Suspended sediment dynamics of a riverine lake of the St. Lawrence River, Canada

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ABSTRACT Seasonal deposition and remobilization of suspended sediment in river systems causes a short-term discrepancy between upstream and downstream transport rates of sediment and associated contaminants. This study was conducted to evaluate the effect of a riverine lake (Lake St. Pierre) on the suspended sediment transport regime of the St. Lawrence River. Discharges and sediment loads were measured on the St. Lawrence River at the inlet and outlet of the lake, and at the mouths of the four main tributaries to the lake. During the period of summer low flow, there was a net export of suspended sediment from the lake by the St. Lawrence River. Exceptions to this pattern occurred for short periods when high flows, caused by rainstorms in the tributary basins, transported more suspended sediment into Lake St. Pierre than the St. Lawrence river exported. The net sediment export is likely the result of the export from Lake St. Pierre of sediment carried into the lake by the tributaries during the spring melt. As a result, the suspended load of the tributaries is of a constant concern for water quality in the St. Lawrence River, not only during the spring melt when tributary sediment loads are high, but also during the summer when suspended sediment originally derived from the tributaries is remobilized in Lake St. Pierre and transported downstream by the St. Lawrence River.

INTRODUCTION

Suspended sediment plays an crucial role in the transport and cycling of nutrients and contaminants owing to the adsorption capacity of the fine fraction (silt and clay) and organic matter. For this reason, investigating the concentrations, loads, and properties of suspended sediment was made an integral part of the contaminant sampling program undertaken by the St. Lawrence Centre to evaluate the fluxes and fate of contaminants in the St. Lawrence River system.

The St. Lawrence River connects Lake Ontario with the Gulf of St. Lawrence, and can be viewed as a sequence of three shallow, riverine lakes (Lakes St. Francois, St. Louis, and St. Pierre) connected by high discharge, high flow velocity river reaches (Allan, 1986). Part of the sampling program of the St. Lawrence Centre was aimed at evaluating the effect of seasonal deposition and remobilization of suspended sediment in one of these lakes (Lake St. Pierre) on the transport of sediment and contaminants in the particulate phase by the St. Lawrence River.

The seasonal aspects of discontinuous sediment conveyance in river systems have been reviewed by various authors (e.g. Walling, 1983; Meade, 1988; Meade et al., 1990). Generally, deposition of suspended sediment on the bed and along the banks of a river occurs at low and falling discharges, or when the slope of the water surface is low. Remobilization of the sediment takes place during the subsequent period of high or rising discharges, or of high water surface slope. The effect of seasonal deposition and remobilization is a short-term discrepancy between upstream and downstream sediment transport rates. Over the long-term, however, its net effect is nil.

In the case of the St. Lawrence River, the effect of seasonal deposition and remobilization of suspended sediment is expected to be pronounced because of the presence of the three riverine lakes which are prime sites for sediment deposition. The present paper provides information on the dynamics of the suspended sediment budget of one of these lakes (Lake St. Pierre), and shows how seasonal storage and resuspension of suspended sediment within the lake cause a short-term discrepancy between the sediment loads of tributaries and the sediment load of the St. Lawrence River downstream.

STUDY AREA

Lake St. Pierre is located 80 km downstream of Montreal in the centre of the St. Lawrence Lowlands (Fig. 1). The lake is approximately 45 km long and has a maximum width of circa 12 km. A large portion of Lake St. Pierre has a depth of less than 2.5 m. This zone is located along the southeast and northwest shores of the lake. Depths are greater along the fast flowing, central channel, but exceed 9 m in the dredged shipping lane only.

Lake St. Pierre should be viewed as a wide part of the St. Lawrence River rather than as a true lake. Hence, it forms an integral part of the river, and Allan (1986) refers to it and similar features as 'riverine lakes.' Because of the lake's integration into the St. Lawrence River, residence times of water and dissolved substances are short and measured in days (Allan, 1986). The situation is likely quite different for suspended sediment.

LAKE ST. PIERRE SEDIMENT DYNAMICS - PREVIOUS RESEARCH

An estimated 20.5% of the annual suspended sediment load at Quebec City is derived from four Quebec tributaries: the Richelieu River, the Yamaska River, the St. Francois River, and the Nicolet River (Frenette et al., 1989). These four tributaries flow into Lake St. Pierre from the southeast (Fig. 1). The contribution of several tributaries from the northwest is far smaller, and estimated as 2.5% of the annual suspended load (Frenette et al., 1989). The drainage areas of the four southeast shore tributaries are 23,698 km^2 for the Richelieu River, 4843 km^2 for the Yamaska River, 10,230 km^2 for the St. Francois River,

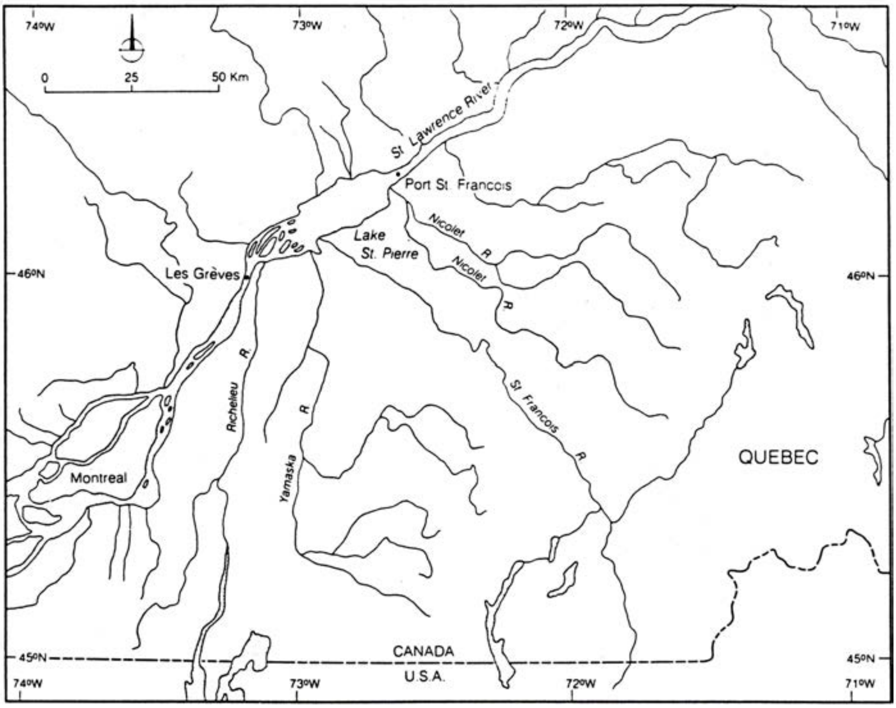

FIG. 1 Location map of the study area.

and 3419 km^2 for the Nicolet River. Each of the basins contains numerous municipal, industrial, and agricultural contaminant sources. The suspended sediment carried by these tributaries therefore has a high potential for contamination and is of considerable interest for the water quality of the St. Lawrence River.

Based on an analysis of sediment load data for tributaries in the region an estimated 60 to 70% of the annual suspended load of the tributaries is transported during the spring melt (Frenette et al., 1989). On springtime satellite images of Lake St. Pierre this tributary contribution is clearly visible as a light colored zone of sediment-rich water along the shores of Lake St. Pierre, which contrasts strongly with the dark-colored, sediment-poor water flowing in the central channel (Bruton et al., 1988). During the summer this pattern is reversed, and a light-colored zone of sediment-rich water is found in the central channel (Bruton et al., 1988). The seasonal variation of the pattern of sediment-rich and sediment-poor water in Lake St. Pierre strongly suggests that suspended sediment carried into the lake by tributaries during the spring melt is temporarily stored within the lake, and subsequently exported by the St. Lawrence River some time later during the summer.

The model of the sediment dynamics of Lake St. Pierre proposed by Bruton et al. (1988) is consistent with the information presented by Allan (1986). The bottom materials of Lake St. Pierre and similar lakes consist mainly of glacial clays, covered with a thin layer of recent sediments with a thickness of usually less then 25 cm. This thin layer of recent sediments is highly susceptible to resuspension, and is mixed completely over its entire thickness owing to bioturbation, waves, and currents (Allan, 1986). The limited thickness and nature of recent sediments indicate that Lake St. Pierre does not function as a long-term storage site for suspended sediment. As a consequence, residence times of suspended sediment in the lake are likely limited to a few months or perhaps years (Allan, 1986).

Suspended sediment concentrations indicate that the interaction between the fast flowing, central portion of the water mass of the St. Lawrence River and the water in the low velocity, shallow, main portion of the lake is limited but far from negligible (De Boer et al., 1991). Waves and currents result in the transfer of sediment to the central water mass, and the role of Lake St. Pierre as a short-term storage site for suspended sediment affects the fluxes and fate of contaminants transported by the St. Lawrence River to a considerable degree. De Boer et al. (1991) used data from Lum et al. (1991) to show that during the summer low flow period the fluxes of Pb and Zn in the central water mass of the St. Lawrence River decreased significantly between the inlet and outlet of Lake St. Pierre. This decrease was explained by the high proportion of Pb and Zn which was transported in the particulate phase, making the flux of these two metals susceptible to depositional effects. In contrast, Cd and Ni, of which a high proportion is transported in the dissolved phase (Lum et al., 1991), were only slightly affected by the passage of the St. Lawrence River through Lake St. Pierre.

METHODOLOGY

Discharge and sediment load data were collected at five sites (Fig. 1). Four of these represent the major inputs of Lake St. Pierre (St. Lawrence River at Les Grèves, and the Richelieu, Yamaska, St. Francois, and Nicolet Rivers). The output of Lake St. Pierre was measured at the fifth site (St. Lawrence River at Port St. Francois). The discharge of the St. Lawrence River was measured weekly from a small boat, whereas tributary discharges were measured daily from bridges close to Lake St. Pierre. Discharges were obtained using standard current meter methods. Discharge data for the four tributaries at several locations upstream of Lake St. Pierre were obtained from the Ministère de l'environnement du Québec (MENVIQ).

On the St. Lawrence River, samples for determining suspended sediment concentrations and contaminants were collected weekly using a depth-integrating bag sampler as described by Meade and Stevens (1990). Sample volume was approximately 1 l. Samples were taken at 10 equidistantly-spaced verticals at each site. Samples were not combined into a cross-section composite, but instead were analyzed individually. For the tributaries, suspended sediment samples were obtained daily with a bag sampler for the Richelieu River, and with a DH-76 depth-integrating sampler for the remaining three tributaries.

RESULTS

Tributaries

For each of the tributaries, two kinds of discharge data were available: (a) a continuous, daily time series of upstream discharges obtained from MENVIQ; and (b) a time series of downstream discharges measured daily close to Lake St. Pierre from 18 September to 30 October 1990.

The downstream discharge time series was extended to cover the period of summer low flow in the following manner: Regression analysis showed that for the period of overlap between the two time series, a simple linear model described the relationship between the daily, upstream discharge and the measured, downstream discharge with a high level of significance for all four tributaries. A continuous time series of downstream discharges was then calculated for the period of interest from the linear model and the continuous time series of upstream discharges. The calculated downstream discharges were subsequently used in the sediment budget for Lake St. Pierre.

The relationship between sediment concentration and measured, downstream discharge was investigated using regression analysis. It was found that this relationship was best described, with a high level of significance, by a multiplicative model for all tributaries but the Yamaska River for which a linear model fitted data best.

The regression models were subsequently used to calculate sediment concentrations and loads at the tributary mouths from the calculated downstream discharges, and the sediment loads were used to establish a sediment budget for Lake St. Pierre.

St. Lawrence River

For both Les Grèves and Port St. Francois, linear interpolation was used to estimate daily discharges and sediment loads for days in between the weekly measurements.

Tidal effects greatly complicated data analysis for Port St. Francois. To negate the daily effect of tide, the discharge and sediment load time series at Port St. Francois were smoothed using a 30-day moving average. A comparison of the untreated (measured and linear interpolation) and the 30-day moving average at Port St. Francois showed that for both discharge and sediment load the 30-day moving average led to a significant smoothing while the overall major trends in the data were conserved. Differences between the measured and smoothed curves were consistent with the tidal phase at the time of measurement, with the measured curve lying above the smoothed curve during falling tide, and below it during rising tide. The application of more sophisticated interpolation and smoothing methods was not justified considering the limited number of data points.

DISCUSSION

For the period from 7 July to 13 September 1990 a daily budget for both discharge and suspended load was calculated from the inputs (St. Lawrence river at Les Grèves, and Richelieu, Yamaska, St. Francois, and Nicolet Rivers) and output (St. Lawrence River at Port St. Francois) of Lake St. Pierre.

Figs. 2 and 3 show the contributions (in %) of each of the four tributaries to the total input of water and suspended sediment of Lake St. Pierre. The fifth contributor is the St. Lawrence River at Les

Grèves, but its contribution is not shown as it is simply the remainder of the total input of 100%. In addition, changes in discharge and sediment load of the St. Lawrence River were relatively small and very gradual so that changes in its relative contribution were dominated by an inverse variation with the rapidly changing tributary contributions.

Each of the four tributaries contributed only a small percentage to the input of water to Lake St. Pierre (Fig. 2). The contribution of the highly regulated Richelieu River was relatively constant, and varied slightly around 3%. The contributions of the remaining three tributaries were much more variable, and showed a well-defined response to rainstorms. The maximum contribution, however, was limited to 6.5% of the total input of water in the case of St. Francois River on 15 August.

The same pattern--a steady contribution of the Richelieu river and much more variable contributions for the other three tributaries--is evident in the tributary contributions of suspended sediment (Fig. 3). Nevertheless, the magnitude of the tributary contributions is considerably larger for suspended sediment than for water. For instance, the Yamaska River contributed 57% of the total input of suspended sediment on 14 August, even though its contribution to the incoming discharge was only 6%. Similar differences were found during low flows. Hence, in spite of their small contribution to the input of water into Lake St. Pierre the tributaries are major contributors to the input of suspended sediment.

A comparison of the actual sediment loads of the tributaries and of the St. Lawrence River (not shown here) confirmed that the sediment transport regimes of the tributaries are much more variable than that of the St. Lawrence River. This contrast can be explained by the

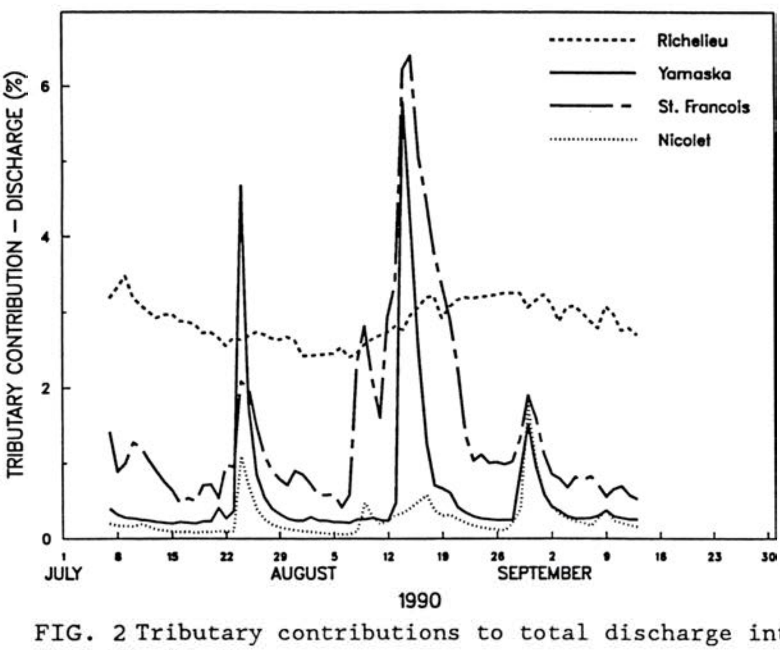

FIG. 2 Tributary contributions to total discharge into Lake St. Pierre.

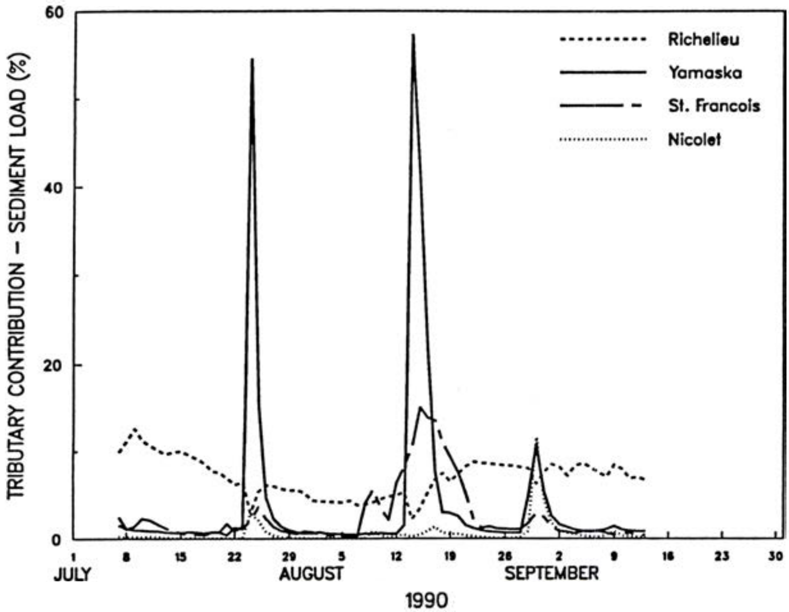

FIG. 3 Tributary contributions to total sediment load transported into Lake St. Pierre.

differences in scale, character, and degree of regulation between the St. Lawrence River and the tributary systems. As a consequence, the sediment budget of Lake St. Pierre can be expected to be highly sensitive to changes in tributary contributions. Rapid changes in the sediment budget, for instance from net export to net import, are unlikely to result from changes in the contribution of the St. Lawrence River.

Fig. 4 shows for both discharge and sediment load the variation through time of the ratio of input and output of Lake St. Pierre. The input/output (io) ratio varied from less than 1, indicating a net export, to greater than 1, indicating a net import. The io ratio for discharge ranged from 0.94 to 1.07, demonstrating that for Lake St. Pierre there was a difference between the input and output of water of maximally 7% over the period of interest. Of course one would expect the difference to be this small, and the io ratio to be close to 1, as a change in the input of water into Lake St. Pierre would rapidly result in a change in output. Nevertheless, the fact that the measured data confirm this expectation instills confidence in the quality of the data, especially in view of the uncertainties in measuring discharges and sediment loads of large rivers.

Conversely, the io ratio for the suspended load ranged from 0.6 to 2.4, making the suspended sediment budget for Lake St. Pierre much more variable than the water budget. The io ratio for suspended load was significantly less than 1 for most of the period of summer low flow, indicating that during this period a net export was the dominant feature of the sediment budget of Lake St. Pierre. Exceptions to this trend occurred in two instances: on July 24 and for a few days around August 14. During these two high magnitude flow events in the tributaries, the io ratio for suspended sediment was considerably

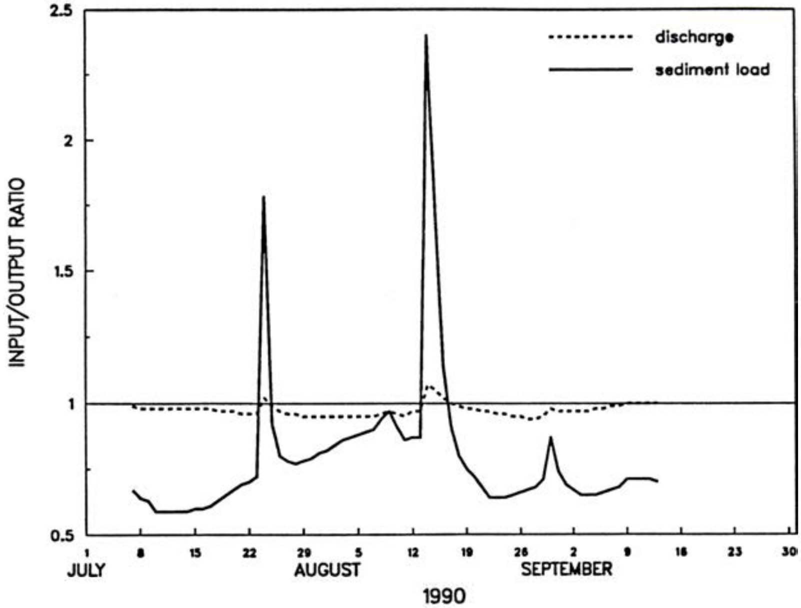

FIG. 4 Ratio of input and output of Lake St. Pierre for discharge and sediment load.

larger than 1, indicating that the import of sediment exceeded the export. Figs. 2 and 3 show that these instances coincided with peak contributions of discharge and sediment load by the tributaries (mainly the Yamaska and St. Francois Rivers). This indicates that during high magnitude events the tributaries transported more suspended sediment into Lake St. Pierre than the St. Lawrence River exported, resulting in a net import of suspended sediment for short periods of time.

In Fig. 4 the effect of a number of smaller storm events is visible in the io ratio as sharp peaks. In these cases the io ratio increased sharply in response to higher discharges and sediment loads from the tributaries but remained less than 1 so that the net export status was maintained.

The net balance of the suspended sediment budget is shown in Fig. 5. The net balance starts at zero at the beginning of the period of interest, and indicates the difference between cumulative import and export. The negative net balance in Fig. 5 indicates that, over the period of interest, there was an overall export of suspended sediment from Lake St. Pierre. The magnitudes of the large sediment inputs on July 24 and around August 14 were not sufficiently high to reverse this prevailing trend.

CONCLUSIONS

A suspended sediment budget for Lake St. Pierre indicates that during the period of summer low flow there was a net export of suspended sediment from the lake by the St. Lawrence River. Exceptions to this pattern occurred when the tributaries during high flows, caused by

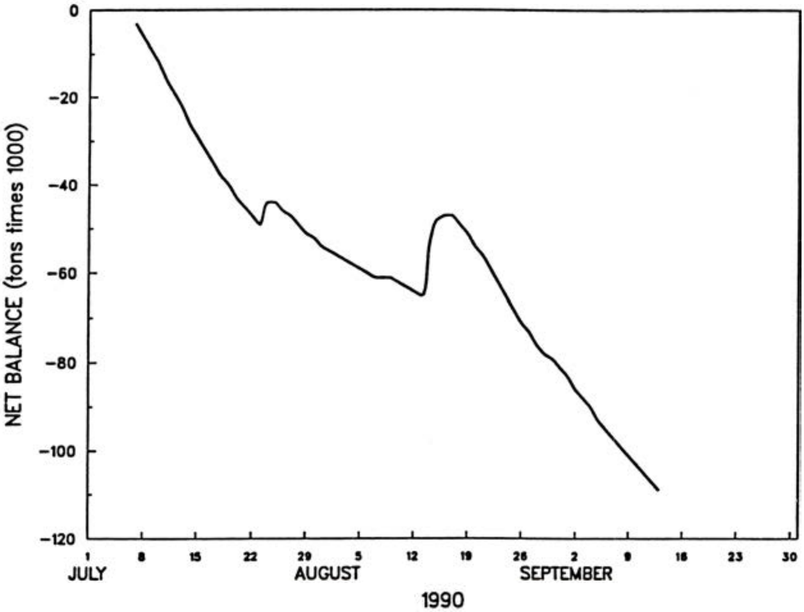

FIG. 5 Net balance of suspended sediment for Lake St. Pierre.

rainstorms in the tributary basins, transported more suspended sediment into Lake St. Pierre than the St. Lawrence River exported. The length of the resulting period of net import of suspended sediment was determined by the magnitude and duration of the tributary flood event, but was maximally a few days long.

Sediment load data for the region indicate that 60 to 70% of the annual suspended load of the tributaries is transported during the spring melt. The high sediment loads of the tributaries during the spring melt suggest that the summer low flow period of net sediment export is the result of the export from Lake St. Pierre by the St. Lawrence River of sediment carried into the lake by the tributaries during the spring melt. As a consequence, a proposed suspended sediment budget for Lake St. Pierre possesses two distinct phases:

(a) during the spring melt, the sediment budget shows a net import of suspended sediment, owing to the high sediment loads of the tributaries which transport more sediment into Lake St. Pierre than the St. Lawrence River exports.

(b) during the summer low flow, a net export of suspended sediment occurs. Sediment loads of the tributaries are low, and the suspended sediment deposited in Lake St. Pierre during the spring melt is now remobilized by waves and currents and transported downstream by the St. Lawrence River.

The sediment dynamics of Lake St. Pierre indicate that sediment export from the lake is controlled by flow conditions in the St. Lawrence River rather than by the tributary discharges and sediment loads. Analysis of spring melt sediment samples is currently in progress. The two phases proposed here on the basis of field data are consistent with the conclusions of Bruton et al. (1988) which were based on an analysis of satellite images.

The suspended sediment load of the tributaries is potentially highly contaminated given the numerous point and non-point contaminant sources in each tributary basin (e.g. Couillard, 1983). Chemical analysis of suspended sediment samples is currently in progress to evaluate the degree of contamination. The effect of the seasonal storage and remobilization of sediment in Lake St. Pierre is that the suspended load of the tributaries is of a constant concern for the water quality in the St. Lawrence River, not only during the spring melt when tributary sediment loads are high, but also, because of remobilization in Lake St. Pierre, during the summer low flow when the tributary sediment loads are low.

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