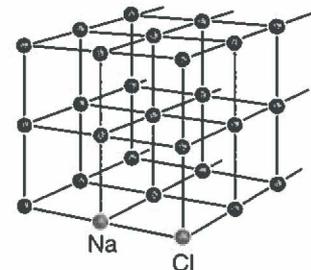
**The geological cycle accounts for the formation of sediment. Mineral and organic particles are ripped from their source and transported to the St. Lawrence by the vast network of rivers, streams and runoff water. In settling gradually to the bottom, the particles undergo a slow transformation.**

**S**ediment is defined as particulate matter of mineral or biological origin that has settled to the bottom of a water body. Most contaminants, when introduced into rivers, have a strong propensity to bind to fine particles transported in suspension on the currents. The transport and deposition of suspended solids therefore play a major role in the pathway taken and the fate of pollutants released into aquatic ecosystems. The sedimentary cycle is made up of four broad stages: weathering, transport, deposition and diagenesis.

### *St. Lawrence sediment reflects the rock and soil in its drainage basin*

For billions of years, the Canadian Shield has been under relentless attack from atmospheric agents that age even its most resistant rocks by physical disintegration or chemical decomposition. This slow aging of rocks, which wears down mountains, is called *weathering* by geologists (Landry and Mercier, 1983).

Magma trapped in fissures in the earth's crust and lava expelled from a volcano mouth cool slowly to form crystals that are the basis of the minerals making up the continental rocks. The crystal's shape (e.g. a cube of table salt or halite; Figure 13) is a macroscopic expression of an ordered arrangement of atoms which are the basic constituents of matter. Like the Biosphere on Île Notre-Dame, which has remained in equilibrium for decades because of its sturdy framework (crystalline structure) of multiple triangles (chemical bonds) connecting the nodes (atoms), rocks are extremely stable owing to the forces of attraction bonding the chemical elements that constitute their minerals.



**Figure 13** Structure of a crystal

The many chemical attacks on rocks by atmospheric agents (e.g. dissolving minerals) alter the very identity of the minerals by slowly destroying their crystalline structure. Chemical weathering of rocks releases ions and molecules that will be transported in solution in surface and subsurface waters, along with solid particles that will be carried in rivers. Rocks weakened by weathering are more vulnerable to erosion.

Mechanical weathering is caused by repeated cycles of freezing and thawing which break rocks into ever smaller pieces without altering their crystalline structure. During the Quaternary period, rocks in the St. Lawrence drainage basin were repeatedly subjected to the action of continental glaciers advancing at an almost imperceptible pace under the force of

gravity. Ice fields are both powerful agents of erosion for the rocky substrate and for transporting the rocky debris crushed under their weight. Glacial erosion also reduces an area's relief by leaving debris of all sizes (unconsolidated deposits) after the ice melts (see Information Supplement, *A River Emerges from the Water*).

For three centuries, human activity, particularly deforestation and agriculture, has accelerated the erosion of unconsolidated deposits and soils. Land cleared for agriculture is exposed to the impact of rainfall and runoff. When rain or snowmelt water cannot seep into the soil, it carries organic matter and fine mineral particles to watercourses. Any pesticides or heavy metals in the soil are carried by surface runoff to rivers. Toxic chem-

ical compounds can remain in soils for long periods. A good example is DDT, which has been banned in Canada since 1969 yet is still found in soils of the Great Lakes watershed (Environment Canada, 1991).

### *The path to the river is fraught with traps*

Most ions released by the chemical weathering of rocks are transported in solution to the ocean, where they precipitate. They therefore have little impact on the composition of St. Lawrence River sediment. By contrast, solid particles produced by mechanical weathering and erosion are carried at the whim of the current once they enter a river. Small gravel and coarse sand roll along the bottom (*traction*) while finer sand moves in

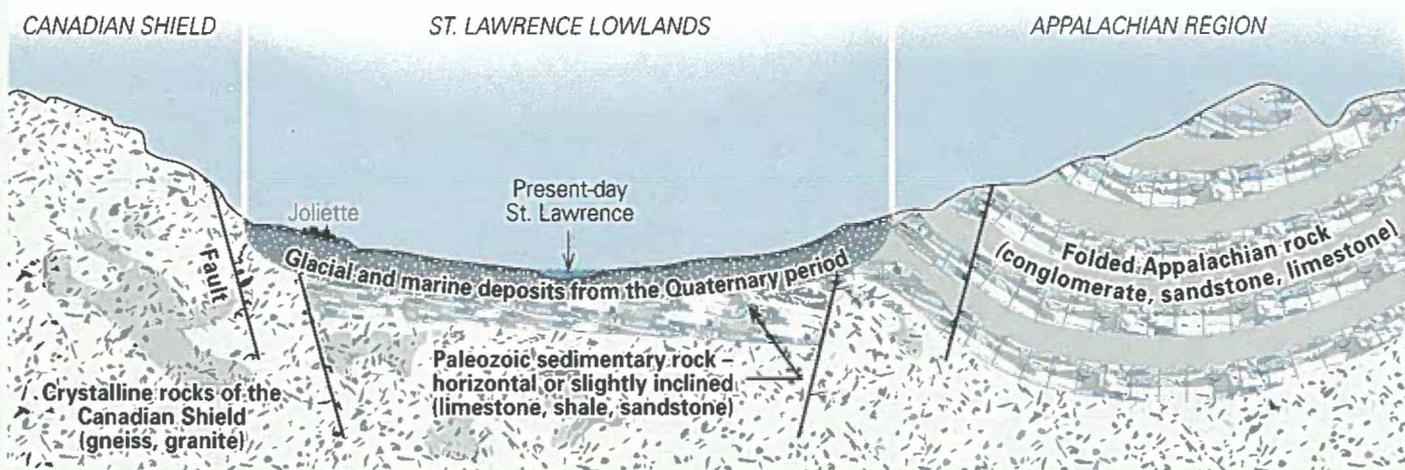
#### Information Supplement **A River Emerges from the Water**

During the Devonian period, 350 million years ago, the predecessor of the St. Lawrence River carved out a deep valley that closely followed the path of the present-day river.

This valley experienced at least four glaciations during the Quaternary

period. When the last glacier retreated 10 000 to 12 000 years ago, the depression was filled by the Champlain and Goldthwait seas. Clays settled in deep-water sections while gravel was deposited along their shores (Figure 14). As these seas receded with the rebound of the earth's crust, freed from the weight of the continental glaciers, a new hydrographic system took shape on the newly exposed land area. The branches of this system finally con-

verged some 7000 years ago to form the present-day St. Lawrence River. Over a relatively short time period, the St. Lawrence changed its river bed a number of times as the earth's crust rebounded. This phenomenon accounts for the many islands between Montreal and Quebec City.



Source: Reproduced from SLC and Université Laval, 1992b, based on Grenier and Hamelin, 1971.

**Figure 14** The St. Lawrence basin and its physiographic regions

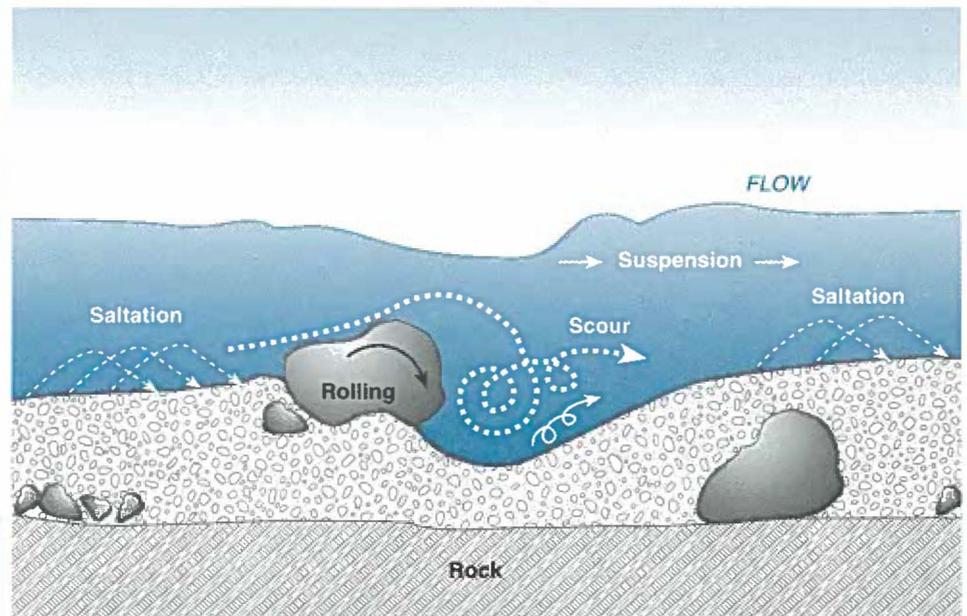
intermittent skips and bounces (*saltation*), and the finest particles remain suspended in the flow (Figure 15). The distance traveled by potentially contaminated suspended particles depends on their size, since they settle only in places where the current slows sufficiently (Figure 16).

The amount of coarse sediment transported by traction cannot be determined easily by existing methods since the grains move very close to the water bottom. Based on theoretical studies, several in situ surveys and volumes of dredged material, transport by traction appears to be quite limited, involving 50 000 to 500 000 t/yr of sediment downstream of Montreal, mainly sand from tributaries (Frenette et al., 1992). By contrast, millions of tonnes of solid material removed from the St. Lawrence watershed annually are transported in suspension to the ocean. Mineral and organic particles (plant and animal detritus) derived from rock and soil erosion in the drainage basin form the terrigenous fraction of the SS load. Organic particles (plankton, detritus), which predominate in the marine environment, constitute its biogenous fraction.

In the Upper Estuary, where fresh and salt water mixes, both terrigenous and biogenous particles are found in suspended matter. The union of fresh and salt water here produces a maximum turbidity zone (MTZ), where SS concentrations are much higher than values observed upstream of Île d'Orléans or downriver of Île aux Coudres. Under the influence of water circulation in the estuary, terrigenous particles transported in the surface waters of the river settle slowly with the biogenous particles, and then are carried back upstream by a deep, counteracting current. This phenomenon also occurs at the mouth of the Saguenay River.

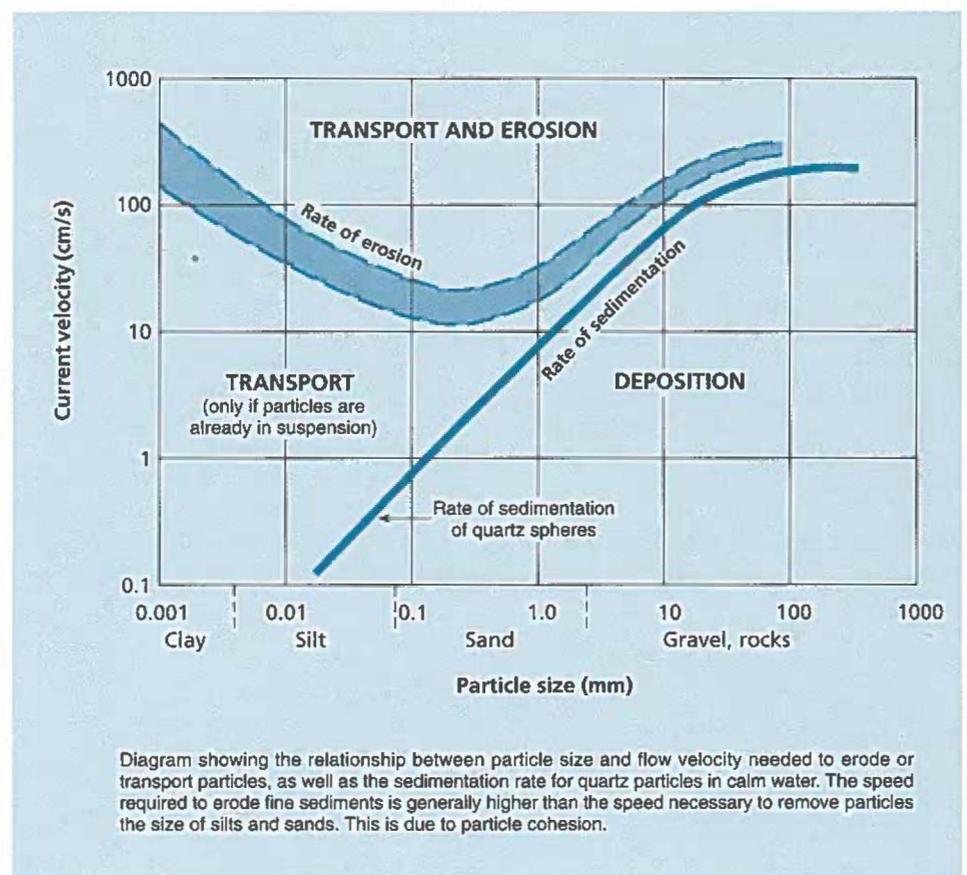
### *Sediment deposition patterns are complex in the St. Lawrence*

The St. Lawrence River can be divided into five hydrographic sections, each presenting a very different sedimentary environment in terms of currents,



Grain size and current velocity determine the mode of transport.

**Figure 15** The three modes of transport of sediment particles



Source: Adapted from Hjulström, 1939.

**Figure 16** Relationship between particle size, flow velocity and bottom deposition

waves, tides and ice. Moving downstream from the river's source, the divisions are called the Fluvial Section, the Fluvial Estuary, the Upper Estuary, the Lower Estuary and the Gulf. Flow characteristics, the main agent controlling the sedimentation of solid particles, are very complex in the St. Lawrence.

The Fluvial Section, running from the outlet of Lake Ontario to Lake Saint-Pierre, encompasses the river proper. Currents here are extremely variable due to the presence of rapids, lakes and archipelagos. Since the beginning of the 20th century, the complex natural flow in this section of the river has been altered by engineering works (ship channel, dams, ports, embankments) and by eutrophication (excessive nutrient enrichment of the water causing aquatic plants to proliferate). Interspersed between the rapids are areas calm enough to permit suspended particles to settle. Lake Saint-François, Lake Saint-Louis, the Lesser La Prairie Basin, and certain channels in the Contrecoeur and Sorel archipelagos have areas of deep water (> 4 m), set back from the main channel, where fine sediments have been accumulating ever since the natural flow of the river was changed. Of course, other shallow lake areas also experience sedimentation, especially in summer when large aquatic plant communities filter particles from the water. However, these deposits are partly stirred up and resuspended in autumn with the senescence of the vegetation that shielded them against the waves. The rising waters of spring breakup quickly dislodge any particles lingering on the bottom.

The Fluvial Estuary, extending from the outlet of Lake Saint-Pierre to the

eastern tip of Île d'Orléans, is characterized by freshwater tides. The strength of the river current is intensified by the falling (or ebb) tide, a factor that greatly limits zones of permanent sedimentation. However, the flats around Île d'Orléans temporarily retain large quantities of fine sediment, and the Traverse du Nord southeast of Île d'Orléans silts up rapidly and requires frequent dredging.

The Upper Estuary, between Île d'Orléans and the mouth of the Saguenay Fjord, is where fresh and salt water begin to mix. In deep areas, intense bottom currents generated by high tidal ranges sweep away fine deposits, leaving behind coarse sediment in dune formations. On the Montmagny flats and in the Île-aux-Grues archipelago, vegetation temporarily stabilizes sediments deposited during the summer until they are driven back into open water by the autumn winds and tides.

The Lower Estuary, from the Saguenay River to Pointe-des-Monts, surrounds the Laurentian Channel, a deep trough that opens on the Gulf of St. Lawrence. The sedimentation rate is very high here (1.5–4.0 mm/yr) due to a bottom current that moves upstream (d'Anglejan, 1990). A substantial portion of mineral particles eroded from the Canadian Shield, and biogenous particles produced locally, settle to the bottom of this part of the Laurentian Channel at a rate of 7 to 8 million tonnes a year (Fortin et al., 1996). Over thousands of years, more than 60 m of Holocene mud has accumulated in the Laurentian trough, and only the top 50 cm is marked by the industrialization of the drainage basin. The imprint of the industrial

age is also evident in the layer of surface sediment collected in the glacial trough of the Saguenay Fjord, which has received more than 100 m of Holocene mud (Syvitski and Praeg, 1989).

Along with terrigenous particles that escape from the estuary, the Gulf of St. Lawrence receives materials from the erosion of its banks and littoral zone, and from biogenous particles produced in the ocean and which penetrate through the Cabot Strait (Fisheries and Oceans Canada, 1996). More than six million tonnes of terrigenous and biogenous particles are believed to accumulate in the gulf annually (Yeats, 1988).

### ***Buried sediments are slowly consolidated***

The set of biological, chemical and physical processes that transform unconsolidated sediments into solid rock is called *diagenesis*. Although it begins as soon as particles settle, the slow consolidation of sediment happens over a geological time scale and can take millions of years. Early diagenesis is generally defined as the chemical changes that occur following the sedimentation of solid particles which influence the fate of contaminants once they are buried in surface sediment layers. These processes include chemical reactions such as oxidation, reduction, precipitation and complexation, along with biological activity including bacterial decomposition, bioturbation and bioirrigation. These phenomena are explained in detail in Chapter 6.

# CHAPTER 4

## Surface Sediment

**In the river section, sediment deposition on the water bottom depends on the behaviour of the water mass. Sediments accumulate in summer in troughs and aquatic plant zones and are resuspended in autumn and spring. Aside from a few isolated areas in the Fluvial Section, the Laurentian Channel and the Gulf are practically the only areas where sediments tend to accumulate on a permanent basis. Elsewhere, they move with the water mass.**

The spatial distribution of surface sediments described in this chapter is shown on the map, *Sediment dynamics of the St. Lawrence*. Their textural classification is explained in the Information Supplement, *Classification of Sediments*.

### *The fluvial lakes: sediment sinks*

Recent sediments in the Fluvial Section (those associated with the current fluvial regime of the past 3000 years) form a deposit that ranges from a few dozen centimetres to 3 m thick over ancient marine clays.

Areas of permanent accumulation, where sediment inputs exceed losses, are generally found outside the main ship channel, where current velocity is under 0.3 m/s and water depth exceeds 4.5 m (Carignan et al., 1993) (Figure 18). These conditions are met in the three fluvial lakes, and permanent accumulation zones cover almost 12 percent of their total surface area. Accumulation rates are not uniform, however. Available data shows rates varying widely from 1 to 19 mm/yr in lakes Saint-François and Saint-Pierre (Carignan et al., 1993).

The amount of sediment deposited permanently in the fluvial lakes is very low in the context of the entire St. Lawrence. It represents only 6 to 8 percent of the solid load measured

at Quebec City, which is estimated at 6.5 million t/yr (Frenette et al., 1989). The thinness of the deposit layers weighed against the high accumulation rates suggest very recent accumulation. Indeed, the age of sediments that are deposited on older sediment corresponds generally with the dates of hydro-electric development or enlargement of the ship channel.

In zones where water depth is less than 4.5 m, sediment accumulation is temporary and depends on hydrological conditions and the presence of aquatic plant communities. Note that there were no permanent sedimentation zones in the St. Lawrence River before the large hydro-electric dams were built. In those days, the spring flood current was powerful enough to resuspend the thin layer of fine sediment that had resisted the strong autumn winds (see Information Supplement, *The Role of Aquatic Plant Communities in Sedimentation*).

The boundary between annual and permanent deposits in the lakes is usually not well defined. It shifts in response to hydrodynamic conditions that are dictated by long-term hydrologic cycles and extreme weather events. Permanent sedimentation zones will cover larger areas during periods of low river flow, whereas in years of strong runoff, currents can erode and resuspend older sediments. Permanent sedimentation zones are therefore found where the

## Information Supplement

### Classification of Sediments

The most common descriptive approach for mapping sediments is based on particle size distribution. Since sediments consist of many particles of different diameters, the classification is determined by the percentage of weight contributed by each size category. Wentworth's grain size classification (1922), one of the most widely used in sedimentology, includes four major classes of particles:

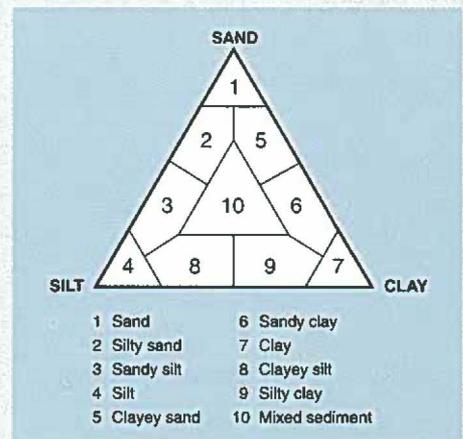
- Gravel:** particles with a diameter greater than 2 mm.
- Sand:** particles between 64  $\mu\text{m}$  and 2 mm in diameter.
- Silt:** particles between 2  $\mu\text{m}$  and 63  $\mu\text{m}$  in diameter.

**Clay:** particles under 2  $\mu\text{m}$  in diameter.

To obtain a qualitative description of texture, the Wentworth classification is entered in ternary diagrams subdivided by relative percentages of gravel, sand and clay found in a sample. The nomenclatures of Folk (1938) and Shepard (1954) are the most widely used in geology. Shepard's nomenclature is presented in Figure 17.

Most studies done on the river and gulf use one of these two classifications. In the river section, Shepard's classification was used by Sloterdijk (1985), Champoux and Sloterdijk (1988) and Hardy et al. (1991b), while the average size of sample particles was used by Centreau (1973; 1974). In the estuary and gulf, a classification based on the dominant fraction (> 30%) and on

the minor fraction (< 30%) was used by d'Anglejan and Brisebois (1978) and Loring and Nota (1973).



**Figure 17 Ternary diagram based on Shepard's nomenclature (1954)**

current strength has thus far been insufficient to resuspend old deposits that have accumulated since dams were built.

The lateral sections of the fluvial lakes — i.e. either side of the ship channel — are susceptible to SS deposition because of their slow currents, longer water residence time (2 to 5 days) than in the channel (8 to 14 hours), and the presence of aquatic plant communities in summer.

The resuspension of surface sediments deposited in water less than 4.5 m deep by natural erosion agents is a cyclical phenomenon. Sediments are often resuspended by storm-generated waves that are especially high in autumn, after the large macrophyte communities have died out and before the ice forms.

#### Lake Saint-François

The bed of the ship channel and smaller channels in the delta at the head of Lake Saint-François consist of highly compacted sand and gravel. The presence of sand and gravel is explained by the river's high transport and erosion capacity in this part of the lake (Lorrain et al., 1993). On the

shoals of the lateral sections, however, clayey silt and silty sands dominate. These are temporary deposits caused by low water conditions. In the centre of the lake, between Pointe Dupuis and Pointe Saint-Louis, sediments contain more sand since the river narrows here and creates a faster current that prevents fine particles from settling. However, there appear to be zones of permanent accumulation of fine sediments in lateral sections outside the channels, where the water is more than 4.5 m deep. These zones cover 16 percent of the lateral areas, including the Lancaster, Saint-Zotique and Grenadier basins.

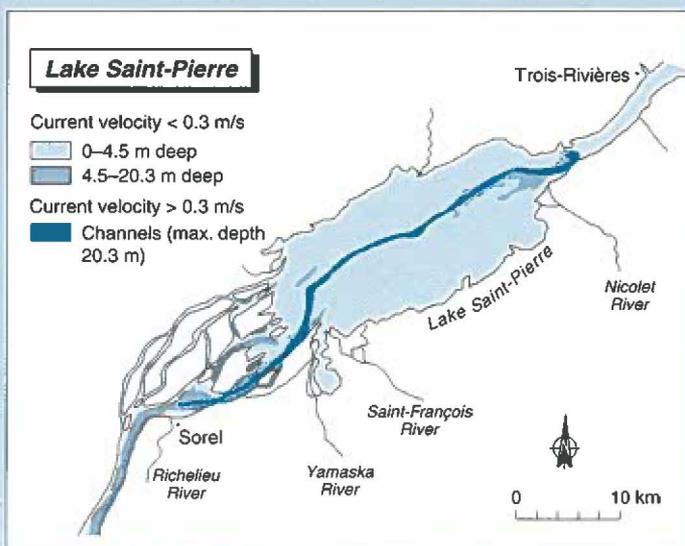
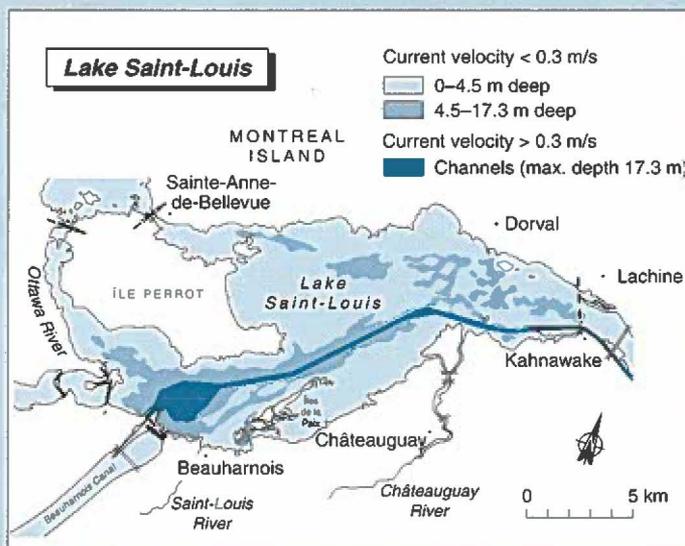
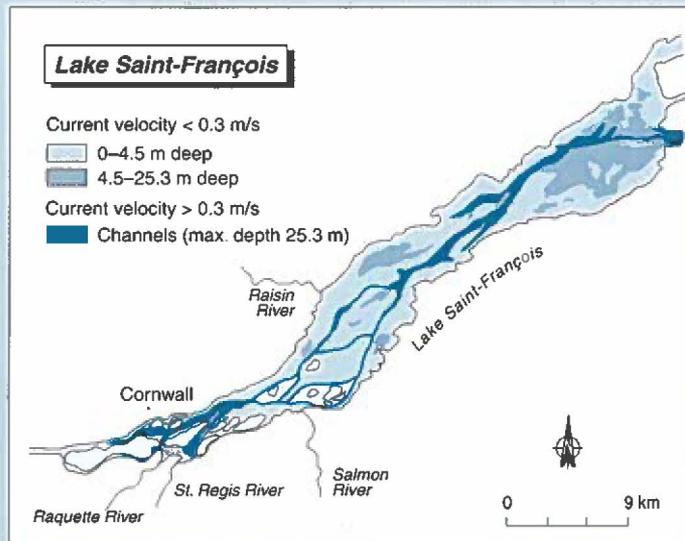
#### Lake Saint-Louis

Both the St. Lawrence and Ottawa rivers empty into Lake Saint-Louis. The Ottawa is responsible for elevated concentrations of ferro-magnesian minerals such as aluminum (Al), iron (Fe) and magnesium (Mg), detected on the north side of the lake (Champoux and Sloterdijk, 1988), where its waters are concentrated.

The bottom of Lake Saint-Louis consists of sand and gravel over half of its surface area. There are two perma-

nent accumulation zones, one south of Île Perrot and the other opposite Pointe-Claire. Sediments here consist mainly of clayey sand, silty sand and clayey silt (Champoux and Sloterdijk, 1988). Despite a large amount of fine sediment around Île Perrot and the Îles de la Paix, everything indicates that a sizable portion of this sediment does not accumulate permanently (Rukavina et al., 1990; Carignan et al., 1993).

In the southeastern part of the lake, the Îles de la Paix sustain serious wave-induced erosion. An early study by Gosselin (1985) pointed to the importance of wake waves produced by ships passing near the islands when entering or leaving the Beauharnois Canal. More recently, Argus Inc. (1995) showed that wind-generated waves are the main erosion agent, while wake waves affect only Pointe de la Traverse at the northeastern end of the archipelago. This area was severely eroded during the first half of the 1970s due to particularly high water levels in the St. Lawrence. The high water first destroyed the tree growth that held the soil in place and which countered the effect of the waves (Lamoureux



and Olivier, 1982). With the riparian strip gone, erosion became very active in the upstream islands and, since then, a substantial downstream input of eroded material has been observed. In fact, the islands are migrating downstream (Gosselin, 1985).

### Lake Saint-Pierre

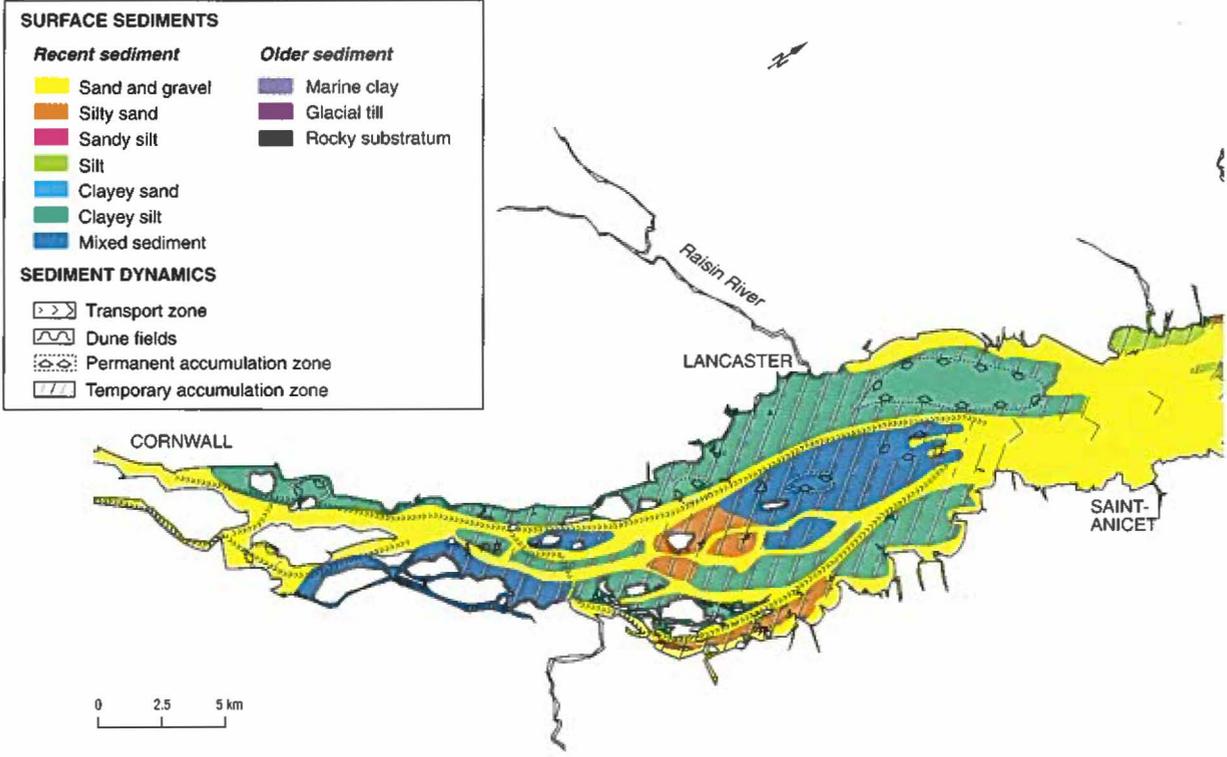
Lake Saint-Pierre stands out for its near-total absence of permanent accumulation zones — this despite a water residence time of just over three days in lateral sections, long enough to allow particles to settle. This is explained by the average shallowness of the lake, which is rarely more than 2.7 m deep except in the ship channel. Only 7 percent of the area of lateral sections is deeper than 4.5 m, the minimum depth required for a permanent accumulation zone. Fine sediments settle in lateral sections due to a combination of factors, including slow currents further retarded by summer aquatic plant growth, and favourable weather conditions at certain times of the year. Violent winds, especially in the fall, help resuspend these sediments in shallow zones and maintain a sediment balance in this body of water. Lake Saint-Pierre lacks a coherent pattern of sediment distribution and its sediments are coarser than in the other fluvial lakes.

The presence of silty sand around the Berthier–Sorel islands seems to be controlled by artificial rock sills (Centreau, 1974) built in the early 1960s to raise water levels in the ship channel. The ancient marine clay is exposed in the ship channel upstream of the Berthier–Sorel islands, while coarse sediment on either side of the channel is indicative of conditions favourable to traction. The current is strong enough here to produce dune fields near Saint-Ignace and Grâce islands. Sediment grain-size increases moving downstream, from mixed mud in the upper part of the lake to sand and gravel below. The deep channels of the Berthier–Sorel islands are the only known areas of permanent fine sediment accumulation in Lake Saint-Pierre (Carignan et al., 1993).

Source: Adapted from Carignan et al., 1993.

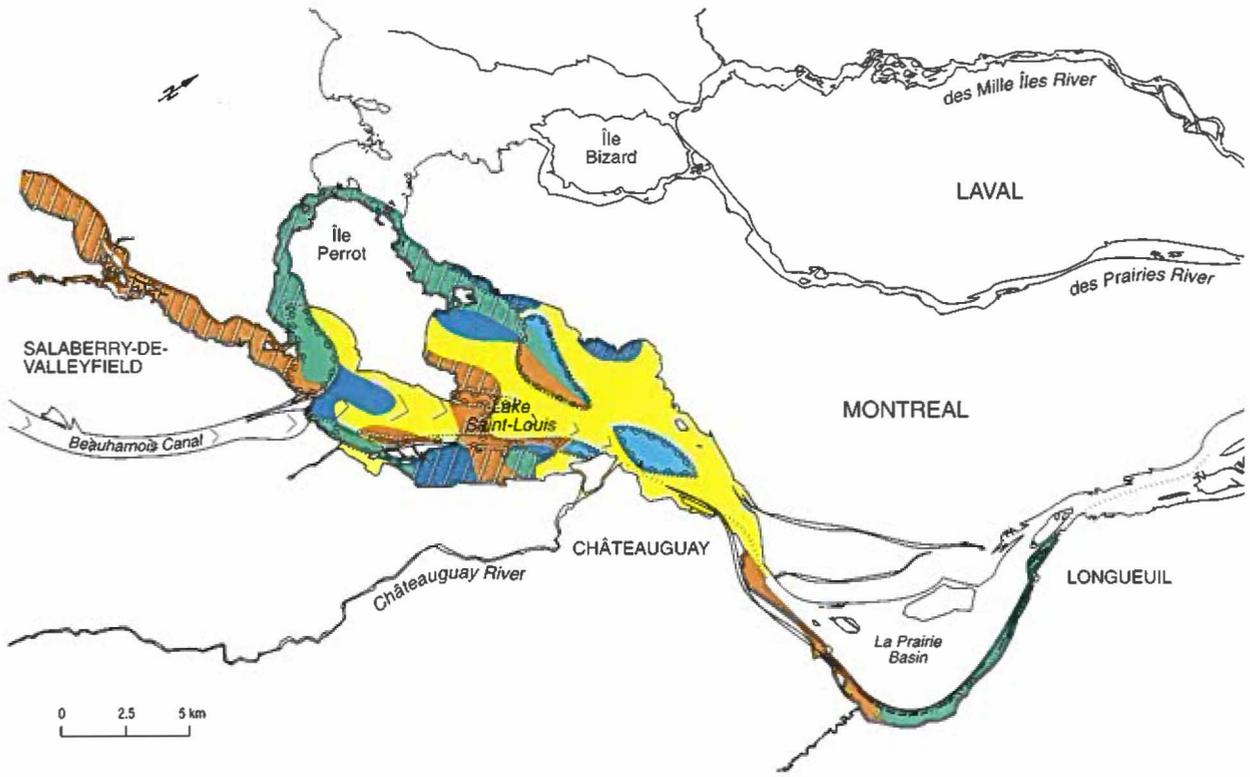
**Figure 18 Bathymetry and current velocity in the fluvial lakes**

**CORNWALL-POINTE-DES-CASCADES**



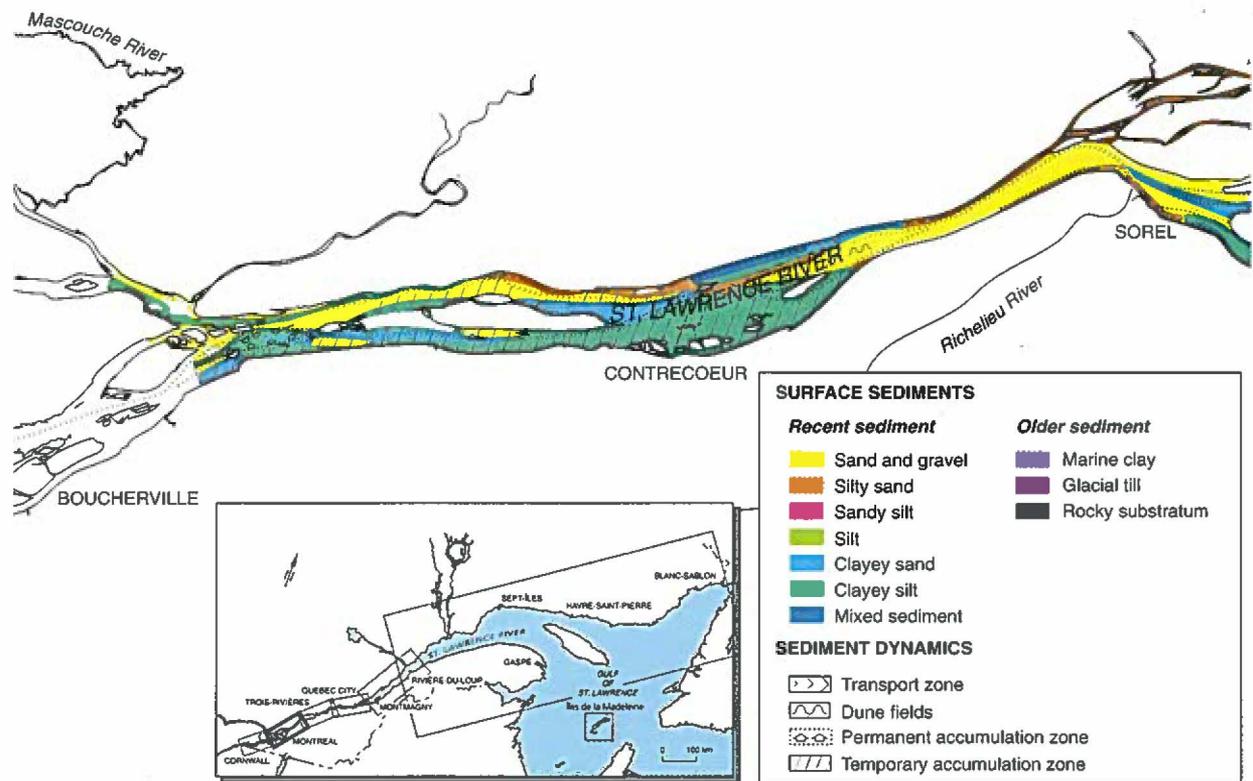
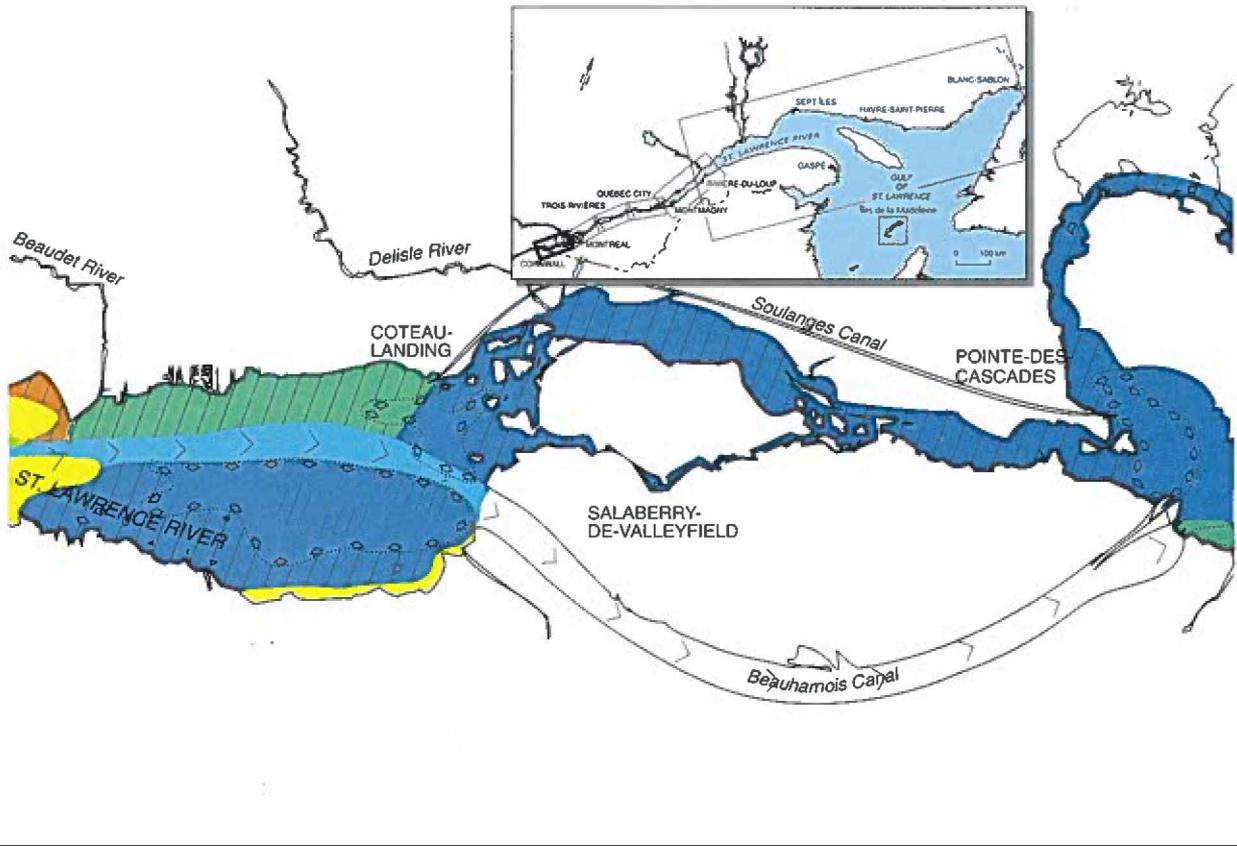
Source: Lorrain, Jarry and Guertin, 1993; Carignan et al., 1993; INRS-Eau, 1974; Fortin and Desrochers, 1990.

**SALABERRY-DE-VALLEYFIELD-SOREL**



Source: Centreau, 1973; 1974.

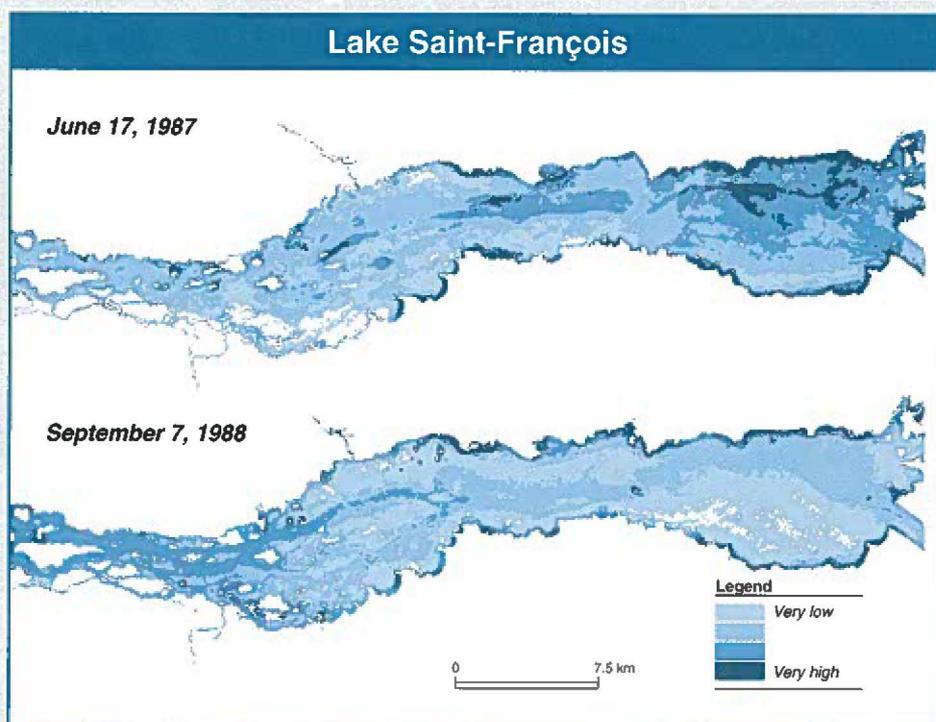
**Sediment dynamics of the St. Lawrence**



## Information Supplement

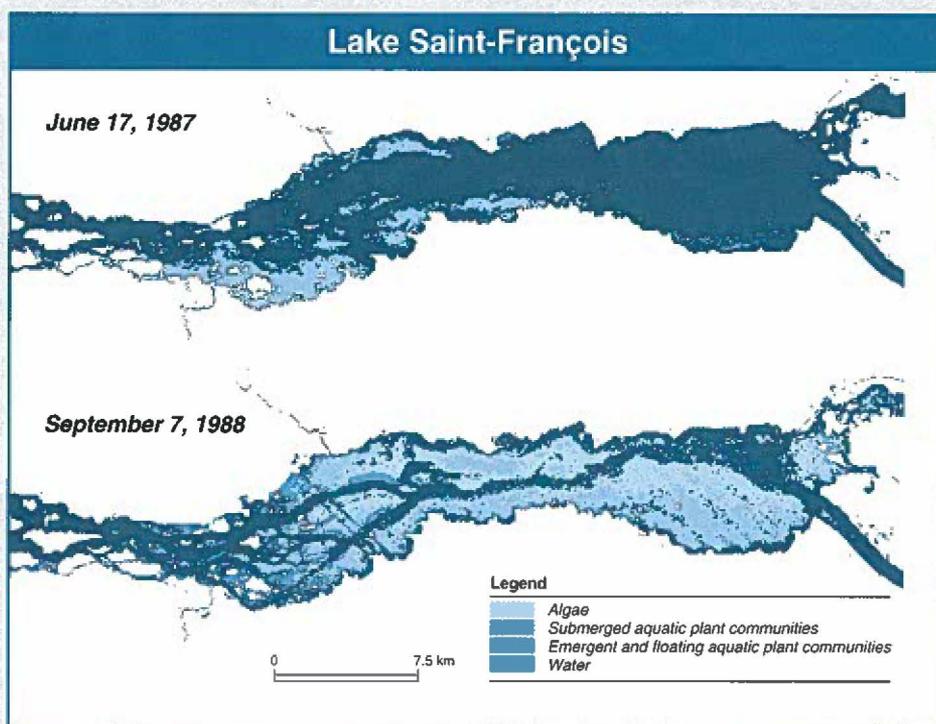
## The Role of Aquatic Plant Communities in Sedimentation

Between 62 and 75 percent of the surface area of the fluvial lakes consists of slow-flow zones where current velocity rarely exceeds 0.3 m/s and water circulation patterns are quite complex. Sediments found here are generally alluvial deposits with a high sand and gravel component. Seasonal water flow variations and plant growth in the lakes play an important role in reducing turbidity and often shift the positions of transport and sedimentation zones (Figures 19 and 20). The transfer of suspended solids from the water column to sediments occurs in part as a result of interaction with the large macrophyte communities. These aquatic plants form dense beds covering areas where the water is less than 5 m deep. In spring, strong currents sweep the substrate bare of aquatic plants. After the spring flood, currents slow down and the water mass loses its capacity to transport material. From June to September, flow characteristics are altered and currents reduced as macrophyte growth becomes denser, creating calm areas where suspended particles can settle. In autumn, the plants die and are uprooted and transported downstream. The substrate is then exposed and sediments deposited during the summer become prone to partial erosion. The seasonal growth cycle of plants combines with the hydrological cycle to influence flow dynamics in areas where macrophyte communities grow.



Source: Lorrain et al., 1993.

**Figure 19** Spatial distribution of turbidity on June 17, 1987, and September 7, 1988, from LANDSAT satellite images



Source: Lorrain et al., 1993.

**Figure 20** Spatial distribution of aquatic vegetation on June 17, 1987, and September 7, 1988, from LANDSAT satellite images

Wake waves appear to be the principal erosion agent attacking the Berthier–Sorel islands. Heavy pleasure craft traffic in the channels is eroding the island banks (Lehoux, 1996). For example, the banks of Île des Barques receded almost 20 m in a single year (Centreau, 1974). Waves generated by large ships mainly affect the banks of islands located less than 600 m from the centre of the ship channel.

### **River corridor sections: transport zones**

The St. Lawrence divides into two main branches at the outlet of Lake Saint-François near Valleyfield and Beauharnois. The south branch forms the Beauharnois Canal, an artificial channel dug between 1929 and 1932 to funnel water to the hydro-electric generating station of the same name. Dug in the ancient marine clay, the Beauharnois Canal takes about 80 percent of the river flow. The other 20 percent follows the natural branch of the river on the north shore, a rapids section with exposed bedrock. The Beauharnois Canal became part of the St. Lawrence Seaway in the late 1950s when two locks were built at its downstream end.

The Lesser La Prairie Basin contains a substantial accumulation of fine materials that probably comes from tributaries and, to a lesser degree, shore erosion (GPR Inc., 1985). The string of islands that isolates the lesser basin from the Greater La Prairie Basin shelters it partially from the wind, creating much calmer hydrodynamic conditions than in the greater basin and therefore promoting sedimentation. With 82 percent of its sediment consisting of silt and clay, the lesser basin is a sedimentation zone for fine particles to which contaminants can adhere (Hardy et al., 1991b).

Very little data have been collected on the Greater La Prairie Basin due to technical difficulties presented by flow characteristics in the basin. Two sediment samples were collected at the beginning of the 1970s near the north shore of the basin and in sheltered areas conducive to sediment accumulation (Sérodès, 1978). They

contained up to 66 percent fine material (silt and clay), which suggests that the greater basin may have several areas where fine sediment accumulates. However, these areas must certainly be limited in number given the strength of the current.

In the Montreal–Sorel stretch, sand and gravel dominate sediments. The pattern of surface sediment deposition suggests a higher fraction of coarse material as water depth increases (Centreau, 1974). The compact marine clays uncovered when the ship channel was deepened are exposed at several places. The river bottom is sandy near the north shore, while downstream of Lanoraie, sand and gravel cover the entire river bed. These sediments are 3 m thick and rest on the ancient marine clays. Exposed bedrock in the Lachine Rapids, Île Sainte-Hélène and Île Verte indicate that this is a transport zone. Flow characteristics here appear to transport coarse sediment by traction. Currents are strong enough in this part of the Fluvial Section to form a dune field near Lanoraie (Centreau, 1974).

Shore erosion in the Montreal–Sorel section is a localized but important problem. Evidence of erosion can be seen on the south shore of the Sainte-Thérèse islands, on the Verchères islands and on certain Contrecoeur islands. Reasons given for the erosion of several kilometres of shoreline in this section are ship's wake waves, strong currents and the removal of more than 800 000 m<sup>3</sup>/km<sup>2</sup> of sediment northwest of Île Saint-Ours to enlarge the

ship channel. The north riverbank seems relatively stable, while the south shore requires erosion protection works along most of its length, as shown in Table 2 (Centreau, 1974; Procéan Inc. et al., 1996).

The Trois-Rivières–Quebec City stretch is a typical transport and erosion zone (Centreau, 1974) as evidenced by the coarseness of sediments that dominate this part of the Fluvial Estuary. Riverbanks are eroded in the Batiscan area, but there is little erosion elsewhere along this section of the river.

### **Brackish and saltwater sections: sediment sinks**

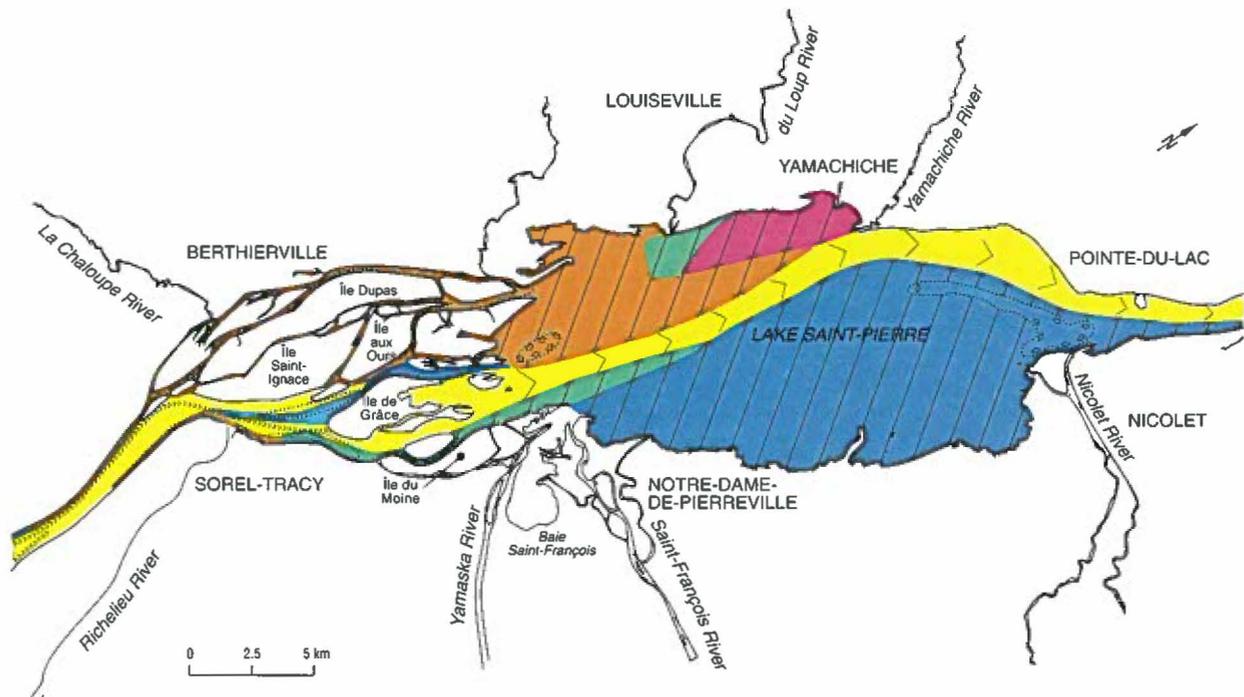
The St. Lawrence Estuary is one of the largest estuaries in the world. Its width and depth grow almost exponentially from Île d'Orléans down to Pointe-des-Monts, expanding from 2 to 50 km in width and from 100 to more than 300 m in depth. More than one billion cubic metres of water transits daily downstream of Quebec City. Taking tides into account, the instantaneous flow rate amounts to 75 000 m<sup>3</sup> and reaches 90 000 m<sup>3</sup> at Montmagny (Verrette, 1990; SLC, 1996). There is, consequently, a certain dilution of suspended solids; once past the maximum turbidity zone around Montmagny, SS concentrations fall to 5 mg/L at Rivière-du-Loup and 2 mg/L at the Saguenay. These values are similar to those found in the St. Lawrence upstream of the Beauharnois Canal (SLC, 1996).

**Table 2 Riverbank protection works between Montreal and Tracy**

<i>Location</i>	<i>Distance protected (km)</i>	<i>Protective structure, by predominant type</i>
Pointe-aux-Trembles	2.1	Wall, riprap, concrete blocks
Varenes	11.7	Riprap, wall, concrete blocks
Verchères	16.0	Riprap, concrete blocks, wall
Contrecoeur	22.9	Riprap, concrete blocks, wall, wooden stakes and riprap
Lanoraie	3.8	Riprap
Tracy	8.0	Wall, riprap, concrete blocks

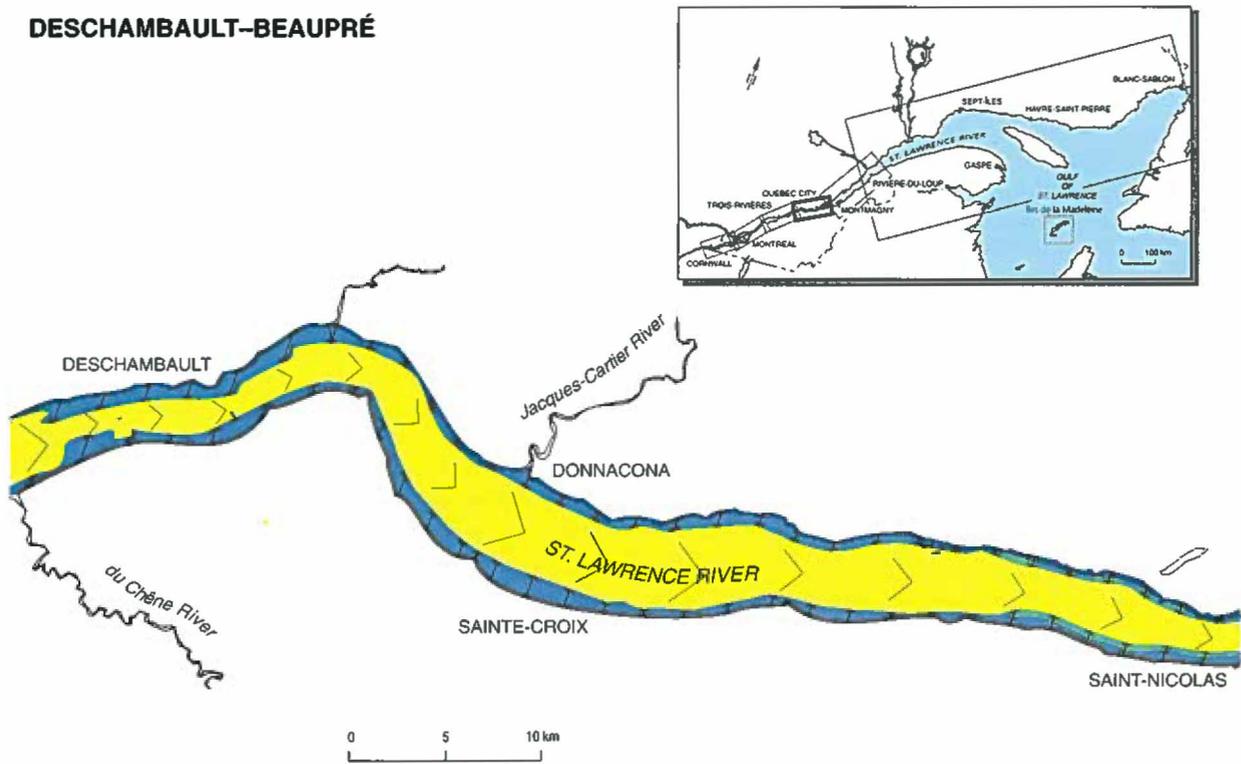
Source: Procéan Inc. et al., 1996.

## SOREL-DESCHAMBAULT



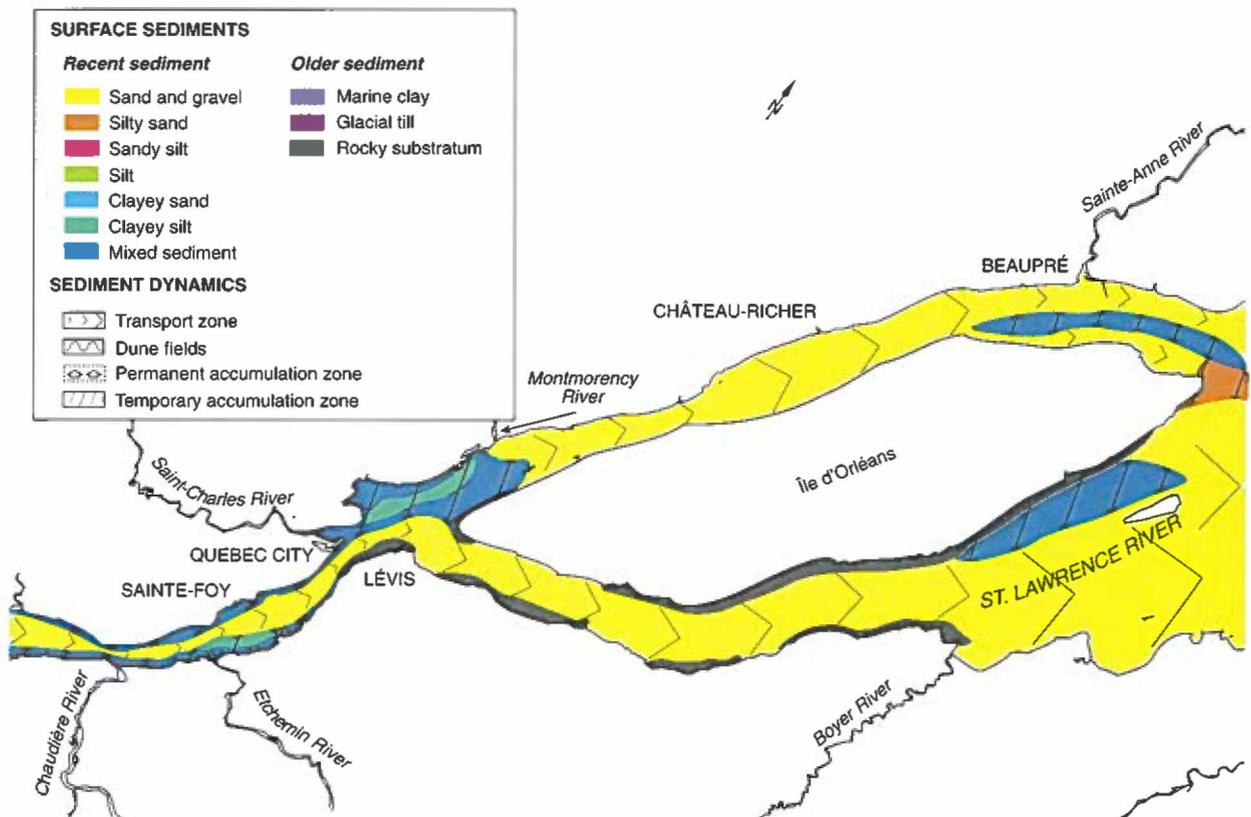
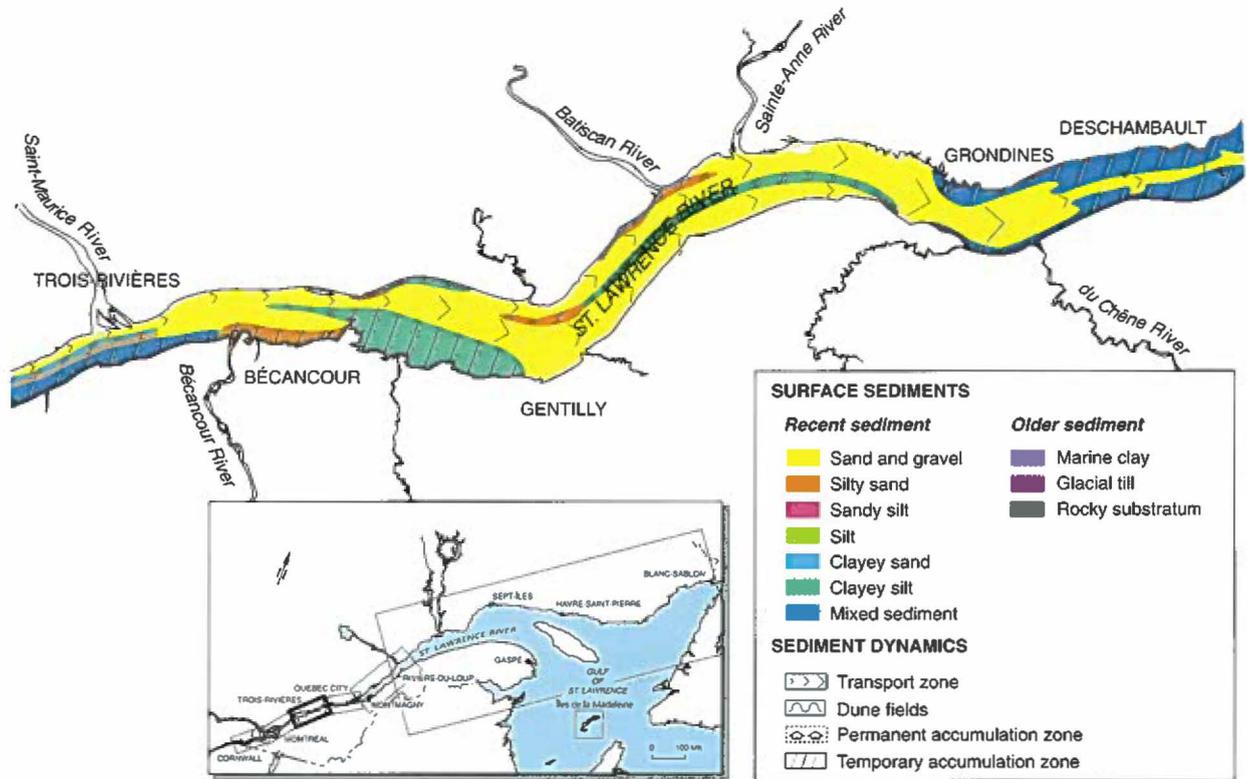
Source: Sylvestre et al., 1992; Centreau, 1974.

## DESCHAMBAULT-BEAUPRÉ



Source: Centreau, 1974; d'Anglejan and Brisebois, 1978.

### Sediment dynamics of the St. Lawrence (continued)



### The Upper Estuary: maximum turbidity zone

The Upper Estuary extends from the eastern tip of Île d'Orléans down to Tadoussac. Its most remarkable feature is the so-called maximum turbidity zone (MTZ) that moves about at the mercy of tides and seasonal variations in river flow, and that exhibits SS concentrations of from 50 to 200 mg/L (d'Anglejan, 1981; 1990). Located between Saint-Joachim and Île aux Oies on the north shore, and Cap-Saint-Ignace and Île aux Grues on the south shore, the maximum turbidity zone extends farther along the estuary's south shore than on its north shore due to the Coriolis effect, which deflects the discharge of the St. Lawrence to the south shore.

Suspended solids circulate under the influence of a surface mass of freshwater flow and the penetration of denser salt water in the depths. These two water masses create a two-level flow, as illustrated in Figure 21. Sediments resuspended by the strong currents of rising tides are transported upstream in deep water and then are taken up by the surface current. Gravity causes them to settle down in the water column as they drift with the water mass. These conditions create a constant vertical gyrotory movement that increases their residence time in the estuary. Also, the bottom profile (or bathymetry) of the Upper Estuary affects the propagation of the tidal wave with a funnel effect that produces a short, strong rising tide and a long, weak falling tide. This assists the upstream transport of particles and the trapping of sediment at the head of the estuary (Allen et al., 1980).

Sediment texture in the Upper Estuary is heterogeneous, mainly coarse, and indicates that this is primarily a transport zone. Temporary sediment accumulation associated with present-day estuary circulation occupies less than 10 percent of the area. It forms a layer less than 0.5 m thick consisting of mud sprinkled here and there with gravel of glacial origin. This estuarine mud is also found in shallow areas of Sainte-Anne Bay and near Île aux Lièvres, where currents are weak (d'Anglejan and Brisebois, 1978). Residence times for recent sediment

in the MTZ appear to be less than 35 years near the south shore of the estuary, and even briefer along the north shore (Coakley and Poulton, 1993). These short residence times can be attributed to intense erosion by tides, storm waves and littoral ice.

Sand and gravel cover large areas of the Upper Estuary bottom. They are probably glacial marine sediments deposited in the Goldthwait Sea or originating from the erosion of glacial deposits and raised beaches on the shore of the ancient sea. However, the deposit with a high sand content in the Passage de l'Île-aux-Coudres and the North Channel is likely formed from material transported by the Gouffre and La Malbaie rivers during this marine invasion (d'Anglejan, 1971). Farther downstream, the sandy deposit north of Île aux Lièvres is likely associated with the Saint-Narcisse moraine (d'Anglejan and Brisebois, 1978). These deposits have been reworked in many places by strong tidal currents that carried off their fine particles.

Transport conditions along the bottom are powerful enough to form dune fields in the Passage de l'Île-aux-Coudres, on the Banc des Anglais and in the South Channel between Pointeaux-Orignaux and Île Verte. The dunes are quite substantial, reaching 15 m in height with crest-to-crest lengths of 100 m. In the Passage de l'Île d'Orléans near Cap-Tourmente, currents are shifting numerous sand banks and transport is very active, as evidenced by the need for regular annual dredging to maintain minimum depths in the ship channel in the Traverse du Nord. Aside from a small area above La Malbaie, there do not appear to be any permanent sedimentation zones in the Upper Estuary. In other words, the bulk of SS present in the river at Quebec City would appear to reach the Lower Estuary (Lucotte, 1989).

The shelf extending from the south shore is covered with a deposit of sand and gravel from 10 to 20 cm thick. This coarse deposit rests on grey clay that lies exposed in the intertidal zone. The clay, which is common in the Montmagny area, was apparently deposited during a brief period of higher sea levels 4400 to

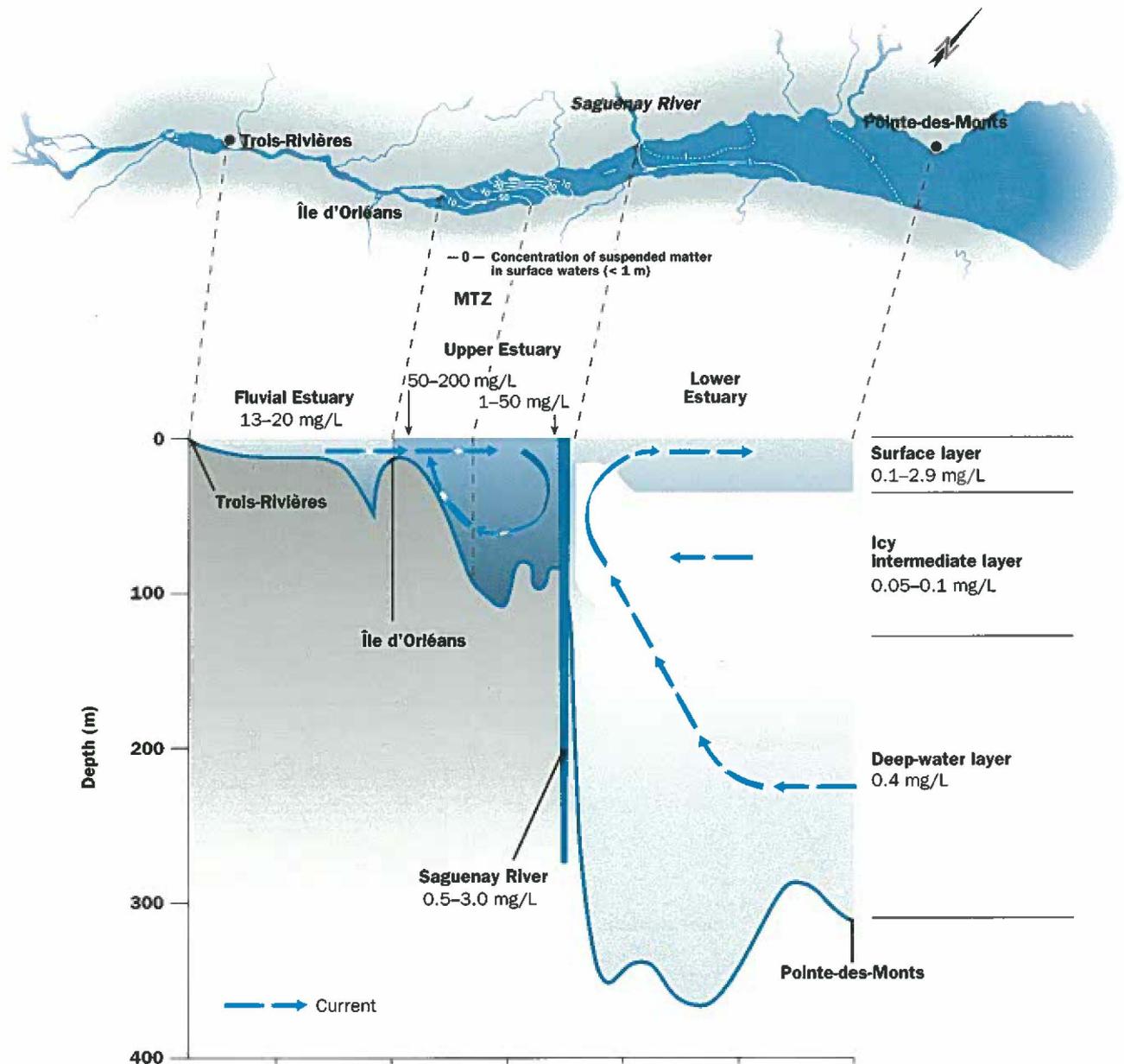
5800 years ago (Dionne, 1988a). Although it is fine sediment, compaction has given it a hardness similar to schist, suggesting transport conditions. Tidal currents are strong enough here to prevent any permanent accumulation of fine material and even erode placer deposits.

Along the shoreline, waves are the main agent of sediment transport. They are also responsible for serious erosion of the escarpment at the upper extremity of the slikke, or mud flat. At Cap-Tourmente, the escarpment is receding at a rate of 2 m/yr. At Rivière-du-Loup on the south shore, this retreat, combined with erosion of the upper part of the foreshore, amounts to 2 to 3 m/yr (see Information Supplement, *Sedimentary Dynamics on Cap-Tourmente Flats*).

Landslides or underwater slides can transport and deposit large volumes of sediment. Over the last century, the Saguenay Fjord experienced several natural catastrophes that probably resulted in the resuspension of older contaminated sediments. The fjord bottom presents a changing morphology believed to be linked to mud flows on its slopes. These flows are usually associated with seismic activity, the most recent being the earthquake at Chicoutimi in November 1988 (Locat, 1994, in Sévigny and Couillard, 1994). In addition, the Saint-Jean-Vianney (Saguenay) landslide of May 4, 1971 (Schafer et al., 1990) and the Saguenay flood of July 1996 (Fisheries and Oceans Canada, 1996) abruptly introduced huge amounts of particulate matter that could have generated a turbidity current near the bottom (Mulder and Syvitski, 1995). This density current, or hyperpycnal plume, may have eroded and resuspended older contaminated sediments as it went by.

### The Lower Estuary: ebb and flow

Concentrations of suspended solids in the Lower Estuary vary from one water layer to another (Figure 20). They are from 0.1 mg/L to 2.9 mg/L in the surface layer, fall to between 0.05 mg/L and 0.1 mg/L in the intermediate layer, and rise again to 0.4 mg/L in the bottom layer (Sundby, 1974).



Source: d'Anglejan, 1990; Environment Canada and *La Revue maritime L'Escale*, 1990; Sundby and Loring, 1978.

**Figure 21 Concentrations of suspended solids between Trois-Rivières and Pointe-des-Monts**

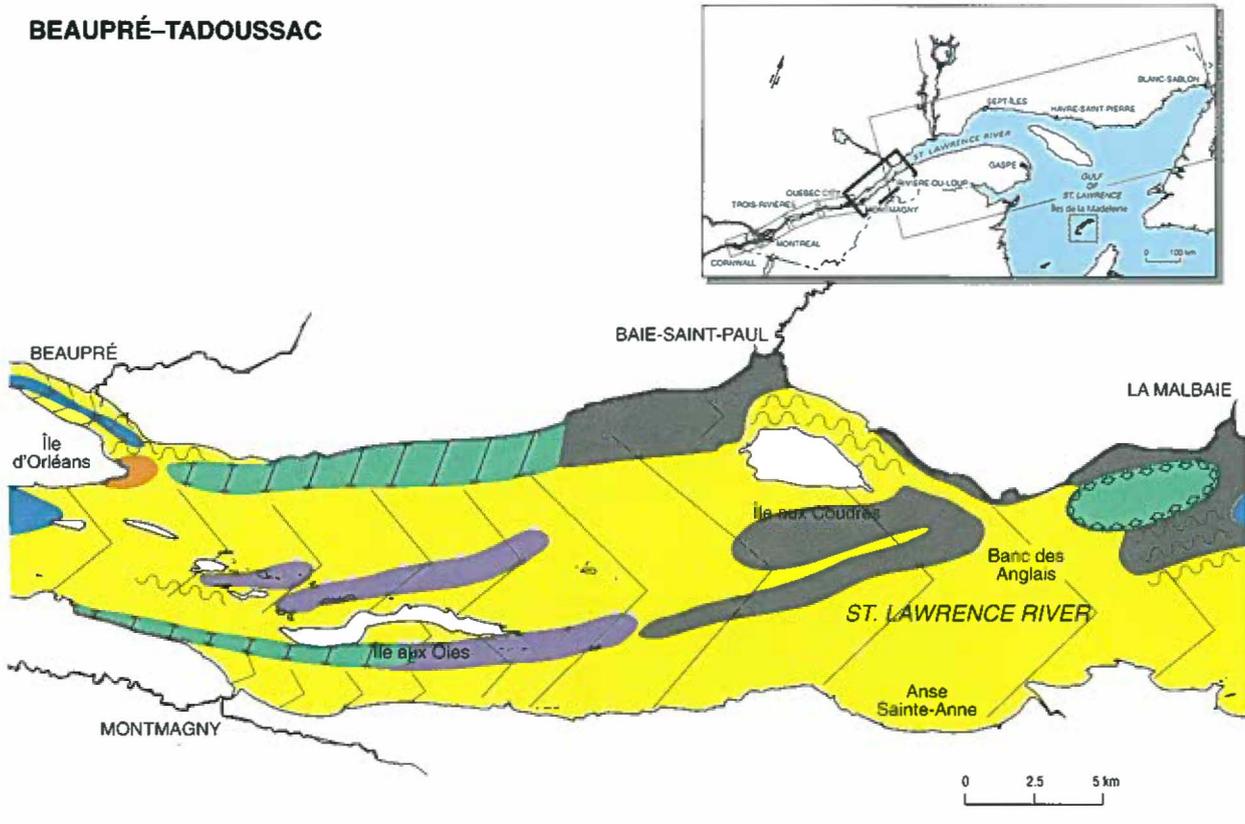
This concentration of SS in the water column promotes sediment deposition on the foreshores and intertidal marshes. However, deposits remain for only a short time since erosion agents are particularly active (Meade, 1972). Waves are considered able to resuspend sediments where the water is less than 5 m deep. Particle size distribution and the fetch, force and duration of the

wind determine erosion of the foreshore. Wave action is stronger in the lower part of the estuary, where the water surface is larger, and on the shallow shelf (0 to 10 m) of the south shore.

On foreshores in the Lower Estuary, energy from waves and tidal currents resuspends material that settled during slack water and calm periods.

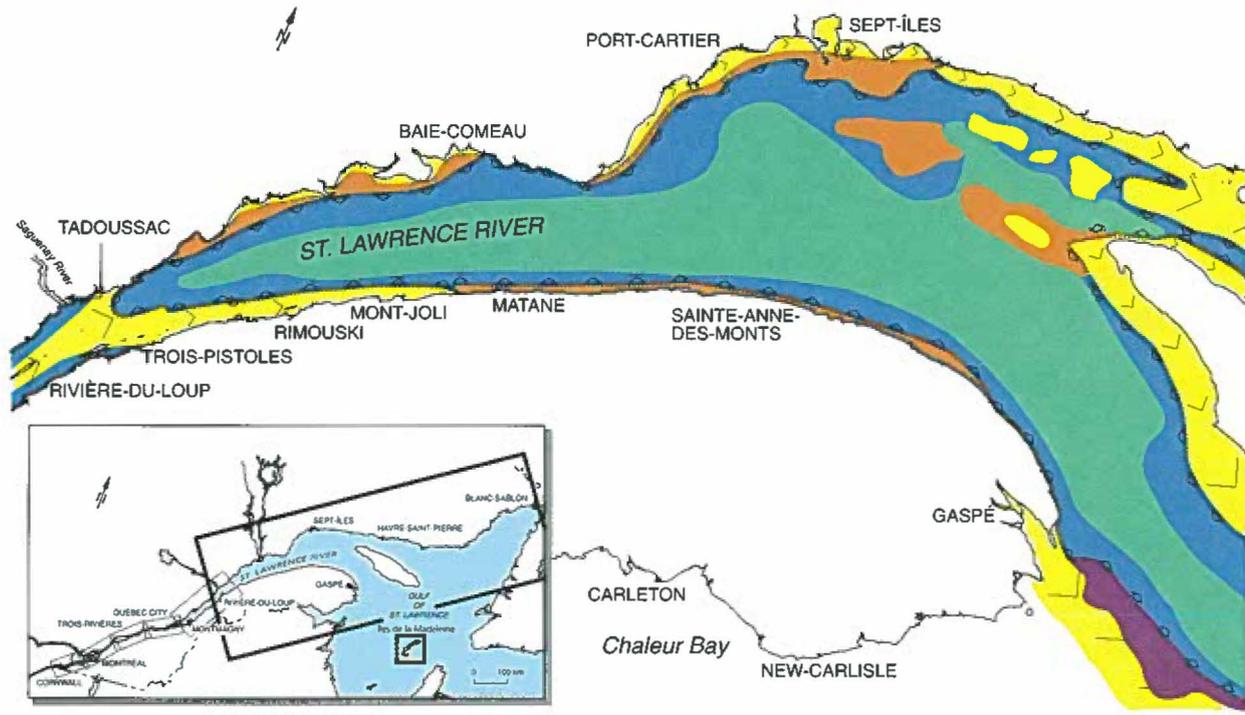
About 2000 tonnes of sediments are mobilized during neap tides and 4000 tonnes during syzygy (or spring) tides (Lorrain, 1992). Residual circulation on the shelf — i.e. water movement including all tidal currents, modulated by the synodical tidal cycle and the passage of the spring flood — causes a sedimentary influx of 1800, 2600 and 4000 tonnes/day during neap tides, spring tides and the

**BEAUPRÉ-TADOUSSAC**



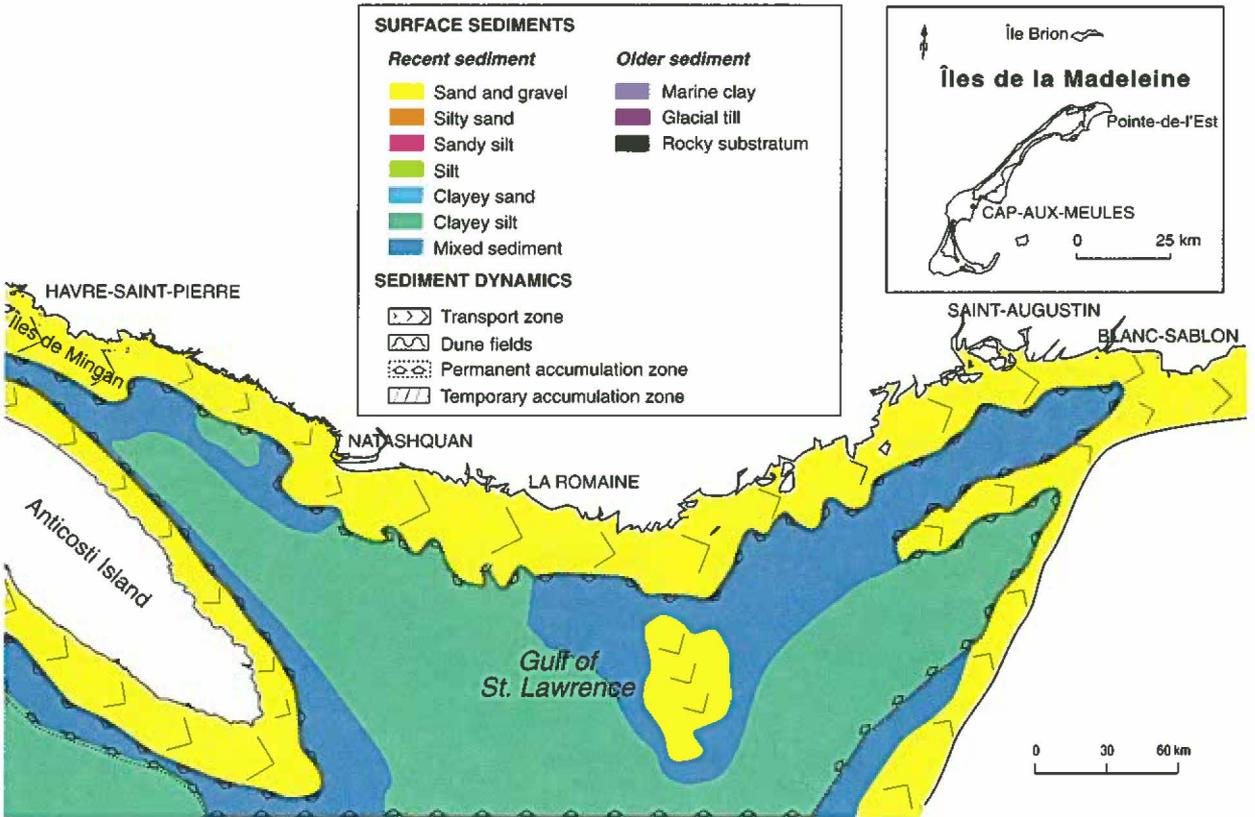
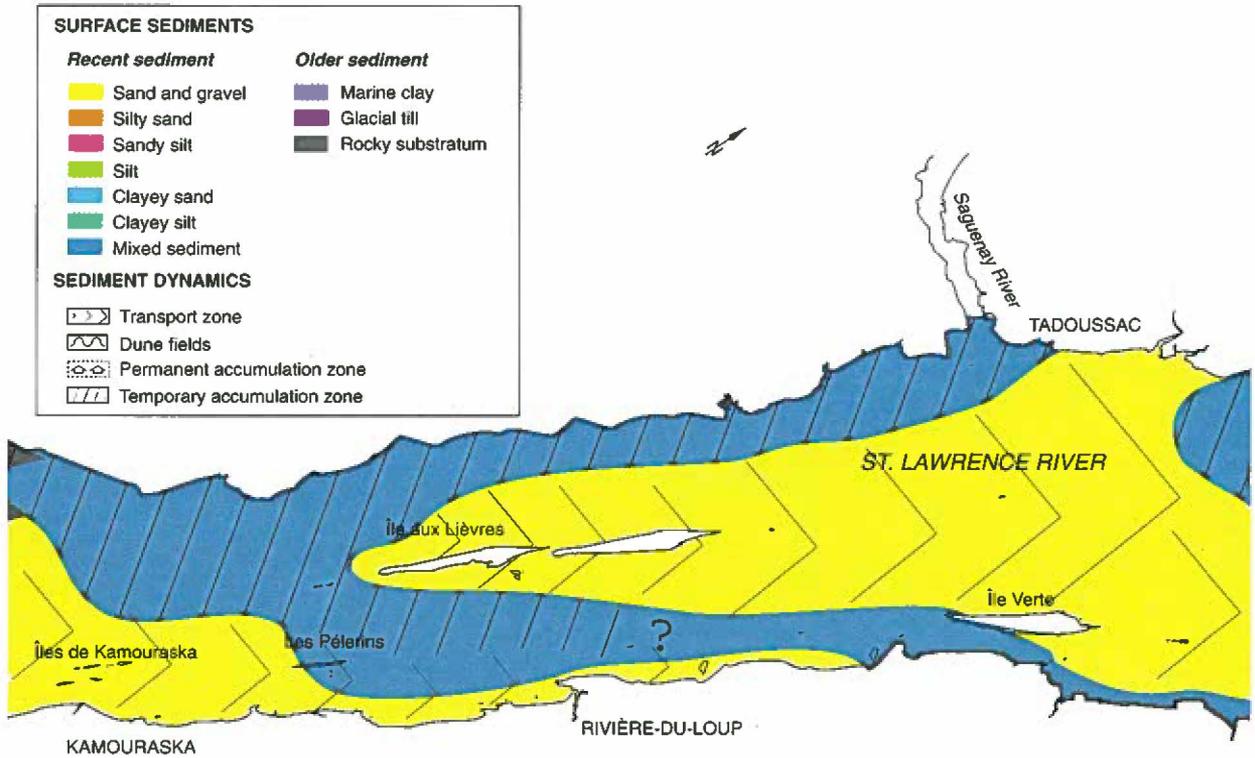
Source: d'Anglejan and Brisebois, 1978; Loring and Nota, 1973.

**TADOUSSAC-BLANC-SABLON**



Source: Loring and Nota, 1973.

**Sediment dynamics of the St. Lawrence (continued)**



spring flood, respectively (Lorrain, 1992). This influx compensates for the 50 000 t of sediment dredged every year in the harbour of Rivière-du-Loup. The influence of the passage of the spring flood is also evident in sediment accumulation rates at the harbour of Gros-Cacouna, which rise appreciably in the spring (Fortin and Drapeau, 1979). The melting of fast ice (ice attached to the shore) and drifting ice also seems to be responsible for transporting sizable volumes of sediment in spring (d'Anglejan, 1990).

Sediment accumulates on the Laurentian Channel floor at an estimated rate of around 0.5 cm/yr (Silverberg et al., 1986). It becomes more homogeneous and finer approaching the bottom of the trough due to slower currents in the depths. Composed of fairly equal proportions of silt and clay originating in the St. Lawrence watershed, this sediment is called *pelite* or mud stone. The pelite becomes more sandy moving up the slopes of the trough, while the trough edge is covered with muddy sand. The pelite accumulation on the floor of the trough is an important sink for contaminants (see Information Supplement, *Ice Action on the Foreshore*).

On the north shore, between the mouths of the aux Outardes and Manicouagan rivers, beach erosion is approaching 0.6 m/yr. Several theories have been advanced to explain the very active erosion in this part of the Lower Estuary. One maintains that this is natural erosion from wave action on littoral deposits. Another attributes it to hydro-electric dam construction on the aux Outardes and Manicouagan rivers, which cut off the source of sediments (Drapeau, 1990).

### The Gulf: favourable for fine material deposition

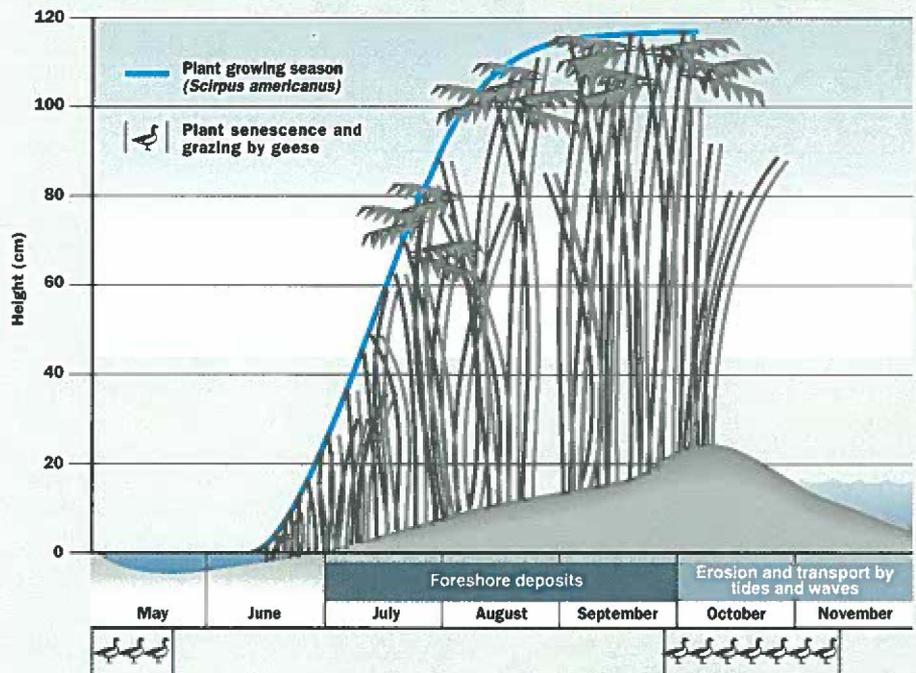
Fine sediment accumulates slowly in the gulf, and the rate decreases as one moves downstream to the sea. Accumulated sediments are sorted by size, with the coarsest material found above the slope between the channel and the shore. This pattern of sediment distribution indicates, for one thing, that the sediments come mainly from the St. Lawrence drainage

#### Information Supplement

### Sediment Dynamics on Cap-Tourmente Flats

About 700 000 tonnes of sediments accumulate on the intertidal marshes of Cap-Tourmente in the summer months, forming a layer as thick as 20 to 30 cm (Sérodes and Troude, 1984; Drapeau, 1990). Calmer weather in summer and aquatic plant growth create highly effective accumulation conditions that neutralize the effect of waves for all practical purposes. In autumn, the erosion cycle starts again, assisted by intensive grazing of American bulrush (*Scirpus americanus*) rhizomes by migrating Greater snow geese (*Chen caerulescens*). This grazing

considerably reduces the density of plant cover on the flats. The action of waves and autumn tides on the denuded flats resuspends about 4500 tonnes of sediment into open water with each tidal cycle (Figure 22) (Troude and Sérodes, 1985). The sediments travel slowly over many months towards the North Channel. In spring, they are transported downstream with the spring flood (Lucotte and d'Anglejan, 1986; Drapeau, 1990). The amount of sediments deposited annually in intertidal zones of the Upper Estuary is estimated at about 2.7 million tonnes, amounting to between 42 and 65 percent of the suspended solids load that flows past Quebec City (Sérodes, 1980).



Source: Adapted from Troude and Sérodes, 1985.

**Figure 22** Sedimentary cycle and the relationship between vegetation and grazing by Greater snow geese (*Chen caerulescens*)

basin (Loring and Nota, 1973) and, for another, that hydrodynamic conditions on the coastal shelf promote the resuspension of fine sediment.

Sediment distribution follows the same pattern in the northern and eastern gulf in the Anticosti and

Esquiman channels. In the Laurentian Channel, the influence of the St. Lawrence on the clay fraction of sediments abates approaching the Atlantic Ocean and sediment composition suggests inputs from local sources. Near Anticosti Island and the Strait of Belle Isle, the chalky

composition of sediments reflect the nature of rocky formations in this area of the gulf.

Sediments on north and south shore coastal shelves are more heterogeneous. They are composed of coarse material dominated by sand and gravel of glacial origin (Loring and Nota, 1973; d'Anglejan, 1990). On the south shelf, in shallow waters around Îles de la Madeleine and Prince Edward Island, sediment texture is coarser and originates locally, mainly from erosion of the bedrock (Loring and Nota, 1973). However, material from the Canadian Shield is found east of New Brunswick and south and east of Prince Edward Island and Cape Breton. These are probably ancient sediments transported during the last ice age and reworked during the change in sea level and by tidal currents.

Sediments are intensely worked in certain areas, as evidenced by the presence of dune fields, especially around the Îles de la Madeleine.

#### Information Supplement

### Ice Action on the Foreshore

**In winter, the ice cover protects the shorelines of the estuary and gulf from the effect of waves. The protective role has its limits, however, since the ice will erode and resuspend sediments come spring. Ice erosion of the foreshore is evident in the many grooves and depressions visible after the ice departs (Dionne, 1971; 1989). This glacial fluting — ice gouges on the foreshore — can reach depths of 50 cm, lengths of 2 km and widths of 4 m.**

**About 10 percent of the ice melts totally or partially before being carried to open water. In melting, the ice is responsible for leaving a mud layer from 10 to 20 cm thick**

**on the foreshore. This mud is later resuspended by the spring flood. At Cap-Tourmente, the glacial sediment load is estimated at 50 000 t/yr, but this can vary from year to year depending on winds that control the movement of floating ice. The glacial sediment load in the Lower Estuary is more on the order of 100 000 t/km<sup>2</sup> (Troude and Sérodes, 1988) to 200 000 t/km<sup>2</sup> (Dionne, 1984). The most spectacular aspect of estuary ice formation is without question the transport of immense blocks weighing several tonnes (Dionne, 1981; Drapeau, 1997). These blocks, related by mineral composition to the North Shore, pile up along the shore, forming a strip 50 to 100 m wide and that is easily visible at the lower limit of the intertidal zone.**

# CHAPTER 5

## *A Deficit Sediment Budget*

**Of the 6.5 million tonnes of sediment that goes past Quebec City annually, 4.2 million comes from tributaries in Quebec. At Quebec City, the St. Lawrence exports several million tonnes of sediment towards the estuary and the gulf, the second largest sedimentation trough after the Great Lakes. The Atlantic Ocean contributes an estimated 0.7 million tonnes of sediment to the St. Lawrence.**

**T**he sediment budgets presented in this chapter cover only particles transported in suspension in the water column. They exclude coarse sediment (sand and gravel) carried by traction along the river bed, as well as organic and inorganic matter dissolved in the water. Only particulate forms of the organic and inorganic (silt and clay) fraction were taken into account. It should be noted that reliable data are available on SS inputs from Lake Ontario and most Quebec tributaries, and SS export at the outlet of the Fluvial Estuary. However, data are only approximate for Ontario and U.S. tributaries, urban and industrial inputs, and permanent sedimentation on the river bottom. Moreover, there is no data available on other SS sources, such as shoreline and bed erosion, direct atmospheric deposition, and in situ biological production.

### *Fresh water*

Studies done in the 1980s showed that the St. Lawrence River exports an average of 6.5 million tonnes of suspended solids annually to the estuary (Frenette et al., 1989; 1992). These studies also indicated that the SS volume exported to Quebec City can vary from 3.5 million to

10 million t per year, depending on runoff conditions in the St. Lawrence basin. Rondeau (1997) found that data collected from 1989 to 1993 implied an export volume between 6.1 million and 7.3 million tonnes. This is one of the lowest sediment loads of any of the world's large rivers in terms of material transported per square kilometre of drainage basin. For example, the Mississippi River, with a discharge only 1.5 times greater than that of the St. Lawrence, exports about 100 times more SS to the Gulf of Mexico (Loring and Nota, 1973). The St. Lawrence owes this distinction to the fact that the bulk of sediment input from the Great Lakes watershed remains in the lakes, with only 3 to 7 percent of SS transported to Quebec City. Furthermore, the St. Lawrence watershed contains large forested areas and tributaries dotted with artificial reservoirs that help retain sediment matter that would otherwise reach the St. Lawrence (see Information Supplement, *Ranking the St. Lawrence among the World's Major Rivers*).

Suspended solids from municipalities and industrial plants located on the St. Lawrence constituted only 2 percent of the load measured at Quebec City in 1985. This was a small

reduction from 1970, when inputs from these sources were estimated at roughly 260 000 t/yr (Frenette et al., 1989). The decline appears to result from the start-up of municipal wastewater treatment plants (which now serve most of the riverside population), as well as primary and secondary treatment of pulp and paper mill effluent, and reduced dumping of dirty snow cleared from streets into the river.

Another source of SS could be the clays deposited on the floor of the St. Lawrence Valley about 10 000 years ago, which are exposed at several points on the river bed, particularly in the ship channel, the Upper Estuary and the Gulf. Erosion of these deposits could be a potential source of SS (Rukavina et al., 1990; d'Anglejan, 1990).

In 1990, 178 000 t of particulate matter resulting from human activity was released to the atmosphere in Quebec (Government of Quebec, 1992). What portion of these particles falls back directly into the St. Lawrence is not known, but it is probably not insignificant, given the proximity of large urban and industrial areas.

Nearly 50 percent of the annual transport of SS to Quebec City takes place in spring (mainly with the spring flood in April), while only 10 percent is transported during the winter (Frenette et al., 1989; Barbeau et al., 1993). Summer and autumn loads each amount to about 20 percent of the annual total. Organic particulate matter constitutes about 8 percent of the annual SS load at Quebec City (Pocklington and Tan, 1987). The organic load is high in fall and spring, and low in winter and summer. Organic matter arising from in situ biological production in the river is present in large amounts only in summer, while terrigenous organic matter, which originates on land from human activity, prevails during the rest of the year, especially in the fall (Pocklington and Tan, 1987).

The volume of SS that settles permanently on the floor of the river section is very small, equal to less than 10 percent of inputs. Permanent sedimentation occurs in Lake Saint-

#### Information Supplement

### Ranking the St. Lawrence among the World's Major Rivers

Classifying rivers by size can be a particularly complex and difficult task. The criteria commonly used are biophysical in nature and, depending on which one is chosen, the river's ranking can change radically. The parameters used to rank the world's major rivers are length, discharge (or flow) rate, watershed size, and population density in relation to drainage basin and discharge.

The longest rivers in the world are the Nile in Africa and the Amazon in South America, both of which extend almost 7000 km. The St. Lawrence is 4000 km long, counting the Great Lakes system, ranking it 19th among the major rivers. Using the measure of mean annual flow rate, the St. Lawrence ranks 13th with a volume of 13 000 m<sup>3</sup>/s, similar to that of the Ganges (Asia) and the Mississippi–Missouri system, but far below the Amazon, which ranks first with a discharge of 174 890 m<sup>3</sup> of water per second. The St. Lawrence drains more than 1 300 000 km<sup>2</sup> (equivalent to 85 percent of the area of Quebec), giving it the second largest drainage basin in Canada after the Mackenzie River (Northwest Territories). By this measure, the St. Lawrence ranks 15th in the world, with a drainage basin similar in size to that of the Volga (Europe), the Ganges (Asia), and the Murray (Australia).

François, Lake Saint-Louis, and the upper part of Lake Saint-Pierre (Berthier–Sorel islands). According to Carignan et al. (1993), this is a recent phenomenon, attributable to major changes in fluvial hydrodynamics with the development of the ship channel starting at the end of the 19th century. The project had the effect of concentrating water flow in the channel dredged through the middle of the lakes, while increasing sedimentation in troughs near the

The St. Lawrence River stands out for having one of the lowest sediment loads of the world's major rivers. Its waters transport 6.5 million tonnes of suspended solids annually to the estuary, compared to more than 900 million t for the Amazon and nearly 1670 million t for the Ganges–Brahmaputra. The sediment load of the St. Lawrence is 3.5 times lower than that of the Fraser River, even though its annual discharge rate is four times greater.

This difference is partly due to the geology of the St. Lawrence watershed. Its bed is formed of granite rock and therefore erodes very little, whereas a river like the Mississippi, which flows on an alluvial plain, transports 210 million t of sediment with a flow 1.5 greater than that of the St. Lawrence. Forest cover and the presence of the Great Lakes and artificial reservoirs in its watershed contribute to the retention of sedimentary material.

A "social pressure" indicator, based on the number of inhabitants per square kilometre of drainage basin, can be used to assess the environmental impact of anthropic pressure on a watershed, which is partly responsible for river contamination. By this measure, the St. Lawrence, with a basin density of 26 inhab./m<sup>2</sup>, ranks far behind the large rivers of Western Europe, with densities of 290, 388 and 900 inhab./m<sup>2</sup> for the Rhine, the Seine and the Thames, respectively. This situation is reflected in lower contamination levels in St. Lawrence waters and sediments compared to these European rivers.

shore. These authors estimate the mass of mobile sediments in the three fluvial lakes of the St. Lawrence to be 7.3 million tonnes.

An SS budget for the Cornwall–Quebec City section is presented in Table 3. To balance this budget, SS inputs from shore and river bed erosion, atmospheric deposition, and in situ biological production would have to amount to 1.65 million tonnes per year. Lehoux (1996) reported an

annual loss of 40 ha of shoreline habitat due to erosion along the Montreal–Sorel section alone. This 40 ha in itself could represent a volume of 500 000 to 1 million tonnes, depending on the type of material and the height of the river-banks. A team from the SLC is now analysing data gathered in recent years for the Mass Balance Project, which is intended to refine the conceptual model used for the SS budget between Cornwall and Quebec City. The results of the team's analysis should shed new light on the budget presented in Table 3 (Rondeau, 1997).

### Salt water

Knowledge of the SS budget for the marine section of the St. Lawrence is limited by the difficulty of collecting

samples in this immense tidal ecosystem. Little precise data are available on the subject, except with regard to inputs from the St. Lawrence at Quebec City and the Saguenay River at Chicoutimi.

Sediment dynamics are more complex in the marine section. First, suspended solids move downstream on the surface water layer and back upstream in deeper water. The Lower Estuary and the Gulf are consequently sources of SS in both upstream and downstream directions. The Atlantic Ocean is also an important source of SS in the gulf. Second, in situ biological production contributes as great a volume of SS as terrigenous sources in the Lower Estuary and Gulf (Pocklington, 1988; Lucotte et al., 1991). Third, the erosion of the shoreline and water bottom appears

to be another very important source of SS in the gulf, although it has never been quantified (Yeats, 1988; Loring and Nota, 1973).

The 6.5 million tonnes of SS exported annually by the St. Lawrence River are retained temporarily in the Upper Estuary during the summer. About half of that amount — 3 to 4 million t — is deposited temporarily in intertidal zones along the upstream part of the estuary, specifically in the Cap-Tourmente–Montmagny area and on the south shore in La Pocatière and Kamouraska. Some 1.5 million t remain suspended in the water column of the upstream end of the Upper Estuary and contribute to the maximum turbidity zone (MTZ) (d'Anglejan, 1990; Lucotte, 1989). As the entire SS load is exported to the Lower Estuary starting in autumn until

**Table 3 SS budget in the Fluvial Section (Cornwall to Quebec City)**

	<i>Tonnes per year</i>	<i>Comments</i>	<i>References</i>
<b>SS INPUTS</b>			
Lake Ontario	230 000	–	Lum et al. (1987)
Ontario and U.S. tributaries	~ 700 000	–	Frenette et al. (1989)
Quebec tributaries	4 160 000	Inputs rising	Frenette et al. (1989); Government of Quebec (1992)
Riverside industrial plants	~ 100 000	87 000 t/yr in effluents of the 37 priority industrial plants of the St. Lawrence Action Plan in 1992	Bouchard and Millet (1993)
Riverside municipalities	~ 20 000	18 800 t/yr in effluents of the 23 wastewater treatment plants operating in 1993 (serving 2 980 000 people)	MEF (1995)
River bed and bank erosion	?	Erosion of glacial marine clays could be an important source of SS	Rukavina et al. (1990); d'Anglejan (1990)
Direct atmospheric deposition on the river	?	Significant input near industrial centres	–
In situ biological production	?	An important source of organic SS exported to the estuary in summer	Pocklington and Tan (1987)
<b>SS LOSSES</b>			
Permanent deposition on the river bed	300 000–400 000	Varies from author to author	Carignan et al. (1993.); Rukavina et al. (1990)
<b>BALANCE AT OUTLET</b> (net export to the estuary)	6 500 000	6 x 10 <sup>6</sup> t of inorganic matter 0.5 x 10 <sup>6</sup> t of organic matter	Frenette et al. (1989); Barbeau et al. (1993); Pocklington (1988)

the following summer, permanent sedimentation in the Upper Estuary is negligible (d'Anglejan, 1990; Lucotte, 1989). Shore and bottom erosion in this area may be a significant source of SS (d'Anglejan, 1990).

The 160 000 t of SS exported annually by the Saguenay River are largely deposited in the upper part of the Saguenay Fjord, specifically the north arm (Schafer et al., 1990). The amount of SS exported to the Lower Estuary is unknown, but is probably negligible.

On reaching the Lower Estuary, SS of terrestrial origin settle quickly on the bottom of the upper part of the Laurentian Channel, together with a portion of SS of marine origin produced locally or imported from the gulf. From 7 to 8 million tonnes of SS are thus deposited annually within the bounds of the Lower Estuary (Yeats, 1988; d'Anglejan, 1990). Seventy-five percent of the organic matter transported by the St. Lawrence mixes with a similar amount of organic matter from marine sources (Lucotte et al., 1991).

The sedimentation rates measured on the bottom of the Laurentian Channel in the gulf indicate that large amounts of SS accumulate here permanently (Yeats, 1988; Silverberg and Sundby, 1990). These suspended

solids come largely from shoreline erosion, the gulf floor, and in situ biological production (Yeats, 1988; Pocklington, 1988). They consist of 70 percent organic matter (mainly marine) and 30 percent inorganic matter (Yeats, 1988).

Most of the transported sediment load settles in the Lower Estuary segment of the Laurentian Channel. More than 700 million t of primarily terrigenous sediment is estimated to have been deposited in the channel trough since the beginning of this century (Fortin et al., 1996). Of course, part of the river's sediment discharge can be found in the several million tonnes of sediment that has accumulated for decades in fluvial lake sections of the St. Lawrence and in sheltered basins. However, these losses are of little importance compared to the overall sediment load of the St. Lawrence, estimated at between 6 and 7 million t/yr. All in all, the St. Lawrence exports about 10 times less SS to the Atlantic Ocean than the estuary receives from the river (Yeats, 1988).

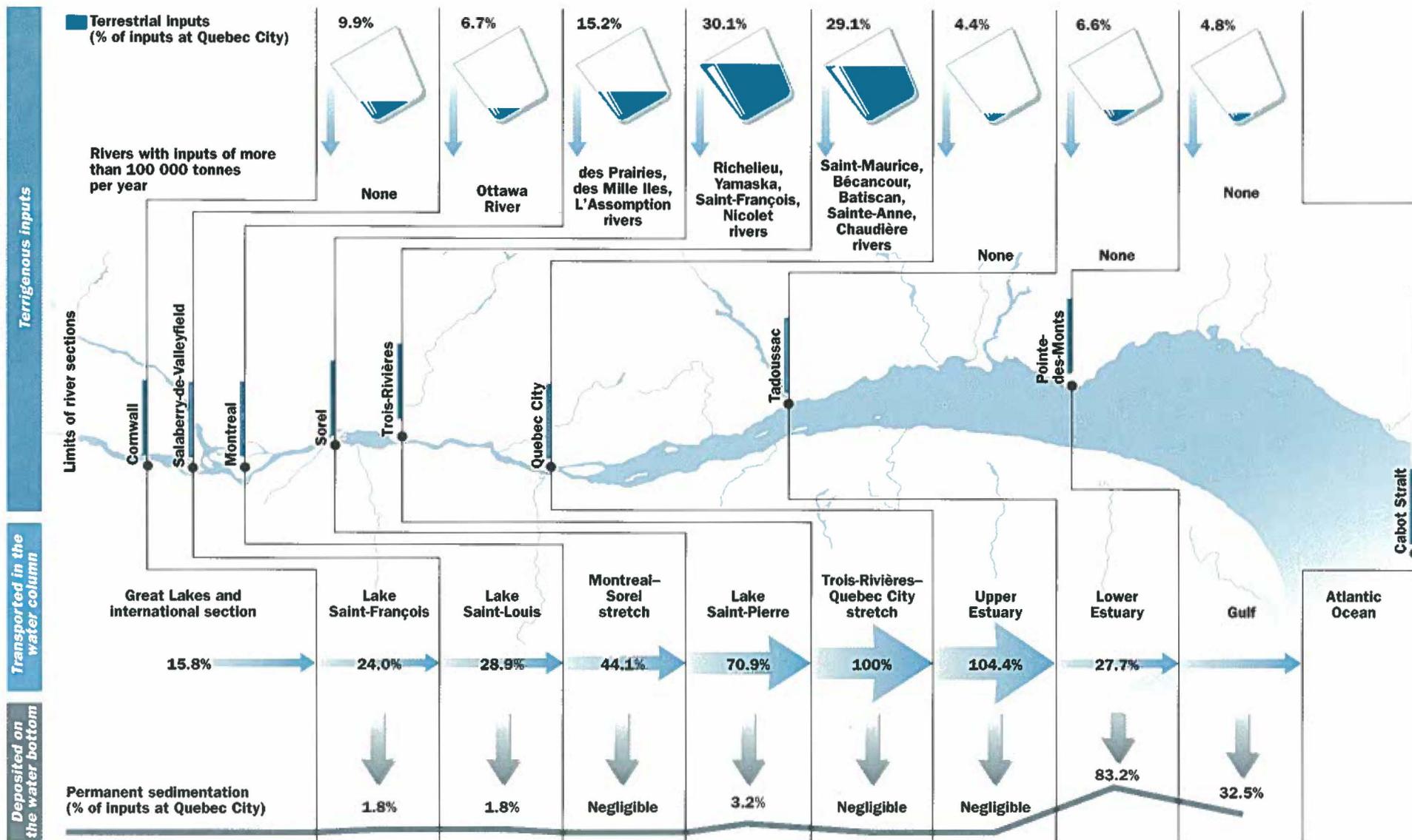
An SS budget for the estuarine and marine sections of the St. Lawrence is presented in Table 4. To balance the sediment budget, bank and bed erosion must be greater than 3.5 million tonnes per year.

### *Input from tributaries in the watershed*

Figure 23 shows the relative contribution of different sections of the St. Lawrence River to the SS budget. The model, which incorporates information published in the first analysis of the St. Lawrence sediment budget (Frenette et al., 1989; 1992), does not take into account certain sources such as bank and bed erosion, in situ biological production, atmospheric deposition, and ocean input. The main terrigenous sources of SS are concentrated in the Fluvial Section between Sorel and Quebec City, where nine tributaries carry an extremely heavy load of more than 100 000 t/yr into the St. Lawrence. Seven of these tributaries are on the south shore and drain land devoted heavily to agriculture. The Fluvial Section and Upper Estuary are environments where SS transport largely prevails over deposition. The Lower Estuary and Gulf, particularly the Laurentian Channel, constitute the principal environments for the deposition of terrigenous suspended solids. The amount of terrigenous SS exported to the Atlantic Ocean is unknown, but is probably negligible. Lignite, an indicator of the presence of terrigenous organic matter, is not found in sediments of the downstream part of the Laurentian Channel (Pocklington, 1986).

**Table 4 SS budget for estuarine and marine sections of the St. Lawrence (Quebec City to Cabot Strait)**

	<i>Tonnes per year</i>	<i>Comments</i>	<i>References</i>
<b>SS INPUTS</b>			
St. Lawrence River (at Quebec City)	6 500 000	6 x 10 <sup>6</sup> t of inorganic matter 0.5 x 10 <sup>6</sup> t of organic matter, mostly terrigenous	Frenette et al. (1989); Barbeau et al. (1993); Pocklington (1988)
Saguenay River (at Chicoutimi)	160 000	–	Fortin and Pelletier (1995); Loring and Nota (1973)
Other tributaries in the Upper Estuary	210 000	–	Frenette et al. (1989)
Lower Estuary and Gulf	~ 570 000	Combined flow of 7250 m <sup>3</sup> /s and mean SS concentration of 2.5 mg/L	Koutitonsky and Bugden (1991); Loring and Nota (1973)
River bed and bank erosion	?	Significant source	d'Anglejan (1990); Yeats (1988); Loring and Nota (1973)
Atmospheric deposition	~ 40 000	–	Yeats (1988)
In situ biological production	~ 5 300 000	Production minus mineralization of organic matter	Pocklington (1988)
Atlantic Ocean	~ 900 000	0.3 x 10 <sup>6</sup> t of inorganic matter 0.6 x 10 <sup>6</sup> t of organic matter	Yeats (1988)
<b>SS LOSSES</b>			
Permanent bottom deposition			
Upper Estuary	Insignificant	–	d'Anglejan (1990); Lucotte (1989)
Lower Estuary	~ 7 500 000	–	Fortin et al. (1996)
Saguenay Fjord	~ 160 000	–	Fortin and Pelletier (1995); Schafer et al. (1990)
Gulf	?	Significant in the Laurentian Channel	Silverberg and Sundby (1990); Yeats (1988)
Export to the Atlantic Ocean in surface waters	~ 1 600 000	0.5 x 10 <sup>6</sup> t of inorganic matter 1.1 x 10 <sup>6</sup> t of organic matter	Yeats (1988); Pocklington (1988)
<b>BALANCE AT OUTLET</b> (net export to the Atlantic Ocean)	~ 700 000	0.2 x 10 <sup>6</sup> t of inorganic matter 0.5 x 10 <sup>6</sup> t of organic matter, mostly marine	Yeats (1988); Pocklington (1988)



Source: Adapted from Frenette et al., 1989; 1992.

**Figure 23** Inputs, transport and sedimentation of suspended solids downstream of Cornwall

# Sediments: Transporters of Contaminants

**Fine sediments, unlike fairly unreactive sands, transport contaminants through the action of chemical and physical bonds. Under certain conditions, they form flocs in a “house-of-cards” structure filled with water that assists ion exchanges.**

A great number of physical and chemical exchanges take place in the aquatic environment. Free ions and organic molecules react with mineral particles and organic matter. Pollutants are captured by suspended solids and deposited on the river bottom where hydrodynamic conditions permit. Most of these physical and chemical exchanges between the water and suspended particulate matter involve adsorption or desorption.

## *Exchanges between water and sediment*

Water-sediment exchanges are made possible by the forces of weathering and abrasion during transport that grind rocks into ever-finer particles, breaking atomic bonds and creating electrical charges on their surfaces.

In nature, clays transported in suspension in water carry a negative charge and can capture metallic cations (e.g.  $Hg^{++}$ ) and other positively charged compounds present in the water phase. To use an analogy, clay particles are like tiny magnets that repel each other but attract metal ions through electrostatic forces.

Compared to metal contaminants, hydrophobic (Greek for “water-hating”) organic contaminants such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) generally spend little time in the water phase because of their strong propensity to bind with organic matter (plant and animal debris) transported in suspension in the water column.

The process by which organic contaminants move from the water phase to the solid phase is sometimes called *hydrophobic partition*. Just as organic particles acquire a contaminant load through hydrophobic partition, clay particles do so through an ion exchange process called *adsorption*. Adsorption binds contaminants to a solid interface (clay, organic matter), making it possible for suspended particles to become efficient transporters of contaminants.

However, the force of attraction between particles and contaminants weakens considerably when all adsorption sites have been occupied by metals and/or hydrophobic compounds. This can happen in highly contaminated environments that receive effluent directly from industrial and municipal outfalls. The particles

then behave like a magnet that has been plunged into a barrel of nails and withdrawn; the last nails picked up can be blown free of the magnet easily because they are held less firmly than the ones picked up first.

The bond between contaminants and sediments becomes very unstable when all adsorption sites are occu-

pled, reducing the effectiveness of sediment interfaces (clay, iron oxide, organic matter, etc.) in trapping contaminants. In these circumstances, contaminants are constantly moving back and forth between the over-loaded particles that have become inhospitable and sediment pore water that is hardly more receptive. When adsorption sites reach this saturation point, sediments lose their capacity to "purify" and the amount of toxic substances dissolved in pore water increases. Contaminants are then said to be bioavailable, meaning that they are available to be taken up by plant or animal life.

### Stowaways

Rocks, which usually combine several minerals, are removed from their place of origin by erosion and transported on currents to new deposition sites (Figure 24). They break apart and crumble on their journey and become ever smaller. When they are smaller than a grain of sand, they generally contain only one mineral with chemical properties determined by its chemical nature and crystalline structure. Quartz, for example, has a crystalline structure that makes it extremely resistant to external chemical and physical agents. By contrast, minerals with more complex crystalline structures, such as clay minerals, are less resistant and can be altered or modified more easily. The crystalline structure of minerals enables them to bind or exchange a certain

number of free ions. The number of ions that can be bound is equal to the number of positive or negative electrical charges on the mineral. The total number of ions attracted to a mineral's surface is called its *ion exchange capacity*. This is the number needed to render the mineral electrically neutral (Figure 24).

Mineral particles may be compared to passenger vehicles with a fixed number of seats. On their journey, they come upon metals and organic substances dissolved in water that can dislodge or move "passengers" already on board, or else simply take an unoccupied seat. Ions dissolved in water tend to occupy free "seats" around the crystalline structure, but sometimes they dislodge ions already in place.

The two processes of adsorption and desorption are driven by an uneven distribution of charges on the surface of the mineral particle or organic matter. This imbalance is generally caused by chemical reactions taking place on the crystal surface or by structural irregularities in the crystalline system. If the particle's net charge is negative (electronegativity), it attracts and binds dissolved positive ions, or cations. A net positive charge (electropositivity) binds negative ions, or anions. Clay minerals, manganese oxides, iron hydroxides and organic matter are the principal materials that adsorb large numbers of cations or anions.

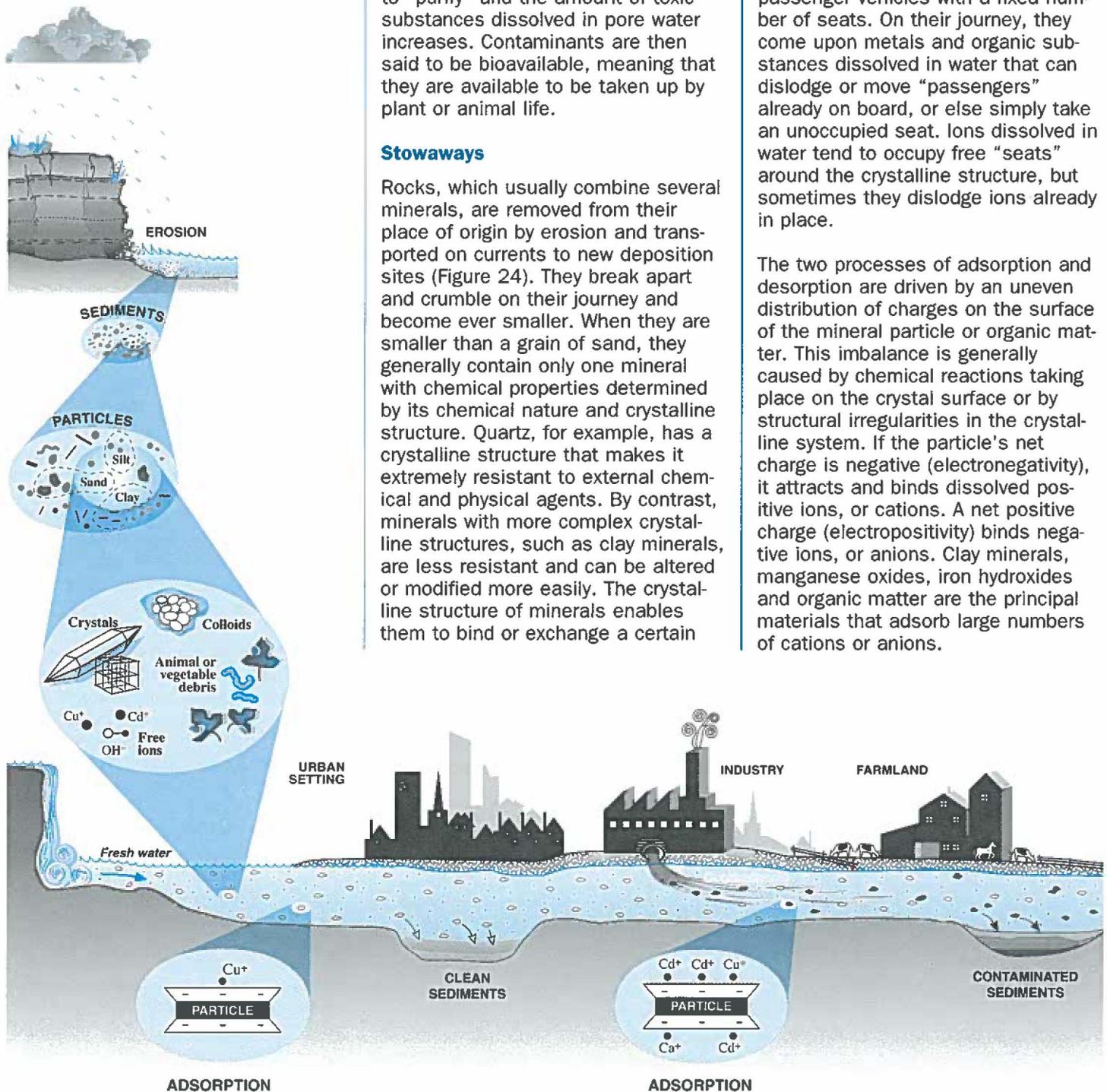


Figure 24 Process of adsorption and desorption of sediment particles

In watercourses, particles with ions adsorbed to their surface move on the currents and conclude their journey in a sedimentary basin, where hydrodynamic conditions permit sediment deposition. The number of ions bound by the particles is generally characteristic of the environment. Some particles may settle to the bottom without having filled all their adsorption sites.

Since particles can travel long distances before settling, contaminants found in sediment may come from far away. The number of ions adsorbed on particles over and above the natural background ions is called the *contaminant load* or *anthropic concentration*. The contaminant load and the capacity of particles to easily release cations (desorption) are taken into account in assessing and classifying sediments in terms of the danger they pose to living organisms.

Adsorption and desorption are strongly controlled by particle size, which in turn determines the number of available sites (or contact surfaces). The finer a suspended or settled particle, the greater its capacity to adsorb pollutants. For example, clayey sediment is always more contaminated, per unit of weight, than sediment composed mainly of sand, with its large component of quartz grains that have almost no adsorption capacity.

Sediments along the edge of watercourses and on lake bottoms, where currents are weak or non-existent, will consist mainly of fine particles. The

fine sediments in these zones tend to be more contaminated than in zones with stronger currents, where sediments are composed of coarser gravel and sand.

Adsorption and desorption operate in both fresh and salt water. However, salt water can affect certain chemical and physical properties of particles, occasionally releasing ions already adsorbed and replacing them with others.

### Particle flocculation

The meeting of fresh water from the Fluvial Section and salt water from the estuary produces complex currents. The constant tide-induced oscillation of water masses creates a substantial upstream intrusion of salt water. Particles are resuspended in the section where the waters mix.

In marine and brackish environments rich in mineral salts, especially sodium chloride (NaCl), clayey particles are surrounded by large numbers of cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ) and water molecules. The cations neutralize the negative charge of the particles and, in so doing, weaken the repellent forces between them. The particles then come together in a random pattern to form clumps, or flocs. Their "house-of-cards" structure contains pores between the layers that are filled with a film of water rich in ions and strongly bound to the particles. This so-called *pore water* facilitates exchanges between solid matter and ions. Flocculation increases the density of particles, which promotes

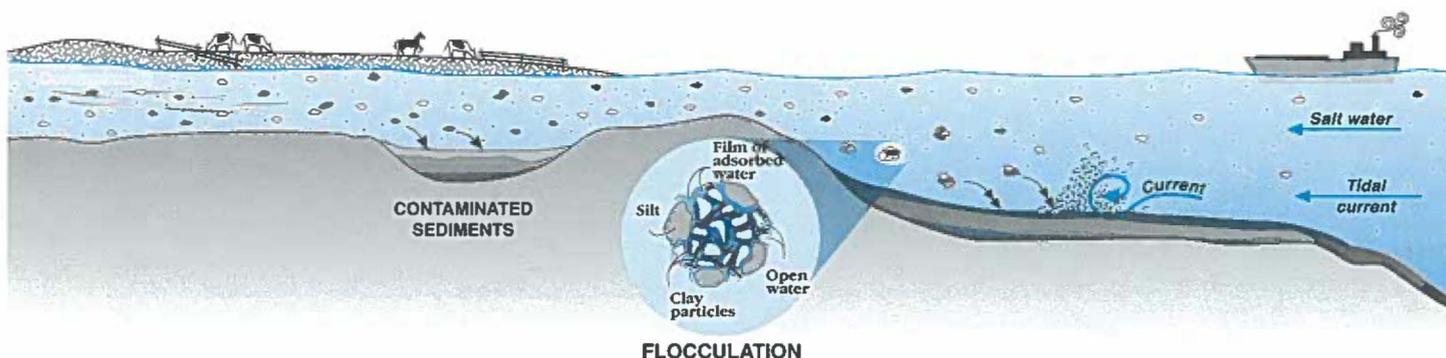
greater sedimentation and reduces the number of particles in the water.

### A complex laboratory

The aquatic environment is a laboratory in which relatively complex chemical and biochemical reactions take place. The carbon cycle and part of the oxygen cycle are completed here. Appendix 1 shows the main chemical reactions of sediment diagenesis.

Oxygen in water comes from both internal and external sources. Internal production results from photosynthesis within the euphotic zone. The external input consists of atmospheric oxygen that enters the water by diffusion when its surface is churned by waves and currents. Photosynthesis also requires elements such as nitrogen (N), phosphorus (P) and certain trace minerals that are essential to cell activity. Without photosynthesis, the earth's oxygen would be entirely consumed by the decomposition of organic matter.

Organic matter begins to decompose in the upper few metres of the water column and continues when the particles settle on the bottom. The presence or absence of oxygen largely controls the type of chemical reactions (oxidation, reduction, breakdown of compounds into elements), biological processes (bioturbation, bacterial decay), metabolic processes (microbial respiration, photosynthesis), and hydrodynamic and physico-chemical processes that take place during sedimentation.



Oxygen penetrates sediments mainly through molecular diffusion and bioturbation (Figure 25). Diffusion is a chemical process involving an ion exchange between two environments, such as air and water or water and sediment. The exchange, which takes place through the medium of sediment pores, is especially active at the water-sediment interface because of greater porosity in the top centimetres of sediment.

Benthic organisms living on or in the sediment introduce varying amounts of oxygen at different depths as they work the sediment. In the St. Lawrence River and Gulf, the action of burrowing creatures is evident in the first 5–10 cm of sediment.

The thickness of the oxygen-containing layer, called the *aerobic layer*, depends on the morphology of the sedimentary basin, the depth, temperature and residence time of the water, the amount of light reaching the sediment, and the level of organic matter. Beneath the aerobic zone lies a second zone completely devoid of oxygen, or *anaerobic*. Its thickness depends on the amount of accumulated sediment in the basin.

### From oxidation to fermentation

Two very important oxidation reactions take place at the water-sediment interface due to the dissolved oxygen content in the sediment. Iron (Fe) and manganese (Mn), two metals comprising the mineral component of the sediment, are oxidized and reach a stable chemical state. This may be a re-oxidation if bioturbation has carried them from the reducing zone towards the surface. Manganese normally oxidizes in a more oxygen-rich environment than does iron. In the most favourable conditions, zones rich in iron oxyhydroxides ( $\text{Fe}(\text{OH})$ ) and manganese oxides ( $\text{MnO}$ ) can be found on the sediment surface. These oxides form a reddish crust that cements the other sediment constituents.

Bacteria and some single-celled organisms are also able to oxidize organic matter. This oxidation of plant and animal tissue uses oxygen dissolved in the sediment and its pore water.

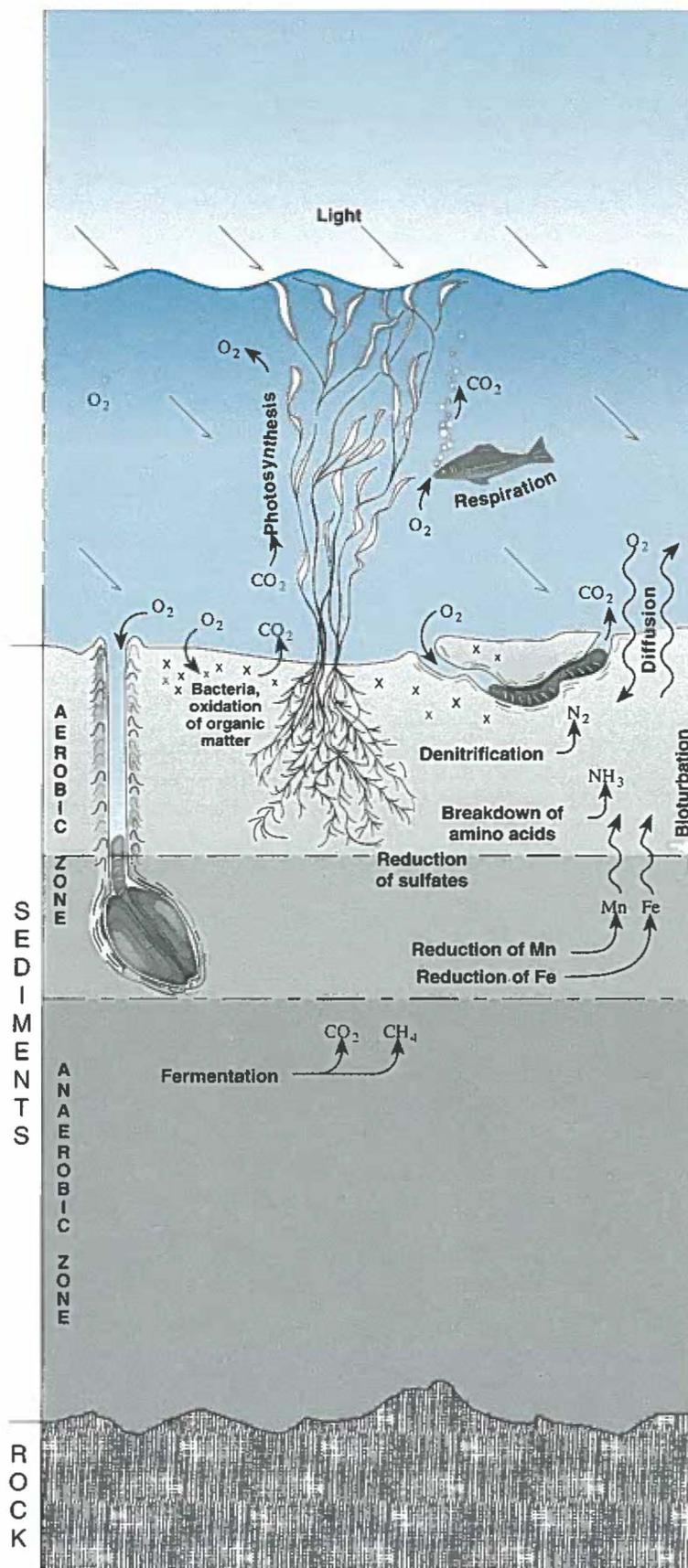


Figure 25 Principal biochemical processes in organic matter decay

When organic matter decomposes and decays, a large number of  $O_2$  molecules are consumed to transform organic carbon into  $CO_2$  gas.

In anaerobic environments, bacteria oxidize organic matter by using oxygen present in other forms such as  $SO_4$ ,  $NO_3$ ,  $MnO_2$  and  $Fe_xO_y$ . In oxygen-depleted environments, bacteria use a series of reactions including denitrification, amino acid breakdown, sulfate reduction and fermentation to decompose organic matter. Denitrification enables the bacteria to use oxygen from nitrates ( $NO_3$ ) and transform the carbon in the organic matter into  $CO_2$ . The reaction also produces free nitrogen ( $N_2$ ) that can circulate towards the surface.

After the nitrates are gone, amino acids, the basic building blocks of life, are broken down into non-nitrogenous organic compounds and ammonia, or  $NH_3$ . Ammonia may be used in a subsequent chemical reaction to form ammonium ( $NH_4^+$ ).

Bacteria also use oxygen from sulfates ( $SO_4^{2-}$ ) to complete the oxidation of organic matter. The transformation of sulfates produces  $CO_2$  and leads to the formation of  $HS^-$ ,  $H_2S$  or  $FeS_2$ , depending on environmental conditions.

When sulfates have all been consumed, fermentation reactions begin and break down the remaining organic molecules. This biochemical process

takes place with the help of enzymes produced by certain micro-organisms. Fermentation produces  $CO_2$  and methane ( $CH_4$ ).

### Mercury methylation

Sediments are chemically unstable deposits acted on by microbes and chemical reactions that alter the chemical bonds of certain metals. In the fermentation zone where methane is produced, as well as in the sulfate reducing zone, physical and chemical conditions (pH, temperature, etc.) normally combine to bring about the methylation of certain metals.

Although there are several methylation mechanisms, it generally proceeds through the intermediation of bacterial activity, especially by sulfate reducing bacteria. Vitamin B12, or methylcobalamin ( $CH_3CoB12$ ), appears to be the principal catalyst in the methylation of mercury (Hg). Methylcobalamin allows the transfer of a methyl group ( $CH_3$ ) to mercury ( $Hg^{2+}$ ) to form molecules of highly toxic methyl mercury ( $CH_3Hg^+$ ) without necessarily altering the vitamin B12 molecule. This process is in fact a bacterial cell detoxification mechanism and occurs mainly in acidic environments and outside the cells. All these processes involve the absorption and transfer of metals into the ecosystem.

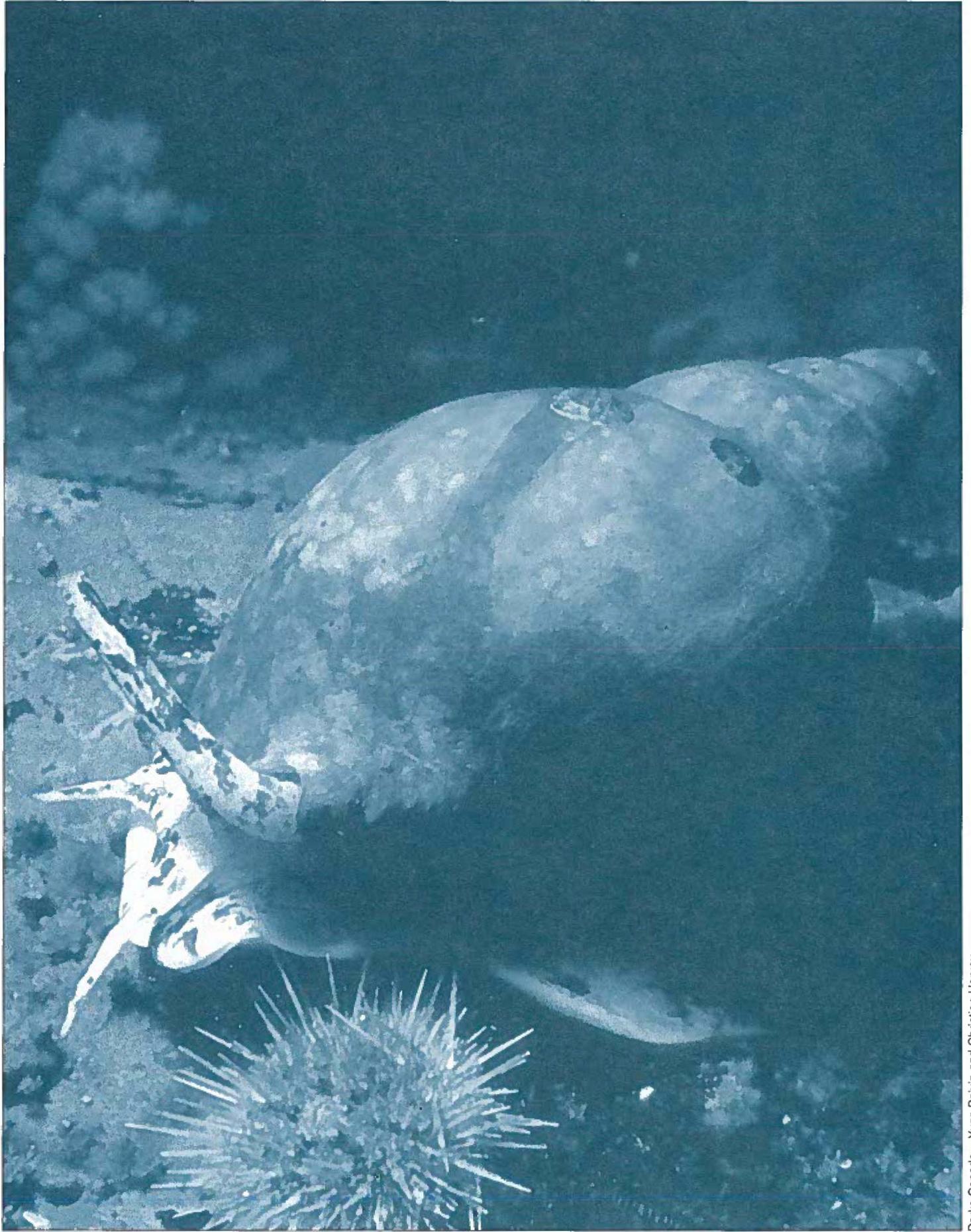
Methyl mercury molecules ( $CH_3Hg^+$ ) formed in this way are highly soluble

and easily assimilated by benthic organisms. Methyl mercury spreads throughout the water column and becomes available for bioaccumulation by living organisms.

### Why isn't the opposite true?

For particles in anaerobic environments (devoid of oxygen), conditions are reductive and more acidic. Chemical reactions are reversed and metals like iron and manganese are reduced. The reduced iron and manganese molecules become more mobile in the sediment and may dissolve in pore water. They then migrate towards the sediment surface by diffusion. As they move through the aerobic zone, they are re-oxidized and become more chemically stable again. The diffusion of iron and manganese towards the sediment surface is driven by the concentration gradient of the metals between the reducing zone (anaerobic) and the oxidizing zone (aerobic).

The diffusion of iron and manganese towards the surface is important when the sediments are contaminated. Iron and manganese oxyhydroxides can easily adsorb several metals and since they are near the surface, the contaminants they adsorb remain in the bioturbation zone, where benthic organisms are most active.



Parks Canada - Yves Bowin and Christian Harvey

# CHAPTER 7

## *The Role of Benthos in Contaminant Transfer*

**The top centimetres of surface sediments form a living matrix. Benthic organisms living there work on this matrix by burrowing in or ingesting particles. Benthic organisms along with other species in the aquatic ecosystem contribute to the transfer of contaminants to higher organisms.**

**U**nconsolidated sediments are colonized by a great variety of organisms ranging in size from about a micron (bacteria) to a few centimetres (benthic macroinvertebrates). These diverse species of the benthic community, known as *benthos*, have different feeding regimes (detritivorous, herbivorous, carnivorous) that determine their trophic level in the food chain. The food chain is based on the energy contained in organic matter deposited on and buried in the sediments. Detritivores convert this matter into living biomass that serves as food for organisms at higher trophic stages (carnivorous benthos, fish, water birds, marine mammals).

Benthic organisms play a very important role in transferring toxic substances from sediments to aquatic vertebrates. They make sediment contaminants more available to the vertebrates through three main processes: they transform some contaminants into a more soluble and easily assim-

ilated form (*biotransformation*); they mix up sediments physically (*bioturbation*); and they concentrate contaminants in their body biomass (*bioconcentration*). If a contaminant lodges permanently in living tissue, it can be transferred from one generation to the next within a single species, or it can migrate to other species through the food chain (*biomagnification*).

### *Continuous mixing of sediments*

Benthic organisms mix the surface layers of sediments as they crawl upon and burrow through them. Certain organisms such as annelids (polychaetes and oligochaetes) ingest sediments in deep layers and expel them at the water-sediment interface in the form of fecal pellets. The continuous mixing of sediment particles and contaminants generally occurs in the top 10 cm of sediments, although the action of some organisms can

have an impact as far down as 15 to 20 cm. Bioturbation has the effect of delaying the burial of contaminated sediment by clean sediment for a long time after the source of contamination has been eliminated.

### *Contaminant transfer to organisms*

Many benthic organisms, especially molluscs, tend to accumulate toxic substances in their body tissue to much higher concentrations than those found in ambient water and sediment. Bioconcentration of a contaminant in an organism occurs when the rate of assimilation of the substance exceeds the rate of elimination. In such cases, concentrations of the contaminant in an organism's body increase as it grows older.

Benthic creatures assimilate toxic substances from sediments in various ways. They can do so through the simple diffusion of substances dissolved in the sediment pore water through dermal, digestive and respiratory surfaces, or by ingesting sediments, detritus and contaminated benthic organisms. Assimilated contaminants can be eliminated passively through ion exchange with the surrounding environment, or actively, with the production of particulate matter (feces, eggs, mucus, molt) and the excretion of by-products arising from the metabolism of contaminants.

Many types of benthic organisms are thus able to regulate the concentrations of heavy metals in their body and can quickly metabolize certain PAHs. As a result, they do not bioconcentrate these substances.

However, this is not true for molluscs, which can concentrate these contaminants to levels several thousand times greater than values found in the ambient environment. Since organochlorine compounds (PCBs, pesticides) are soluble in lipids, they are easily assimilated by aquatic organisms. However, most organisms cannot efficiently eliminate these compounds, so they quickly bioconcentrate in lipid-rich tissue. The PCB contamination of whelk in Baie des Anglais (St. Lawrence Estuary) is a well documented case of the biocon-

centration of contaminants from sediments. The PCB concentration in the flesh of this omnivorous gastropod is directly proportional to the concentration of PCBs in the sediment; levels in whelk flesh ( $\mu\text{g/g}$  wet weight) are on average three and one-half times higher than in the sediments ( $\mu\text{g/g}$  dry weight) (Langlet et al., 1991).

### *Infiltrating the food chain*

Biomagnification occurs when concentrations of a contaminant increase moving up the food chain. A contaminant is biomagnified when concentrations found in organisms at the top of the food chain are much higher than those found at the bottom (Figure 26). Some heavy metals and PAHs do not biomagnify in aquatic ecosystems because many species in the food chain can metabolize and control their body burdens or eliminate the contaminants. This is true for many species of crustaceans, annelids and fish. However, high concentrations can still be found where contaminant intake exceeds the organism's capacity to metabolize or excrete it. For example, very high PAH levels have been detected in lobster hepatopancreas. Mercury is excreted very slowly by many species, making biomagnification possible. This is evident in the rise in maximum concentrations found in St. Lawrence aquatic organisms as one moves up the food chain. By contrast, some organisms are able to regulate their body burden of essential minerals such as copper and zinc, which are normal constituents of haemolymph (the blood of crustaceans).

Organochlorine compounds such as PCBs and DDT tend to accumulate in the fatty tissue of aquatic organisms and remain there long after exposure to the contaminant ends. These substances therefore reach much higher concentrations in fish, aquatic birds and marine mammals than in benthos. The two best documented examples of biomagnification in the St. Lawrence system involve PCBs and Mirex (an organochlorine pesticide originating exclusively from the Great Lakes) in the St. Lawrence Estuary (Figure 26). Both these toxic

substances are found in the milk of nursing Beluga whales at concentrations 100 000 times higher than in macrobenthos and zooplankton (Béland and Martineau, 1988).

### *Toxic effects*

Most aquatic organisms can avoid the toxic effects of heavy metals they assimilate by storing them in cell components (lysosomes) or deactivating them using special proteins capable of bonding to free metals (metallothioneins). However, these detoxification mechanisms have limits, and toxic effects appear when they are exceeded.

Metals have a variety of toxic effects. In general, they cause disorders in physiology, reproduction, and growth promotion and inhibition. There is no universal rule, however, and effects depend on the tolerance of the species. For example, certain benthic algae (Fucales, Laminariales) can bioaccumulate heavy metals without it altering their growth. Heavy metals can also change feeding behaviour, respiratory metabolism and digestion. Chronic exposure to contaminants often results in pathologies such as tissue inflammation and degeneration, inhibited regeneration of damaged tissue, tumour formation, and genetic mutation.

Some PAHs metabolized by aquatic organisms are transformed into by-products that are more toxic than the original substances. This bioactivation of PAHs can have teratogenic effects (birth defects) and carcinogenic effects (tumours). PAHs can also have direct toxic effects that inhibit growth, alter the immune system (increased vulnerability to viral and bacterial infection), upset the endocrine system (changes in hormone levels and function), and reduce reproductive potential.

The toxic effects of PCBs and other organochlorine compounds are more pronounced in aquatic vertebrates than in invertebrates due to the process of biomagnification. In fish, PCBs increase the incidence of fin erosion, skin lesions and anemia, and alter the immune system. In birds,

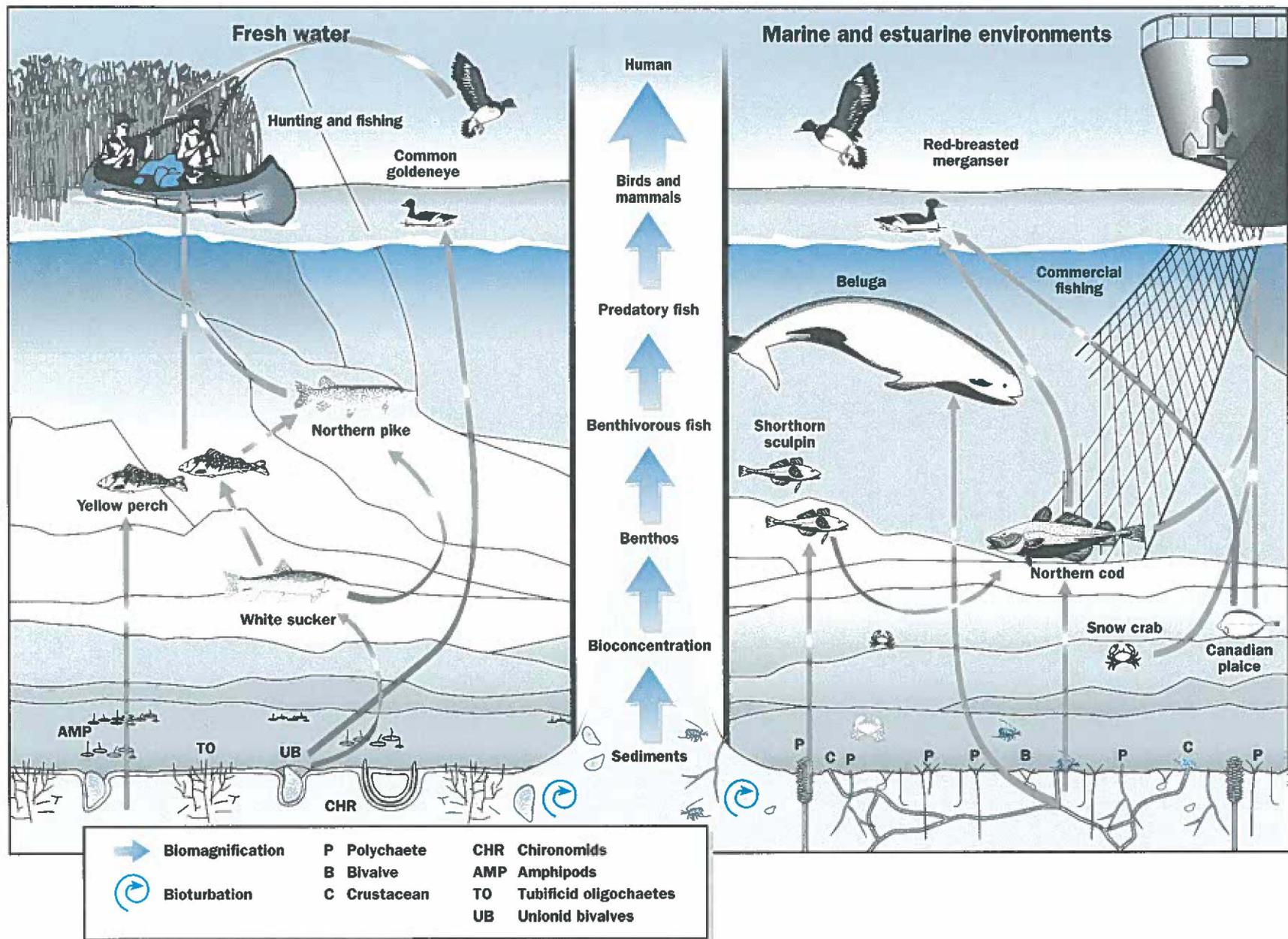


Figure 26 Transfer of sediment contaminants to higher organisms

PCBs affect reproductive behaviour and hatching success. In mammals, they affect ovulation and embryo development.

From the standpoint of overall populations, toxic substances reduce numbers and, in the worst cases, eliminate the population. In the benthic community, contamination reduces productivity and diversity. Sediments that are heavily contaminated by toxic substances typically have a poorly diversified benthos dominated by one or a few very tolerant species such as tubificid oligochaetes, which are widespread in freshwater environments. This change in the benthic community could destroy the area's attractiveness as a feeding ground for bottom-feeding fish and species of aquatic birds and marine mammals that eat mainly benthic organisms (see Information Supplement, *Benthic Species as Indicators of St. Lawrence Water Quality*).

Although transfer up the food chain is the most common pathway by which contaminants enter higher animals, other routes of exposure are possible. For example, lead shot that lodges in sediment is contaminating several species of ducks on the St. Lawrence (see Information Supplement, *Lead Shot Contamination of Waterfowl in the St. Lawrence*).

### Information Supplement

## Benthic Species as Indicators of St. Lawrence Water Quality

The harmful effects of toxic discharges on the aquatic environment have been evident since the beginning of the Industrial Revolution. Various methods have been devised to assess the toxicity of discharges. Some are conducted in laboratories (bioassays, toxicity tests) while others involve studying organisms in their environment (indicator species, community integrity indicators). The term *bioindicator* refers to an organism or species, either animal or plant, with characteristics that allow its use to determine the nature of certain environmental factors, or to detect or measure the extent of pollution. The parameters used are based on biochemical, physiological, morphological or ecological measurements.

An *indicator species* is a sensitive species that provides information on environmental quality by its presence, absence or abundance.

The term *community integrity indicator* refers to the structural composition of a community or, more precisely, a particular taxonomic group such as the macroinvertebrates.

Bioindicators must be widely distributed geographically, relatively abundant and easy to sample. They must also be large enough to allow accurate chemical analysis, have a reasonably long life cycle and offer an easy way to determine their age. Among macrophytes, American eelgrass (*Vallisneria americana*) has shown potential as an indicator species for trace-metal contamination in the St. Lawrence. Concentrations of Cd, Cr, Cu, Ni, Pb and Zn

in the green part of this ubiquitous submerged plant in lakes Saint-Louis and Saint-Pierre reflect the spatial variation of local contamination (Saint-Cyr et al., 1992; Saint-Cyr and Campbell, 1994).

Molluscs have also been studied for their capacity to accumulate contaminants and reflect sediment contamination. Significant relationships have been observed between trace-metal concentrations in sediments and in the flesh of the gastropod *Bithynia tentaculata* for Cr and Fe (Flessas, 1994), and for Hg (Désy et al., 1997). The freshwater mussels *Elliptio complanata* and *Lampsilis radiata* have been assessed for their usefulness as biomonitors by studying the influence of sex (Metcalf-Smith, 1994), age and growth rate (Metcalf-Smith et al., 1996) on trace-metal bioaccumulation.

These two mussel species would also make good indicators (Metcalf-Smith and Charlton, 1990) for biomonitoring organic contaminants, as would Zebra mussels (*Dreissena polymorpha*) (Comba et al., 1996). The amphipod *Gammarus fasciatus*, a crustacean widely distributed in submerged aquatic plant communities of the St. Lawrence, has also been studied for its capacity to reflect trace-metal contamination in sediments (Amyot et al., 1994).

More study is needed to determine the effectiveness of using reptiles (Snapping turtles, *Chelydra serpentina*) and amphibians (Mudpuppy, *Necturus maculosus*) as bioindicators in a biomonitoring program on the St. Lawrence. The Mudpuppy has many of the characteristics of a good bioindicator, but wide variations have been found in contaminant concentrations among individuals from the same site exposed to the same environmental conditions (Bonin et al., 1995).

## Information Supplement

## Lead Shot Contamination of Waterfowl in the St. Lawrence

Ingested lead shot is one of the main sources of lead exposure and poisoning for waterfowl and other bird species. Lead shot that settles on the bottom and in the sediments of a water body is not chemically or environmentally inert and its complete destruction will take tens or hundreds of years.

A study done in 1988-89 on the diving and dabbling duck populations of the St. Lawrence found those most contaminated by lead were in the Gaspé area, Baie-Comeau and on

the shoreline from Cornwall to Île d'Orléans (Dickson and Scheuhammer, 1993).

The effects of lead shot contamination are not limited to the birds that ingest it. It also strikes raptors whose prey is contaminated by lead shot. In Canada and the United States, the mortality rate of immature Bald eagles (*Haliaeetus leucocephalus*) and Golden eagles (*Aquila chrysaetos*) is estimated at 10 to 15 percent (Scheuhammer and Norris, 1996).

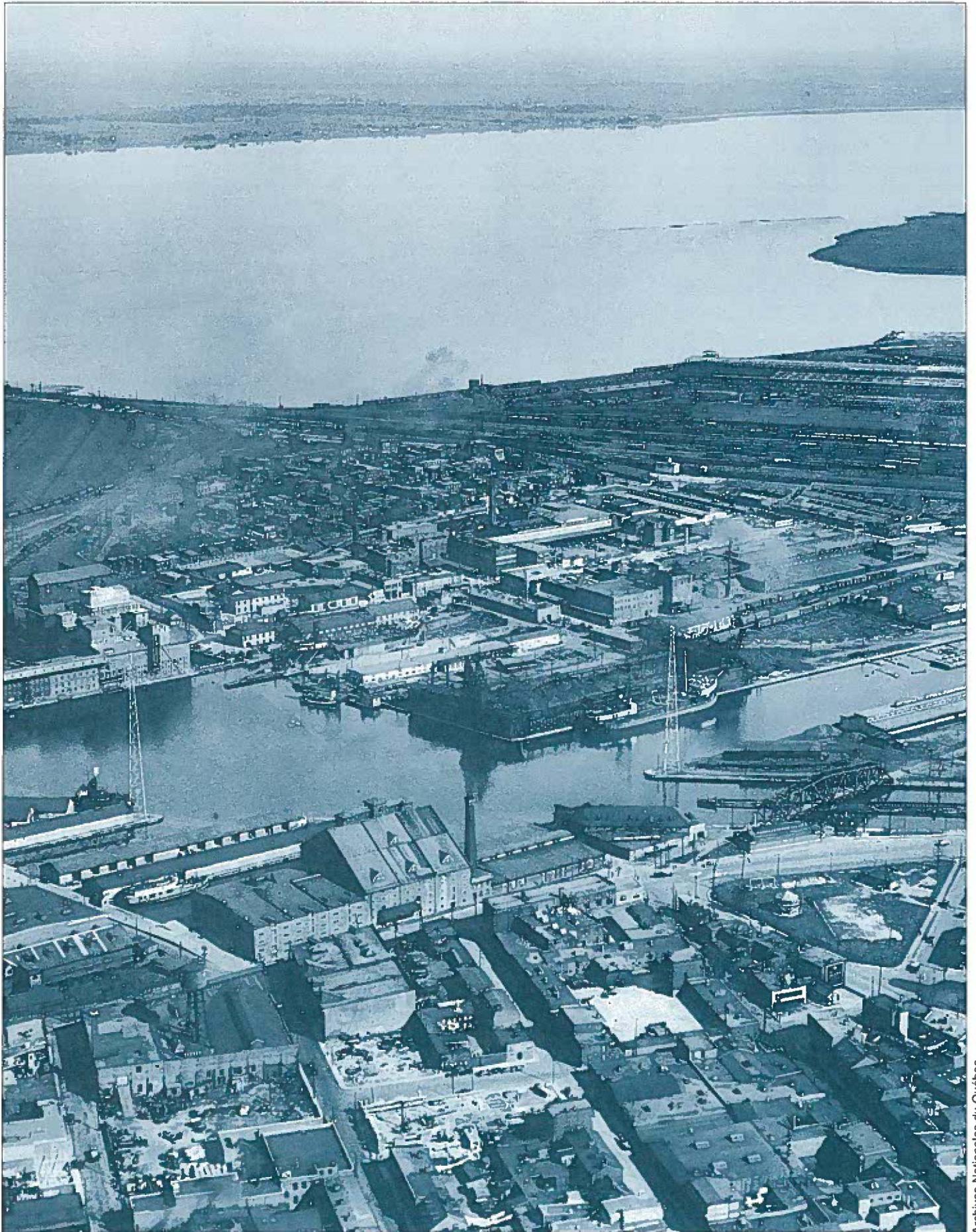
Alternatives to toxic lead shot now exist, including steel shot. Shot made of a bismuth and tin mixture as well as zinc will also be commercially available in North America (Scheuhammer and Norris, 1995).

Bismuth-tin mixtures are still at the testing stage, but they appear to possess ballistic properties (trajectory, velocity, energy) similar to lead.

Since most birds exposed to lead shot contamination belong to migratory species oblivious to borders, international cooperation is required to restrict its use. In the United States, lead shot is now banned everywhere in waterfowl hunting. In Canada, a similar measure took effect in 1997, banning the use of lead shot within 200 m of any watercourse or water body. It will apply everywhere in Canada by 1999. In Mexico, on the other hand, only the state of Yucatan has established areas where lead shot is restricted.



Canadian Wildlife Service - Léo-Guy de Repentigny



# Contaminated Areas of the St. Lawrence

**The harbours of Montreal and Quebec City are the most heavily contaminated zones in the St. Lawrence. Since the start-up of toxic discharge reduction programs, a gradual decrease in St. Lawrence sediment contamination levels has been noted.**

**M**ost aquatic ecosystems are affected by contaminants carried from elsewhere by water, living organisms, and atmospheric circulation. There are few places on earth where the physico-chemical composition of sediment is identical to the natural environment. One example is nuclear bomb testing, which sends radioactive material into the upper atmosphere to later fall upon Arctic regions far from the blast site. Sediments are said to be contaminated when their natural chemical composition is altered by anthropic inputs of elements such as heavy metals, pesticides and other synthetic organic compounds. The difference between levels of these substances in contaminated sediments and natural values is known as the *anthropic enrichment* of contaminants.

## Sources of contamination

Contamination in the St. Lawrence is a complex phenomenon not limited to adjacent sources of contaminants. Along with contaminants from sources at riverside, toxic substances introduced by humans into the St. Lawrence drainage basin and else-

where in the biosphere end up in the river through the water cycle and/or atmospheric circulation. Figure 27 shows the main points at which contaminants enter the St. Lawrence. They are grouped into four broad categories: internal (local) sources, continental waters, ocean waters and atmospheric deposition.

Internal or local sources comprise contaminant inputs from human activity taking place along the St. Lawrence shore. They include direct discharges of urban, industrial and agricultural effluent as well as dumping of snow. There are also nonpoint sources such as riverside dumps, farming, shipping, port operations, dredging and the dumping of dredged material.

At the head of the St. Lawrence River, continental waters come entirely from the Great Lakes water mass, which supplies three-fifths of the river's flow as measured at Quebec City. All along its course, contaminant inputs from the Great Lakes are joined by inputs from local sources and tributary waters that may be contaminated by point- and nonpoint-source discharges in their own drainage basins. Tributaries also contribute toxic substances acquired when contaminants are

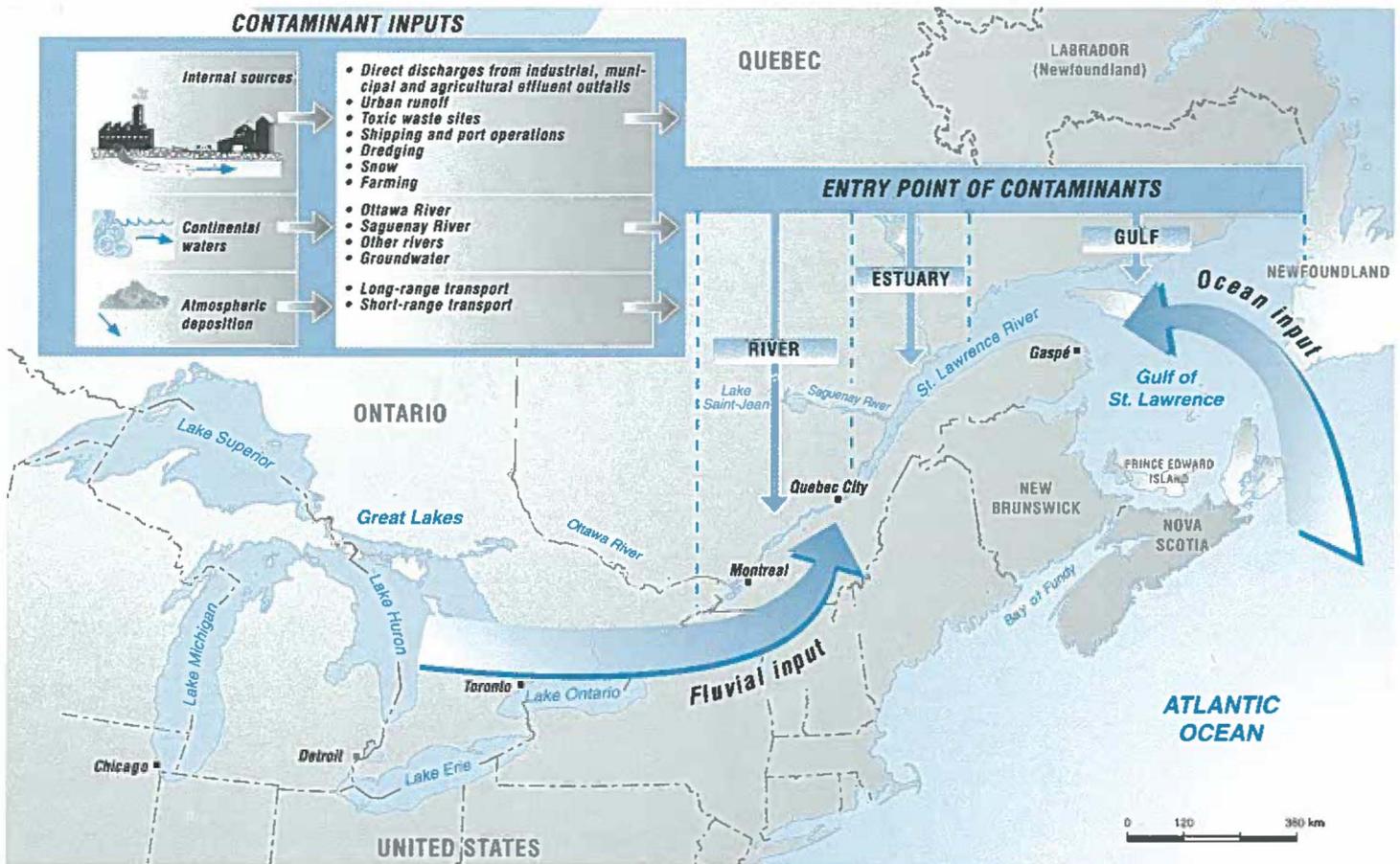


Figure 27 Principal points of entry of contaminants into the St. Lawrence

transferred from the atmosphere to soil and watercourses. At Quebec City, for example, “fluvial input” refers to all contaminants introduced by continental waters from the St. Lawrence River watershed.

Ocean waters carry contaminants into the St. Lawrence Estuary by way of the Gulf. These contaminants were introduced into the Atlantic Ocean by the long-range transport of airborne pollutants (atmospheric deposition) and shipping activities (accidental and intentional hydrocarbon spills).

Atmospheric sources refer to airborne pollutants that fall directly on the St. Lawrence. Along with emissions from local sources (e.g. factory smokestacks), contaminants introduced into the atmosphere by distant sources (e.g. coal-burning thermal power plants) can be dispersed over great distances by atmospheric circulation and fall on the St. Lawrence.

### *How to judge whether contamination is significant*

The anthropic contribution to sediment contamination cannot always be determined precisely. For one thing, the natural concentration of certain heavy metals and organic compounds (e.g. PAHs released during forest fires) rises in direct proportion to the clay content of the sediment. For another, natural, geochemically normal concentrations may vary in sediments of the same texture, depending on the geology of the drainage basin.

Due to the limited number of contaminant readings in the preindustrial sediment of the St. Lawrence, we cannot precisely determine the relationship between the fine-particle component of sediment and natural levels of heavy metals and PAHs. A knowledge of these relationships would allow us to identify, with a reasonable certainty

(using statistical tests), any anomalies attributable to sediment contamination of human origin. Such a relationship was determined for concentrations observed at several hundred bottom sediment sampling points in the Beaufort Sea (Canadian Arctic). Recent sediment in the Beaufort Sea derives mainly from rapid erosion of the coast and the watershed of the Mackenzie River, which flows over igneous and sedimentary rock. A characterization study of sediment samples from this environment, far from major contamination sources, clearly showed a rising gradient of heavy metal and PAH levels as clay content increased (Wainwright and Humphrey, 1988). For example, it showed that coarse sediment can contain as little as 0.01 µg/g of mercury, while sediment consisting of clay alone can contain more than 0.1 µg/g. This makes for a natural enrichment factor of 10. Moreover, maximum concentrations of cadmium, chromium, copper, mercury, nickel, lead, zinc and PAHs in this

Arctic sea, barely touched by contamination, were reported to be as high as 2.5 times above average concentrations. Clearly, natural concentrations of heavy metals and PAHs in sediments vary widely.

For the St. Lawrence, we assume that concentrations detected in fine sediments dating from the turn of the century — i.e. the early days of industrialization in the drainage basin — best represent average values in sediment that is free of contamination (see the mercury example, Table 5). For the purposes of this analysis, we consider that concentrations exceeding 2.5 times those found in preindustrial St. Lawrence sediments cannot be explained solely by variations in sediment texture and/or geology. Concentrations greater than this multiple imply relatively important anthropic inputs. Consequently, we say that a Threshold of Significant Contamination (TSC) has been reached when contaminant levels exceed preindustrial values by a factor of 2.5. Appendix 4 gives the heavy metals and PAH concentrations observed in preindustrial St. Lawrence sediments. For arsenic, a natural background level of 8 µg/g (Quémerais, 1996) was used in the absence of reliable data on preindustrial levels (see Information Supplement, *Arsenic in the St. Lawrence Ecosystem*).

### *How to judge whether sediments are polluted*

Since contaminants are present in most compartments of the ecosystem, the challenge is to determine what concentrations of a toxic substance can seriously harm the natural environment. We then speak of "pollution" rather than "contamination" of sediments. For example, the air in our neighbourhood is contaminated by minute amounts of chemicals (lead, mercury, PAHs, etc.). It becomes polluted only when public health authorities believe the concentration of chemicals has reached a level harmful to our health. Similarly, a river bed may be contaminated by a host of chemicals that are potentially harmful to benthic organisms, but it is considered polluted only after the pollutants in the sediment are shown to be harmful to the integrity of living creatures due to their elevated concentrations. The harm usually takes the form of toxic effects on organisms living in or near the sediment and who depend on it for their subsistence.

In polluted ecosystems, quality criteria are interpretative tools for comparing the concentration of a pollutant (toxic substance, bacteria, nutrient) to a maximum permissible target level beyond which living organisms will be

harmful by the pollution. This is called *apprehended pollution*. The quality criteria were developed using the best information to date on harmful effects associated with the presence of pollutants in the environment. They will have to be revised from time to time in light of new scientific knowledge, particularly in the field of bioassays.

Quality criteria developed for Quebec by the federal and provincial governments classify sediments into three levels of apprehended pollution (Table 5) (SLC and MENVIQ, 1992). The first, or No Effect Threshold (NET), corresponds to natural background levels of a chemical substance in sediment at a site known to be free of contamination. The presence of the substance in this concentration has no chronic or acute effect on benthic organisms. The second level, the Minimal Effect Threshold (MET), is the concentration believed to affect organisms most sensitive to contamination, although it is tolerated by most organisms. The third level is the Toxic Effect Threshold (TET). Ninety percent of benthic organisms are thought to be harmed by a pollutant present in concentrations exceeding the TET. Sediment quality criteria are based essentially on the tolerance levels of benthic organisms exposed to pollutants. They therefore give an appreciation of the sediment pollution

**Table 5** Criteria for mercury contamination vs. criteria for mercury pollution in sediments

	Contamination criteria (µg/g)		Pollution criteria (µg/g)		
	PIL (AEF=1)	TSC (AEF=2.5)	NET	MET	TET
Beaufort Sea	0.05*	0.13**	NT	NT	NT
St. Lawrence River	0.05	0.13	0.05	0.2	1.0
St. Lawrence Estuary and Gulf	0.03	0.08	0.05	0.2	1.0
Saguenay Fjord	0.10	0.25	0.05	0.2	1.0

Source: Taken from various sources.

\* Average concentration (n = 431).

\*\* More than 98 percent of mercury concentrations found in Beaufort Sea sediments are below 0.13 µg/g.

PIL: Preindustrial Level.

AEF: Anthropic Enrichment Factor.

NET: No Effect Threshold.

MET: Minimal Effect Threshold.

TET: Toxic Effect Threshold.

NT: Not applicable.

## Information Supplement

**Arsenic in the St. Lawrence Ecosystem**

Estimates of anthropic inputs of arsenic into the environment worldwide vary widely from tens to hundreds of thousands of tonnes per year. According to the most conservative estimates, the relative contribution from human activity is at least twice the natural input from soil erosion. In Canada, including Quebec, the metallurgical industry was responsible for more than 98 percent of arsenic inputs to the environment during the 1980s. In Quebec, copper and nickel refining processes produced the bulk of arsenic from industrial sources. Minor inputs (< 2 percent) came from heavy oil and coal combustion and arsenic herbicides.

Our governments believe that inorganic arsenic compounds form a highly toxic group of substances that pose a health risk. A good example is arsenic trioxide (As<sub>2</sub>O<sub>3</sub>). Total arsenic concentrations detected in St. Lawrence River waters between 1985 and 1990 showed little spatial variability, ranging between 0.2 and 2.5 µg/L. The highest values were obtained in waters influenced by Montreal's harbour. The median value was 0.6 µg/L, more than four times over the water quality crite-

level, subject to confirmation by toxicity tests. Appendix 3 gives the values used to establish the different contamination thresholds (NET, MET, TET).

**How to assess the degree of contamination**

The relative contribution of human activity to natural background levels of sediment contamination is often expressed as the Anthropogenic Enrichment Factor (AEF)<sup>2</sup>. To determine the AEF for synthetic substances

2.  $(AEF = [Anthropic\ input + Preindustrial\ level] / Preindustrial\ level)$ .

tion (0.14 µg/L) established to protect human health against ingestion of aquatic organisms contaminated by arsenic. In fluvial lake sediments, total arsenic levels range between 0.3 and 11.1 µg/g, for an average of about 3 µg/g. Little is known of preindustrial arsenic levels in St. Lawrence sediments, while values obtained in recent sediments approach geochemical norms (8 µg/g). Ambient arsenic concentrations in St. Lawrence River water and sediments are similar to values detected in the Great Lakes.

Elevated arsenic concentrations resulting from direct discharges into the receiving environment are found in the Montreal and Quebec City harbours, the mouth of the Saint-Louis River (Beauharnois) and the Lesser La Prairie Basin. Aside from these areas, is there really a problem of sediment contamination by arsenic for the St. Lawrence as a whole? An Environment Canada study (Quémerais, 1996) found relatively high arsenic concentrations in river water and fish. But it noted that our knowledge of arsenic in fresh water is sketchy, particularly concerning concentrations in the dissolved and solid phase, bioaccumulation, and speciation of this non-metal. It stressed the need for more information on the behaviour and the fate of arsenic in the St. Lawrence.

in the environment (e.g. PCBs), the NET level is used instead of the preindustrial level in the calculation. AEF calculations for the most recent sediment layers basically show the multiples by which contaminant levels exceed natural values. As noted above, an AEF value of 2.5 is assumed to represent a contamination level at the limit of the variability range of natural concentrations (Table 5). This level of anthropic enrichment is generally around the Minimal Effect Threshold (MET), the pollution level above which harmful effects are feared for benthic organisms that are most sensitive to the pollutant.

**How to determine the history of contamination**

Core samples from recent sediment layers can be used to construct a historical record of contamination, with good time resolution, if the cores are long enough and the sedimentation rate is high enough and accurately known. By examining variations over time in a contaminant from a sedimentary sequence not significantly affected by bioturbation, we can usually determine its preindustrial concentration, establish a geochronology of inputs, and assess recent contamination levels. The vertical distribution of contaminant levels measured in sediment core samples is presented in terms of AEF in order to simplify the graphic presentation of the extensive data obtained by core sampling. This standardized presentation of concentration profiles gives a general overview of broad historical patterns of sediment contamination in the St. Lawrence.

**How to describe contaminated areas of the St. Lawrence**

The human contribution to sediment contamination has been studied for the most widely distributed and best documented toxic substances in the St. Lawrence system. They include arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), zinc (Zn), PAHs and PCBs. Since the mid-1980s, characterization studies have established the spatial distribution of these substances in most large areas of fine sediment accumulation in the St. Lawrence. Chemical analysis of the sediment found chromium and nickel present in concentrations generally below the Threshold of Significant Contamination (TSC), so they were not included in the data calculations. Besides, very few recent sediment studies have been done on their presence in estuary and gulf sediments. This report considers the seven PAHs<sup>3</sup> for which there exist government quality criteria for the Toxic

3. Five heavy compounds: benzo(a)anthracene, benzo(a)pyrene, chrysene, fluoranthene and pyrene, and two light compounds: naphthalene and phenanthrene.

**Effect Threshold.** PCB concentrations are calculated by adding together the analytic results for several congeners (different synthetic molecules), which may vary in number from study to study.

Three types of analysis were used to simplify the presentation of data from different sources: spatial distribution of contamination, degree of contamination, and the apprehended effects on benthic organisms.

First, the spatial distribution of contaminated sediments in a specific river section (e.g. Lake Saint-François) was established by drawing a map of zones contaminated by at least one metal or organic substance beyond the TSC. These maps are based on the premise that the TSC takes into account natural variations in sediment chemical composition and also assumes a relatively substantial input of human-source contaminants. For each contaminant studied (e.g. mercury), the percentage of sampling stations where concentrations exceeded the TSC compared to the total number of stations gives an overview of the extent of contamination by the substance.

Second, the degree of contamination is determined by calculating the AEF using the maximum concentration for each contaminant in a given section (e.g. Lake Saint-François).

Third, the potential health risk to benthic organisms exposed to excessive contaminant concentrations is considered high when levels of a pollutant exceed the TET in a zone where contaminated sediments accumulate. With the exception of mercury, sediment quality criteria were established for the extractible phase of the metal since this phase is assumed to form the bulk of total concentrations in heavily contaminated areas (e.g. harbour areas, municipal and industrial outfalls). However, the majority of assessments of St. Lawrence sediment contamination measure concentrations for the total fraction of metals present. Such assessments include not only the potentially contaminating (i.e. extractible) fraction of ions in the area (exchangeable ions, ions adsorbed on particles, and ions in carbonates and oxides), but also

ions in lithogenous form with very low bioavailability. As a result, the sediment quality criteria cannot be applied directly to St. Lawrence sediments (except in Lake Saint-François, where extractible and total fractions were analysed), because comparing total concentrations to the criteria generally over-estimates the degree of contamination of river sediment. However, concentrations measured in St. Lawrence harbour areas are values for the extractible fractions of metals and there are no problems applying the criteria.

Our data on the contamination of St. Lawrence River sediment come from different sampling operations conducted since the mid-1980s in the fluvial lakes and harbour basins. The areas sampled had already been identified as historical accumulation zones for contaminated sediment in studies done from 1972 to 1976 for the Comité d'Étude sur le Fleuve Saint-Laurent. They include the lacustrine sections formed by lakes Saint-François, Saint-Louis, Saint-Pierre, the Lesser La Prairie Basin, and the port areas of Montreal, Trois-Rivières and Quebec City. The historical data collected from 1972 to 1976 cannot be used to analyse contamination of recent sediments. Instead, the mapping of contaminated sections is based on sectoral studies conducted since 1984 in previously-identified accumulation zones for contaminated sediment. The more recent data are reliable and provide adequate spatial coverage to map most contaminated sections of the St. Lawrence. The data used to map contaminated areas are given in Appendix 5.

In the estuarine and marine sections, historical data collected in the early 1970s in a regional survey in the estuary and gulf and in the Saguenay River identified large areas of accumulation of contaminated sediments for later study. Apart from the Upper Estuary, the description of marine sediment contamination is based mainly on a series of core samples collected at the Laurentian Channel axis and in the Saguenay Fjord during the 1980s and 1990s. Data used for the Upper Estuary were gathered in a regional survey done in 1989-1990 from 200 sediment sampling sites (Coakley and Poulton, 1993).

## *Contaminated areas of the St. Lawrence*

Since hydrodynamic conditions have changed little in the St. Lawrence over the past decade, the geographic distribution of zones of potentially contaminated fine sediment should have remained about the same over the period. The only change might be a decline in sediment contamination levels due to clean-up efforts in the watershed since the sampling period. In permanent sedimentation zones, older contaminated sediments may have been gradually buried by sediment of similar texture but better quality. In temporary sedimentation zones, contaminated sediments are regularly resuspended by agents such as floods and storm winds, only to resettle in other basins farther downstream or else to finally reach the ocean. They are replaced by less contaminated sediments.

### **Lake Saint-François**

Toxic substances entering Lake Saint-François come from three main sources. They are, in descending order of importance, the combined inputs of the Great Lakes and the international section of the river, the St. Lawrence tributaries, and municipal effluents (Fortin et al., 1994a). The only large city in the region is Cornwall, located at the head of the lake. No large industrial plants are located on the lakeshore, but several plants in the Cornwall-Massena area have contributed to Lake Saint-François' contamination in the past by discharging toxic substances such as cadmium, copper, lead, mercury, zinc, PAHs and PCBs.

Lake Saint-François can be divided into three sections for purposes of examining its sediment quality: a) the area north of the Seaway, contaminated by heavy metals, especially mercury; b) the area south of the Seaway, also contaminated by heavy metals, but mainly by PCBs; and c) the centre of the lake used by the Seaway channel, where no significant contamination has been detected. In the delta area of the lake, contaminated sediments are generally confined to lentic zones with shoals where the temporary deposition of fine particles is controlled by the growth (sedimentation)

and senescence (resuspension) of macrophyte communities. In the Lancaster basin and other deep lake basins such as Saint-Zotique and Grenadier, the thickness and texture of contaminated sediments indicate that these are zones of long-term accumulation.

Contaminant levels observed in Lake Saint-François sediments in the late 1980s often exceeded the TSC for cadmium, mercury, zinc and PCBs. Extensive areas of the lake were contaminated, with cadmium and mercury concentrations exceeding the TSC in almost half the sites visited (Table 6).

Maximum concentrations of mercury and PCBs gave Anthropogenic Enrichment Factors (AEF) above 13. The highest mercury concentrations were recorded in the Lancaster basin, although heavy concentrations were also detected in the Saint-Zotique basin. In addition to river inputs, this contamination pattern points to a historic source of mercury on the Ontario shore (a chloralkali plant in Cornwall that shut down in 1994). PCBs were also present in all contaminated

zones along the south shore, especially around Île Christatie. These zones are subject to the influence of historic PCB sources identified in the Massena, N. Y. area. Although extensive areas of Lake Saint-François are contaminated, apprehended pollution levels nowhere exceed the TET (Table 6).

A sediment core taken in 1992 in the Saint-Zotique basin shows that contamination by heavy metals peaked between 1960 and 1970 and then fell considerably between 1970 and 1992 (Figure 28A). Surface sediments showed lead, copper and zinc contamination approaching the TSC, with cadmium levels remaining at four to six times higher than preindustrial values. Contamination by organic substances, including PCBs, also fell from the mid-1960s to the early 1980s (Carignan et al., 1994). Between 1979 and 1989, average concentrations of PCBs and mercury in Lake Saint-François sediments declined by 89 percent and 34 percent, respectively (Lorrain et al., 1993).

### Lake Saint-Louis

Contaminants in Lake Saint-Louis sediment come from four major known sources: the St. Lawrence, its tributaries (especially the Ottawa, Saint-Louis and Châteauguay rivers), industrial discharges and municipal effluent (Fortin et al., 1994b). In addition to effluent point sources, direct atmospheric deposition and hazardous waste dumps in the Beauharnois industrial area constitute potential nonpoint sources of contamination.

Contaminated areas are found along either shore of Lake Saint-Louis. All are contaminated by heavy metals and PCBs. Unlike Lake Saint-François, Lake Saint-Louis bears the imprint of major local sources of contamination. Ambient contamination detected on the north side and in the basin south of Île Perrot reflects nonpoint-source inputs from the St. Lawrence and Ottawa rivers (Fortin et al., 1994b). In areas adjacent to industrial zones, such as the mouth of the Saint-Louis River, south of Îles de la Paix and the mouth of Bouchard Creek, contamination from local sources is added to

**Table 6 Significant contamination, apprehended pollution and maximum contamination in Lake Saint-François in 1989**

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropogenic Enrichment Factor (AEF)	Area
Arsenic	20.0	1	17.0	0	1.1	Île Christatie
Cadmium	0.50	51.5 <sup>b</sup>	3.0	0	6.2	Raquette River
Copper	50.00	6.1	86.0	0	3.4	Île Christatie
Mercury	0.13	50.0	1.0	0	13.2	Lancaster basin
Lead	50.00	3.0	170.0	0	3.2	Île Christatie
Zinc	200.00	24.2	540.0	0	7.5	Lancaster basin
PAHs <sup>a</sup>	1.47	1.5	<sup>c</sup>	0 <sup>d</sup>	2.8	Raquette River
PCBs	0.05	24.2	<sup>e</sup>	0	13.5	Île Christatie

Source: SLC, unpublished data (As, Cd, Cu, Pb, Zn, PAHs); Lorrain et al., 1993 (Hg, PCBs).

a. Sum of the 7 PAHs for which a TET has been established (see Appendix 3).

b. TSC exceedance test for cadmium used extractable levels in the absence of total level data. As a result, contamination may be slightly underestimated for cadmium.

c. Varies depending on PAH being considered (see Appendix 3).

d. Percentage of stations where at least 1 of 7 PAHs > TET.

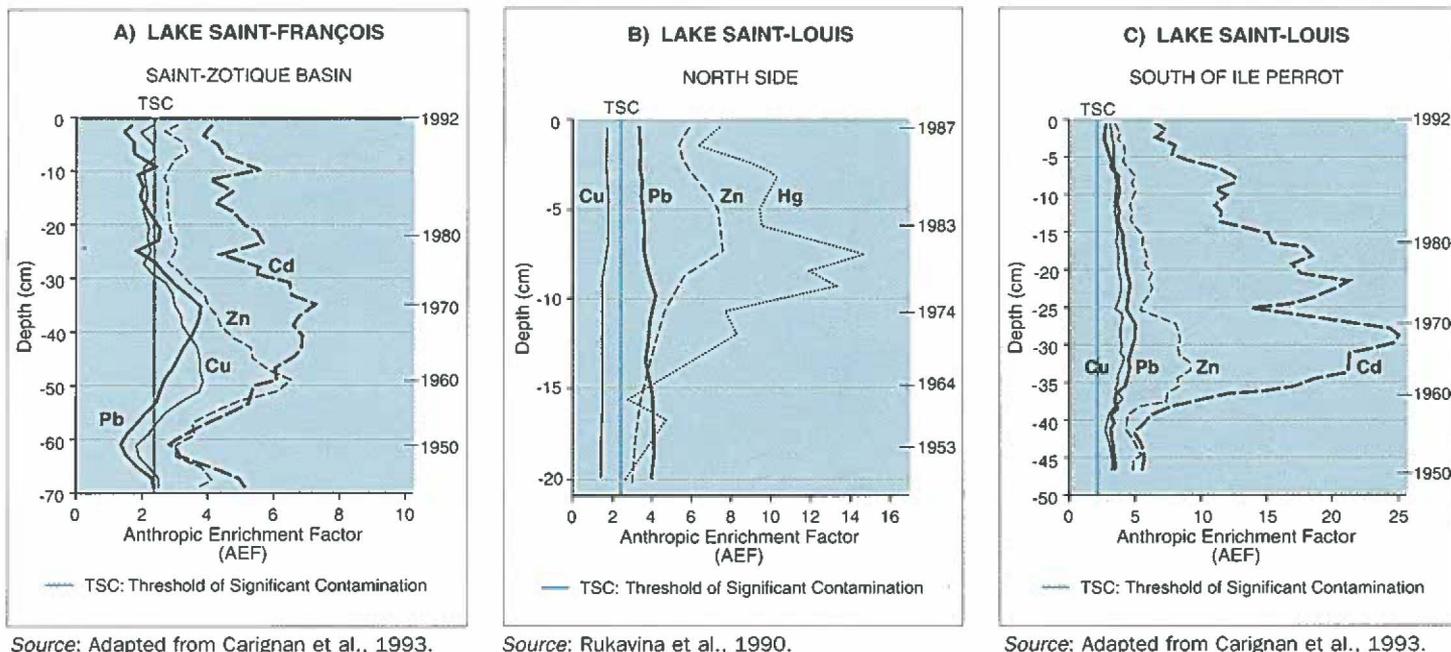
e. Varies depending on organic component in sediment (see Appendix 3).

the base level to produce very high values.

In the mid-1980s, the mouth of the Saint-Louis River was the most heavily contaminated area in Lake Saint-Louis. Maximum mercury and cadmium levels here reached 698 and 93 times their preindustrial values,

respectively (Table 7). Mercury contamination was also very high south of Îles de la Paix. Apprehended pollution levels for mercury exceeded the TET near the mouth of the Saint-Louis River and south of Îles de la Paix. The heavy mercury contamination in these two areas seems largely attributable to point- and nonpoint-

source discharges of mercury from the Beauharnois industrial zone. The principal historic sources of mercury here are the discharges of a chlor-alkali plant into the Saint-Louis River and a riverside disposal site for mercury sludge (Fortin et al., 1994b). The mouth of Bouchard Creek showed the highest AEF values for copper (7.7),



Source: Adapted from Carignan et al., 1993.

Source: Rukavina et al., 1990.

Source: Adapted from Carignan et al., 1993.

**Figure 28** Evolution of sediment contamination in lakes Saint-François and Saint-Louis

**Table 7** Significant contamination, apprehended pollution and maximum contamination in Lake Saint-Louis in 1984 and 1985

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Arsenic	20.0	3.0	17.0	NA	4.1	Pointe-Claire
Cadmium	0.38	81.0	3.0	NA	93.3	Saint-Louis River
Copper	42.50	28.8	86.0	NA	7.7	Bouchard Creek
Mercury	0.13	71.2	1.0	17.0	698.0	Saint-Louis River
Lead	37.50	35.8	170.0	NA	9.2	Bouchard Creek
Zinc	195.00	37.3	540.0	NA	8.8	Saint-Louis River
PAHs <sup>a</sup>	1.47	5.9	<sup>b</sup>	0 <sup>c</sup>	2.7	Valois Bay
PBCs	0.05	44.8	<sup>d</sup>	0	33.0	Bouchard Creek

Source: Raw data from a characterization study by Champoux and Sloterdijk, 1988.

a. Sum of the 7 PAHs for which a TET has been established (see Appendix 3).

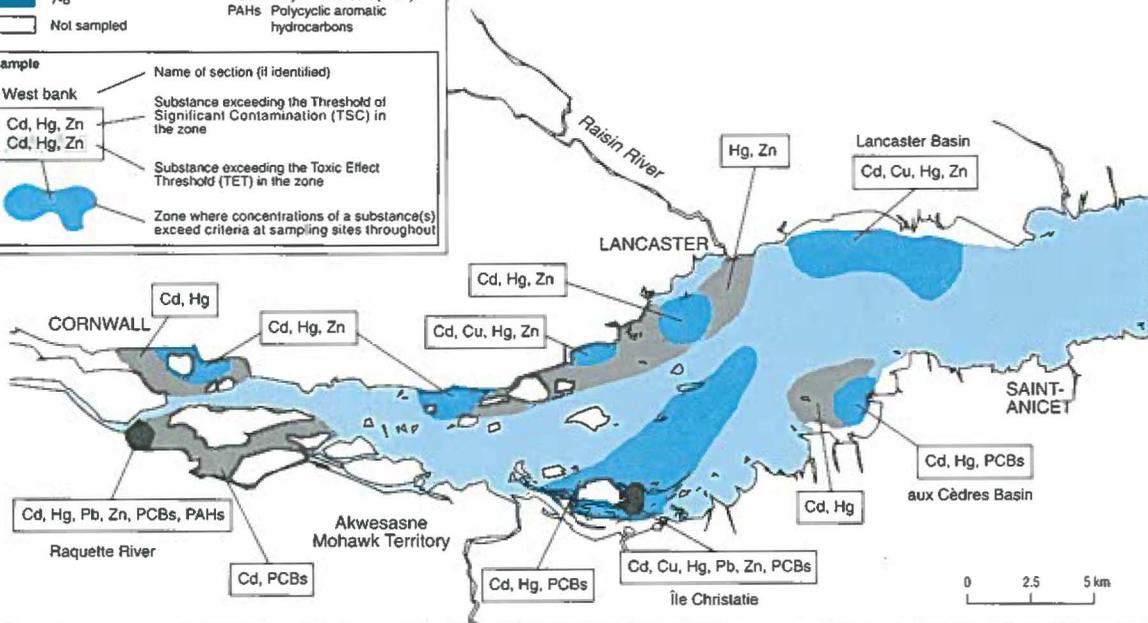
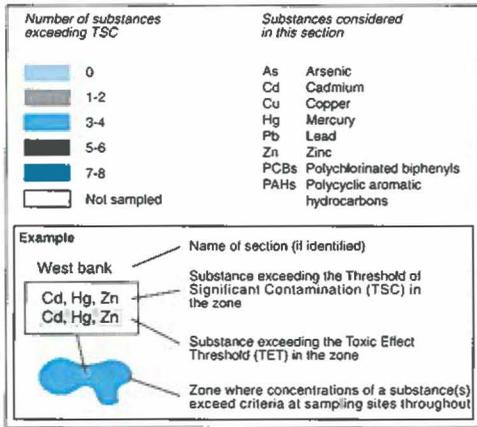
b. Varies depending on PAH being considered (see Appendix 3).

c. Percentage of stations where at least 1 of 7 PAHs > TET.

d. Varies depending on organic component in sediment (see Appendix 3).

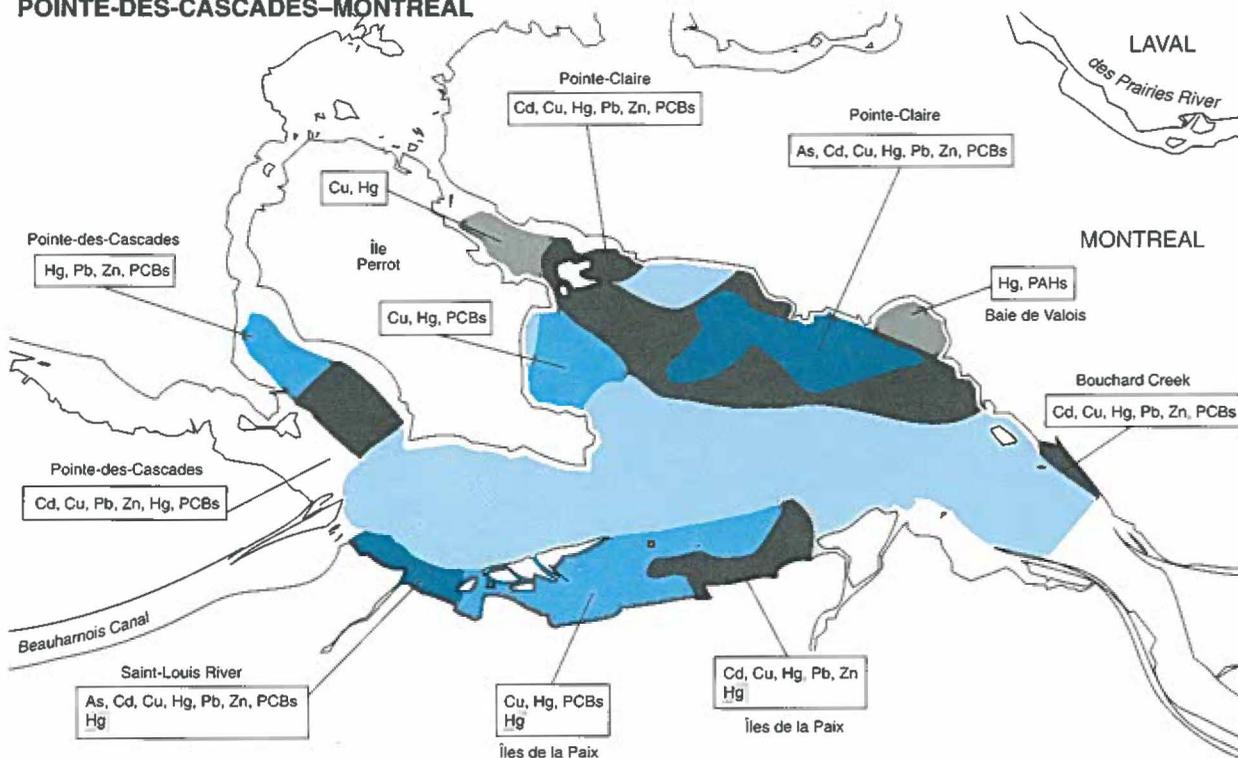
NA: TET exceedance tests were not done due to a lack of data on extractible concentrations.

**CORNWALL-POINTE-DES-CASCADES**



Source: SLC, 1989.

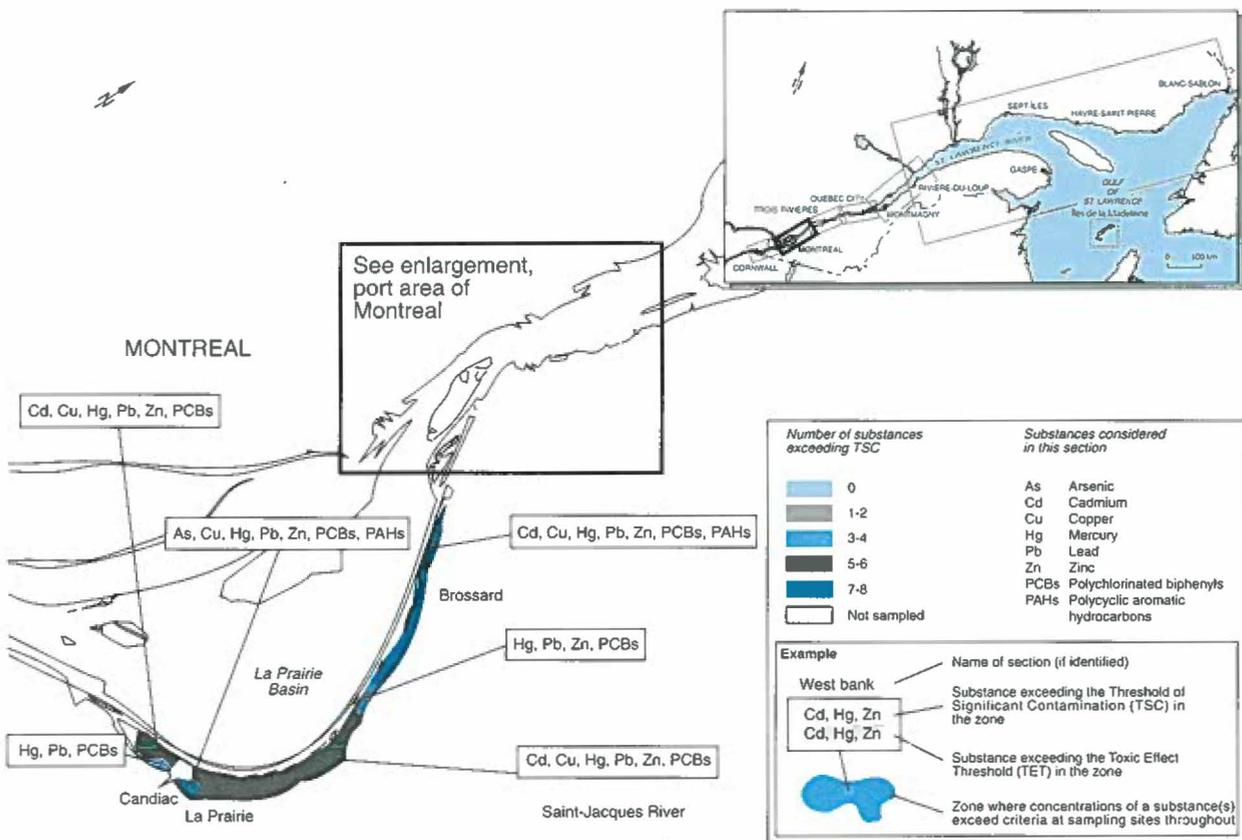
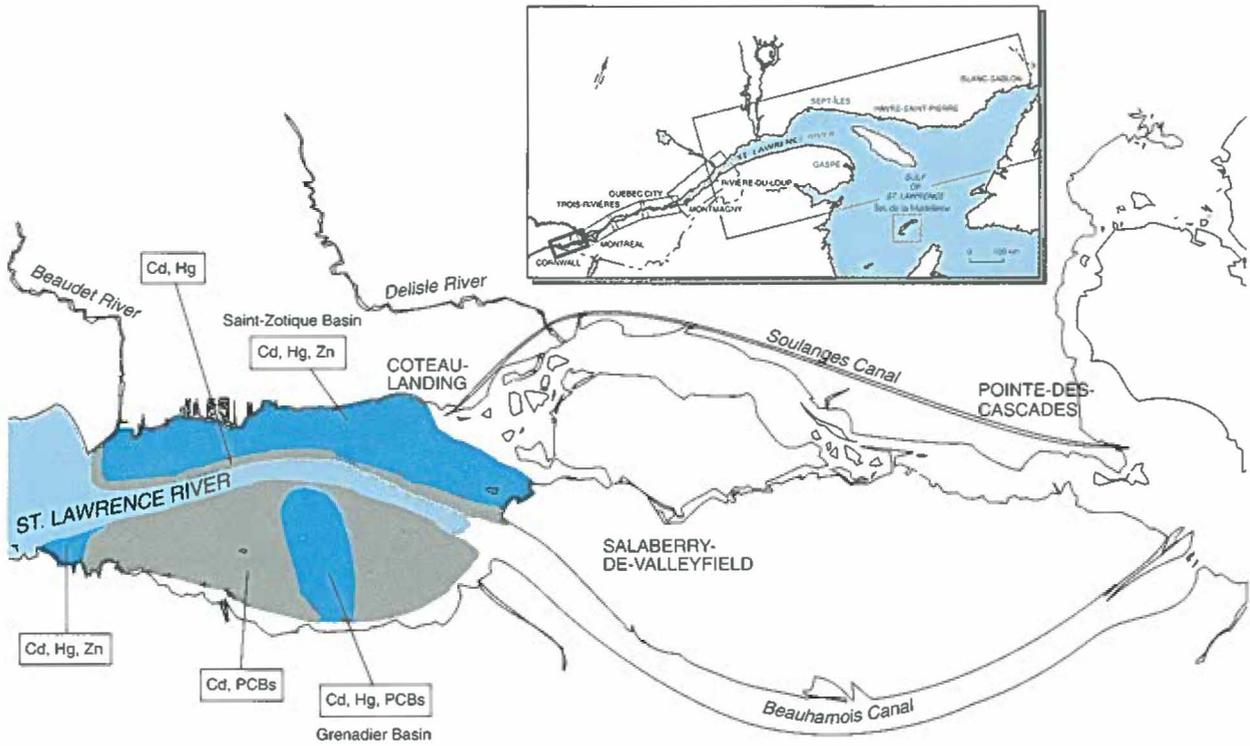
**POINTE-DES-CASCADES-MONTREAL**



*In the absence of detailed data on the ship channel, this map assumes lack of significant contamination in the ship channel due to the strength of the current and the coarse texture of the sediments (sand and gravel).*

Source: Champoux and Sloterdijk, 1988 (Lake Saint-Louis); Hardy et al., 1991a (La Prairie Basin).

**Location of contaminated zones in the St. Lawrence**



lead (9.2) and PCBs (33.0) in Lake Saint-Louis (Table 7). Bouchard Creek is an urban stream that drains Dorval Airport and the industrial zones north-east of the City of Dorval.

Core samples taken from the north side of Lake Saint-Louis (Figure 28B) show mercury contamination rising until the end of the 1970s, followed by a downward trend during the 1980s, and culminating in AEF values of 6 to 8 by the end of that decade. It should be noted that mercury discharges from the Beauharnois area cannot reach this part of the lake due to the hydrodynamic barrier (water wall) created by strong currents in the Seaway channel. A sediment core sample taken south of Île Perrot (Figure 28C), an area influenced by St. Lawrence waters that pass through the Beauharnois Canal, showed rising levels of cadmium and zinc contamination in the early 1960s, followed by declines since the start of the 1970s. This contamination correlates with direct discharges of effluent containing cadmium and zinc into the Beauharnois Canal by a large metallurgical plant since 1963 (Malo and Gouin, 1977).

### Lesser La Prairie Basin

The Lesser La Prairie Basin is isolated from the greater basin by an embankment built during construction of the St. Lawrence Seaway. Bounded by locks at its upstream and downstream ends, the lesser basin is a sediment sink between the chain of artificial islands bordering the Seaway and the south bank of the river. Its contaminants come from four major known sources: St. Lawrence input at the outlet of Lake Saint-Louis, three tributaries (the Tortue, St. Regis and Saint-Jacques rivers), and direct discharges of industrial and urban effluent (Fortin et al., 1997).

In 1987, bottom sediments in the Lesser La Prairie Basin were contaminated by heavy metals, arsenic, PCBs and PAHs. Contamination extended over the entire basin; mercury and lead concentrations exceeded the TSC at all sampling stations, while exceedance levels for copper, zinc and PCBs were frequent (Table 8). While PCB contamination was ubiquitous near the old Candiac sewage outfall, where the AEF reached 127, the apprehended pollution risk did not

reach the TET. This is because of the low bioavailability of PCBs due to the high organic component of the sediments. Since more than 95 percent of water flow through the Lesser La Prairie Basin comes from the water mass surrounding the contaminated areas of southern Lake Saint-Louis, St. Lawrence input is probably responsible for the base level of contamination throughout the basin. Its input is supplemented by contributions from three tributaries that drain industrial areas, contaminated soil and agricultural lands, as well as discharges from numerous municipal sewer outfalls. Until 1990, the old Candiac outfall discharged essentially untreated industrial and urban wastewater into the lesser basin.

### Lake Saint-Pierre

In 1986, a characterization study was done on Lake Saint-Pierre sediment covering the Sorel delta and north of the ship channel. The south side of the lake was not sampled because of the danger posed by the military test firing range. In addition to inputs from the St. Lawrence, which includes contaminants from the Montreal area,

**Table 8 Significant contamination, apprehended pollution and maximum contamination in the Lesser La Prairie Basin in 1987**

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Arsenic	20.0	5.6	17.0	NA	3.4	Candiac
Cadmium	1.00 <sup>a</sup>	38.9	3.0	NA	11.3	Upstream
Copper	42.50	88.0	86.0	NA	4.6	La Prairie
Mercury	0.13	100.0	1.0	0	10.0	Upstream
Lead	37.50	100.0	170.0	NA	19.7	Upstream
Zinc	195.00	88.8	540.0	NA	11.8	Candiac
PAHs <sup>b</sup>	1.01	11.1	<sup>c</sup>	0 <sup>d</sup>	3.3	Candiac
PCBs	0.05	100.0	<sup>e</sup>	0	127.5	Candiac

Source: Raw data from a characterization study by Hardy et al., 1991b.

- Analytic detection limit.
  - Sum of 4 PAHs (phenanthrene, benzo(a)pyrene, fluoranthene and pyrene).
  - Varies depending on PAH being considered (see Appendix 3).
  - Percentage of stations where at least 1 of 4 PAHs > TET.
  - Varies depending on organic component in sediment (see Appendix 3).
- NA: TET exceedance tests were not done due to a lack of data on extractible concentrations.

**Table 9** Significant contamination, apprehended pollution and maximum contamination in Lake Saint-Pierre in 1986

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Arsenic	20.0	0	17.0	NA	0.7	Sorel delta
Cadmium	1.00 <sup>a</sup>	5.6	3.0	NA	12.5	Sorel delta
Copper	42.50	44.4	86.0	NA	7.2	Chenal du Moine
Mercury	0.13	44.4	1.0	0	10.0	Sorel delta
Lead	37.5	33.3	170.0	NA	7.3	Chenal du Moine
Zinc	195.00	22.2	540.0	NA	4.2	Sorel delta
PAHs <sup>b</sup>	0.59	38.1	<sup>c</sup>	0 <sup>d</sup>	5.5	Sorel delta
PCBs	0.05	88.8	<sup>e</sup>	0	15.5	Chenal du Moine

Source: Raw data from a characterization study by Hardy et al., 1991a.

a. Analytic detection limit.

b. Sum of 2 PAHs (benzo(a)pyrene and fluoranthene).

c. Varies depending on PAH being considered (see Appendix 3).

d. Percentage of stations where at least 1 of 2 PAHs > TET.

e. Varies depending on organic component in sediment (see Appendix 3).

NA: TET exceedance tests were not done due to a lack of data on extractible concentrations.

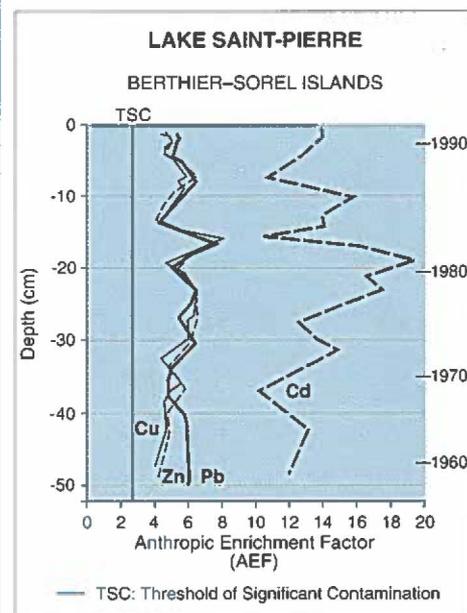
local sources of contamination on the south shore come from heavy industry in the Sorel–Tracy area and several large tributaries, such as the Richelieu, Yamaska and Saint-François rivers, draining farmland (Sylvestre et al., 1992).

In the 1986 study, sediments in the Sorel delta and upper part of Lake Saint-Pierre showed levels of contamination by copper, mercury, lead, zinc, PCBs and PAHs that exceeded the TSC at several locations (Table 9). In Chenal du Moine, the AEF for PCBs reached 15.5, while contamination levels for copper and lead were more than seven times preindustrial values (Table 9). Historically, the water mass flowing through Chenal du Moine has been influenced by the Richelieu River and direct discharges of urban and industrial effluent in the Sorel–Tracy area. Local metallurgical and titanium pigment plants are notorious for their historical dumping of large amounts of toxic substances such as copper, zinc and lead. However, discharges from Sorel–Tracy industries cannot cross the water wall created by the ship channel and reach the Sorel delta or lake areas north of the

Seaway. Contaminated sediment in these areas comes mainly from inputs from the St. Lawrence, Ottawa and L'Assomption rivers. Conditions in the Sorel delta are conducive to long-term accumulation of toxic substances (Figure 29). In fact, the natural water flow in many of its channels was slowed down by embankments built to divert river flow to the ship channel.

Sedimentation in upper Lake Saint-Pierre follows a seasonal pattern controlled mainly by the cycle of aquatic plant growth. In summer, a thin sediment layer is deposited as large macrophyte plant communities on either side of the ship channel reduce the current velocity (Fortin et al., 1993; Boudreau et al., 1994). When autumn comes, this sediment is resuspended after the aquatic plants die and no longer offer adequate protection against storm waves. Under these conditions, the level of contamination in the annual deposit depends on the quality of SS transported in the river water. Since sediment accumulates through the deposition of suspended matter, the level of contamination detected in sediment is a

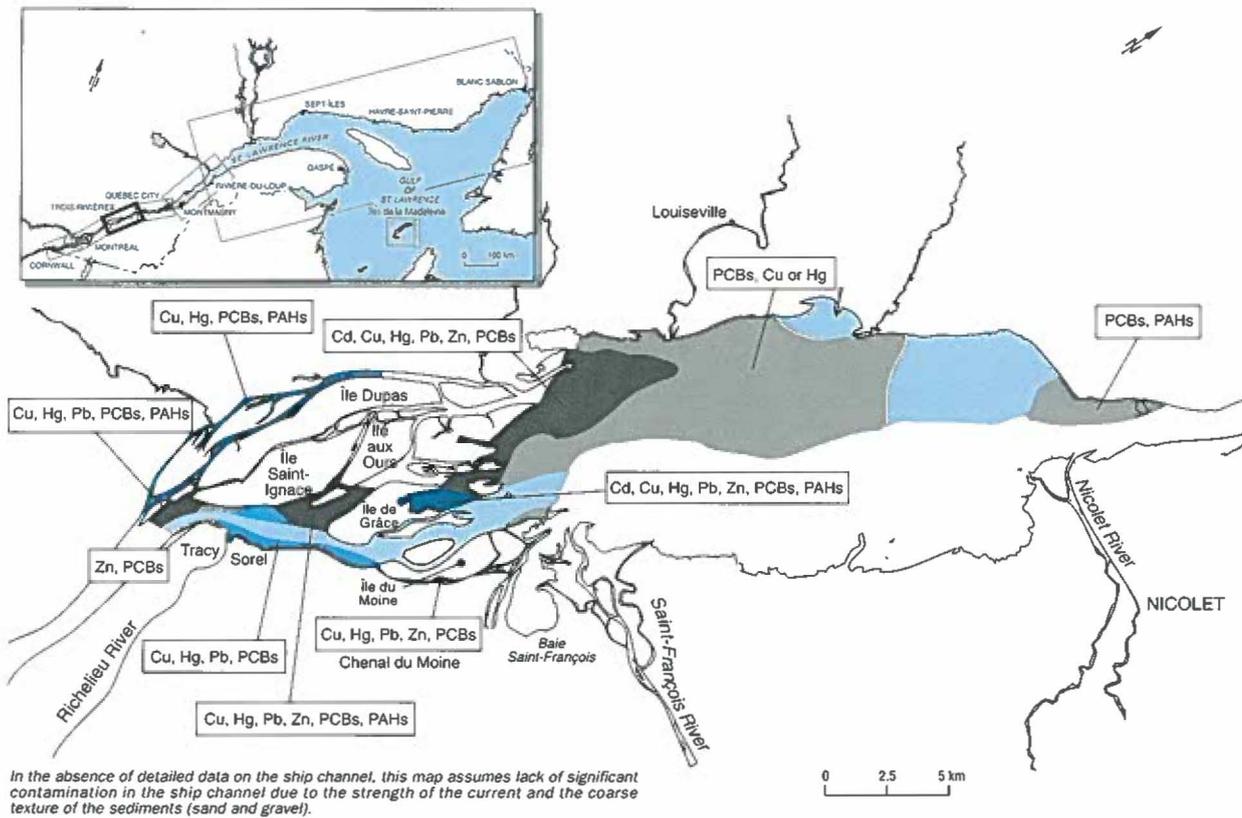
function of the contaminant concentrations found on particles suspended in the water.



Source: Adapted from Carignan et al., 1993.

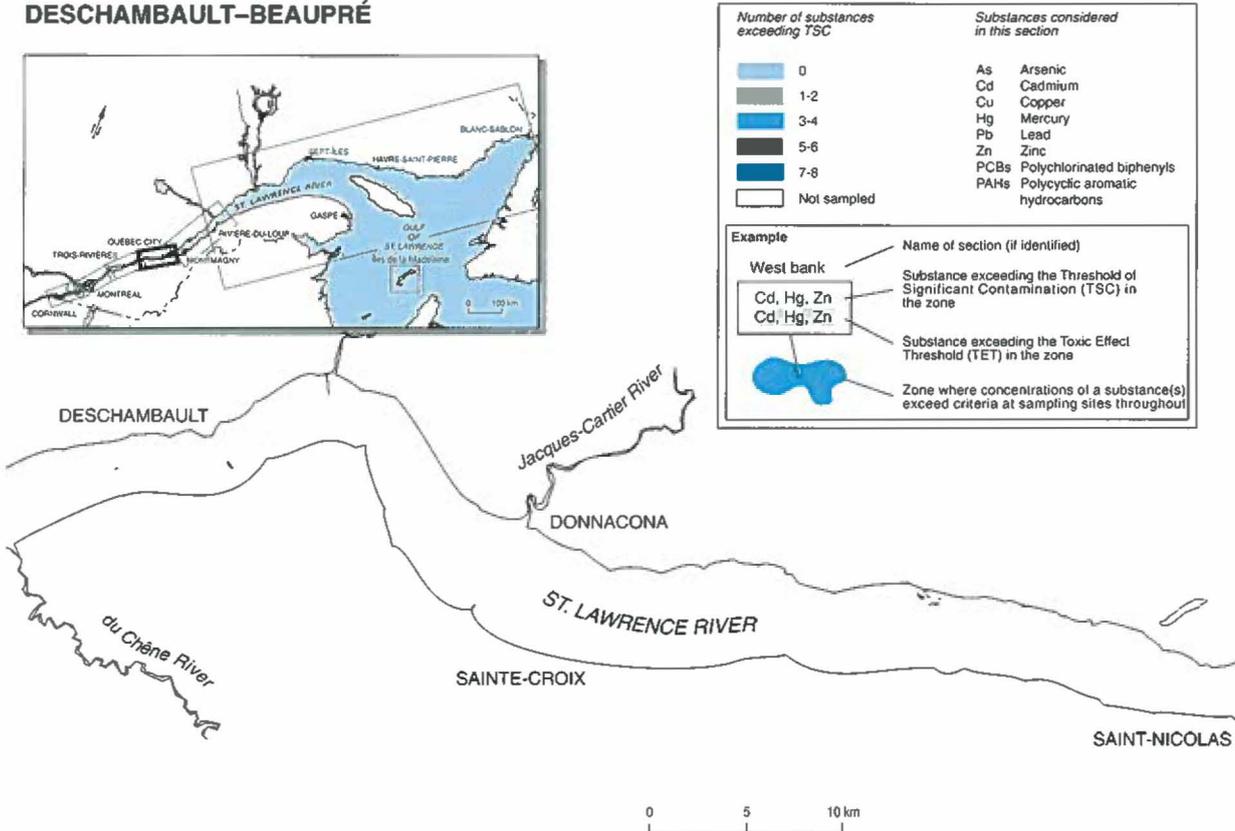
**Figure 29** Evolution of sediment contamination in Lake Saint-Pierre

**SOREL-DESCHAMBAULT**



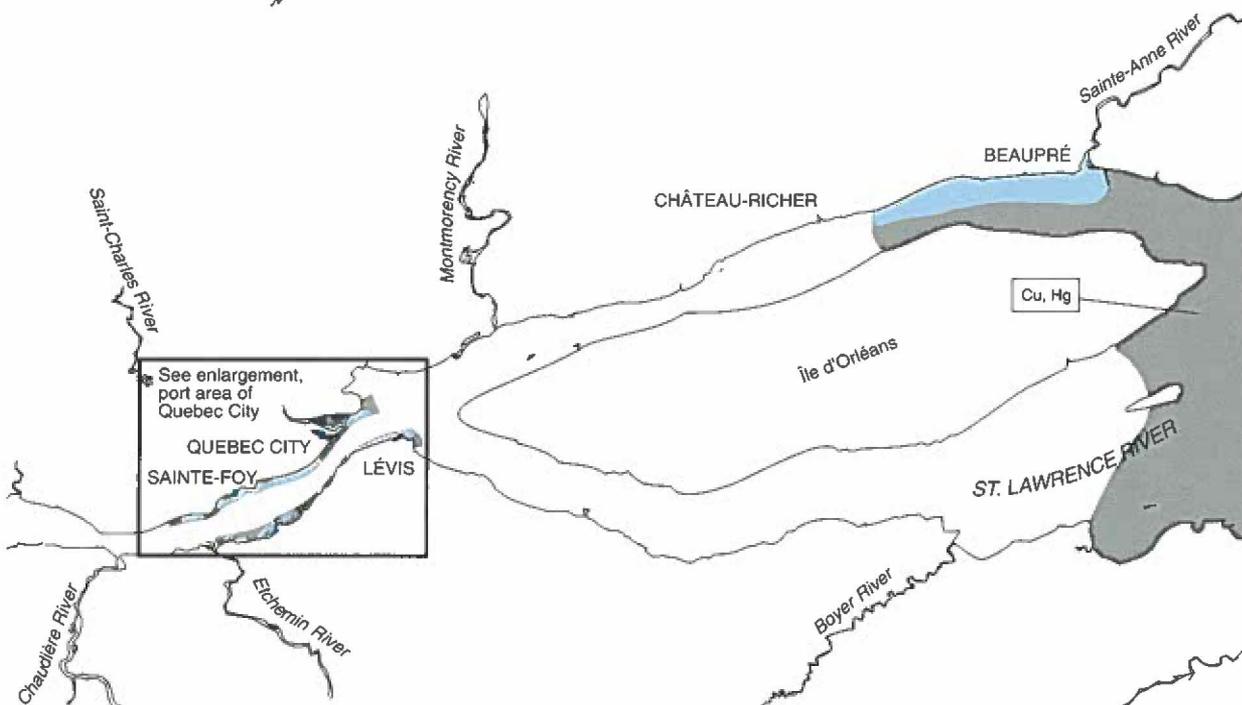
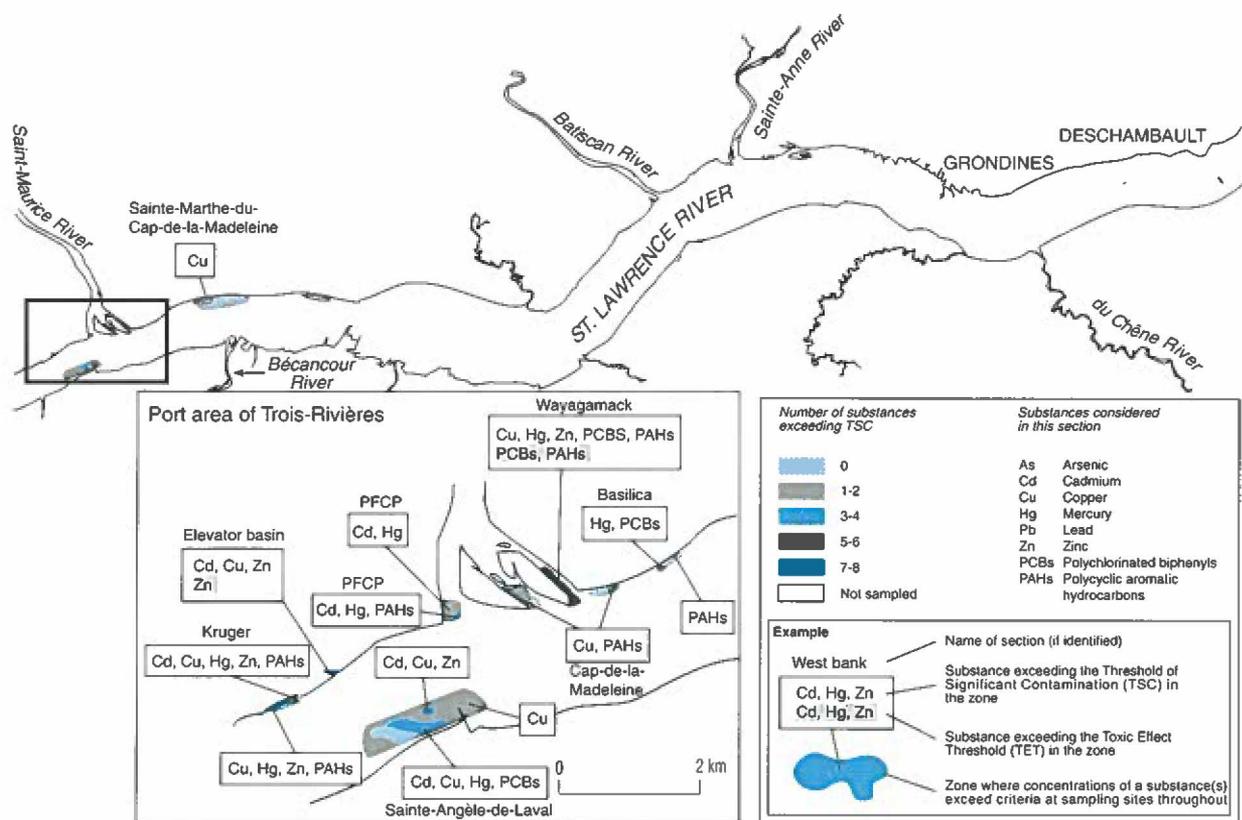
Source: Hardy et al., 1991a; GDG Environnement Ltée, 1993.

**DESCHAMBAULT-BEAUPRÉ**



Source: Procéan Inc., 1990 (port area of Quebec City); Coakley and Poulton, 1993 (Upper Estuary).

**Location of contaminated zones in the St. Lawrence (continued)**



## Port areas

The port facilities built to serve ship traffic on the St. Lawrence River attracted industry to wharf areas. The population explosion that followed gave rise to the urban centres of Montreal, Quebec City and Trois-Rivières. However, contaminant discharges from intensive industrial, shipping and urban activities associated with the port have contributed to the degradation of the receiving environment over the past centuries. The industrial age has profoundly marked the harbour areas of Montreal, Quebec City and Trois-Rivières.

### Montreal harbour

Montreal's port facilities cover a 150-hectare area shaped like a narrow strip of land stretching 15 km along the riverfront. This location favoured the creation of sewer systems with multiple outfalls for discharging industrial and urban effluent. Until the beginning of the 1990s, industrial and municipal wastewater was dumped untreated into harbour basins. Port activity still occupies most of the available area. The remaining land consists of green space (Promenade Bellerive) or has been developed for recreation and tourism (Old Port area). Also, most of

the wastewater is now conducted to the Montreal Urban Community regional wastewater treatment plant. The chief remaining sources of contamination are runoff water from wharfs, sewer overflow during storms, and input from the Lachine Canal (Fortin, 1995). Montreal's harbour area is one of the most contaminated aquatic sites on the St. Lawrence (see Information Supplement, *Sediment Contamination in the Lachine Canal*).

Sediment samples collected in 1990 showed that the main contaminants were heavy metals, particularly cadmium, copper, mercury, lead and zinc, as well as PCBs and PAHs (Table 10). AEFs detected in the most heavily contaminated basins were tens if not hundreds of times preindustrial concentrations (Table 10). Maximum copper concentrations in basins of Sector 103, where effluent from a copper refinery was once discharged, were more than 300 times the preindustrial value. Maximum AEF values calculated for cadmium and PCBs were 127 and 103, respectively, in Vickers Basin, which contained a shipyard. Apprehended pollution levels for heavy metals exceeded the TET at all stations for cadmium and copper, while exceedances were frequent

(> 50 percent) for zinc, lead and mercury (Table 10). Although PCB and PAH concentrations were very high, they never or rarely exceeded the TET owing to the high organic component in the sediment, which reduces their bioavailability.

### Quebec City harbour

Quebec City's port area extends to both banks of the St. Lawrence. It includes four areas open to the public: the Old Port (comprising the Saint-Charles River estuary and Louise Basin), the Beauport flats and Wolfe's Cove (L'Anse au Foulon) on the north shore, and the old port of Lévis on the south shore. There are also large private facilities with special functions such as the Ultramar refinery dock and MIL Davie shipyard on the south shore, and the Sillery and Lévis marinas on the north and south shores, respectively.

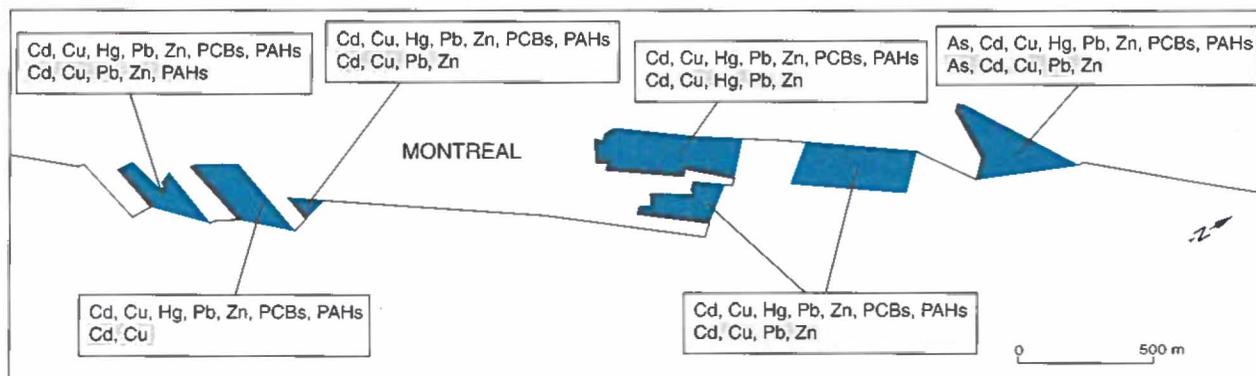
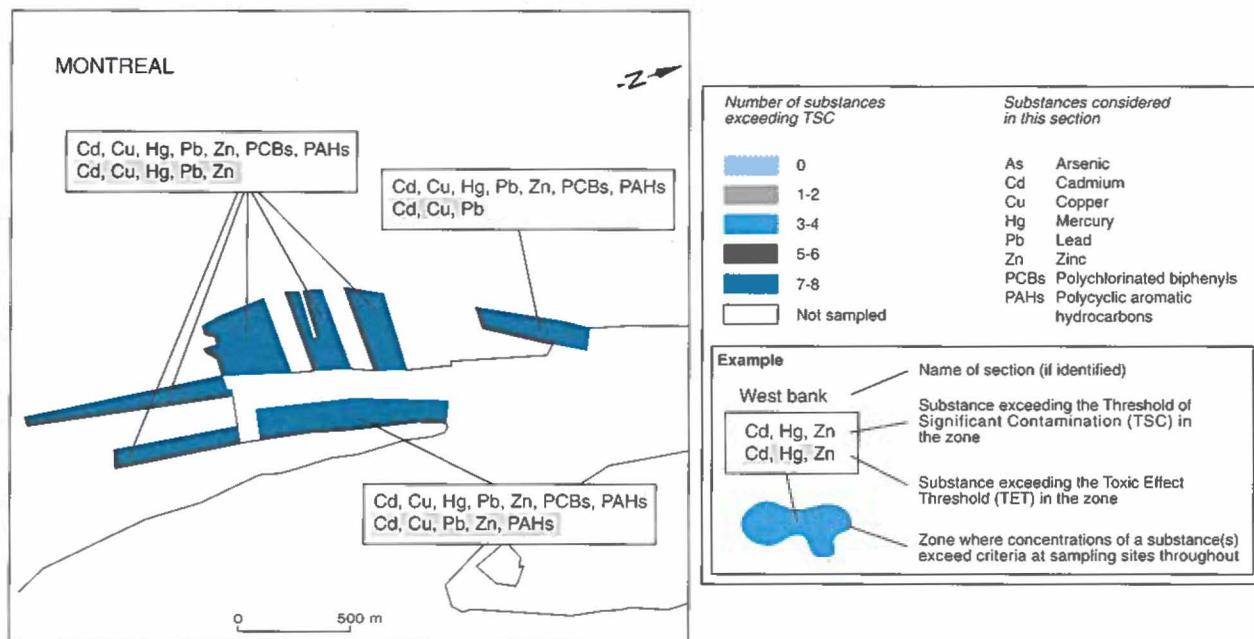
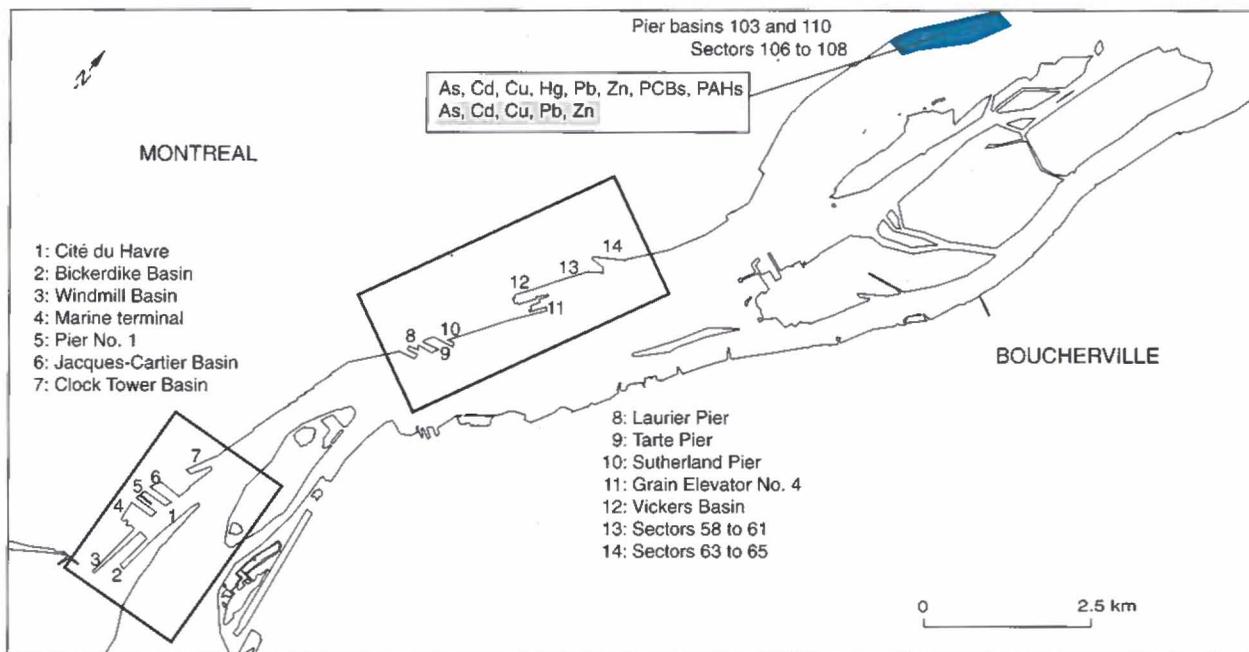
The St. Lawrence water mass, which transports a substantial load of toxic substances towards the estuary, leaves little contaminated sediment around Quebec City because of strong currents. This is not true for the harbour basins, especially the Louise Basin and the Saint-Charles River estuary, which contain sizable amounts of contaminated sediment

**Table 10** Significant contamination, apprehended pollution and maximum contamination in Montreal harbour in 1990

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Arsenic	20.0	10	17.0	10	13.8	Pier 103 Basin
Cadmium	0.38	100	3.0	100	127	Vickers Basin
Copper	42.50	100	86.0	100	318	Pier 103 Basin
Mercury	0.13	100	1.0	50	44	Marine terminal
Lead	37.50	100	170.0	70	33	Windmill Basin
Zinc	195.00	100	540.0	90	53	Windmill Basin
PAHs <sup>a</sup>	1.47	100	<sup>b</sup>	10 <sup>c</sup>	62	Marine terminal
PCBs	0.05	95	<sup>d</sup>	0	103	Vickers Basin

Source: Raw data from a characterization study by Environnement Illimité Inc. and Lavalin Environnement, 1991.

- Sum of the 7 PAHs for which a TET has been established (see Appendix 3).
- Varies depending on PAH being considered (see Appendix 3).
- Percentage of stations where at least 1 of 7 PAHs > TET.
- Varies depending on organic component in sediment (see Appendix 3).



Source: Environnement Illimité Inc. and Lavalin Environnement, 1991; 1992.

**Port area of Montreal**

## Information Supplement

**Sediment Contamination in the Lachine Canal**

The Lachine Canal was built in the 19th century to improve shipping by providing a way around the Lachine Rapids. Factories then appeared along its banks and contributed greatly to contaminating the canal. It was closed to commercial shipping when the St. Lawrence Seaway opened in 1959. It is now managed by Parks Canada and the Old Port of Montreal Corporation Inc. Parks Canada is responsible for the section west of the Bonaventure Expressway and the Old Port Corporation for the eastern section.

In 1982, Parks Canada prohibited recreational use of the canal due to poor water quality and contaminated sediments. When the industrial sewers that emptied into the canal were hooked up to the Saint-Pierre collector, the situation improved to the point where canal water no longer presents a risk for recreation involving secondary water contact (no direct contact with the water). Throughout almost the entire canal, sediments contain concentrations of copper, lead, zinc and PCBs exceeding the TET

Parks Canada has assessed six treatment options using 12 economic, technical and environmental (permanent and temporary) criteria. It is pursuing the clean-up of the aquatic environment, even though the sediments pose no human health risk.

*The Six Options*

- 1) **Containment on land:** Sediments excavated by dredge, transported and contained at a selected site.
- 2) **Containment on canal floor:** Geotextile membrane covering sediment on the canal bed, with crushed stone on top.
- 3) **Sealing on canal bank:** Sediments excavated by dredge, then sealed in watertight cells built beside the canal.
- 4) **In situ solidification/stabilization:** Fix sediments with chemical reagents and cement. The sediments become solid and no longer permeable.
- 5) **Ex situ solidification/stabilization:** Same as previous method except that work is done outside the water. Requires sediment dredging and a storage site.
- 6) **Physico-chemical extraction:** Sediments excavated by dredge, then

treated to remove contaminants (inorganic and organic). The sediments are regenerated and can be reused.

In October 1990, a joint federal-provincial commission was created to study the issue of cleaning up the Lachine Canal. In its public consultations and hearings, however, participants were more concerned about the vocation and development of the canal.

Based on information it received, and since there is practically no risk to human health, the commission concluded after public consultations that it was not essential to clean up the sediment in the Lachine Canal, since this would bring very few environmental benefits. It would have no influence on contamination levels in fish or the bacteriological quality of the water. The commission therefore recommended taking no action on the contaminated sediments of the Lachine Canal. Instead it proposed that Parks Canada attempt to control present sources of canal water contamination. If the Lachine Canal is to be reopened to through navigation, Parks Canada should assess the risk of resuspending contaminated sediments and decide if it is acceptable.

(Fortin and Pelletier, 1995). Although fluvial inputs contribute some contamination, local sources are chiefly responsible for the high levels of sediment contamination in the Old Port. The lower reach of the Saint-Charles River has historically sustained high pollution pressure due to its riverside population of hundreds of thousands of people, together with extensive industry. The Saint-Charles River is a major continuing source of contamination of its estuary. The estuary has also been contaminated by the transshipment of bulk ores and metals, organic residue from a paper mill (wood chips, logs), direct wastewater discharges and accidental hydrocarbon spills. In the early 1980s, sediments in the Louise Basin and the Saint-Charles River estuary were heavily contaminated by heavy metals, PCBs and PAHs (Table 11). Concentrations of heavy metals in Old Port

sediments showed median values 1.4 to 4.8 times greater than in other fluvial areas in the Quebec City harbour. However, they were 1.4 to 3.7 times lower than median values observed in Montreal harbour for the same period. The level of apprehended pollution in Old Port sediments exceeds the TET for many heavy metals and PAHs.

Core samples collected in the early 1990s showed that sediments in the inner Louise Basin (isolated from the outer basin by a lock structure) were heavily contaminated in all layers of the sedimentary sequence. By contrast, sediments in the outer basin, which is open to the river, showed little contamination in the surface layer (top 75 cm) compared to the deep layer. This suggests an abatement of local contamination sources in the Louise Basin and an improvement in the quality of river sediment.

In the Saint-Charles River estuary, like the inner Louise Basin, all sediment layers are highly contaminated. The absence of a natural containment layer consisting of largely uncontaminated material is evidence of active sources of contamination of the Saint-Charles River estuary.

Contamination levels are low in sediments elsewhere in the Quebec City harbour, except in rare sheltered areas where fine materials can settle. Such conditions are found in the Sillery marina on the north shore, the MIL Davie dry dock, and in the vicinity of the Ultramar and Lévis wharfs on the south shore.

**Trois-Rivières harbour**

The Trois-Rivières harbour area extends from Lake Saint-Pierre on the west to the mouth of the Bécancour



River on the east. Historically, the harbour area has been influenced by nonpoint-source inputs mainly from the St. Lawrence and Saint-Maurice rivers. In addition to inputs from continental waters, local contamination sources include urban and industrial effluent discharge, snow dumping, port operations and dredging.

In general, contaminant concentrations in Trois-Rivières harbour are below levels in Montreal and Quebec City. Aside from elevated PCB and PAH levels detected in one channel of the mouth of the Saint-Maurice (Wayagamack sector), sediment contamination in the Trois-Rivières port area in 1992 was basically due to the presence of heavy metals (Table 12). AEFs calculated for PAHs and PCBs in the Wayagamack channel were 10.8 and 15.0, respectively.

The relatively low contamination in Trois-Rivières harbour in 1992 is in part attributable to the instability of its sediments, which are continually being replaced by cleaner material. This continuing natural restoration of the harbour floor can be expected to become more pronounced as active contamination sources are partly or completely shut down: a wastewater

treatment system was started up at the end of 1992 in the Trois-Rivières area, and paper mills began secondary treatment of their effluent in late 1995.

### Marine areas

The transition zone between river and ocean is characterized by a silt plug known as the maximum turbidity zone, (MTZ) which forms in the Upper Estuary. The area, a sink for suspended solids, is not known for the permanent sedimentation of fine particles. Strong tidal currents quickly resuspend the muddy deposits that accumulate on foreshores in the Upper Estuary, carrying them to deep zones of the Lower Estuary. Toxic substances attached to terrigenous particles that escape the MTZ and reach the Lower Estuary are greatly diluted in mixing with the enormous marine water mass. However, the contaminated particles are again concentrated when they settle on the sea floor. As a result, the level of sediment contamination in coastal zones is greatly influenced by the quality of terrigenous inputs. Reconnaissance surveys in the 1970s found permanent accumulations of

contaminated sediments that were introduced mainly by continental waters. They were in the Laurentian Channel, the Saguenay Fjord and the western part of Chaleur Bay, off the New Brunswick coast.

### Upper Estuary

A regional survey done in 1989 and 1990 showed that coastal areas in the Upper Estuary were contaminated by heavy metals. The contaminated sediments were removed from shallow intertidal zones where deposition is temporary, except at the downstream end of the North Channel, where sediments can remain for long periods because the water is deeper. With the exception of mercury, which often exceeded the TSC in contaminated areas, the degree and the extent of contamination is low in most contaminated areas (Table 13). Mercury levels seem to be highest on the Saint-Roch-des-Aulnaies flats, where the AEF factor is almost 10.

Coakley and Poulton (1993) showed that sediments found on south shore foreshores come from the discharge waters of the St. Lawrence River. The low contamination of these muddy foreshore areas is attributable to the

**Table 12 Significant contamination, apprehended pollution and maximum contamination in Trois-Rivières harbour in 1992**

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Arsenic	20.0	0	17.0	0	0.7	Sainte-Angèle-de-Laval
Cadmium	0.38	22.0	3.0	0	8.1	Elevator basin
Copper	42.50	35.5	86.0	1.3	4.5	Kruger
Mercury	0.13	36.4	1.0	0	13.4	Marina
Lead	37.50	0	170.0	0	2.7	Marina
Zinc	195.00	13.2	540.0	1.3	9.4	Elevator basin
PAHs <sup>a</sup>	1.47	17.6	<sup>b</sup>	2.3 <sup>c</sup>	10.8	Wayagamack
PCBs	0.05	12.2	<sup>d</sup>	3.8	15.0	Wayagamack

Source: Raw data from a characterization study by GDG Environnement Ltée, 1993.

a. Sum of the 7 PAHs for which a TET has been established (see Appendix 3).

b. Varies depending on PAH being considered (see Appendix 3).

c. Percentage of stations where at least 1 of 7 PAHs > TET.

d. Varies depending on organic component in sediment (see Appendix 3).

**Table 13** Significant contamination, apprehended pollution and maximum contamination in the Upper Estuary in 1989 and 1990

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Copper	40.00	12.1	86.0	NA	4.5	Baie-Saint-Paul
Mercury	0.08	79.3	1.0	0	9.7	Saint-Roch-des-Aulnaies
Lead	40.00	3.5	170.0	NA	2.7	Baie-Saint-Paul
Zinc	287.50	0	540	NA	1.4	Saint-Roch-des-Aulnaies

Source: Raw data from a characterization study by Coakley and Poulton (1993). Arsenic, PAHs and PCBs were not analysed. Cadmium was found in low quantities and the data were not made public.

NA: TET exceedance tests were not done due to a lack of data on extractible concentrations.

dilution of contaminants by inputs of clean sediment from recent erosion of intertidal marshes (Dionne, 1986). By contrast, the main source of deposits on the north shore would appear to be the erosion of rocks in the drainage basins of the Canadian Shield. These rock formations are rich in mercury, copper and lead, which may explain the high natural concentrations found near the north shore (Coakley and Poulton, 1993).

### Saguenay Fjord

The pulp and paper industry and sawmills have historically dumped large amounts of organic debris (sawdust, wood fibre) into the Saguenay River. This debris makes up a high proportion of the river's suspended solids load. The other main historical sources of contamination for the Saguenay are mercury discharges from a chloralkali plant that operated from 1945 to 1976, and PAHs released from aluminum smelters employing the outdated horizontal-stud Söderberg process, in use since the late 1930s. Currents that disperse organic matter have been identified as the main agents of mercury transport to the Saguenay Fjord and St. Lawrence Estuary (Loring, 1975; Loring and Bewers, 1978).

A sizable portion of the Saguenay River's sediment load settles in the upper fjord area, in the north arm near Saint-Fulgence, as a result of estuary circulation and the floccula-

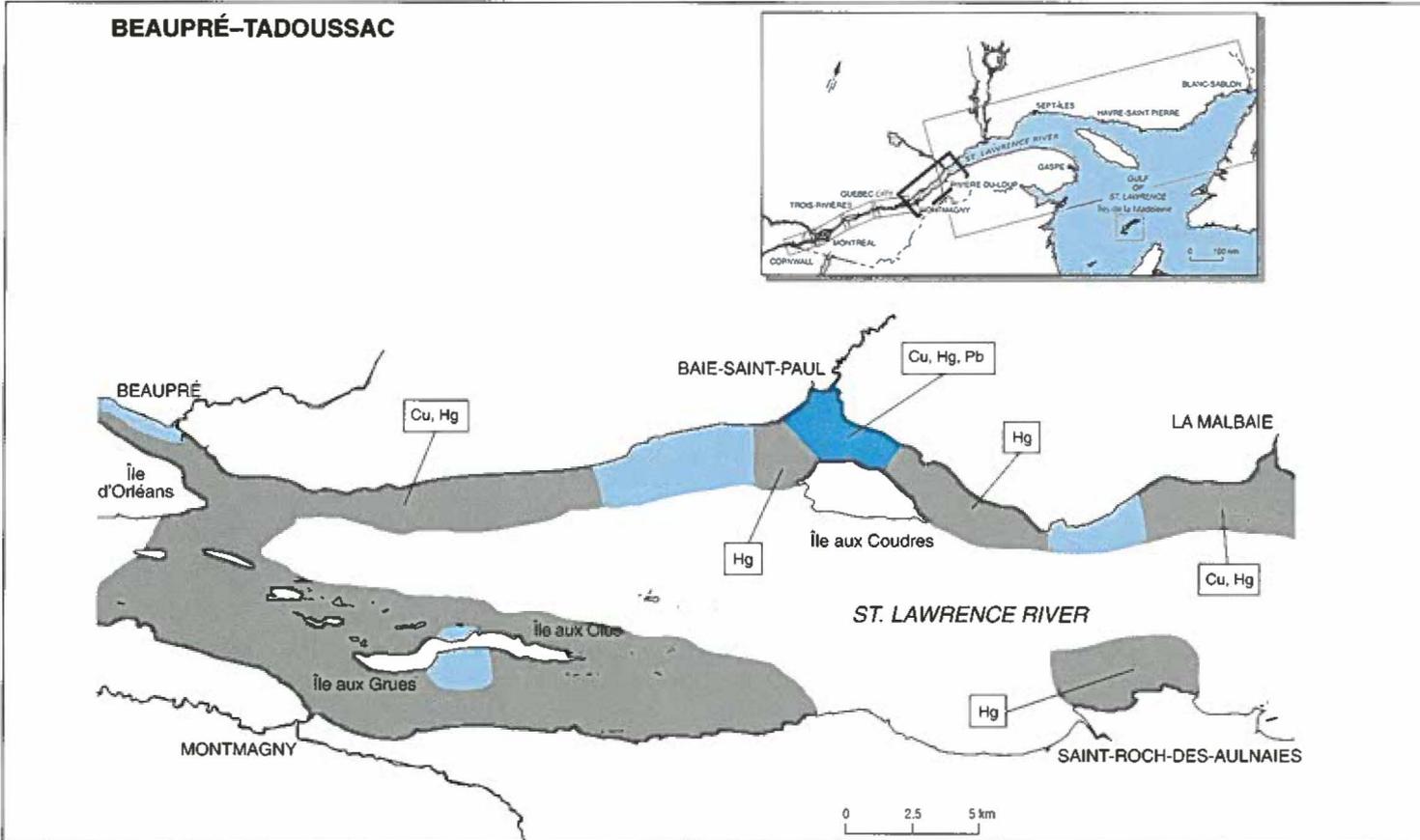
tion and deposition of sediment where river waters mix with marine waters of the fjord (Fortin and Pelletier, 1995). Moreover, the decomposition of fermentable organic matter in north arm sediments greatly reduces their oxygen content, explaining the lack of benthic organisms and bioturbation in this area. In 1986, the north arm and upper basin of the Saguenay Fjord and Ha! Ha! Bay were contaminated by mercury to levels exceeding the TSC. In the fjord as a whole, more than 80 percent of sampling sites were contaminated by mercury (Table 14). The maximum mercury enrichment of surface sediments (AEF = 12) was found in the upper basin, where apprehended pollution exceeded the TET in 1986 (Table 14). Low PAH contamination was also found at this time in the north arm and upper basin of the fjord. Sediments in the north arm contain the highest number of toxic substances and were contaminated by cadmium, mercury, zinc and PAHs.

The most recent data on mercury and PAH contamination in the fjord come from core samples collected in 1992 in the upstream section of the upper basin. Mercury concentrations in the surface sediment layer here were close to preindustrial values (AEF of 4 to 6) (Figure 30A). Similarly, a reconstruction of the geochronology of contamination in the fjord from core samples showed that PAH contamination in sediments was nearing pre-

industrial levels after peaking in the early 1970s in the north arm (Figure 30B). Core samples taken in Ha! Ha! Bay penetrated a sediment layer from the 1960s and 1970s that was heavily contaminated by mercury and PAHs (Figure 30C). This contamination correlates with discharges of mercury from a chloralkali plant and PAH-tainted liquors from the scrubbers of an aluminum smelter in the Upper Saguenay. Since the end of the 1980s, the contaminated layer has been gradually overlaid with a thin bed of cleaner sediment.

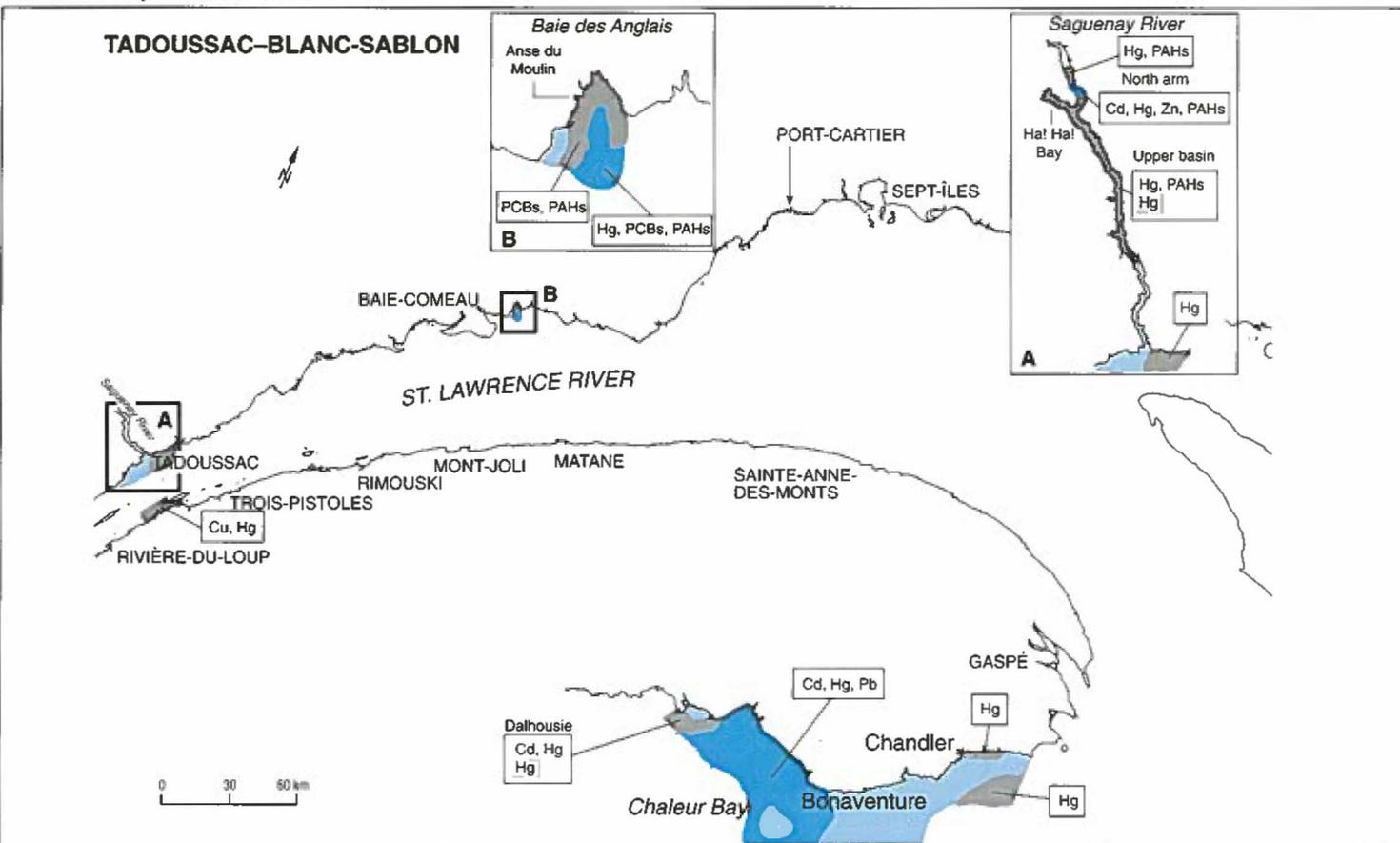
This portrait of contamination in the fjord has no doubt changed in the wake of the dramatic flooding caused by torrential rains and collapsed dams in the Saguenay area in July 1996. Millions of tonnes of sediments were ripped from drainage basins and transported by swollen rivers to accumulate in the upper section of the fjord and in Ha! Ha! Bay. Deposits left on the floodplains of these swollen rivers and on basin slopes, as well as the immense deltas that rapidly formed at river mouths, are in disequilibrium under the present hydro-sedimentological regime of these water bodies. It will take years to return to a state of balance, during which time sedimentation rates in the fjord will remain very high. The positive and negative impacts of this catastrophe on the environment will be assessed in the years to come.

**BEAUPRÉ-TADOUSSAC**



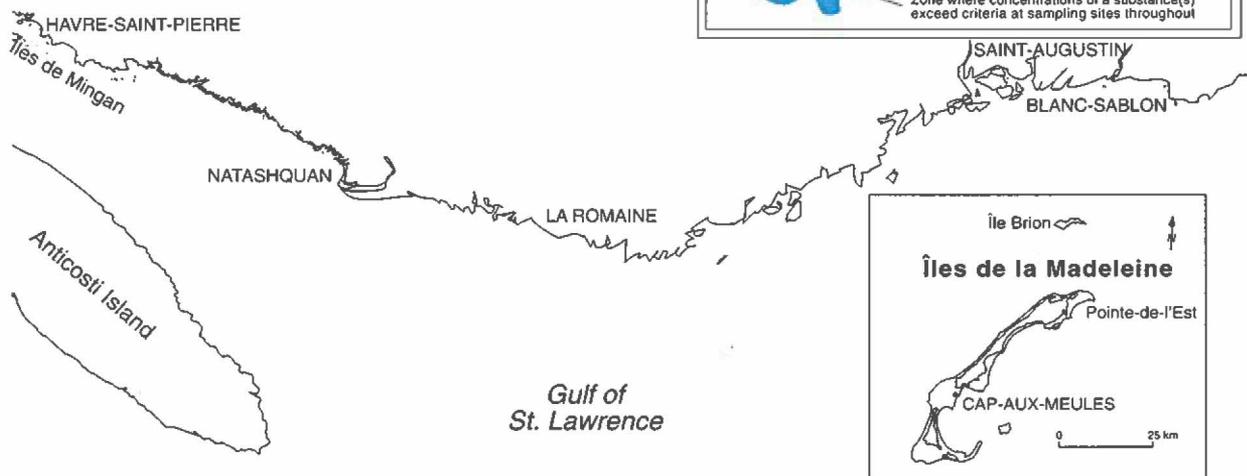
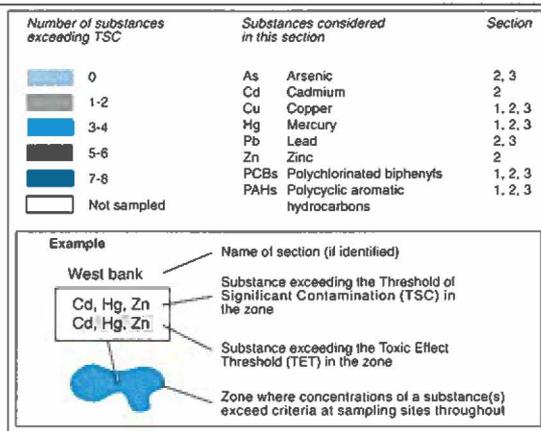
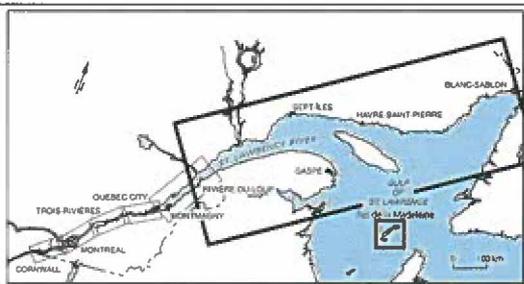
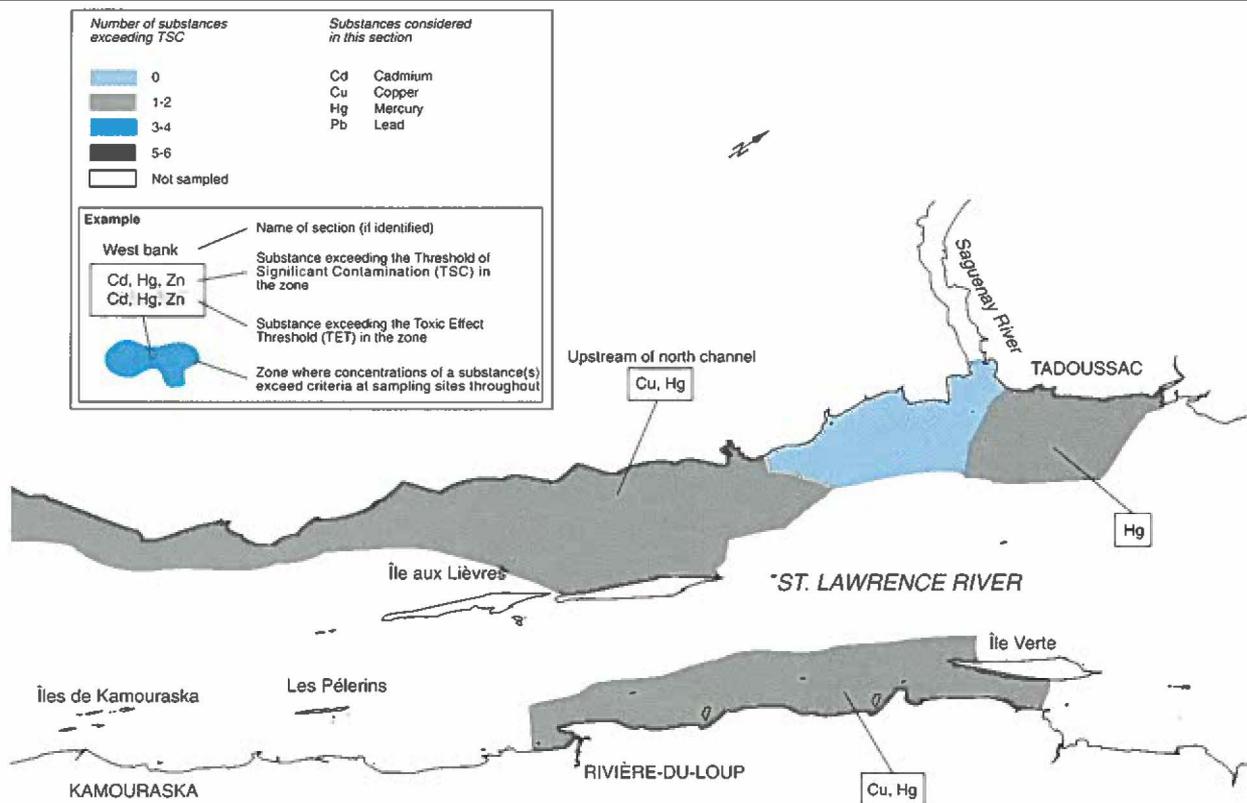
Source: Coakley and Poulton, 1993.

**TADOUSSAC-BLANC-SABLON**



Source: Pelletier and Canuel, 1988; Martel et al., 1986 (Saguenay); GTBA, 1993 (Baie des Anglais); Matheson and Bradshaw, 1985 (Chaleur Bay).

**Location of contaminated zones in the St. Lawrence (continued)**



**Table 14 Significant contamination, apprehended pollution and maximum contamination in the Saguenay Fjord in 1986 (metals) and in 1983 (PAHs)**

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Cadmium (1986)	0.38	5.9	3.0	NA	3.1	North arm
Copper (1986)	52.50	0	86.0	NA	2.5	Ha! Ha! Bay
Mercury (1986)	0.25	82.4	1.0	11.8	12.0	Upper basin
Zinc (1986)	212.5	5.9	540.0	NA	2.7	North arm
PAHs <sup>a</sup> (1983)	1.26	41.0	<sup>b</sup>	0 <sup>c</sup>	2.6	North arm

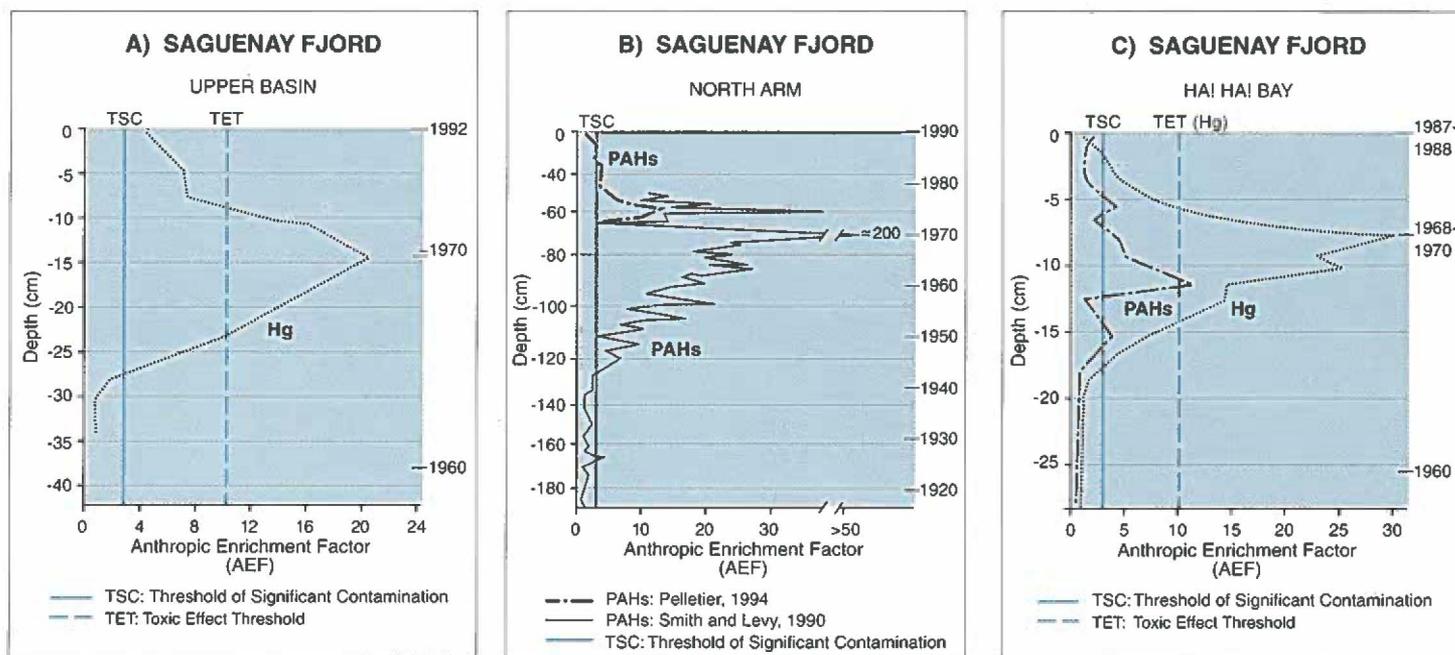
Source: Raw data on heavy metal concentrations taken from Pelletier and Canuel (1988) and on PAHs taken from Martel et al. (1986). Data on arsenic, lead and PCBs not available.

a. Sum of 5 PAHs (fluoranthene, pyrene, chrysene, benzo(a)anthracene and benzo(a)pyrene).

b. Varies depending on PAH being considered (see Appendix 3).

c. Percentage of stations where at least 1 of 5 PAHs > TET.

NA: TET exceedance tests were not done due to a lack of data on extractible concentrations.



Source: Adapted from Gagnon, 1994.

Source: Smith and Levy, 1990; Pelletier, 1994.

Source: Pelletier et al., 1990.

**Figure 30 Evolution of mercury (Hg) and total PAH concentrations in sediments of the Saguenay Fjord**

### Laurentian Channel

The Laurentian Channel is a trough nearly 500 m deep that opens onto the Atlantic Ocean. It extends over 1300 km from the Lower Estuary near the mouth of the Saguenay across the Gulf of St. Lawrence and out to the edge of the continental shelf.

Continental waters mixed with ocean waters flow along the surface to the gulf, while ocean waters penetrate the depths of the trough to return abruptly to the surface around Tadoussac (an upwelling zone). The Laurentian Channel is flanked on both sides by narrow coastal shelves sloping gently

seaward. The Baie des Anglais is wedged into this shelf off Baie-Comeau on the North Shore. This bay has the worst case of contamination by industrial discharges of PCBs and PAHs of any coastal area in eastern Canada (see Information Supplement, *Refloating the Irving Whale*).

## Information Supplement

**Refloating the *Irving Whale***

On September 7, 1970, the barge *Irving Whale* sank with its cargo of fuel oil in the Gulf of St. Lawrence around 60 km from Prince Edward Island and 100 km from the Îles de la Madeleine. After resting almost 26 years under the cold gulf waters, it was refloated on July 31, 1996. The initial goal of the project was to recover the approximately 3400 tonnes of fuel oil on board. Before raising the barge, however, authorities had to decide how to deal with oil consisting of 80 percent PCBs from its cargo heating system.

The *Irving Whale* presented a challenge. Oil spills generally occur on the surface, but the *Irving Whale* was a potential contamination source 67 m below the water surface. Had there been an oil spill during the recovery, the entire water column would have been affected since fuel

oil is lighter than water and tends to rise to the surface. They also had to consider the direction and strength of currents near the sea floor.

For the impact assessment study, three scenarios were examined in light of the potential hazards of a PCB spill over the short and long term. The first was a "no-action" approach. This involved the risk of the continued leakage of PCBs, which would accumulate in nearby sediments in the short term, with adverse effects on the benthic organisms present near the barge. The second scenario assumed an oil spill on the ocean floor, producing, in the short term, a negative impact over a 2500 m<sup>2</sup> area, with acute and sub-lethal effects on benthic organisms. The third scenario envisaged a PCB leak on the surface during recovery. This would mean lower short-term concentrations than the second scenario, but over a greater area (6000 m<sup>2</sup>) (Sawyer Enviroeconomic Consulting, 1996). An emergency

measures plan to deal with an oil spill was prepared by Fisheries and Oceans Canada and Environment Canada.

Project managers estimated that only 90 to 300 kg of PCBs were lost during the barge recovery. They estimate that sediment within a 50-m radius of the barge contains approximately 150 kg of PCBs, most of which escaped when the barge sank, some thereafter.

A sampling program at the end of the summer 1996 detected high levels of sediment contamination in the 6000 m<sup>2</sup> area immediately around the site of the barge. In October 1996, Fisheries and Oceans Canada began sampling to assess PCB contamination in marine organisms such as the Snow crab. Observed concentrations were within Canadian guidelines for human consumption. The Department will conduct environmental monitoring in the area in coming years.

The Laurentian Channel is one of the largest troughs of permanent sedimentation in the St. Lawrence system, along with the basins of the Great Lakes and the Saguenay Fjord. Its upstream section retains the bulk of sediments carried to the St. Lawrence Estuary by continental waters. The trough is the final stop for a large portion of toxic compounds released by human activity in the St. Lawrence drainage basin, as well as contaminants that escape from Lake Ontario and the Saguenay River and airborne pollutants falling to earth. They can remain bioavailable here for centuries (Fortin et al., 1996). The remainder of these contaminants are found in the several million tonnes of sediments that have accumulated over the decades in the fluvial lakes and harbour basins of the river.

The broad historical trend revealed by sediment cores taken in the Lower Estuary show that early industrialization in the St. Lawrence drainage basin had a negative impact on sediment quality in the Laurentian

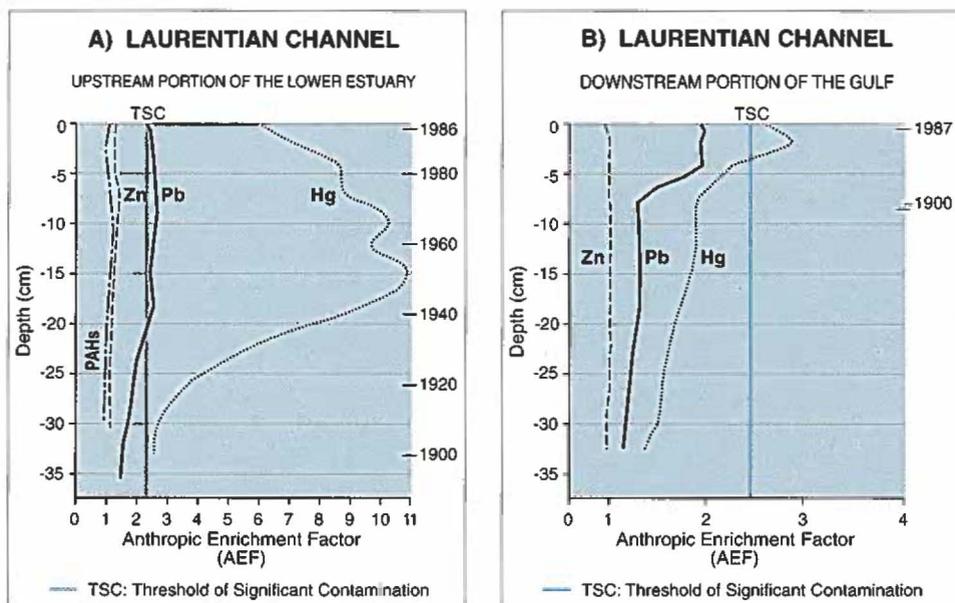
Channel (Figure 31). Chemical concentrations (heavy metals, DDT, Mirex, PCBs, dioxins and furans) exhibit their highest values in the 1960s and 1970s, when contaminant inputs peaked. The 1980s brought a decline in levels of most toxic substances in the upper Laurentian Channel. Recent studies (Lebeuf et al., 1995a; 1995b; 1996a) show a marked decline in some of the most toxic PCBs, dioxins and furans in surface sediments in the Channel. These observations reflect recent reductions in terrigenous contaminant inputs that correlate with the steps that have been taken ever since the late 1970s to treat effluent discharges to the drainage basin. The reduction in lead inputs is due to the gradual withdrawal of leaded gasoline starting in the early 1970s.

Concurrent with the recent decline in sediment contamination, atmospheric inputs have become more important than terrestrial inputs for certain contaminants (mercury, dioxins, furans). Research currently under way suggests that long-range airborne trans-

port of mercury and its transfer from the atmosphere to ocean waters is responsible for a non-negligible share of mercury deposited in the Laurentian Channel (Cossa et al., 1995) (see Information Supplement, *Mercury Mass Balance in the Lower Estuary*).

**Baie des Anglais**

The Baie des Anglais forms a triangle with an area of 11 km<sup>2</sup>. Its main bathymetric feature is a channel 60 to 100 m deep open onto the sea. Port development (wharf building, filling, dredging) has profoundly altered the natural physical environment of Anse du Moulin at the foot of the bay. The contamination of Anse du Moulin sediment has historically been attributed to PCB-laden discharges from an aluminum smelter's hydraulic systems, PAHs released during the electrolytic processing of aluminum (Söderberg method), and pitch lost during transshipment. Contaminated deposits are almost 4 m thick around the docks (SNC-Lavalin, 1995). Some of the contaminated sediment was dumped



Source: Hg: Gobeil and Cossa, 1993;  
Pb: Gobeil et al., 1995; Zn: Gobeil,  
1991; PAHs: Gearing et al., 1991.

Source: Gobeil, 1991.

**Figure 31 Evolution of sediment contamination in the Laurentian Channel**

#### Information Supplement

### Mercury Mass Balance in the Lower Estuary

For the past two decades, high mercury (Hg) contamination has been detected in sediments in the St. Lawrence watershed. Two patterns of anthropic input emerge from an examination of sediment age and Hg concentration in vertical profiles. First, increased inputs dating from the turn of the century, followed by higher inputs at the end of World War II, peaking in the early 1970s and subsequently diminishing. These trends reflect the combined results of atmospheric deposition and direct discharges into water.

Based on estimates from weekly monitoring, St. Lawrence waters carry almost 800 kg of Hg a year

in dissolved and particulate form past Quebec City and into the estuary. However, annual sediment accumulation of Hg in the Lower Estuary is estimated at 1184 kg. To balance the mercury "budget" in this area, atmospheric inputs would have to supply the difference between sedimentary accumulation (1184 kg) and fluvial input from the St. Lawrence (800 kg).

Estuarine circulation that brings in gulf water is probably responsible for some of the approximately 384 kg of Hg from the atmosphere, since the Hg that accumulates in St. Lawrence gulf sediments is essentially of atmospheric origin. Atmospheric sources therefore appear to account for just over 30 percent of the Hg accumulated in sediments in the Lower Estuary.

into the bay during maintenance dredging in the port. The dispersal of contaminated sediments following ocean dumping and their periodic resuspension by storm waves may explain the contamination of the bay (SNC-Lavalin, 1995).

In 1990, most PCB and PAH concentrations in Anse du Moulin and Baie des Anglais sediment exceeded the TSC (Table 15). The most severe contamination was found in Anse du Moulin, where maximum PCB concentrations were 70 times the NET and maximum PAH concentrations were more than 230 times preindustrial levels (Table 15). In 1990, PAH apprehended pollution exceeded the TET almost everywhere in Anse du Moulin. Comparable PCB and PAH levels were found in a dredged material disposal site located in Baie des Anglais. The bay is also contaminated by mercury and lead (Table 15). A recent study (Lebeuf et al., 1996b) concluded that PCB and furan contamination in surface sediments (0–3 cm) in Baie des Anglais is at least ten times higher than values observed in sediments of the Laurentian Channel.

Preliminary results of a 1994 study confirm the extent of contamination and estimate the quantity of sediments contaminated by PCBs and PAHs in Anse du Moulin and the adjacent part of Baie des Anglais. About 300 000 m<sup>3</sup> of sediment is heavily contaminated (> TET), nearly half of it in the top metre of sediments (SNC-Lavalin, 1995). Between 1985 and 1993, measures were taken to reduce local sources of contamination, and today PCB and PAH leaks into the environment have been almost totally eliminated (Fortin et al., 1996). In 1995, studies began on the usefulness of taking action to restore contaminated areas. The conclusions of these studies are still being awaited.

#### Chaleur Bay

In 1984, vast areas of Chaleur Bay were contaminated by mercury and cadmium (Table 16). The most heavily contaminated zones were situated on the New Brunswick north shore off

Dalhousie and Belledune. Near Dalhousie, mercury levels were more than 80 times preindustrial concentrations and the apprehended pollution level exceeded the TET (Table 16). Effluent from a chloralkali plant in Dalhousie is the principal historical source of mercury contam-

ination in Chaleur Bay. Furthermore, material dredged from Dalhousie harbour and dumped near the docks is likely responsible for contamination by heavy metals such as cadmium. Sediment collected near Belledune harbour in 1984 was contaminated by cadmium, mercury and lead. The an-

thropic enrichment of sediments was found to be 27 times preindustrial levels for cadmium, while the apprehended pollution level exceeded the TET (Table 16). Discharges from a lead refinery in Belledune were identified as the main source of this contamination.

**Table 15** Significant contamination, apprehended pollution and maximum contamination in the Baie des Anglais and Anse du Moulin in 1990

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Cadmium	0.50 <sup>a</sup>	0	3.0	NA	—	—
Copper	40.00	0	86.0	NA	2.1	Baie des Anglais
Mercury	0.08	47.1	1.0	0	8.3	Baie des Anglais
Lead	40.00	11.8	170.0	NA	3.0	Baie des Anglais
Zinc	287.50	0	540.0	NA	1.0	Baie des Anglais
PAHs <sup>b</sup>	1.47	94.1	<sup>c</sup>	94.1 <sup>d</sup>	231.3	Anse du Moulin
PCBs	0.05	94.1	<sup>e</sup>	11.8	72.5	Anse du Moulin

Source: Raw data from a characterization study by GTBA, 1993.

a. Analytic detection limit.

b. Sum of the 7 PAHs for which a TET has been established (see Appendix 3).

c. Varies depending on substance being considered (see Appendix 3).

d. Percentage of stations where at least 1 of 7 PAHs > TET.

e. Varies depending on organic component in sediment (see Appendix 3).

NA: TET exceedance tests were not done due to a lack of data on extractible concentrations.

**Table 16** Significant contamination, apprehended pollution and maximum contamination in Chaleur Bay in 1979

Substance	Significant Contamination		Apprehended Pollution		Maximum Contamination	
	Threshold of Significant Contamination (TSC) (mg/kg)	% of stations where concentration > TSC	Toxic Effect Threshold (TET) (mg/kg)	% of stations where concentration > TET	Anthropic Enrichment Factor (AEF)	Area
Cadmium	0.38	42.4	3.0	NA	27.3	Belledune
Mercury	0.08	34.2	1.0	2.6	83.3	Dalhousie
Lead	40.00	13.2	170.0	NA	5.6	Belledune
PCBs <sup>a</sup>	0.015	0	<sup>b</sup>	0	1.5	Centrale

Source: Raw data from a characterization study by Matheson and Bradshaw, 1985.

a. Aroclor 1254 only.

b. Varies depending on organic component in sediment (see Appendix 3).

NA: TET exceedance tests were not done due to a lack of data on extractible concentrations.



St. Lawrence Centre - Christiane Hudon

# CHAPTER 9

## *The Resuspension of Sediments*

**The ship channel is dredged regularly to maintain the depth required for commercial shipping. Dredging activity is concentrated in the section between Montreal and Quebec City as well as the Upper Estuary and Gulf. Dredging, digging, filling, straightening and dumping dredged material on the banks are all activities governed by federal or provincial law, depending on the jurisdiction of the site.**

**T**oxic substances tend to bind with fine organic and inorganic particles suspended in the water column and settle to the bottom in areas of slow current. Ships can cause bottom turbulence and resuspend this sediment when they anchor or scrape bottom due to insufficient channel depth. Sediment also escapes into the water column through dredging work or when dredged material is dumped on the river bottom. Locally, a certain amount of sediment can be resuspended by tidal currents, storm winds and slides on the slopes of channels, but these events are poorly understood and volumes are hard to quantify (see map, *Draining, backfilling and dredging in the St. Lawrence*).

### *Capital and maintenance dredging*

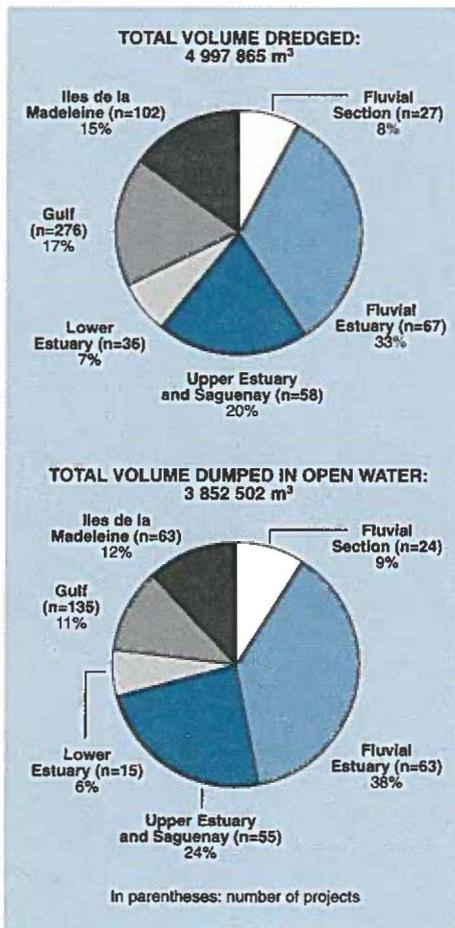
The ship channel is sounded annually to ensure safe navigation conditions. Maintenance dredging, which removes the most recent sediment layer, is done at regular intervals to counteract the river's natural tendency to regain its original profile. Creating new shipping lanes (i.e. capital dredging), demands the excavation of substantial volumes of materials ranging in texture from rock to marine clay. This material is generally less contamin-

ated if dredging reaches layers that date from preindustrial times.

Between 1983 and 1993, five million cubic metres of sediment was dredged from the St. Lawrence River and gulf, four million of which was dumped into open water (Figure 32). The volume of sediment dredged each year from the ship channel as a whole is estimated at just over 450 000 m<sup>3</sup>, with just under 400 000 m<sup>3</sup> dumped into open water.

During this same period, there were 276 and 102 dredging projects in the Gulf of St. Lawrence and Îles de la Madeleine, respectively, representing 67 percent of all projects, but only 32 percent of volume dredged (Figure 32). The Fluvial Estuary ranked first in terms of average annual volume of sediment dredged per project, with the 1 614 692 m<sup>3</sup> dredged between 1983 and 1993 representing an average volume of 24 099 m<sup>3</sup> per project. The average volume of sediment dredged per project in the gulf was only 3106 m<sup>3</sup> during the same period.

The St. Lawrence Seaway from Cornwall to the Lesser La Prairie Basin is almost never dredged. The only areas of the Fluvial Section requiring dredging are around



Source: SLC, 1993c.

**Figure 32** Relative volumes of dredging and disposal between 1983 and 1993

Montreal, Boucherville and Contrecoeur, but the volumes removed are minor — between 2000 to 10 000 m<sup>3</sup>. There are five major dredging sites in Lake Saint-Pierre concentrated mainly near the Berthier–Sorel islands, in the centre and at the lake outlet. Sediment volumes dredged here are quite substantial and often exceed 10 000 m<sup>3</sup>. In the Fluvial Estuary further downstream, extensive dredging is required at the Course de Becancour, the Batiscan anchorage area, the Traverse Cap-Santé, and the Portneuf anchorage area. However, the greatest number of dredging sites, and where dredged volumes are greatest, are found in the channel opposite Quebec City and east of Île d'Orléans, including the Île aux Coudres. There are about 20 sites here and seven of

them generate an annual average sediment volume exceeding 50 000 m<sup>3</sup>. Maintenance dredging is never needed in the Lower Estuary and Gulf, where the ship channel runs through deep waters. However, most harbours along the Gaspé coast are affected by heavy sedimentation and need frequent maintenance dredging involving volumes of less than 10 000 m<sup>3</sup>. The Îles de la Madeleine stands out in this regard, having about eight sites dredged almost once a year, with volumes of 10 000 m<sup>3</sup> or more.

Sediment dredged from the St. Lawrence and the Gulf is usually only slightly contaminated and it is disposed of in open water near the work sites. This is done at Contrecoeur, Bécancour, Lake Saint-Pierre, Cap-de-la-Madeleine, the mouth of the Saint-Maurice River, Batiscan, Saint-Pierre-les-Becquets, the eastern tip of Île d'Orléans, Rivière-du-Loup and the Îles de la Madeleine. Between 1983 and 1993, each of these disposal sites received more than 10 000 m<sup>3</sup> of sediment dredged from the river on at least one occasion. Sediment is sometimes transported up to 40 km from the dredge site when there are no suitable troughs for depositing material, or nearby sites are filled to capacity.

#### Apprehended Impact of dredging operations

Even under the best conditions, dredging inevitably releases a certain amount of sediment into the water column. Water quality near a dredge site can be altered with an increase in turbidity due to a rise in SS. Moreover, contaminants can be dispersed if PCBs and PAHs with their low solubility are adsorbed to the organic and mineral particles. A high concentration of organic matter in sediments will disperse nutrients and raise the chemical oxygen demand (Environment Canada, 1994).

Dredged sediment generally consists of medium-size grains — silt and sand. However, coarse sands and gravel are the dominant materials in Upper Estuary areas with strong currents and high turbidity. Depending on the level of organic matter, sediments may contain heavy metals in the form of sulfides, which are stable compounds

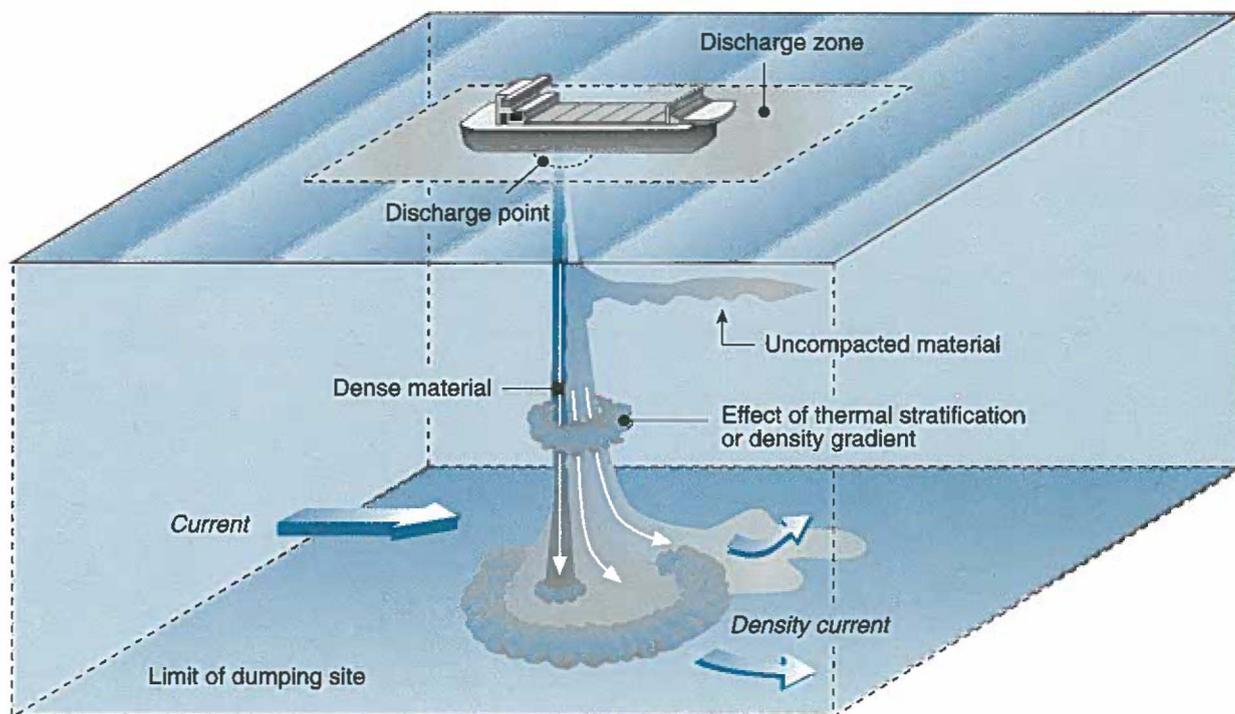
in the absence of oxygen where the pH is neutral. However, if the sulfides are dried out or drained in a landfill site, they oxidize and release metals dissolved in the landfill runoff water (leachate). Given their very low solubility, pesticides, PCBs, PAHs, organohalogens and hydrocarbons of mineral origin adsorb to particles and organic matter.

The amount of sediment lost during dredging operations depends on particle grain size, flow conditions at the work site, and the type of dredge used. An estimated 2–6 percent of dredged sediment is lost in the water column, 50–70 percent of which is deposited on the river bottom within 500 m of the work site (Environment Canada, 1994). Fine sediment, which has a higher affinity for contaminants, remains suspended in the water long after the dredging operation. Finer and less cohesive sediments have a greater tendency to form SS plumes in water layers of unequal density or in the presence of currents. Coarser sediment such as sand and gravel, rocks and fragments of ancient clay settle quickly to the bottom (Figure 33).

In areas that are regularly dredged and disturbed by ship traffic and movements, benthic communities are generally impoverished and dominated by opportunistic species. The physical modification of new dredge sites can destroy habitats important to benthic organisms and fish.

Repeated dredging in the same area reduces the species diversity, overall biomass and density of organisms of the benthic community (Wildish and Thomas, 1985 cited in Environment Canada, 1994). However, open-water disposal sites for dredged matter can be recolonized in under two weeks if the sediment deposited is of the same nature as the old sediment, and if the new sediment layer is no more than 15 cm deep.

Fish can be temporarily affected by a decline in dissolved oxygen caused by an increase in suspended organic particles in water. As long as spawning areas and food sources are not destroyed by the dredged material, the impacts of open-water dumping are generally minor and temporary for



Source: Environment Canada, 1994.

**Figure 33 Sediment behaviour during open-water disposal**

most fish species. Some species are more vulnerable, however, including herring, which deposits its eggs on the river bottom, and Sand lance, which buries its eggs in sediment. Filling troughs with dredged matter can harm species such as the Lake sturgeon, a bottom-dwelling fish that uses the deep holes as a refuge from heat in the summer months (Appendix 7 shows the potential impacts of a dredging operation). Even if the sediments are not contaminated and dredged matter is coarse (e.g. sand), the risk of impact in troughs and wetlands near the dredge site cannot be ignored. In marshes, plants can adapt to changes in sedimentary conditions (particle grain size, sedimentation rate), but beyond a certain point, plant and animal species disappear.

#### Legislative framework and administrative procedures for dredging and open-water dumping

Capital and maintenance dredging is governed by the *Canadian Environmental Assessment Act* (CEAA).

Dredging outside federal property or areas of federal jurisdiction is subject to the *Quebec Environment Quality Act* (Q-2, r.9). Any dredging, digging, banking, filling, reshaping and shore disposal work over a distance of 300 m or more, or over an area of 5000 m<sup>2</sup> or more, must be subject to an environmental impact study (SLC, 1993b). For work covering a smaller area, contractors must apply for an authorization certificate from the Ministère de l'Environnement et de la Faune (MEF) pursuant to Section 22 of the *Environment Quality Act*.

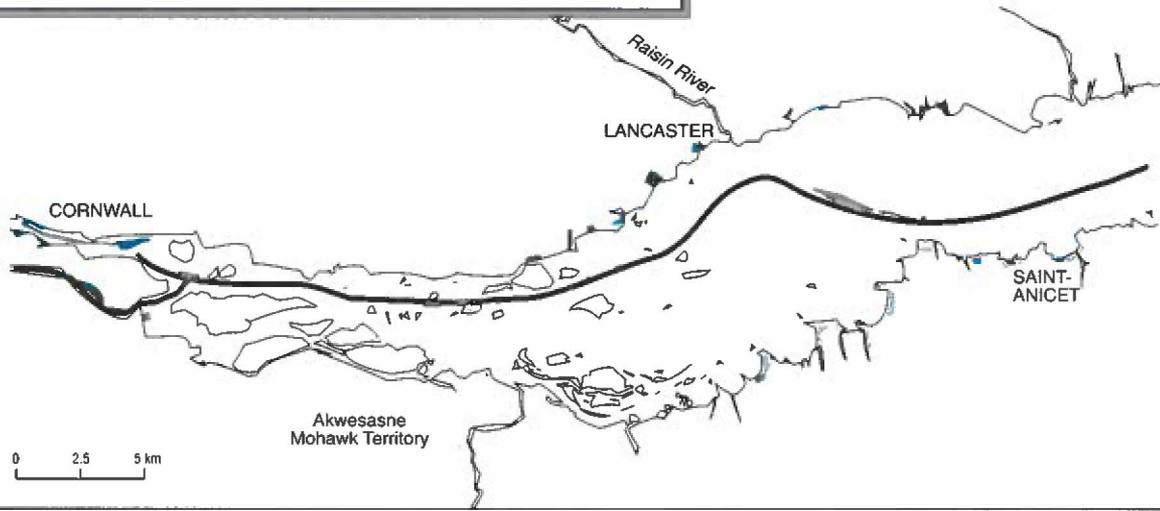
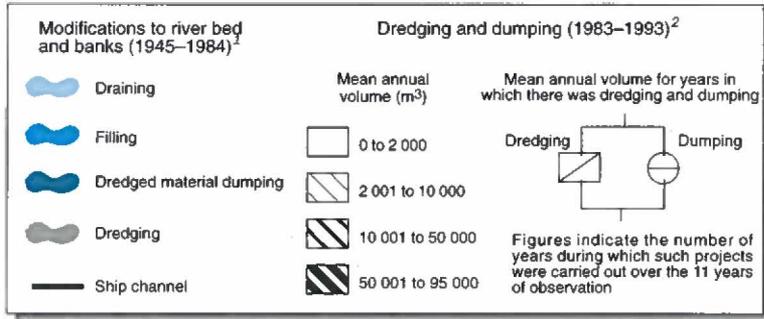
Dredging in the Lower Estuary and Gulf, where sediment is dumped in open water, requires a prior application to the Ocean Dumping Advisory Committee. This applies in areas east of the 63rd degree of west longitude, and east of a line passing through Cap-des-Rosiers and the western tip of Anticosti Island, including the Quebec portion of Chaleur Bay.

A prior environmental examination attempts to identify any significant

toxic effects on benthic organisms, using standardized bioassays. If the dredged sediment contains levels of heavy metals or organic compounds equal to or below the Minimal Effect Threshold (MET), open-water dumping can be authorized since toxic effects on benthic organisms will be minimal. Open-water dumping is an option where sediment contamination is equal to or below levels at the receiving site. If contamination levels are higher and exceed the MET, the recommended disposal method is secure containment in the water, on the banks or on land. The Toxic Effect Threshold (TET) marks the critical limit beyond which benthic organisms are believed to experience major toxic effects. When sediment contamination exceeds this threshold, the only course of action is to control the pollution sources and restore the site (SLC and MENVIQ, 1992).

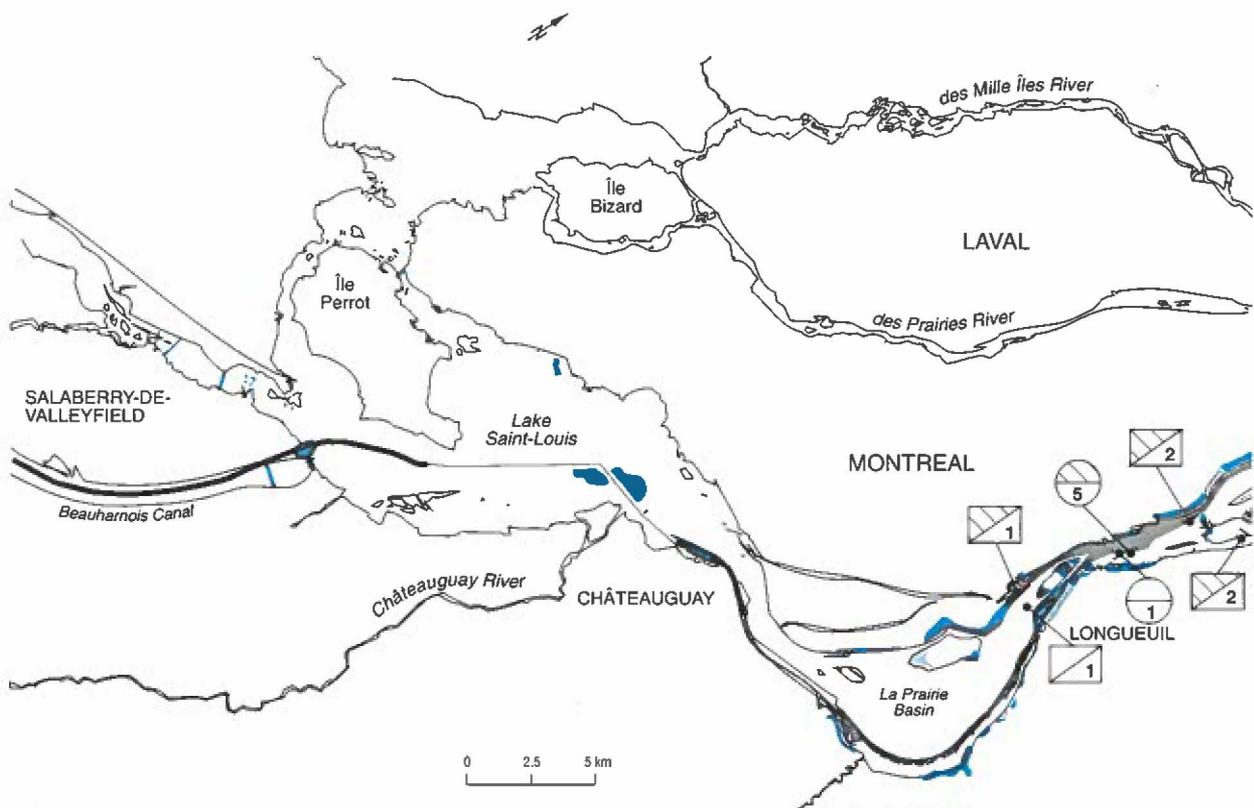
Environment Canada, in cooperation with various partners, has published a series of guidebooks outlining recommended practices in dredging to ensure that environmental impact is

**CORNWALL-POINTE-DES-CASCADES**



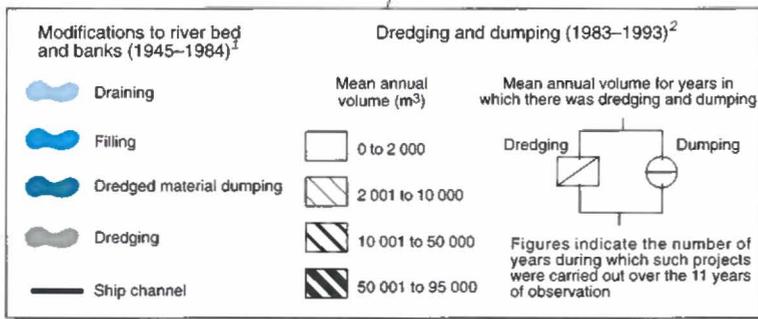
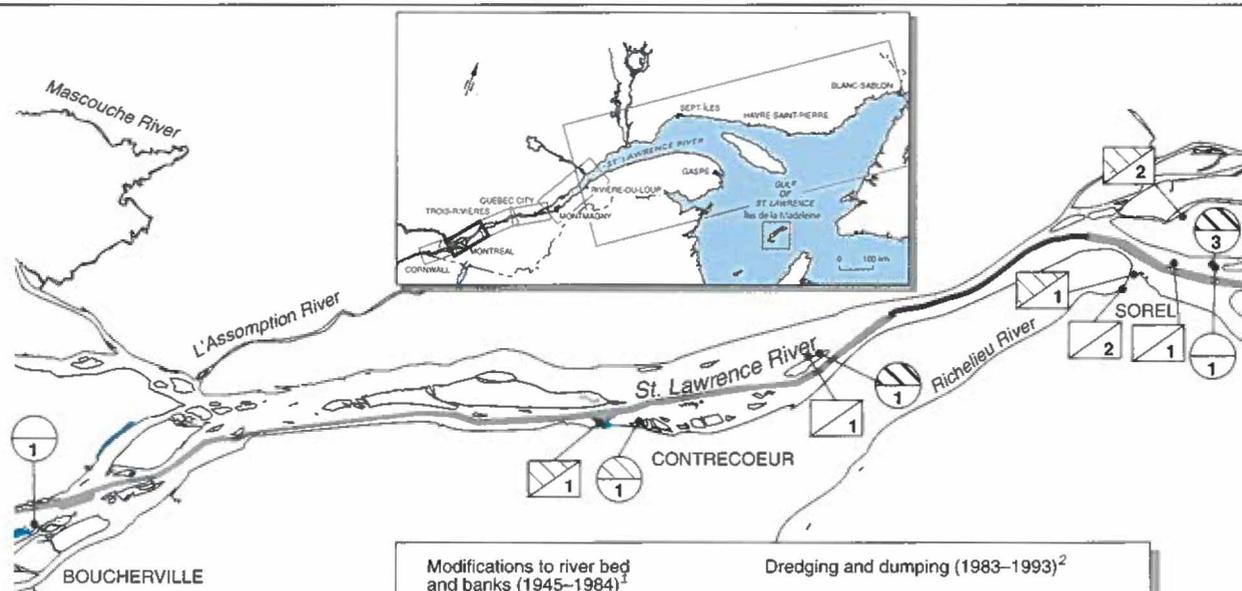
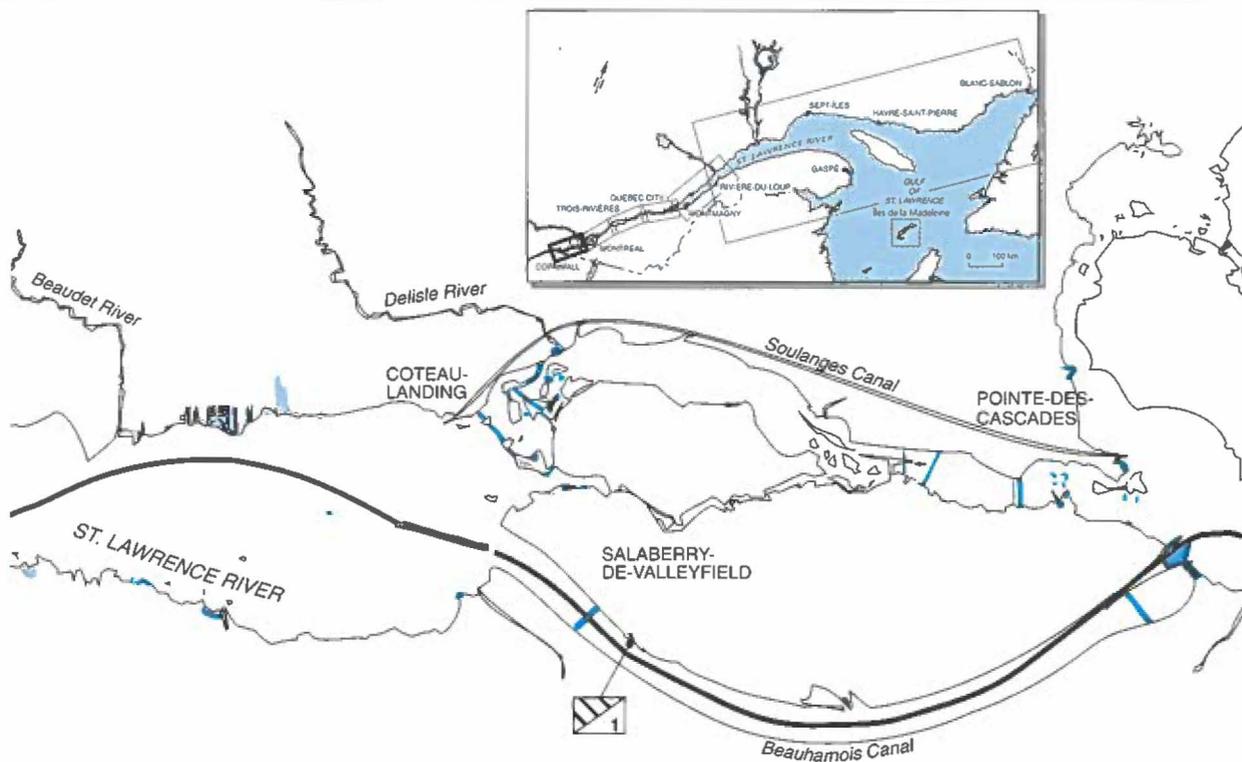
Source: <sup>1</sup> Marquis et al., 1991. <sup>2</sup> SLC, 1993.

**MONTREAL-SOREL**

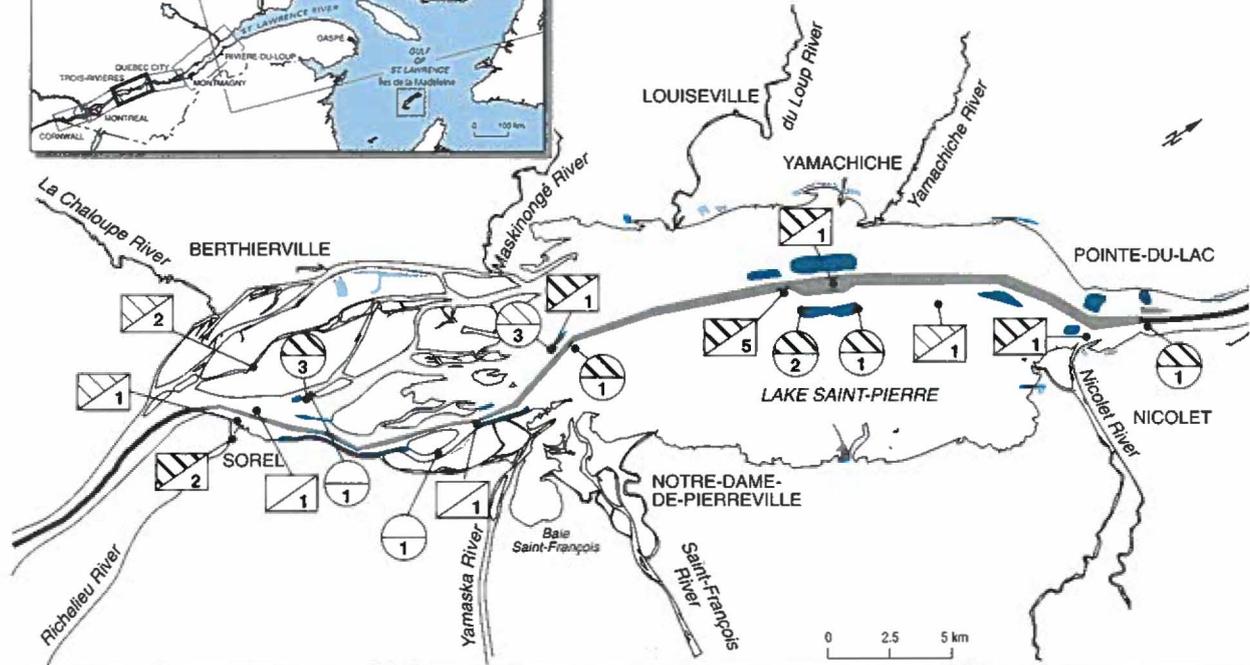
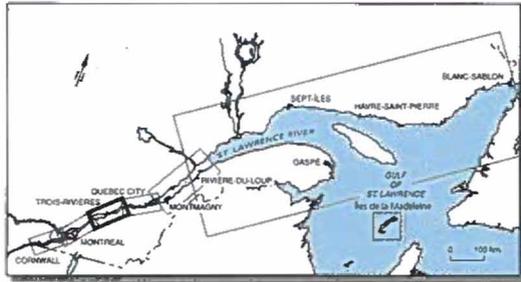


Source: <sup>1</sup> Marquis et al., 1991. <sup>2</sup> SLC, 1993.

**Draining, filling and dredging activities in the St. Lawrence**

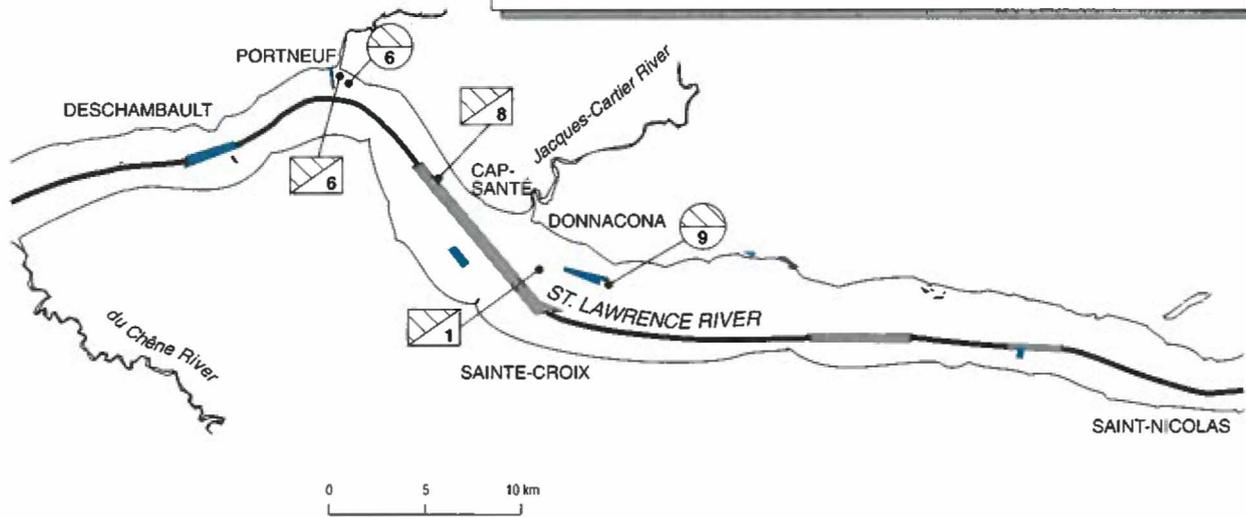
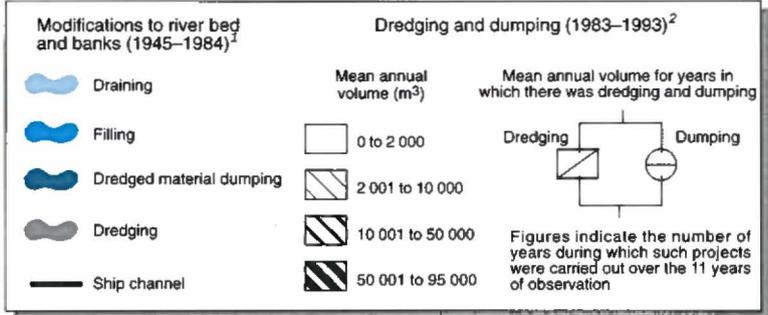


**SOREL-DESCHAMBAULT**



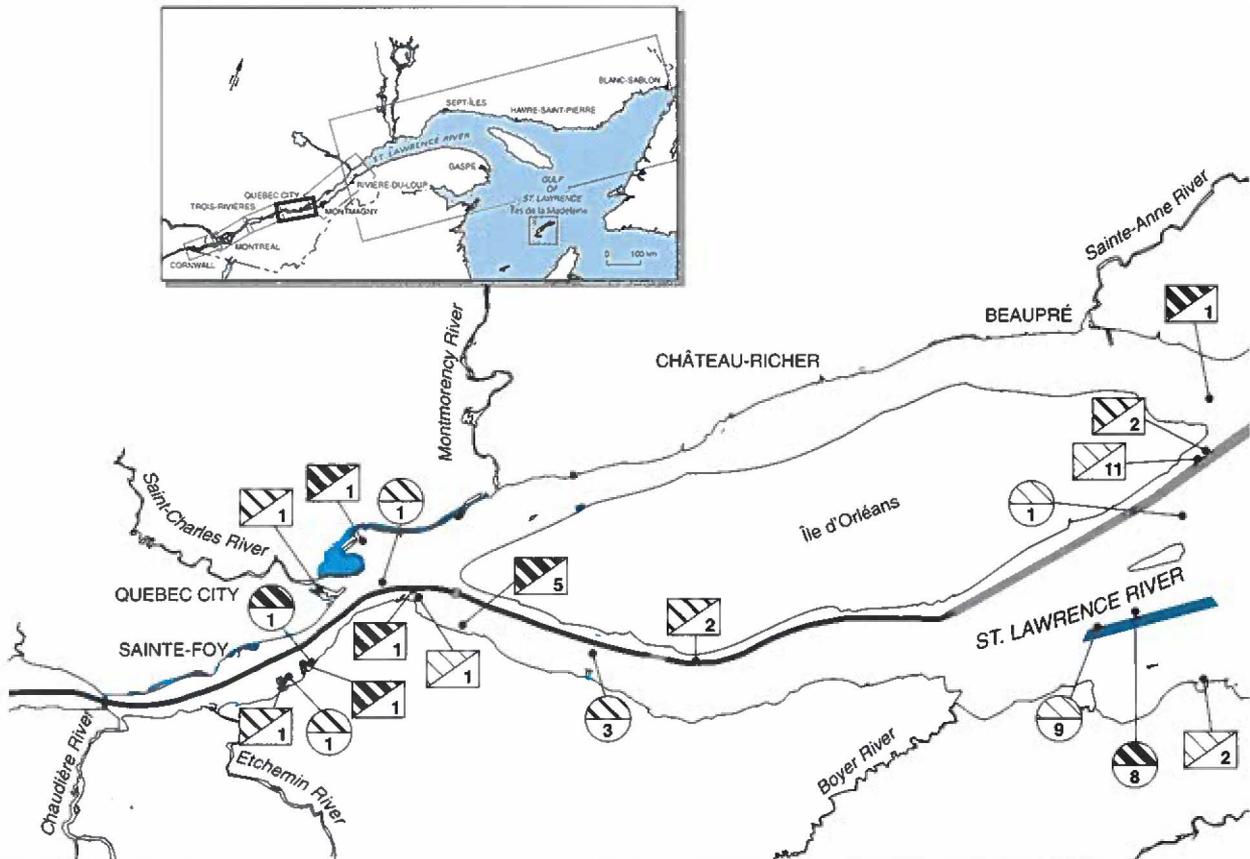
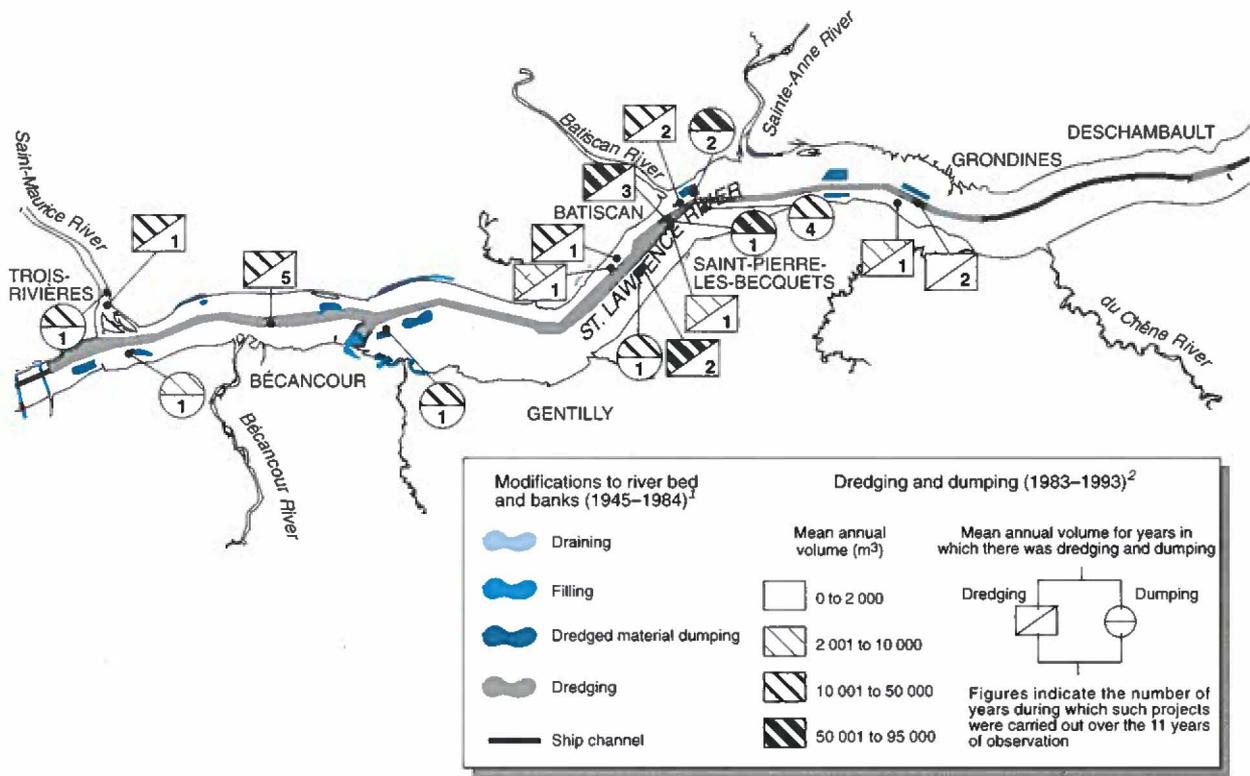
Source: <sup>1</sup> Marquis et al., 1991. <sup>2</sup> SLC, 1993.

**DESCHAMBAULT-BEAUPRÉ**

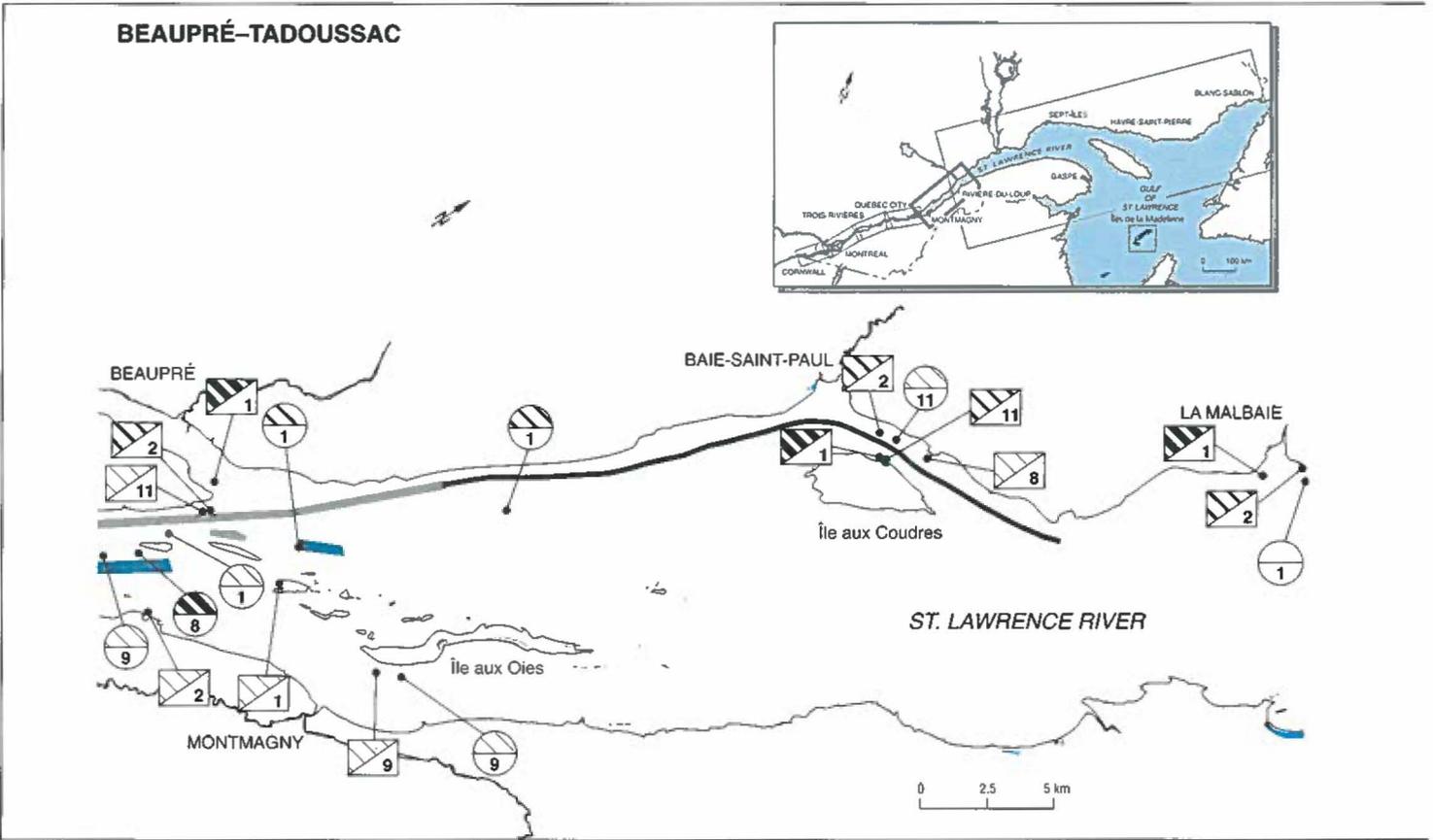


Source: <sup>1</sup> Marquis et al., 1991. <sup>2</sup> SLC, 1993.

**Draining, filling and dredging activities in the St. Lawrence (continued)**

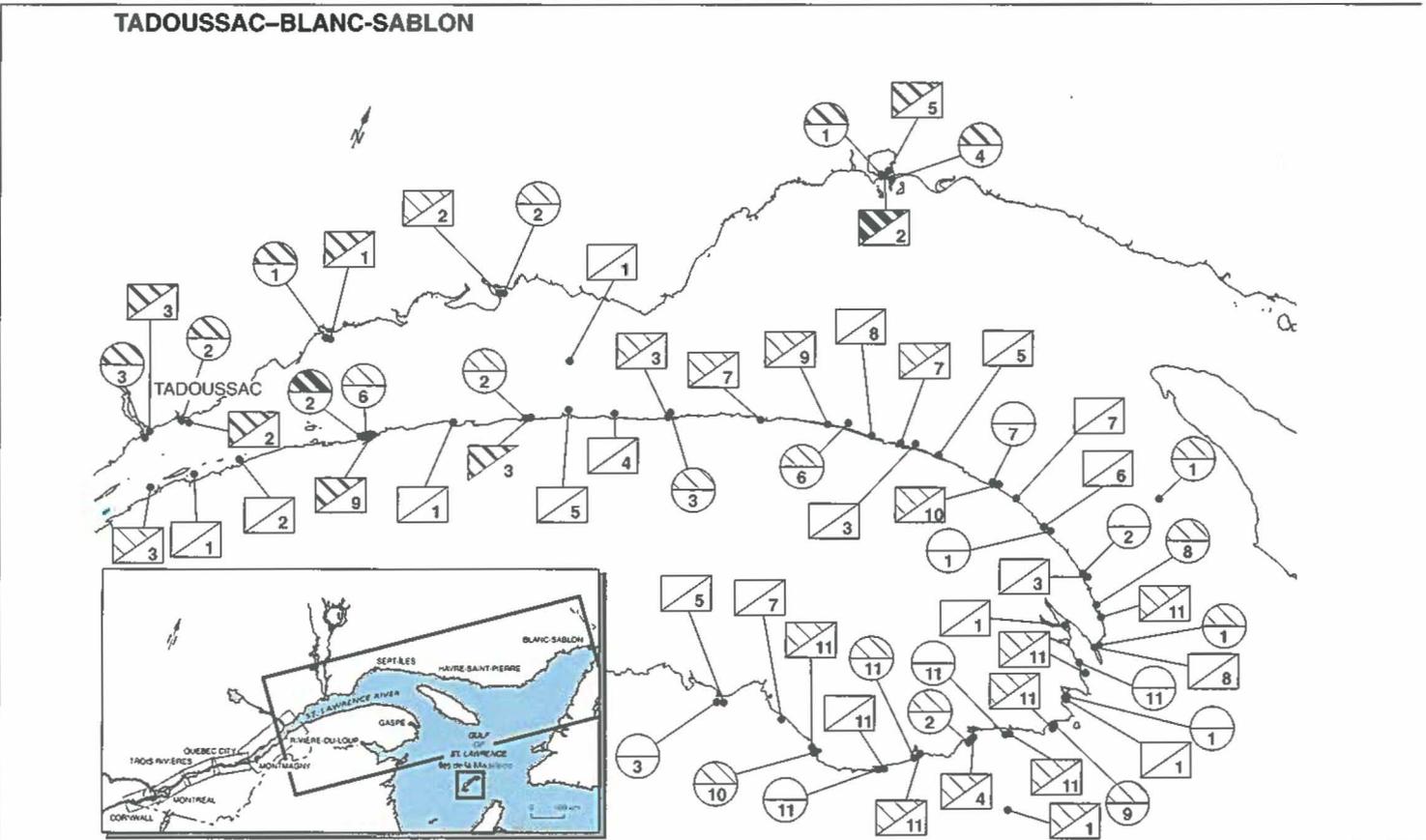


**BEAUPRÉ-TADOUSSAC**



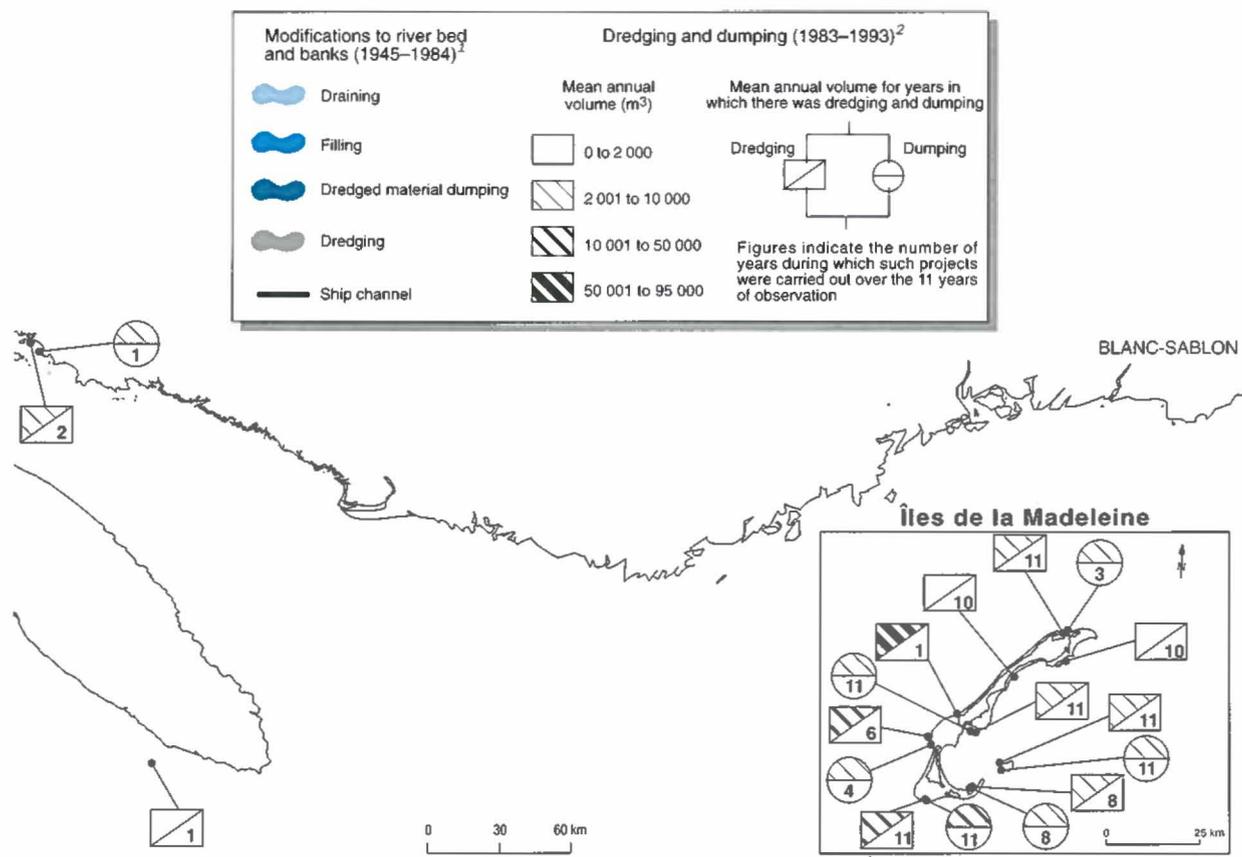
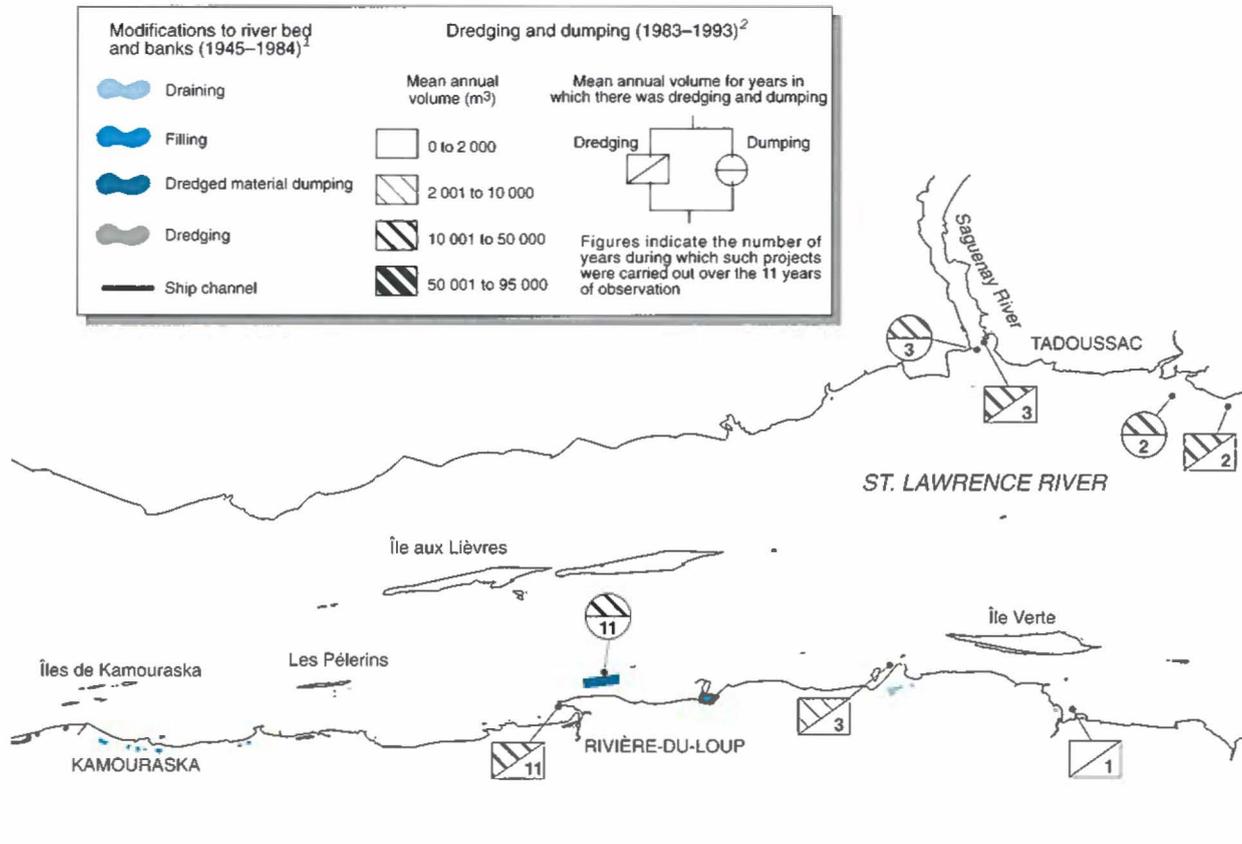
Source: <sup>1</sup> Marquis et al., 1991. <sup>2</sup> SLC, 1993.

**TADOUSSAC-BLANC-SABLON**



Source: <sup>1</sup> Marquis et al., 1991. <sup>2</sup> SLC, 1993.

**Draining, filling and dredging activities in the St. Lawrence (continued)**



either avoided or attenuated. These publications are widely used by project promoters, environmental consulting firms and government managers for all dredging projects along the St. Lawrence. They will be revised as new developments are made in this field.

### How to handle contaminated sediments

Secure containment in water involves depositing contaminated sediments in a depression or some other location where hydrodynamic conditions provide stability, and covering them with a layer of uncontaminated sand or silt. This method has the advantage of avoiding soil and groundwater contamination on land while confining the sediment in an anaerobic, reducing environment. Stable hydrodynamic conditions are critical. It is generally considered safe up to a depth of 90 metres. A 30-cm-thick layer of

clean material should be placed over the contaminated sediment; a layer of 50 cm is needed to keep the sediment beyond the reach of burrowing benthic organisms. The main problem with this method is that pore water migrates toward the covering layer during the settlement of contaminated sediment in the first weeks after it is applied (Environment Canada, 1994).

An other method is to move the sediment to an on-land site and place it on a waterproof layer of either natural (clay, peat moss) or artificial (sand-bentonite, synthetic membrane) material. It is then covered with an insulating material to minimize surface runoff and oxidization of the sediments. In this case, a drain must be installed to collect the leachate. However, there is no ideal material for containing highly contaminated sediment. Acids and bases can dissolve clay, while peat moss can become

saturated and solubilize heavy metals, and a sand-bentonite mixture is never completely impervious (Environment Canada, 1994).

Controlled disposal consists of creating a settling basin for the capture of suspended solids and to prevent their dispersal into the water column. After fine particles have settled out, the water is discharged over permeable dikes, sills, weirs or through filtration units. These structures can be located either on land or in the water. Their shape and size will depend on expected volume, conditions specific to the site, and amount of usage planned (Environment Canada, 1994).

Containment on land must conform to guidelines in the Contaminated Sites Rehabilitation Policy and the *Guide d'implantation et de gestion de lieux d'enfouissement de sols contaminés*.

# CONCLUSION



Canadian Wildlife Service — Léo-Guy de Repentigny

**T**he main conclusions arising from this compilation of available information on St. Lawrence sediment are as follows:

- Permanent sedimentation in the fluvial lakes is a recent phenomenon resulting from changes in the hydrodynamic regime since the mid-20th century. The regime has not changed significantly over the past decade and the spatial distribution of accumulation zones of fine sediment has stayed the same.
- Fine particles, particularly silty sands and clayey silt, are found in the fluvial lakes and in the deep-water zones of the Lower Estuary and Gulf. Sand and gravel dominate in areas where current velocity and turbulence are greater; that is, in the fluvial channels, the Upper Estuary and on the littoral shelves of the gulf.
- A relatively small quantity of SS from the Great Lakes, the international section of the river and Quebec sources settles in the fluvial lakes and in harbour basins for long periods. The majority of SS is transported directly to the ocean or else is retained for a while in the river and on estuary foreshores. It is later resuspended by currents, tides, floods and storm winds, finally settling in the Laurentian Channel, the second largest sedimentation trough after the Great Lakes.
- Sediments contaminated beyond the Threshold of Significant Contamination (TSC) occupy large areas where currents are slow-moving in the fluvial lakes and harbour areas of Montreal, Quebec City and Trois-Rivières. In the marine environment, heavily contaminated areas are generally more localized. This is true in

the upper basin of the Saguenay Fjord and in certain parts of the gulf (Baie des Anglais, Chaleur Bay).

- The interim criteria developed by the federal and Quebec governments relative to toxic effects are, at present, the only criteria for assessing the apprehended effects of contamination on benthic communities. This analysis shows that certain sections of Lake Saint-Louis, the Saguenay Fjord and Chaleur Bay contain sediments thought to threaten the survival of benthic organisms due to high mercury levels found in the mid-1980s. The present level of contamination of surface sediment layers has no doubt declined following a shutdown of sources and the covering of contaminated sediment by cleaner deposits, including material flowing into the Saguenay Fjord during the floods of July, 1996. It should be noted that, in this study, the interim toxic effects criteria could only be applied to mercury, since most studies consulted reported only total concentrations of metals in sediments.
- The evolution of contaminant levels in sediment core samples shows that values have been gradually falling since the 1970s. In permanent sedimentation zones, contaminated sediments have been gradually covered by sediments of similar texture but better quality. However, the ability to analyse contamination profiles is limited in parts of the river where sediments are continually resuspended, such as the Upper Estuary. It is also limited by the fact that the behaviour of metals in salt water is still poorly understood.
- Sediment contamination is a complex phenomenon not limited to adjacent sources of contamination. Toxic compounds also enter the drainage basin through the water cycle and atmospheric circulation. This is true for mercury, which enters Laurentian Channel sediments partly through atmospheric inputs.
- Some heavy metals are not generally biomagnified in the aquatic ecosystem. Many aquatic organisms have defence mechanisms that annul or diminish the toxicity of heavy metals. Vertebrates such as fish and mammals can metabolize PAHs and thereby effectively eliminate them from their tissues or break them down into other substances (metabolites). However, some metabolites can have toxic effects on certain aquatic organisms. PCBs accumulate permanently in living tissues, as do PAHs in invertebrates (mussels, shrimp, polychaetes, etc.). In general, if inputs exceed the capacity of the organism's defence mechanisms, toxic biomagnification can occur. Cases of bioaccumulation and biomagnification have been reported in benthic organisms living in close contact with contaminated sediments (*Bithynia tentaculata* in Lake Saint-Louis and whelks in the Baie des Anglais). Contaminated sediments can also harm benthic communities. Contamination reduces the productivity and biodiversity of the benthos, potentially destroying food sources for aquatic animal life. The issue of the potential transfer of sediment contaminants to fish, which are not usually in close contact with the sediments, will require

research to identify transfer pathways and their significance.

- Construction of the St. Lawrence Seaway greatly altered the river's hydrodynamics. The Seaway, together with works carried out on the river bed and banks during the 1960s, is considered partly responsible for the problems faced by several species of fish. Maintenance dredging is done mainly in the Fluvial Estuary, Upper Estuary and the Gulf. In the river as a whole, just over 450 000 m<sup>3</sup> of sediment is dredged each year and most of it is dumped in open water because of its low level of contamination. An environmental assessment procedure has been used for each dredging project since the end of the 1970s to predict negative impacts on the receiving environment and attenuate them as needed.

The concept of a TSC was developed to establish a level of contamination that can be attributed solely to human activity. It is based on preindustrial levels for naturally occurring chemical substances or, alternately, on concentrations of synthetic substances (like PCBs) thought to have no effect on benthic organisms. When preindustrial levels are known for a wide range of sediment textures covering the entire St. Lawrence and its sub-systems, it will be possible to assess more accurately sediment contamination levels and identify contaminated areas posing potential harm to living creatures. The validity of such an analysis depends on our knowledge of preindustrial levels, which will improve as the scientific community continues its efforts to characterize St. Lawrence sediments.

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**Adsorption**

Process by which molecules of gases, liquids or dissolved substance are taken up by the surfaces of a solid substance (atom, ion, molecule) with which they are in contact.

**Barchois**

Tidal pond.

**Bay**

Portion of shoreline with pronounced concavity capable of modifying path of coastal currents.

**Benthic**

Refers to the bottom underlying a body of water and the creatures who live on or near it.

**Bioturbation**

Transformation or degradation of sediments by the stirring and churning of organisms.

**Cation**

Positively-charged ion.

**Coastal shelf**

Part of a watercourse bed that is the extension of the adjacent coast.

**Community**

Set of living organisms occupying the same biotope.

**Contamination**

Introduction of a substance into an environment making it unsuitable for desired uses.

**Detrivorous**

Refers to a living organism that feeds on dead organic matter (e.g. cadavers, excrement, etc.).

**Diagenesis**

The set of physico-chemical processes by which sediment deposits are gradually transformed into solid rock (e.g. sand becoming sandstone).

**Drainage basin**

Natural geographic region drained by one or more rivers and their tributaries; *watershed*.

**Effluent**

Liquid generated by an industrial process that may be discharged into the environment.

**Electrostatic (force or attraction)**

Force generated by atoms that have lost or gained electrons.

**Essential metal**

Metallic element found in certain concentrations that are physiologically necessary in certain tissues or biological liquids.

**Evapotranspiration**

Natural phenomenon combining evaporation from the soil and transpiration by plant life.

**Fetch**

Refers to the distance that a wind blows over water without encountering an obstacle.

**Flats**

Part of the shore area uncovered at low tide.

**Flood**

Exceptional rise in water levels due to heavy rains or snowmelt.

**Flow**

Volume of water passing through a watercourse, pipe, etc. per unit of time; *discharge*.

**Foreshore**

Shoreline area between the high and low water marks.

**Glacial trough**

Valley which is overdeepened and invaded by the sea, shaped by a glacier with a characteristic U-shaped cross-section and steep sides.

**Groundwater**

Refers to water found under the surface of the earth.

**Habitat**

A defined space where biotic and abiotic factors allow a species or given population to satisfy its vital needs such as feeding, reproduction, migration and shelter. Habitat is therefore the place where a given species lives.

**Holocene**

An epoch of the Quaternary period that began about 11 000 years ago; *Recent epoch*.

**Ions**

An atom or molecule that has lost or gained one or more electrons and become charged electrically.

**Leachate**

Soluble part of solids carried in runoff water.

**Low water**

Lowest water level in a river or ocean.

**Macrophyte**

Refers to plants visible to the naked eye.

**Marine transgression**

A change in sea level that reduces the continental shoreline and is accompanied by changes in shoreline formation and facies.

**Neap tide**

That part of the tidal cycle when tidal range is lowest.

**Nonpoint-source discharge**

Substance introduced into a habitat from no precisely identified source.

**Peat bogs**

Acidic environment constituted of peat which characterizes wetlands.

**Photosynthesis**

Set of physiological processes by which plants containing chlorophyll produce organic molecules from carbon dioxide and water using energy from sunlight.

**Pitch**

Pasty residue from the distillation of tars, oil and other organic matter.

**Pollution**

Alteration of environmental quality caused by the presence of substances having harmful effects.

**Pore water**

Refers to water contained in the pores of soil on land or sediments lying under a water body.

**Primary treatment**

Wastewater treatment stage consisting of removing macroscopic matter using mechanical and physical methods.

**Radioactivity**

Property of certain isotopes to emit ionizing radiation by spontaneous disintegration.

**Runoff**

Rapid flow of rainwater or snowmelt on the surface of drainage basins that feeds rivers.

**Secondary treatment**

Biological wastewater treatment (bacterial beds or activated sludge).

**Sediment budget**

Method for assessing the source, transport and deposition of suspended solids (SS) introduced into a hydrological system. To balance a sediment budget, SS transiting volume less settling volume must be equal.

**Sediment load**

Total amount of sediment that remains suspended in the water column for a relatively long time.

**Senescence**

Natural degeneration of plants from full maturity to death.

**Ship channel**

Area within the limits of the dug and maintained channel.

**Shoreface**

Zone extending seaward from the low water shoreline, which is always submerged.

**Slack water**

Period when the water level of a sea or watercourse is stable.

**Slikke**

Lowest part of a salt marsh not colonized by vegetation. It is flooded at every high tide; *mud flat*.

**Solid phase**

Substance in a solid state; ice is water in the solid phase.

**St. Lawrence Seaway**

Section with locks where water levels are artificially controlled.

**Surface water**

Refers to flowing or stagnant water on the earth's surface.

**Suspended solids (SS)**

Solid particles floating in a liquid or maintained in the water column by turbulence. They can be removed by deposition or filtering.

**Synodical**

Relating to the conjunction of celestial bodies.

**Syzygy tide**

That part of the tidal cycle when tidal range is greatest; *spring tide*.

**Terrigenous (fraction or particles)**

Refers to different types of debris (rock fragments, minerals, etc.) that originate from the erosion of continental formations and the sediments of which they are composed.

**Tidal range**

Difference in height between successive high and low water periods.

**Traction**

Transport of coarse sediment along the river bottom by rolling and sliding.

**Trophic level**

The link in the food chain represented by an organism.

**Turbidity**

A cloudy condition in water caused by the presence of fine suspended matter (silt, clay, micro-organisms, etc.).

**Water phase**

Liquid state of a substance.

**Weathering**

The set of mechanical, physico-chemical and biochemical actions on rocks subject to atmospheric agents (gelification, dissolution and hydrolysis are all forms of weathering).

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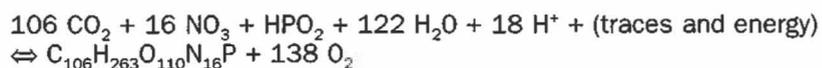
# A PPENDIXES

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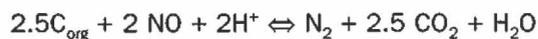
**Appendix 1**  
**Chemical reactions**  
**involved in diagenesis**

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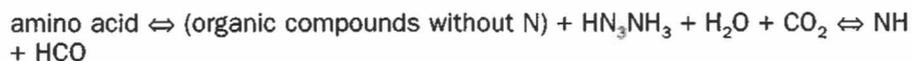
Photosynthesis of organic matter by algae (simplified reaction)



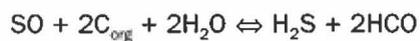
Denitrification



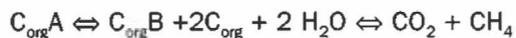
Breakdown of amino acids



Reduction of sulfates



CO<sub>2</sub> fermentation



## Appendix 2 Comparison of nomenclatures from studies used to map surface sediment

<i>Loring and Nota (1973) d'Anglejan and Brisebois (1978)</i>	<i>Centreau (1973- 1974)</i>	<i>Hardy et al. (1991a)</i>	<i>Lorrain et al. (1993) (modified from Shepard 1954)</i>	<i>Champoux and Sloterdijk (1988) Procéan Inc. (1990)</i>	<i>Shepard (1954)</i>	<i>Composition (Shepard 1954)</i>
Pelite	Silt Silt + clay  Clay	Fine silt	Silt + clayey silt	Silt Clayey silt Silty clay Clay	Silt Clayey silt Silty clay Clay	> 75% silt < 20% sand, 50–75% silt < 20% sand, 50–75% clay 75% clay
Sandy pelite	Sand + silt + clay Sand + clay		Muddy sand Clayey sand	Mixed sediment Clayey sand	Mixed sediment Clayey sand	> 20% clay, silt, sand > 50% sand, < 20% silt
Pelitic sand	Sand + silt	Sand	Mixed sediment	Silty sand Sandy clay	Silty sand Sandy clay	< 20% clay, 50–75% sand > 50% clay, < 20% silt
Very sandy pelite		Coarse silt	Silty sand + sandy silt	Sandy silt	Sandy silt	< 20% clay, 50–75% silt
Sand	Sand	Sand and gravel	Sand and gravel	Sand	Sand	> 75% sand
Bedrock	Bedrock		Bedrock	Bedrock	Bedrock <sup>1</sup>	
Marine clay	Marine clay		Marine clay		Marine clay <sup>2</sup>	
Glacial till					Glacial till <sup>3</sup>	

1. Where unconsolidated sediments are absent or rocky outcrops are exposed.

2. Where compacted and plastic grey clay deposited in the Champlain Sea period is exposed.

3. Rough textured sediments with physical properties inconsistent with the present sedimentary regime. These unconsolidated deposits can be of glacial origin (till) or have been deposited prior to the present fluvial and estuarine regime.

**Appendix 3**  
**Interim criteria**  
**for quality assessment**  
**of St. Lawrence River**  
**sediment (April 1992)**

Parameters in µg/g or µg/g for 1% TOC**	Level 1* (NET)	Level 2 (MET)	Level 3 (TET)**
<b>HEAVY METALS</b>			
Arsenic***	3	7	17
Cadmium***	0.2	0.9	3
Chromium	55	55	100
Copper***	28	28	86
Mercury***	0.05	0.2	1
Nickel	35	35	61
Lead***	23	42	170
Zinc***	100	150	540
<b>ORGANOCHLORINES</b>			
Total PCBs***	0.02	0.2	<b>1</b>
Aroclor 1016***	-	0.01	<b>0.4</b>
Aroclor 1248***	-	0.05	<b>0.6</b>
Aroclor 1254***	-	0.06	<b>0.3</b>
Aroclor 1260***	-	0.005	<b>0.2</b>
Aldrin	0.000 6	0.002	<b>0.04</b>
Total BHC	-	0.005	<b>0.1</b>
α-HC	0.000 3	0.01	<b>0.08</b>
β-BHC	0.000 2	0.03	<b>0.2</b>
γ-BHC	0.000 9	0.003	<b>0.009</b>
Chlordane	0.001	0.007	<b>0.03</b>
DDD and p,p3-DDD	0.002	0.01	<b>0.06</b>
p,p1-DDE	0.002	0.007	<b>0.05</b>
DDT	0.006	0.009	<b>0.05</b>
Dieldrin	0.000 1–0.000 8	0.002	<b>0.3</b>
Endrin	0.001	0.008	<b>0.5</b>
HCB	0.001	0.03	<b>0.1</b>
Heptachlor	0.000 3	0.000 3	<b>0.01</b>
Heptachlor epoxide	0.001	0.005	<b>0.03</b>
Mirex	0.000 1	0.011	<b>0.8</b>
<b>POLYCYCLIC AROMATIC HYDROCARBONS</b>			
PAHs (high molecular weight)	1	-	-
Benzo(a)anthracene***	0.05–0.1	0.4	<b>0.5</b>
Benzo(a)pyrene***	0.01–0.1	0.5	<b>0.7</b>
Benzofluoranthene	0.3	-	-
Benzo(ghi)perylene	0.1	-	-
Chrysene***	0.1	0.6	<b>0.8</b>
Dibenzo(ah)anthracene	0.005	-	-
Fluoranthene***	0.02–0.2	0.6	<b>2</b>
Indeno(1,2,3 cd)pyrene	0.07	-	-
Pyrene***	0.02–0.1	0.7	<b>1</b>
PAHs (low molecular weight)	0.1	-	-
Acenaphthene	0.01	-	-
Acenaphthylene	0.01	-	-
Anthracene	0.02	-	-
Fluorene	0.01	-	-
2-methylnaphthalene	0.02	-	-
Naphthalene***	0.02	0.4	<b>0.6</b>
Phenanthrene***	0.03–0.07	0.4	<b>0.8</b>

Source: SLC and MENVIQ, 1992.

\* When the lower limit of the field of application of an analytic method is greater than the level 1 criterion, this limit must be used until developments in methodology lower it to the level of the criterion adopted.

\*\* All parameters are expressed in micrograms per gram (µg/g) of dry sediment except for Level 3 non-polar organic substances, which are expressed in micrograms per gram of wet weight for 1% of total organic carbon (TOC). **To establish the quality criterion for a Level 3 non-polar organic parameter (shown in bold), in a given situation, multiply the criterion in this table by the TOC percentage of the sample being assessed, to a maximum of 10% TOC (e.g. the TET for total PCBs in a sample containing 2% TOC will be 1 µg/g × 2 = 2 µg/g).** Values under 10 will be rounded off to one significant figure, while values above 10 will be taken to two significant figures.

\*\*\* Substances included in this study.

## Appendix 4 Preindustrial levels of heavy metals and PAHs in sediment

**Table 1** Preindustrial levels (PIL) measured in sediment cores from permanent sedimentation zones and comparison with the NET

Substance	PIL (mg/kg)					NET (mg/kg)	TET (mg/kg)
	Lake Saint-François <sup>1</sup>	Lake Saint-Louis <sup>2</sup>	Saguenay Fjord <sup>3</sup>	Laurentian Channel			
				Lower Estuary <sup>4</sup>	Gulf <sup>5</sup>		
Arsenic <sup>6</sup>	8.0	8.0	8.0	8.0	8.0	3.0	17
Cadmium	0.20	0.15	–	–	–	0.20	3.0
Copper	20	17	21	16	–	28	86
Mercury	–	–	0.10	0.03	0.03	0.05	1.0
Lead	20	15	17	16	16	23	170
Zinc	80	78	85	115	110	100	540
PAHs*	–	–	–	0.587	–	~ 0.60	**
PCBs	0	0	–	–	–	0.02	***

Source: 1 and 2: Carignan et al., 1993.  
 3: Barbeau et al., 1981.  
 4 and 5: Cu and Zn: Gobeil, 1991.  
 Pb: Gobeil et al., 1995.  
 Hg: Gobeil and Cossa, 1993.  
 PAHs: Gearing et al., 1991.  
 6: Quémerais, 1996.

\* Sum of 7 PAHs for which a TET has been established (see Appendix 3).

\*\* Varies depending on the PAH being considered (see Appendix 3).

\*\*\* Varies depending on organic component in sediment (see Appendix 3).

## Appendix 4 (continued)

**Table 2 PIL values used in each section to calculate the Anthropic Enrichment Factor (AEF) and determine the Threshold of Significant Contamination (TSC)**

Substance	PIL (mg/kg)											
	Lake Saint-François	Lake Saint-Louis	Lesser La Prairie Basin	Port area of Montreal	Lake Saint-Pierre	Port area of Trois-Rivières	Port area of Quebec City	Upper Estuary	Saguenay Fjord	Baie des Anglais	Chaleur Bay	Laurentian Channel
Arsenic	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Cadmium	0.20	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Copper	20	17	17	17	17	17	17	16	21	16	16	16
Mercury	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.10	0.03	0.03	0.03
Lead	20	15	15	15	15	15	15	16	17	16	16	16
Zinc	80	78	78	78	78	78	78	115	85	115	115	115
PAHs*	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
PCBs	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

\* Sum of 7 PAHs for which a TET has been established (see Appendix 3).

## Appendix 5 Sediment quality characteristics and data sources used in this report

Section	Type of data	Year of sampling	Source
Fluvial portion	Surface sediment quality (all heavy metals)	1976	Sérodes (1978)
Lake Saint-François	Surface sediment quality (all selected substances)	1989	Unpublished SLC data Lorrain et al. (1993)
	Sediment core (Lancaster basin)	1990	Lorrain et al. (1992)
	Sediment core (Saint-Zotique basin)	1992	Carignan et al. (1994)
Lake Saint-Louis	Surface sediment quality (all selected substances)	1984–85	Champoux and Sloterdijk (1988)
	Sediment core (Zone 1)	1992	Carignan et al. (1994)
	Sediment core (Zone 3)	1987	Rukavina et al. (1990)
Lesser La Prairie Basin	Surface sediment quality (all selected substances)	1987	Hardy et al. (1991b)
Montreal harbour	Surface sediment quality (all selected substances)	1990	Environnement Illimité Inc. and Lavalin Environnement (1991)
Lake Saint-Pierre	Surface sediment quality (all selected substances)	1986	Hardy et al. (1991a)
	Sediment core (Zone 2)	1990	Lorrain et al. (1992)
Trois-Rivières harbour	Surface sediment quality (all selected substances)	1990–92	G.D.G. Environnement Ltée (1993)
Quebec City harbour	Surface sediment quality (all selected substances)	1989	Procéan Inc. (1990)
Marine portion	Surface sediment quality (Cd, Cu, Hg, Pb, Zn)	1972–74	Loring (1975, 1978, 1979)
Upper Estuary	Surface sediment quality (Cd, Cu, Hg, Pb, Zn)	1989–1990	Coakley and Poulton (1993)
Saguenay Fjord	Surface sediment quality (Cd, Cu, Hg, Zn)	1986	Pelletier and Canuel (1988)
	Surface sediment quality (PAHs)	1983	Martel et al. (1986)
	Sediment core (Hg, PAHs; Ha! Ha! Bay)	1988	Pelletier et al. (1990)
	Sediment core (PAHs; North arm)	1978	Smith and Levy (1990)
	Sediment core (PAHs; North arm)	1990	Pelletier (1994) in Fortin and Pelletier (1995)
	Sediment core (Hg; Upper basin)	1992	Gagnon (1994)
Baie des Anglais	Surface sediment quality (all selected substances)	1990	GTBA (1993)
Chaleur Bay	Surface sediment quality (As, Cd, Hg, Pb, PCBs [Aroclor 1254])	1984	Matheson and Bradshaw (1985)
Laurentian Channel	Sediment core (Cu, Zn; upstream part)	1986	Gobeil (1991) Station 23
	Sediment core (Hg; upstream part)	1986	Gobeil and Cossa (1993) Station 23
	Sediment core (Pb; upstream part)	19??	Gobeil et al. (1995) Station 23
	Sediment core (PAHs; upstream part)	19??	Gearing et al. (1991)
	Sediment core (Hg, Pb, Zn; downstream part)	1987	Gobeil (1991) Station 12

## **Appendix 6**

### ***Riverbank remediation methods***

#### **Slope reshaping and fascine placement**

This technique stabilizes slopes with a mat of brushwood bundles arranged in rows parallel to bank contours and held in place with stakes. It was tried on the north bank of one of the Lacroix islets in the Contrecoeur archipelago in autumn 1993 (Argus Inc., 1993b).

#### **Cedar log cribs**

This method involves installing cedar log cribs on riverbanks after they have been excavated and reshaped. The cribs are placed on top of one another to form a solid, stable structure. Earth between the cribs is stabilized with a geotextile sheet and brushwood bundles gathered on site. Spaces between cribs can be closed with fill material. This method was tested in autumn 1991 at Île du Pilier and Île Chipeau in the Contrecoeur archipelago, and also at Île aux Corbeaux, in the Sorel area (Argus Inc., 1993a; 1993b).

#### **Vertical palisade**

This structure consists of vertical stakes placed about 30 cm apart parallel to the ship channel. The stakes dissipate the energy from ship wake waves and storm-generated waves by breaking up and diverting the wave. This allows suspended particles to settle behind the structure. The stakes can be inclined at a 45° angle towards the banks, in which case buffers are added to strengthen the structure. Inclining the stakes reduces the dynamic force of waves on the structure (Argus Inc., 1993b).

#### **Islet with protective palisade**

A palisade is constructed as above except that the stakes are placed side by side in a row. Dredged sediment is placed in a geomembrane between the palisades. The islet blocks the waves, creating an area of calmer water behind. Although the wave force against the structure is stronger, since the palisade forms an unbroken line, the sedimentary islet compensates for this by absorbing some of the wave energy (Roche Ltée, 1993).

#### **Embankment of concrete blocks**

A barrier of concrete blocks is laid parallel to the ship channel.

#### **Foreshore deflection bar**

This method moves the erosion zone to the front of the zone to be protected, which then becomes an area of sediment accumulation. It involves laying down a bar of material (sand and gravel, fine sediment) parallel to the bank. The technique is effective if sand is used to create the bar and water levels vary little (Argus Inc., 1993a).

#### **Boom**

This method involves creating a line of floating items (logs, tires) held in place by anchoring them to the water bottom. The structure is placed in front of the erosion zone and blocks the wave energy. The boom can be laid out between fixed structures such as natural or artificial islands. It has the advantage of allowing water to circulate freely (Argus Inc., 1993a).

## **Appendix 6** *(continued)*

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### **Sedimentary islet**

Small, artificial islands solve the problem of containing contaminated sediment while creating habitats for wildlife. A concept was developed keeping in mind conditions in the likely trial area (in this case Lake Saint-Pierre), such as wave and ice erosion, a clayey lake bottom, abundant wildlife, and the nature and the amount of material to be contained. Different kinds of structures can be built: round islet with marshes, round island with marshes and shoals, marshes and shoals. The "atoll" form is suitable for areas where the ice cover is unstable. The marsh-and-shoal islet has the capacity to hold 42 000 m<sup>3</sup> of dredged material. Its construction is staged over several years as dredged sediment is removed from the bed. The cost is estimated at about \$6 million (Roche Ltée, 1993).

### **Riprap**

Riprap stabilizes banks that are exposed to erosion agents. The rock fill consists of large granite-like stones generally greater than 70 cm in diameter. The slope angle is generally 1:1.5. The steep angle of the slope and large cavities between the rocks discourage the growth of plant cover. While effective, this technique has the disadvantage of being heavy and stark. Different vegetation techniques were tried in 1991 over a 100-m stretch of the Dufferin-Montmorency highway. Good results were obtained from placing mulch in the rock gaps and planting fast-growing shrubbery (Siberian pea-shrub, American green alder, Sweet gale, etc.) (Argus Inc., 1994d).

### **Sedimentation confines**

This structure consists of blocks of concrete or wood (cedar stakes and wood planks) arranged so as to retain the suspended solids naturally present in the area. The technique was tried along Highway 20 in Rivière-du-Loup. Three such confines, 22 m wide and 75 cm high, were built to combat the erosion of intertidal marshes beside the highway (Argus Inc., 1993c; 1994a).

### **Bank reshaping and vegetation**

This method involves reshaping the talus slope to reduce the impact of waves. A slope greater than 1:1 and up to 1:3 is recommended. Species adapted to the ecological conditions of the site and abundant in the area are then planted. Around Montreal, for example, appropriate species would be Pussy willow, Red-osier dogwood, and Common nine-bark. The effectiveness of this method depends on how strong the erosion agents are. It is not effective in protecting banks exposed to high waves (Argus Inc., 1994b; 1994c).

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## Appendix 7

### Potential impacts of dredging on the river environment

<i>Environmental component</i>	<i>Potential impact</i>
Hydrodynamics, ice and sedimentation	<ul style="list-style-type: none"> <li>• Modification of bathymetric profile, water flow and sediment transport at sites affected by dredging</li> <li>• Modification of ice regime</li> <li>• Acceleration of erosion or sedimentation in adjacent areas</li> </ul>
Nature and quality of river bottom	<ul style="list-style-type: none"> <li>• Currents carry polluted sediments to areas of unpolluted sedimentation</li> <li>• Modification of nature and quality (particle texture and size) of sediment</li> </ul>
Water quality	<ul style="list-style-type: none"> <li>• Temporary increase in turbidity and suspended solids</li> <li>• Decrease in transparency</li> <li>• Resuspension of pollutants at dredging site and adjacent areas</li> <li>• Possible persisting turbidity resulting from the erosion of deposits by currents, tides and shipping</li> <li>• Possible contamination of runoff waters and the water table</li> </ul>
Bird life and riparian habitat	<ul style="list-style-type: none"> <li>• In the case of capital projects, loss or alteration of habitats caused directly by excavation</li> <li>• Dumped dredged material sometimes creates new habitats for birds</li> <li>• Loss or alteration of habitat as a direct result of dumping dredged material in the aquatic environment, particularly in aquatic plant communities</li> </ul>
Wildlife and land habitat	<ul style="list-style-type: none"> <li>• Habitat alteration caused by dumping dredged material on land</li> <li>• Contamination of plant life</li> </ul>
Wildlife and aquatic habitat	<ul style="list-style-type: none"> <li>• Disturbance of spawning or nursery activity</li> <li>• Disturbance of marine mammals</li> <li>• Loss or alteration of habitats used by fish and other aquatic organisms for reproduction or feeding, especially by capital projects, (spawning, rearing, feeding, resting or migration areas)</li> <li>• Living organisms sucked up by hydraulic dredging (fish, benthos)</li> <li>• Possible toxicological incidents due to the deterioration of water and sediment quality during dumping (contamination of fish flesh)</li> <li>• Burial of benthic organisms as well as eggs and larvae of fish and other organisms (sponges and coelenterates); smothering or disturbance of buried organisms, predominance of tolerant species</li> <li>• Modification of substrate at dumping site, resulting in changes in benthos (mortality, increased intra- and inter-species competition, attachment of mollusc impossible or delayed)</li> </ul>

## Appendix 7 (continued)

<i>Environmental component</i>	<i>Potential impact</i>
Wildlife and aquatic habitat (continued)	<ul style="list-style-type: none"> <li>• Temporary obstruction to movement and migration (fish, crustaceans, etc.)</li> <li>• Degradation of spawning beds and disappearance of food sources (benthos and plankton)</li> </ul>
Heritage and protected site	<ul style="list-style-type: none"> <li>• In the case of capital projects, loss or degradation of known or potential archeological sites</li> </ul>
Recreation	<ul style="list-style-type: none"> <li>• Disturbance of recreational activity in or on water around the dredging site</li> <li>• Interference with pleasure boating and sport fishing</li> <li>• Pollution and deterioration of recreation areas and beaches</li> </ul>
Commercial and sport fishing, hunting and commercial shipping	<ul style="list-style-type: none"> <li>• Obstruction of boating, fishing and hunting</li> <li>• Influence of dredging on commercial shipping (navigation ease when dredging is finished, lack of access to water body during works)</li> <li>• Sites that can be affected by changes in water quality include areas where commercial fishery uses fixed gear and fish farm areas</li> <li>• Fishing areas can be affected by changes to bottom morphology</li> </ul>
Land use	<ul style="list-style-type: none"> <li>• Conflict with actual or desired use for site</li> <li>• Creation of new land areas available for development</li> </ul>
Quality of life	<ul style="list-style-type: none"> <li>• Temporary noise nuisance (truck transport, dredge operation, etc.)</li> <li>• Nuisance due to odours or dust</li> </ul>
Water intake	<ul style="list-style-type: none"> <li>• Temporary degradation in water quality associated with dredging or dumping dredged material</li> </ul>
Scenery	<ul style="list-style-type: none"> <li>• Modification of quality of scenery around sites affected by dredging (altered land forms, back-fill on riverbanks, creation of visual barriers and altered scenic views)</li> </ul>