LITERATURE REVIEW AND BIBLIOGRAPHY OF THE GEOLOGICAL PROCESSES AND BOTTOM SEDIMENTS OF THE ST. LAWRENCE RIVER

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MANAGEMENT PERSPECTIVE

The St. Lawrence River, including the estuary, forms the link between the Great Lakes and the Atlantic Ocean. As such, it is an important element in the ultimate fate and pathways of toxic contaminants introduced into the Laurentian Great Lakes. It also carries a burden of contaminants originating from its own watershed. Many of these contaminants show a preferential association with the suspended particulate phase, so it is clear that geological processes play a significant role in the behavior of these elements, primarily through adsorption, dilution with clean sediments, and ultimately, burial. This report summarizes the geological and sedimentological literature on the St. Lawrence and serves as an initial point of departure for further investigations into modern sediment dynamics in the St. Lawrence system.

FOREWORD

This review consists of two parts. The most important is a comprehensive bibliography of literature on the geology and sediments of the St.Lawrence valley, from Kingston to the mouth of the Saguenay River. The bibliography pertaining to the section from Lac St. Pierre to the Saguenay was written, for the most part by Denis Brodeur, under the direction of Dr. J.-C. Dionne (Université Laval). The review is introduced at the beginning by a general summary of the St. Lawrence River geology and sediments, based on the available literature.

PERSPECTIVE DE GESTION

Le St-Laurent, avec son Estuaire, relie les Grands Lacs à l'océan Atlantique. À ce titre, c'est un élément important dans l'évolution ultime et le cheminement des contaminants toxiques des Grands Lacs laurentiens. Il charrie également des contaminants provenant de son propre bassin hydrographique. Beaucoup de ces contaminants entrent en association préférentielle avec les particules en suspension et c'est pourquoi les processus géologiques jouent un rôle important dans le comportement de ces éléments, surtout par adsorption, par dilution avec des sédiments propres et, en dernière instance, par enfouissement. Le présent rapport résume les données géologiques et sédimentologiques sur le St-Laurent et constitue le point de départ des futures études sur la dynamique des sédiments contemporains dans le bassin du St-Laurent.

AVANT-PROPOS

Cette étude comprend deux parties. La plus importante est une bibliographie exhaustive de la littérature sur les sédiments et la géologie de la vallée du St-Laurent, de Kingston à l'embouchure du Saguenay. La bibliographie portant sur le secteur allant du lac St-Pierre au Saguenay a été rédigée, en grande partie, par Denis Brodeur, sous la direction du Dr. J.-C. Dionne (Université Laval). La revue est précédée d'un sommaire général des sédiments et de la géologie du St-Laurent basé sur la littérature existante.

INTRODUCTION

The St. Lawrence River (Figure 1) is the sole natural outlet of the Laurentian Great Lakes. From its exit from Lake Ontario near Kingston, Ontario, it flows northeast, finally meeting the Atlantic Ocean some 750 km later at the Gulf of St. Lawrence. Over this distance it falls approximately 75 m; 69 m of this drop occurs in the first 250 km between Lake Ontario and Montreal, where steep river gradients and rapids are common. The St. Lawrence and its major tributaries - the Ottawa, St. Maurice, Richelieu, and St. Francois Rivers - drain a huge watershed of approximately 1,200,000 km^2 in area. Because the St. Lawrence River forms part of one of the largest interior navigation systems in the world (the St. Lawrence Seaway), flow and water levels in the river are partially controlled by works located in the river section between Kingston and Beauharnois, near Montreal. These works also serve to generate hydroelectric power.

Mean discharge of the St. Lawrence at Beauharnois averages 6000 m^3/s, excluding the 2000 m^3/s brought in by the Ottawa River slightly downstream of the Beauharnois gauge (Anonymous, 1985b). Further along at Nicolet, slightly upstream from the entry of the St. Maurice at Trois-Rivières, the mean river discharge has risen to 10,100 m^3/s. Downstream from Trois-Rivières, the effect of marine tides becomes increasingly important, making discharge figures less meaningful. However, the final discharge at the river's mouth has been estimated at more than 14,000 m^3/s (Holeman, 1968). In any event, with a discharge greater than that of the McKenzie, the Volga, or the Ganges, the St. Lawrence ranks as a major world river by any criterion (Table 1).

Furthermore, the intense concentration of cultural and industrial activity in the river and its watershed has resulted in severe water quality problems. Major sections of the river are severely contaminated by a variety of toxic chemicals originating both from Lake Ontario and from industrial and municipal effluents discharged directly into the river. This situation has aroused much concern for the indigenous biota, especially for those near the top of the food chain: fish, beluga whales, eels, and Man. In the recently renewed interest on the ecology of the St. Lawrence, attention has been drawn to the role of physical geology and sedimentology in contamination impacts (Serodes, 1976).

The goal of this report is to review the existing literature on the geological and geophysical setting of the St. Lawrence River, and to summarize those aspects most relevant to ongoing studies at the National Water Research Institute on the St. Lawrence River. The summary is therefore aimed at providing background information to investigations into fluvial sediment processes and contaminant dynamics. Unfortunately, this review predates the International Symposium on the Fate and Effects of Toxic Chemicals in Large Rivers and their Estuaries, held in October 1988, and whose proceedings are expected in late 1988. These prooceedings will no doubt add a wealth of detail on the St.Lawrence.

The review is restricted to that section of the river between Kingston and the mouth of the Saguenay River or fjord. This includes the upper portions of the estuary region as well. Beyond that point, tidal and wave effects dominate, and the St. Lawrence estuary behaves more like a marine embayment than a river.

REGIONAL GEOLOGY

The St. Lawrence River lies within the geological province known as the St. Lawrence Platform (Poole et al., 1970; Wilson, 1946). This region extends from the Lower Great Lakes, along the St. Lawrence valley, to as far east as the northwestern tip of Newfoundland (Fig. 1). The platform is characterized by flat-lying or gently dipping beds of lower Paleozoic carbonate and clastic rocks, and is sharply bounded to the north by the Precambrian Canadian Shield. East of the Great Lakes, the platform is bounded to the south by the folded and metamorphosed sedimentary rocks of the Appalachian Highlands. Broadly speaking, the stratigraphic column for the study area (Table 2) is comprised of crystalline metamorphic rocks at the base, overlain by sedimentary rocks, overlain by Quaternary deposits. The river is cut into these materials, and thus, in areas of non-deposition, they form the channel walls and floor, supplying much of the eroded debris carried by the river. A more detailed description of these materials and their spatial distribution follows.

Precambrian rocks

Metamorphic rocks of Precambrian age, i.e. older than 1 Billion years, form the basement onto which the younger rocks of the area were deposited. They outcrop at the surface and form the river channel in the 40-km reach between Gananoque and Brockville, where the Canadian Shield salient known as the Frontenac Arch crosses southeastward into New York. Canadian Shield rocks do not outcrop along the river again until the area just east of Quebec. From this point east, these rocks form the northern shore of the estuary and the Gulf. The Shield rocks lie within the southern part of the Grenville Province (or Formation), a distinct east-west-trending zone composed of highly metamorphosed rocks. Rock types range from anorthosite gneiss and granite plutons and metamorphosed sediments (marbles, quartzites) in the west, to amphibolite gneiss in the eastern regions (Wilson, 1946). These rocks are very resistant to weathering and erosion by all except glacial processes. They represent the major pebble type found in the tills of the area (see Section on Quaternary deposits).

Paleozoic rocks

This section comprises the Cambrian and Ordovician sedimentary rocks of the St. Lawrence Platform, resting unconformably on the eroded surface of the Canadian Shield basement. The 600 million years of erosion separating these two groups of rocks left no geological record, but it is generally believed that the area was subjected to intense weathering and erosion prior to its inundation by the Paleozoic seas. The Paleozoic rocks consist primarily of pure quartz sandstones at the base, and carbonates and shales in the upper part of the section (Table 2), and represent the major bedrock type in contact with the river. These rocks are generally flat-lying, but drape over basement highs at the Frontenac Arch and near Beauharnois (Fig. 1). These areas, where the more resistant beds dip most steeply and are closer to the surface, are usually associated with the presence of rapids in the river channel.

The Paleozoic rocks of the Platform are separated from the Precambrian Shield rocks to the north (and are internally dissected) by normal faults trending generally east-west. The term "normal" means that the younger rocks to the south of the fault, and lying above the sloping fault-plane are displaced downward relative to the older Shield rocks below the fault-plane. The surface trace of these faults is characterized by sharp topographic breaks, generally marked by rapids and waterfalls on south-flowing streams north of the St. Lawrence River, e.g., at Montmorency Falls to the east of Quebec.

The Platform rocks are separated from the folded Appalachian Highlands to the south by a major zone of reverse faults (in which the rocks above the fault-plane (Appalachian) move up and over the Platform rocks below). This fault zone is known as Logan's Line, after Sir William Logan, the first Director of the Geological Survey of Canada. The Logan's Line fault initially follows the north-south trend of the Champlain valley, then curves eastward to meet the St. Lawrence valley at a point near Quebec (Kay and Colbert, 1965; Poole _et al._, 1970).

The physiographic result of the above system of normal faults to the north and reverse faults to the south is an elongated structural depression, or graben, oriented roughly east-west, parallel to the direction of the river. The total vertical displacement in the graben reaches more than 450 m in places. This long, fault-bounded depression has long been the focus of much of the ongoing earthquake activity in Eastern Canada (Basham et al., 1979), and its tectonic significance was compared to that of the East African Rift Valley System, the contact zone between two major crustal plates (Kumarapeli and Saul, 1966).

Younger rocks

During the 450 My interval from the Ordovician period to the Quaternary, the St. Lawrence valley was exposed almost continuously to subaerial weathering and erosion (Goldthwait, 1933), and no sedimentary deposition corresponding to this interval is preserved in the rock record. Fragments of Lower Devonian limestones occur in Cretaceous volcanics described below, indicating that post-Ordovician rocks once existed but were later eroded away. During the Cretaceous period (70 - 130 My ago), the St. Lawrence area experienced renewed tectonic activity, accompanied by widespread intrusions of volcanic rocks, and active faulting. The most visible result of this phase is the high-relief, stock-like masses comprising the Monteregian Hills scattered over the area from Montreal to northern Vermont. These very resistant rock masses protrude starkly from the generally flat Platform plains, as at Mount

Royal and Mont Saint-Hilaire (Kay and Colbert, 1965; p. 433-435). Alkaline volcanic rocks also occur below the river bed in the Montreal area, and consist primarily of nepheline syenite plugs, andesite and rhyolite dykes, and diatreme brecchias.

Quaternary deposits

The most recent deposits now lying directly on the eroded surface of the Precambrian and Paleozoic rocks are the largely unlithified deposits of glacial and marine origin. These materials were deposited during the period of intermittent advance and retreat of the continental glaciers during the Pleistocene epoch, which lasted from approximately 1,000,000 to 10,000 years ago. The deposits that remain comprise ice-deposited tills, water-deposited stratified silts of both glaciolacustrine and glaciomarine origin, and more recent alluvial deposits. These deposits now form the banks and channel of the river over most of its length, and being easily eroded, supply much of the river's natural sediment load. For purposes of discussion, the Quaternary deposits can be subdivided into two main stratigraphic groups: Pleistocene deposits (i.e., generally related to glacial times, i.e., up to 10,000 years Before Present or B.P.) and Holocene deposits (non-glacial deposits dating from then to present).

Pleistocene sediments

Although it can be deduced, primarily from bedrock topographical evidence, that the St. Lawrence valley has been occupied by a major river system since it became emergent in the mid-Paleozoic (Spencer, 1891), no deposits dating to this preglacial phase have been reported. The oldest glacial deposits found in the St. Lawrence valley date from the early Wisconsinan stage (the youngest of the four Pleistocene glacial stages, it lasted from 100,000 to 10,000 years ago). These deposits have been dated at around 70,000 years ago (B.P.), and comprise a thin, reddish, varved silt resting directly on Ordovician bedrock in the Trois-Rivières area (Gadd, 1967). The term, "varved" is defined as fine-grained deposits laid down in an ice-dammed glacial lake, and showing characteristic thin, regular banding, each couplet of which corresponds to an annual cycle of deposition. This silt is directly overlain by the brick-red Becancour Till, a 3-15 m thick calcareous, sandy, clay till (Gadd, ibid.; Prest, 1970). The Becancourt Till is now found only in the area south of the river. Where the till occurs, it is overlain by a thin red and grey varved silt. This sequence therefore is interpreted as indicative of initial deposition in an ice-dammed lake in the central St. Lawrence River valley, formed at the time of the first Wisconsinan glacial advance (indicated by the varved silt), followed by the eventual occupation of the valley by ice (till), and the return to glaciolacustrine conditions when the ice retreated (varved silt).

Above the grey - red varved silt, the sediments change to non-glacial sands and gravels, with abundant interlayers of compacted Sphagnum peat, collectively termed the St. Pierre Sediments by Gadd (1967). These beds average around 8 m in thickness and are interpreted as representing a brief interstadial (ice-free) period in the area, dated at around 65,000 years B.P. Although temperatures were cooler than at present, normal riverine conditions, including extensive wetland development, apparently prevailed in the valley.

The St. Pierre episode was followed by a long period of glacial cover in the St. Lawrence valley, lasting from around 65,000 to 12,000 years ago. The familiar sedimentary sequence associated with an advancing glacier is again noted. Grey, varved silty sediments deposited in an ice-dammed glacial lake, Lake Deschaillons, make up the base of the section. Overlying these is a second till: the grey, sandy, calcareous Gentilly Till. At the top of the sequence, reflecting a return to lacustrine, then marine conditions, is a section made up of varved silt, overlain by fossiliferous marine clay. Because of the long duration of ice-cover, the dominant facies of the above sequence is the Gentilly Till, which occurs below most of the central St. Lawrence Lowland (Gadd, 1967), and might probably form the river bed in most areas. The till reaches up to 20 m in thickness (but is generally 2-3 m), and is exposed in river-bank sections below the younger marine sediments. The finer fraction of the till is predominantly composed of relatively unaltered rock flour; pebbles and boulders are predominantly made up of Precambrian granitic rock types, although local limestones and shales are represented in minor amounts. The Gentilly Till is not as well expressed in the western part of the valley, where it is very thin and patchy. This is probably due to the high bedrock elevations between Kingston and Cornwall.

When the glacial ice vacated the Lake Ontario basin to the west, it still blocked the St. Lawrence valley, and the only drainage for upstream waters was through higher-level outlets to the southeast of Lake Ontario, and later on through the Lake Champlain - Hudson Valley area. A high-level glacial lake, known as Lake Iroquois, formed in the Ontario basin and the southern St. Lawrence lowlands, eventually reaching to the east and south of Montreal. Wave action and currents in this large lake eroded the till and moraine ridges in higher areas in the western part of the valley, and left behind extensive fields of wave-washed gravel and boulders. In the lower areas to the east, the till was further obscured by the deposition of lacustrine silts over much of the area. As the ice retreated further to the north-east, and progressively exposed more of the central and eastern portions of the lowlands, this lacustrine phase expanded briefly to cover much of the St. Lawrence valley. Parent and Occhietti (1988) named this expanded lacustrine phase Lake Candona.

When the valley was finally cleared of ice around 12,000 years ago by the glacier's northward retreat, the large lake occupying the lowland was rapidly replaced by marine waters. This marine phase, known as the Champlain Sea, occurred because the weight of the glacier had depressed the valley and surrounding area to hundreds of metres below sea level. Ice blockage at the topographic restriction of the valley in the Quebec area allowed marine conditions to the east to be established somewhat earlier and prompted the subdivision of the marine phase into two: the Goldthwait Sea (east of Quebec; see Dionne, 1977; Parent and Occhietti, 1988), and the Champlain Sea proper (west of Quebec). Marine waters extended as far west as Brockville, within 80 km of Lake Ontario, and up the Ottawa valley past Pembroke (Prest, 1970). Maximum water depths, however, were slightly north of the Montreal area. The St. Lawrence now flows through what were the lowest depths of the Champlain Sea, so the most common Champlain Sea sedimentary facies that it traverses is a thick, uniform, massive clay. This clay, known as the Leda Clay or Champlain Sea clay, is bluish-grey in colour, fossiliferous, and silty in places. It is usually layered, with alternating sand and clay bands. Its most well-known characteristic is its thixotropy, an extra-sensitive condition which could cause it suddenly to lose all its normally-high bearing strength, and to flow like a viscous fluid when violently disturbed. These clays form part of the upper sequence exposed in the river banks in many areas, and are responsible for the many catastrophic land-slides that have occurred over the years in the St. Lawrence lowlands.

Holocene sediments

The gradual removal of the tremendous weight of the glacial ice from central and eastern Canada, beginning about 12,000 years ago, resulted in an isostatic rebound of the depressed crust beneath the St. Lawrence Lowlands. Because of the generally northeastward direction of the ice retreat, the rate of rebound was greater, and persisted longer, in areas to the north and northeast. The resulting differential tilting, combined with the overall uplift of the area resulted in the progressive shoaling and retreat of the Champlain Sea, and the re-establishment of fresh-water, fluvial and lacustrine conditions in the St. Lawrence valley. By approximately 10,000 years ago, fresh-water conditions were established, beginning in the upper (western) reaches of the valley, and gradually migrating downstream as the marine phase retreated. Elson (1969) also identified a lacustrine phase (Lampsilis Lake) which existed upstream of Quebec between the fluvial and the marine reaches of the valley. This lake was apparently formed by the blockage of the river by the rapidly-deposited delta of the ancestral St. Maurice River at Trois-Rivières. However, when this blockage was finally eroded away, the river continued to develop eastward, rejuvenated by the reduction in base level caused by the breach of the delta and by on-going postglacial uplift. The channel between Lac-St.- Pierre and Quebec was cut during this period. Because of ongoing uplift, the river has continued to excavate its bed downward to maintain its gradient, especially in the more easterly downstream sections. As a result, the older shallow-water Champlain Sea and alluvial sediments are now preserved tens of metres above the river level in the form of terraces, known as the high and low terraces.

The high terraces are most visible north of the river and occur at elevations between 25 and 100 m (Cremer, 1979). They are composed of sands whose internal structures indicate that they were deposited by both wave and current action. These deposits grade imperceptibly into the Champlain Sea sediments below, but their contrasting lack of marine fossils suggests a fresh-water origin. The high terrace sands range in thickness from 1 to 25 m and indicate rapid infilling of topographic lows by abundant coarse sediment inputs during the initial non-marine period. They sometime correlate with large relict deltas, as at Trois-Rivières and Lanoraie. The low terrace, labelled the Mic-Mac terrace by Goldthwait (1933), is composed of fine alluvial sands with silt and few pebbles. The terrace generally is found between 5 and 10 m above the normal river level, thus attesting to the continued persistence of postglacial uplift in the area. This lower terrace presently serves as the site of many of the settlements bordering the south side of the St. Lawrence River.

SUMMARY OF GEOLOGICAL EVOLUTION OF THE ST. LAWRENCE RIVER

Preglacial evolution

No rock record is preserved for the period between the early Paleozoic and the Quaternary eras. However, the tectonic activity which created the existing fault-bound graben structure probably occurred prior to the mid-Paleozoic, and was resumed much later during the Cretaceous period of vulcanism in the area. The total vertical displacement in the graben reached more than 450 m in places. This fact, combined with the absence of non-volcanic rocks younger than Devonian age (300 My), suggests that the area was subaerially exposed during much of this long interval, with a mature river drainage system passing through the structure (Spencer, 1891). Goldthwait (1933) drew attention to the general lack of knowledge regarding the location of the pre-glacial bedrock channel; however, he noted that the deep bedrock gorge (30-45 m below present sea-level) which the river follows in the area opposite Quebec is evidence that in preglacial times, the river occupied roughly the same position as it now does, as its form and orientation clearly precludes excavation by ice scour.

Glacial and postglacial evolution

With the advent of the repeated periods of continental glaciation during the Quaternary era, the St. Lawrence valley was, in turn, occupied by rivers, freshwater lakes, ice-sheets, marine waters, and presently, by a river drainage system again. The main contribution made by the ice was the deposition of glacial sediments throughout the valley. The present-day St. Lawrence River dates back to the end of the maximum Champlain Sea phase, when marine waters reached almost to Lake Ontario. This phase ended less than 10,000 years ago. As marine and estuarine waters retreated eastward because of postglacial uplift, the St. Lawrence River developed accordingly, and progressively approached its present extent. Initially it flowed into Lampsilis Lake, formed by the blockage of the valley by the delta of the ancestral St. Maurice River. Previous river channels have been identified near L'Asomption (Lasalle, 1966) and at Lac St. Paul, near Trois-Rivières. Cremer (1979) cited evidence of a progressive northward shift in the river position in the reach upstream from Deschaillons (between Trois-Rivières and Quebec). This shift is apparently caused by the fact that the river there follows the contact between the northward-dipping bedrock and the thin overlying glacial sediments. The progressive erosion of these sediments results in the gradual northward channel shift.

Because of ongoing uplift and the erosion of the delta, the St.Lawrence River has continued to excavate its bed downward to maintain its gradient, especially in the more easterly downstream sections. As a result, the initial alluvial sediments are now preserved high above the river level in the form of terraces. This incised valley gives sections of the river the appearance of youth despite its geological age.

REVIEW OF MODERN PROCESSES AND SEDIMENTS

The major geological processes now taking place in the St. Lawrence River are bank and channel erosion, and sediment transport and deposition. To these natural processes must be added those due to cultural activities, such as flow regulation, channel dredging, and maintenance of Seaway control works. More long-term processes include differential postglacial uplift of the outlet, and neotectonic processes (mainly earthquakes. Because of the use of the river and its headwater Great Lakes as repositories of human, municipal, and industrial wastes, some of which are toxic, much of the sediment load carried by the river, and making up its bottom deposits are contaminated to a greater or lesser degree. In contrast, the glacial sediments comprising the river banks and channel bed in many areas, are relatively contaminant-free. A knowledge of relative amounts of each making up the sediment load of the river, and their general patterns of dispersal is critical in the understanding and remediation of environmental problems in the St. Lawrence River.

Unfortunately, the sediment studies carried out to date still leave large information gaps. Although considerable excellent work have been done covering much of the Quebec section of the river, these studies are usually in unpublished report form, and are sparsely distributed. They do not give a comprehensive picture of the river as a whole. Also, they are, for the most part, in the French language, which constitutes a major obstacle for anglophone readers. The Federal Department of the Environment has recently encouraged investigations of the entire river (e.g., by N.A. Rukavina, A. Mudroch and K. Lum of the National Water Research Institute (NWRI), and H. Sloterdijk, Environment Protection Service, Quebec). The following section attempts to summarize the findings and insights obtained from these studies and others available in the existing literature (Appendix 1).

For this discussion, the river will be subdivided into two physiographically distinct sectors: fluvial and estuarine. Each sector corresponds to major changes in the physical, sedimentological, or geological regime of the river. The fluvial sector is further divided into two zones: the zone of rapids and the alluvial zone, while the estuarine sector follows the accepted division of upper, middle, and lower zones (Figure 1).

Fluvial sector (Kingston - Trois Rivières)

a. Zone of rapids (Kingston - Montreal)

This zone, extending approximately 250 km, corresponds to a fall of almost 70 km in river elevation. Because of the relatively steep river gradient, and the closeness to the surface of the resistant bedrock, the river is characterized by major rapids. To harness the hydraulic power of the rapids and to facilitate navigation, this zone has been subjected to considerable physical alteration by Man, especially between Montreal and Cornwall. Among the most striking engineering works are the St. Lawrence Seaway (locks, dredged channels) and hydroelectric power generation stations (the Moses-Saunders Dam at Cornwall and the Beauharnois Dam, near Montreal). Both these dams regulate river levels and dramatically alter the river flow regime.

Suspended sediment load at Kingston, at the outlet of Lake Ontario, averages only 1630 tonnes/day (Table 1; Frenette and Larinier, 1973). No major tributary enters the zone upstream of Cornwall, and this factor, combined with the non- erodible river channel in its upper reaches explains the river's very low suspended sediment load (4800 t/d or 1750 x 10^3 tonnes/year) at Cornwall. Most of this load is probably supplied by bank erosion of the thin cover of glacial sediments exposed along the shore.

Potential sites for sediment deposition are few, with the exception of widened portions of the river behind artificial dams and control works. These "riverine lakes" are: Lac St. Francois, near Cornwall, and Lac St. Louis, near Montreal (Figure 1). Also, largely because of relatively high river velocities and the effect of almost constant ship traffic, the zone is primarily one of sediment erosion and transport, especially in the river channel and upstream from the control dams at Cornwall. Nevertheless, Serodes (1976) and CENTREAU (1973) note that fine sediment, contaminated to a greater or lesser degree, is being deposited close to the low-lying river banks where slower currents and abundant vegetation are factors. Some controversy exists as to whether the above two "lakes" are indeed sites of major sediment accumulation. In view of the amounts of contamination released by sources upstream of Montreal, it is important to verify whether these lakes trap the polluted sediment or not. Serodes (1976) shows large sections of these areas containing sediments that are contaminated to some degree by toxic metals and organics.

According to Serodes (1976), the drop in flow velocity at Lac St. Francois results in the deposition of most of the river's sediment load. Furthermore, CENTREAU (1973; p.87) notes the sharp decline in measured suspended sediment in the river between Cornwall and Valleyfield as evidence for sediment accumulation in Lac St. Francois. This report also draws attention to the frequent dredging necessary to maintain safe navigation depths in this region as evidence for sediment accumulation there. Frenette and Verrette (1976) conclude that much of the relatively high suspended sediment inflow from the Chateaugai River is deposited in Lac St. Louis. They also contend that sediments entering Lac St.Louis from the Ottawa River is relatively low, due mainly to the trapping effect of the Carillon Dam just upstream. Bottom sediment survey and sediment trap data for this lake are now being prepared for publication (N.A. Rukavina and N.M. Charlton, NWRI, pers. comm., 1988) are available for this lake. It is interesting to note that measured suspended sediment loads at Varennes, immediately east of Montreal (Table 3) are virtually the same as those at Cornwall. When the inputs located within this reach are taken into account (Ottawa and Chateaugai Rivers), this relationship supports the view that net deposition is taking place in Lac St.Louis, at least some of the time.

On the other hand, Sloterdijk (1983) and Couillard (1982) cite the predominance of coarse sandy deposits in these lakes as indications that they are not major sediment sinks. This view is supported by core data collected in Lac St. Louis by Rukavina (1986). Sediment thicknesses overlying glacial sediments or bedrock were found to be less than 15 cm; in the navigation channel they were even less. These data suggest that Lac St. Louis acts over the long term as a conduit for sediments coming into it from upstream sources.

b. Alluvial zone (Montreal - Trois Rivières)

In this zone, the river has a flatter gradient, although its course still remains fairly straight. Because of the presence of some large islands, e.g. Montreal Island, the channel is divided in two; the main channel runs along the south side of the river, and is maintained to a depth of approximately 11 m by dredging. Inflows from tributaries north of the river (e.g., Ottawa and Asomption Rivers) remain virtually unmixed with the main river for long distances downstream and tend to follow the northern channel. Although deposition takes place along the shore zone of the river, assisted by seasonal flooding, flow in the channels is fast enough that no modern sediment accumulates, and the bottom is floored by Champlain Sea clay. The northern channel is floored by coarser materials, probably brought in by the above major tributaries, or derived by shore erosion which is intense in this area. Bottom sediment surveys in the area are sketchy (Cremer, 1979), and the intense dredging makes any further generalization on surface sediment distribution questionable.

The major site of sediment deposition in this zone appears to be Lac St. Pierre (Cremer, 1979; Serodes, 1976). Into this widening of the river, suspended sediments flow from important tributaries such as the Richlieu, Yamaska, St. Francois, and Nicolet Rivers, in addition to the upstream St. Lawrence. Most of the sediments carried by the St. Lawrence are deposited in the vicinity of the Sorel delta, at the entrance to Lac St. Pierre (Fig. 1), and this material contributes to the growth of the large number of islands at this point. Other sites of alluvial sedimentation (fine sand and silt) are located along the south side of the "lake" close to shore, and these are supplied mainly by inflows from the four tributary rivers mentioned above. The thickness of these deposits decrease toward the central portions of the lake, where the bottom sediments are characterized by a thin cover of alluvial materials overlying Champlain Sea clay. In fact, the central areas of the "lake" are apparently accumulating very little modern sediments (Serodes, 1976). As for coarser sediments, only in the area of the lake close to the outflow are deposits of coarse sand and gravel important, reflecting bottom erosion due to increasing current and wave action in this area. Most of this coarse material, however, is derived from erosion of the relict delta of the ancestral St. Maurice River, which forms the northern shoreline.

Estuarine sector (Trois Rivières - Saguenay Fjord)

The estuarine sector of the St.Lawrence is divided into 3 sections: the fluvial estuary; the upper estuary (or estuaire moyen in French terminology); and the lower estuary (estuaire maritime)(Figure 2). This subdivision of the estuary, most recently used by Lucotte (198-) and Hamblin et al. (1988), has apparently superceded the two-part (lower and upper) classification used by earlier authors (d'Anglejan and Brisebois, 1974; d'Anglejan et al., 1973). Because the area covered by this review ends at the Saguenay Fjord, only the first two sections (fluvial and upper) will be discussed.

a. Fluvial estuary (Trois Rivières - Quebec)

The major change in the river at this point is the increasing effect of tides on the river hydrology. The river is characterized by a more sinuous channel, a more variable width, and the bottom topography is a more complex mix of shoals and channels. In the area near Trois-Rivières, the channel is rather shallow and requires much dredging. Near Quebec, the river reaches its minimum width and maximum depths, and occupies its original pre-glacial bedrock channel.

Because of the effect of tides, especially the ebb tide, current velocities are relatively high (60 cm /s to 3 m/s) depending on tidal phase and location in the section (Cremer, 1979). When the turbulence generated by the passage of ships through this relatively narrow section is also added in, it is not surprising that this section is characterized by net erosion, both of the channel and the shoreline. The bottom sediments consist of either bedrock, or a very resistant cover of lag materials (coarse sand to cobbles). However, the necessity for dredging of the channel indicates that even such materials can be moved as bedload, and deposited in the channel by the swift currents in this area. What little fine-sediment deposition that takes place is confined to local backwater zones along the shore. Processes and sediments on this section are described in more detail in Pelletier (1982), and Long et al., 1980.

b. Upper estuary (Québec - Saguenay Fjord)

This section comprises the brackish-water, tide-dominated section of the estuary. In addition to the tidal influence, this area is marked by an abrupt widening of the river from less than 5 km at Quebec to more than 20 km at Ile-aux-Coudres, 100 km downstream. At Quebec, the river splits into 2 distinct channels to bypass Ile d'Orleans: north and south - the wider, shallower south channel carrying approximately 90% of the total flow. Past Ile d'Orleans the south channel branches into two, with the north traverse arm turning north to rejoin the north channel, now very deep and rock-bound. The north traverse and the north channel comprise the main navigation route east of Ile d'Orleans. Intense dredging is required to keep the north traverse open. The shallower south channel continues downstream to near St.Jean-Port-Joli, where it turns north to join the middle and north channel seaward of Ile aux Coudres. Downstream, the combined channel is split again into two channels by prominent shoals and islands. The sinuous and irregular nature of the flows create sheltered zones of fine sediment accumulation on the intertidal flats along the shore and around the islands. These shallow zones are exposed at low tide as extensive muddy tidal flats, e.g. near Montmagny on the south shore (Dionne, 1985; Serodes, 1980).

The sediment dynamics in the area reflects the complex and energetic circulation environment of the upper estuary. In addition to unidirectional fluvial currents and semi-diurnal tidal reversals, the effect of waves is also becoming important. Generally the circulation pattern is anti-clockwise, with net transport inward along the north shore and outward along the south shore. The bottom sediments of the upper estuary are distributed in a complex manner, with large areas covered by lag coarse materials or glacial clay (Brisebois, 1975; d'Anglejan, et al., 1974). Both Serodes (1980) and Dionne (1985) conclude that deposition on these intertidal areas is seasonal, and is controlled by the seasonal presence of vegetation on the flats. Net accumulation occurs during the months of June - September, and erosion from October to March. The other months are marked by a quasi-stability. He estimates the accumulation during the summer months at 2.7×10^6 tonnes. Other areas of fine-sediment deposition were noted in the south channel and in the channel north of Ile d'Orleans. Studies on these fine sediments (CENTREAU,

1975) indicate that these sediments have high levels of cesium, DDT, and organic matter. Local sedimentation rates were measured at more than 1 cm/y.

In the areas more exposed to intense currents and tides, coarser, bedload sediments are also transported in large quantities. Between Ile d'Orleans and Ile-aux-Coudres, a broad shallow platform, less than 10 m in depth occurs. This platform is covered by migrating sand waves and dunes, some of which can reach wavelengths of 100 m and amplitudes of 12 m (d'Anglejan et al., 1973). The coarse material is mostly relict deposits eroded from the pre-existing glacial sediments. In localized areas, these coarse sediments have significant fine mud fractions. In any event, the presence of unfilled depressions in the north channel suggests that net sedimentation is generally low, and that most of the sediment load is by-passing the upper estuary, to be deposited in the lower estuary and the Gulf of St.Lawrence (d'Anglejan, et al., 1973). This conclusion is supported by the small thicknesses of modern sediment (almost always <20 m) d'Anglejan and colleagues found overlying the glacial surface.

The region between Quebec and Ile-aux-Coudres is important as it constitutes the transition zone between marine and fluvial waters. It is therefore a site of enhanced turbidity, where salinity-related processes such as sediment flocculation and coagulation intensify, greatly changing the settling characteristics of the sediments. This zone of abrupt increase in turbidity is referred to as the maximum turbidity zone (MTZ). Soucy et al. (1976) were the first to describe the MTZ of the estuary and to relate it to sediment flocculation and recycling due to residual gravitational circulation, especially the latter. d'Anglejan and Smith (1973) related surface and bottom suspended sediment distributions to vertical density differences over the tidal cycle. The turbidity increase is enhanced by the strong reversing currents which typify this section. Kranck (1979) stated that the increased turbidity is maintained by the the asymmetry in the tidal currents, in which there is a net residual current along the bottom directed upstream (at the flood tide) against the river flow. This result was confirmed by more recent studies (Hamblin <u>et al.</u>, 1988) of suspended sediment concentration and current profiles over several tidal cycles.

d'Anglejan and Ingram (1976) found that, insofar as sediment transport was concerned, horizontal advection is more important than local resuspension over a tidal cycle in the deeper portions of the estuary, and that maximum concentrations were found at mid-depth rather than near the bottom. Silverberg and Sundby (1979) studied the sediments of the entire estuary section to the Saguenay fjord. They noted that maximum turbidity values occurred just after the flood tide. Local resuspension was noted to be more important than horizontal transport in the shallower upper reaches.

d'Anglejan <u>et al.</u> (1973) measured mean suspended sediment concentrations ranging up to 50 mg/L near Quebec. Others have recorded mean concentrations as high as 70 mg/L (Soucy <u>et al.</u>, 1976), and maxima of up to 400 mg/L (Serodes, 1978). These values decline in a seaward direction to around 2 mg/L at the Saguenay Fjord end. The turbidity front cuts the estuary diagonally (east - west) below Ile-aux-Coudres. At the front, the increased turbidity appears to be a permanent feature (concentrations always >10 mg/L).

Microscope examination of the suspended sediment in the MTZ showed that the mean diameter was around 5 m, and few particles were larger than 20 m. Silverberg and Sundby (1979) noted that particle size was more uniform within the turbidity maximum than in the sections upstream and downstream. Kranck (1979) found that in the MTZ, the modal particle size ranged from 10 - 20 µm.

Using the above suspended sediment concentration figures, along with velocity cross-sections in the estuary near the Saguenay Fjord give a total solid transport flux of 0.45 - 0.91 x 10^6 tonnes/year (converted from d'Anglejan <u>et al.</u> (1973)). This figure is clearly lower than the 3.6 x 10^6 tonnes/year estimated by Holeman (1968; shown in Table 1) at Quebec. The difference could indicate some net sedimentation in the upper estuary between these two locations, possibly in the channels and on the extensive tidal flats along the south shore. These tidal flats form the most readily identified sites of sedimentation in the middle estuary. However, observations of the mud content of the ice cover on the tidal flats around Montmagny have also demonstrated that significant quantities of fine sediments (as much as 5 to 6 x 10^6 tonnes/year) incorporated in the winter ice cover may also be exported from these areas with the breakup and departure of the ice in the Spring (Dionne, 1984; Brochu, 1957). These ice-bound fine sediments may come from both the surface of the tidal flat as well as the direct freezing of water in the MTZ offshore. In addition, Dionne identified other significant erosive processes acting on the flats, including intensive human and waterfowl activity (Dionne, 1985f; 1985d). His sediment budget for the middle estuary thus puts the sediment inputs and outputs in quasi-equilibrium, and led him to the same conclusion as d'Anglejan and Sérodes (1989, pers. comm.), namely that there is presently very little permanent mud deposition in the area.

In the remaining part of the sector, i.e. between La Pocatière and Saguenay Fjord, data on sediments are sparser. The bottom materials appear to be dominated by exposed bedrock or glacial sediments, or coarse sands and gravels (Brisebois, 1975; Couillard, 1982). The source of these coarse sands and gravels is believed to be the local glacial materials. Because of the net upstream residual transport on the bottom, some of this material could also be derived from the more seaward parts of the estuary. The two main channels (south and north) are separated by the shoals of the English Bank and Ile-aux-Lièvres. The fine deposits that do accumulate are largely of a transitional or seasonal nature. The deeper channel, referred to as the Ile-aux-Lièvres basin by d'Anglejan (1978), reaches depths of over 100 m and is apparently the main site of fine sediment deposition.

APPENDIX 1

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Table 1. Hydraulic characteristics of major world rivers (from Holeman, 1968, except where otherwise noted)

River / Location	Drainage area (x10^3 km^2)	Average discharge (m^3 / s)	Suspended sediment (x10^3 t/y)
St.Lawrence / Canada	1200	14,200	3,600
McKenzie / Canada	1800*	9,900*	160,000**
Amazon / Brazil	6,100	181,200 (212,000*)	362,900
Congo / Central Africa	4,000	39,600	64,700
Nile / NE Africa	3,000	283	110,500
Volga / USSR	1,300	8,000	18,800
Ganges / India, Bangladesh	1,100	14,100	1,451,500
Yangtse / China	1,000	21,800	500,800

* Hydrological Atlas of Canada (Anonymous, 1975b)
** Brunskill (1974)

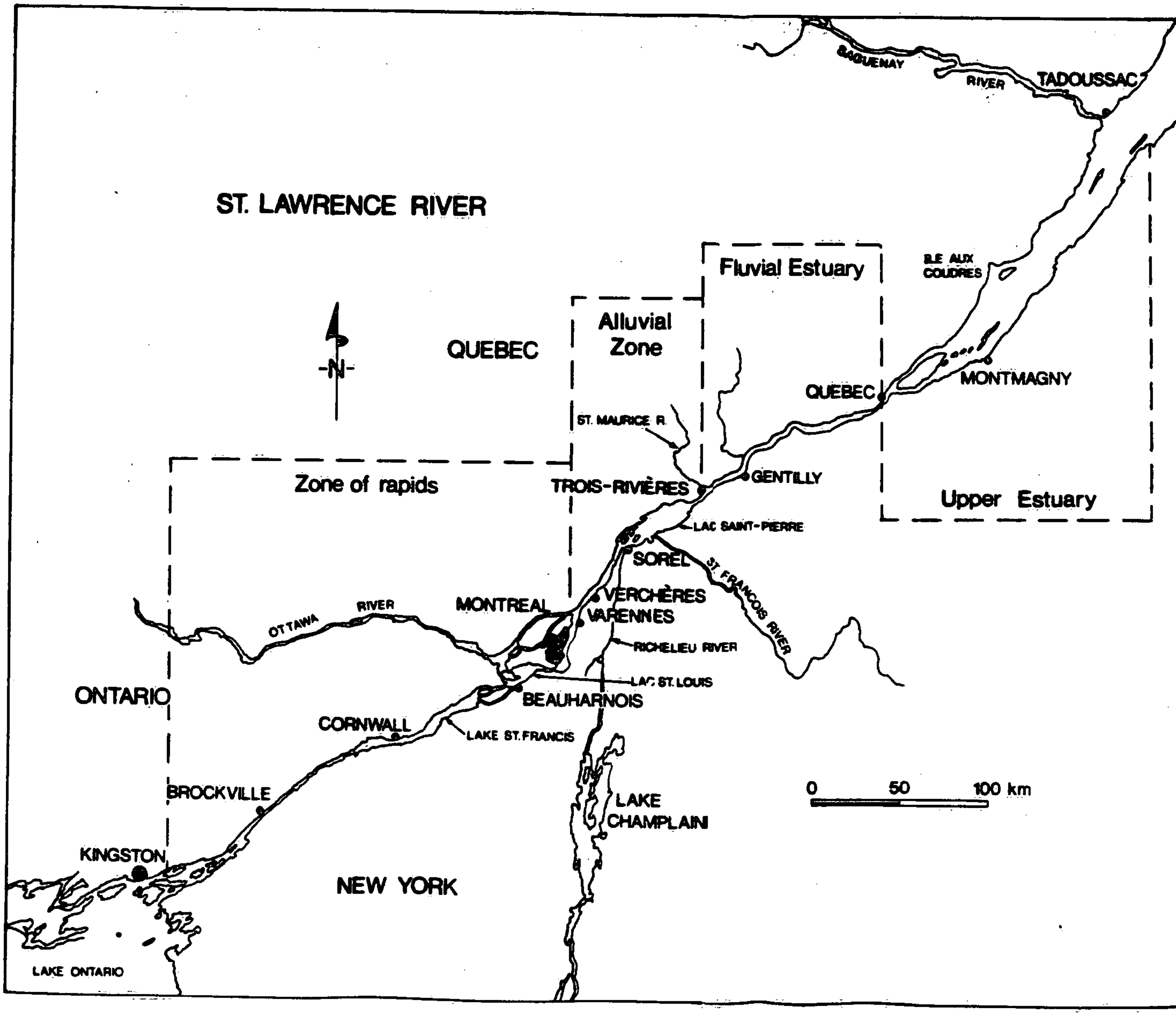

Figure 1. Location map of the St. Lawrence River and upper estuary.