CGU HS Committee on River Ice Processes and the Environment
18th Workshop on the Hydraulics of Ice Covered Rivers
Quebec City, QC, Canada, August 18-20, 2015

Significance of Javes in Transporting Suspended Sediment during River Ice Breakup

Spyros Beltaos[1]
[1]Watershed Hydrology and Ecology Research Division,
National Water Research Institute, Environment Canada,
867 Lakeshore Road, Burlington, ON, L7R4A6
Spyros.Beltaos@ec.gc.ca

During the highly dynamic flow conditions that often occur during the breakup of the winter ice cover, erosion of channel boundaries by the flow and removal of sediment by floodwaters and runoff-generated overland transport can greatly increase in-stream sediment concentrations and loads, which have significant effects on aquatic ecology and the environment. Javes are sharp waves that accompany the releases of ice jams; they may cause very high flow velocities and shear stresses. However, very limited quantitative information is available on how javes influence the transport of suspended sediment even though their effects on it are visually evident to local observers. Suspended sediment concentrations (SSCs), obtained during a 5-year study of ice and sediment processes in the Saint John River (NB), reveal occasional "spikes" in concentration, consisting of relatively brief upward excursions to nearly order-of-magnitude higher values. Such spikes were almost concurrent with the resulting javes associated with the earlier release of upstream ice jams, as well as with the surface concentrations of rubble in the ensuing ice runs. The purpose of this paper is to present documented cases that form a unique data set demonstrating the existence as well as the temporal and spatial characteristics of these spikes. Taking into account that sediment load involves the product of SSC and water discharge, contributions to total sediment load are expected to be sizeable because javes amplify both quantities. Possible methods of determining water discharge and sediment load during the passage of a jave are discussed.

1. Introduction

When ice breakup is underway, a large increase in sediment content of the water causes visible changes to the colour of the river surface. This is corroborated by sporadic measurements indicating that the SSC (suspended sediment concentration) in rivers can increase many-fold during breakup (Prowse 1993; Beltaos et al. 1994; Milburn and Prowse 1996).

Large concentrations of suspended sediment at breakup can have both positive and negative effects on aquatic ecology and the environment. During ice breakup, scouring of the bed and banks produced by rapidly moving ice breakup fronts and the removal of material by the flow of flood waters over riparian land increases in-stream sediment concentrations and loads. Dissolved and particulate matter flushed into the river from shorelines and flood plains often contain important nutrients and organic material for lotic food webs. Transport and deposition of these nutrient and organic inputs benefit downstream biotic productivity. However, large sediment concentrations at breakup can also reduce species abundance due to reductions in the quantity and quality of available habitat and to difficulties in feeding. Since various contaminants are absorbed by, or adsorbed on, sediment particles, water quality and aquatic biology are also affected by suspended sediment (Waters 1995). Despite its importance, sediment transport during the breakup of the ice cover remains largely unexplored.

A five year study of ice breakup and jamming along the Saint John River (SJR for short) from the Dickey area in Maine, United States, to Saint Leonard, New Brunswick, Canada, was initiated in December 1992 as a joint project of the National Water Research Institute (NWRI), New Brunswick Power (NBP), and the New Brunswick Department of the Environment (NBDOE). One of the study goals was to obtain information needed for understanding and quantifying ice and sediment processes, their interactions and dependency on river morphology and climatic inputs, as well as their potential impact on the aquatic ecosystem. The need for this kind of information for an economically and ecologically important international river such as the Saint John is accentuated by the issue of climatic variability and change, which has significant implications to the hydrology and thence to the ice regime and ecology of cold-regions rivers (Beltaos and Prowse 20011, 2009; Beltaos and Burrell 2003; Prowse and Beltaos 2002).

Sediment-related measurements focused on suspended sediment concentration and particle size distributions during the breakup events of the study years 1993 to 1997, inclusive. These data were supplemented by bed material information (1993) and by dissolved and total concentrations of seventeen trace metals (1997 breakup event). Changing priorities did not permit full analysis and reporting of this material until now, though partial aspects of the data have been presented at past conference proceedings (Beltaos et al. 1994; Beltaos and Burrell 1999; 2000).

The most striking effect of ice-related processes on the concentrations and loads of suspended sediment is the occurrence of sediment pulses, which appear as brief but very sharp sediment “waves” in sedigraphs, that is graphs of SSC versus time during any particular breakup event (Beltaos and Burrell 2000). These pulses are concurrent with javes that are generated by the releases of ice jams. A causal relationship can be deduced by the fact that javes greatly amplify hydrodynamic and erosional properties of the flow such as velocity, discharge and boundary shear stress.

The objectives of this paper are to present unique data on breakup sediment pulses and their relationship to various javes and ice runs, as well as discuss how to compute associated sediment loads. Following brief descriptions of the study area and methodology, various sedigraphs are presented and discussed in conjunction with concomitant water level hydrographs and approximate surface ice concentration values. Implications of these results to erosional processes during breakup and to computation of pulse sediment loads are considered next. Associated complications and future research needs are identified.

2. **Study area**

The Saint John River basin (drainage area: 55 100 km^2) is an international and interprovincial basin lying in a broad arc across southeastern Quebec, northern Maine (USA), and western New Brunswick. The upper part of the basin is within an Appalachian range peneplain ranging in elevation between 200 m and 325 m and broken by valleys, ridges and peaks underlain by sandstone, shale and limestone. The basin upstream of Dickey, Maine is forested with little development.

The study reach, in which sediment samples were taken, extends along the Saint John River from Dickey, Maine, USA to St.-Leonard, New Brunswick, Canada (Figure 1). Over this stretch of the river are four highway bridges, one at Dickey, and three international bridges: Clair-Ft. Kent (about 48.5 km downstream of Dickey), Edmundston-Madawaska (about 81.9 km downstream of Dickey) and St. Leonard-Van Buren (about 124.1 km downstream from Dickey).

Within the study area, there are three hydrometric stations on the SJR (Table 1): at Dickey, Fort Kent, and Edmundston. The former two stations are operated by USGS (United States Geological Survey) and the third by WSC (Water Survey of Canada). A WSC station located at Grand Falls lies beyond the downstream limit of the study area (Fig. 1), but is also useful for estimating flows downstream of Edmundston. Unlike the other three stations, it is located downstream of the Grand Falls Control Structure (GFCS), a hydropower dam and generating station operated by NB Power.

The mean monthly flows for the SJR at Fort Kent are 75, 110, 744, 923, and 294 m^3/s for the months of February, March, April, May and June (for the period of record 1927 to 2012 inclusive). To determine flow at the Clair bridge site (river km 96.2, Fig. 1) the SJR flow at Fort Kent is reduced by the flow of the Fish River (Table 1), which enters the Saint John 0.8 km downstream of the bridge and 0.5 km upstream of the SJR station.

During most of the past 90 years, a solid ice cover has been the norm from freezeup (late November to early January) until spring breakup (late March to mid-May). Sheet ice thickness at Fort Kent (measured by Environment Canada) averaged 0.29 m in early January (for four years) and 0.48 m in early-March (for six years). The thickness also varies along the river, being largest at Dickey and least within the Fort Kent – Edmundston segment (Beltaos et al. 2003). As in other rivers, the ice cover is mobilized by the increased spring flow, which results from snowmelt runoff that is frequently combined with rain water. On occasion, midwinter thaws result in rain-on-snow events that increase flow and cause breakup, changing antecedent conditions for the spring event (Beltaos 2002; Beltaos et al. 2003).

The 1993, 1994, and 1997 ice seasons developed as expected, with the ice cover forming in December and breaking up in April (Beltaos et al. 1994). Three mid-winter breakup events (one in 1995 and two in 1996) took place during the study's field program from 1992 to 1997 inclusive. While such occurrences complicate the ice regime, they provide important insights about possible impacts of global warming on Canadian rivers (Beltaos and Prowse 2001; Beltaos 2002).

Samples obtained in the stretch between Edmundston and St. Leonard revealed a predominantly sand-gravel river bed, while a large percentage of gravel exists in some channels around islands. Averaged values of D_{50} (median size by weight) were approximately 4.8 mm near mid-stream and 0.8 mm near the banks, while D_{84} was on the average about twice D_{50}. Comprehensive particle size sampling and analyses have indicated that the median and 90th percentile sizes of primary particles in suspension were ~10 and 50 μm while a slight trend to decrease with SSC was detected. There was evidence of flocculation occurring in the river, leading to larger composite particles (flocs), but in situ size measurement with a field particle size analyzer was not possible owing to the presence of moving ice (Beltaos and Burrell 2015).

3. Methodology

During the five field seasons of the SJR ice and sediment study, suspended-sediment sampling was carried out to document the temporal and spatial variation of the SSC using the four bridges spanning the Saint John River in the study area (Fig. 1) as access platforms. Standard 750 mL glass bottles were used for sediment sampling, either by dipping in the river, or using a P72 point-integrating fish-type sampler. The latter method is, of course, the preferred one as it allows a controlled bottle filling rate and provides more representative sediment samples. However, the P-72 can only be deployed where there are no moving ice floes in the river and its use is time consuming. On the other hand, dip samples can be obtained rapidly, even during heavy ice runs. Upon return to the laboratory, samples were filtered (0.45 μm pores). The weight of retained sediment was then determined by subtracting the filter weight (measured one minute after baking the filter at 105°C for one hour) from the weight of filter and sediment (again measured one minute after baking at 105°C for one hour). The difference was then divided by the sample volume to obtain the suspended sediment concentration.

Nearly concurrent with the P-72 deployments, vertical and transverse variations of velocity were measured with a standard WSC current meter. It was thus possible to compute the product of concentration with velocity and integrate over the cross-sectional area to derive the sediment flux and thence the flow-weighted average concentration.

4. Results

4.1. Cross-sectional distributions of velocity and sediment concentration

Vertical and transverse distributions of velocity and SSC were measured at Clair and St. Leonard in 1993, 1994 and 1996 as soon as ice had cleared the site and instruments could be safely deployed from the respective bridges. In addition, velocity-concentration measurements were performed at all four bridges of the study reach in May 1997 in conjunction with deployment of an in situ particle size analyzer (field Malvern unit; Beltaos and Burrell 2015).

Examples of the results of these measurements are illustrated in Figs. 2 and 3. The former presents all five vertical distributions of concentration measured at Clair on April 11, 1993. The concentration generally increases toward the river bed, though the trend is often reversed. At other times, the highest or the lowest concentration may occur at mid-depth. Such variations are difficult to explain without knowledge of the complete 3-dimensional structure of the velocity field as well as the inputs from various tributaries. For instance, the relatively high concentrations at z = 30 m in Fig. 3 are likely due to a sizeable creek that enters on the left bank of the river, some 4 km upstream of the bridge.

Integration of the velocity and of the product of velocity times concentration, first over the vertical and then over the river width, results in the values of flow discharge (Q) and of sediment discharge (G_s), respectively [Q is expressed in m^3/s and G_s in kg/s]. The flow-weighted average SSC, denoted by $<C_s>$, is then given by

$$\langle C_s \rangle = G_s / Q = \frac{\int_A u C_s dA}{\int_A u dA} \qquad [1]$$

in which u = streamwise velocity at any one point in the cross section; and A = area of the cross section. In all of eight such flow-concentration measurements, which were obtained in 1993, 1994, and 1997, the value of $<C_s>$ was very close to the simple arithmetic average of all measured concentrations within the cross-section (maximum deviation = 7%; arithmetic average = $1.019<C_s>$, $R^2 = 0.999$).

At each vertical, a dip sample was also obtained, and the arithmetic average of the corresponding concentrations was found to be strongly related to $<C_s>$

$$\langle C_s \rangle = 1.39 \langle C_{sdip} \rangle \qquad (R^2 = 0.983) \qquad [2]$$

This result indicates that dip-sample concentrations (C_{sdip}) are lower than concentrations in samples obtained with the P-72 point-integrating sampler, likely reflecting a "lag" in the rate at which sediment enters the dip bottle relative to that of the water. Under highly dynamic ice conditions, dip sampling is the only sampling option and Eq. 2 provides a means of estimating the flow-weighted average concentration.

4.2. Suspended sediment concentrations during spring breakup events

Though SSC was measured during the mid-winter breakup events of 1996, no sediment pulses were detected in these data sets. This is consistent with the typical lack of javes in such events because ice jams do not usually release but freeze in place when cold weather resumes following the brief thaw.

Table 2 lists the ranges of SSC values determined during the study at different locations. The highest values were obtained from analysis of single dip samples, taken during ice runs and javes. Much as happens during open-water periods, the rise of flow in the spring is accompanied by a rise in the SSC. The presence of ice in the river does not seem to play a major role in this process, until breakup is initiated and ice jams begin to form and release. Ice jam releases generate javes, which in turn create highly dynamic flow conditions, characterized by amplified flow velocities and boundary shear stresses (Beltaos 2013).

Though not as detailed as those of subsequent years, the 1993 SSC measurements clearly demonstrated that ice jam releases are followed by large sediment “pulses” that produce much higher concentrations than would be expected from the river’s response to runoff. This is illustrated in Fig. 4 where the pulse peaks are seen to be much higher than the runoff-generated peak of about 120 mg/L. With few exceptions the data points in Fig 4 represent averages of 5 or more dip samples; the highest measured SSC value was 615 mg/L (St. Leonard, 1100 h, April 13). Since the 1993 measurements only captured a single point of the first pulse and a few points along the falling limb of the second pulse, the true peak concentrations could well have exceeded the measured values.

These findings are consistent with limited data presented by Prowse (1993) that indicate a gradual SSC rise in the lower Liard River to ~120 mg/L up to May 4, 1987 followed by a value of ~ 1100 mg/L, which was indicated by a sample obtained on May 6. Ice-jam release influence is evinced by the water level record of a nearby gauge (Liard River near the mouth, station No. 10ED002) showing passage of a 2 m jave on May 5. Again, it is possible that the single measured high SSC value was exceeded by the actual peak of the pulse.

Figure 5 summarizes the evolution of the SSC and flow discharge during the 1994 breakup event. The small pulse at Clair on April 16 was preceded by the release of an ice jam located ~39 km upstream. The release occurred at ~1140 h and produced a 0.3 m wave height at the Ft. Kent gauge, which is located 1.3 km downstream of the Clair bridge. The ice from the released jam was arrested again at km 117.2 and its length may have increased considerably after it was first observed to be 3.4 km long (1730 h on the 16th). The new jam likely released very late on the 16th or very early on the 17th, producing a 3-m jave at Fort Kent in the morning of the 17th; the accompanying ice run was starting to thin out at Clair by 0630 h on the 17th and advanced to well beyond St. Leonard (km 20.5), where the large sediment pulse of April 17 was recorded. At St. Leonard, the ice ran at 100% surface concentration for at least 4 hours, starting at 13:45, almost coincident with the SSC peak. Unlike the prolonged heavy run of ice rubble, the SSC decreased to pre-pulse values by ~14:10.

Figure 6 summarizes flow and sediment data for the 1995 breakup event and shows a similar pattern as in the previous years, though the peak runoff-generated concentration is much less than in 1993 and 1994, consistent with a similar comparison of peak flows. The various sediment pulses are again associated with javes, as shown in Fig. 7. Though the jave heights are modest (~0.5 m), the sediment pulses can be so intense as to amplify the SSC several-fold.

Javes are invariably accompanied by ice runs that comprise not only the rubble from the released jam but also ice that may be dislodged by the jave itself as it advances downriver. Consequently, we would expect approximate concurrence of sediment pulses and ice runs. This is illustrated in Fig. 8 for the pulse of April 20, 1995. Unlike the extensive 1994 ice run, the 1995 run was of limited duration, attaining a peak surface concentration of 80% and lasting for ~ 3 hours. This is likely due to the “parent” jam” being relatively short (~ 4 km). The modest jave height of April 20 (Fig. 7) is attributed to the large travel distance (~ 30 km) as well as to the relatively low flow conditions prevailing during the 1995 breakup events (compare discharge hydrographs in Figs. 5 and 6). Though not shown herein, the 1996 and 1997 results also exhibited sediment pulses, all associated with javes and ice runs.

5. Discussion

The preceding findings document the characteristics of breakup sediment pulses and their linkages to javes and ice runs. At the same time, they raise a number of questions, pointing to a need for further study. Of these, the most important relates to the potential impacts of sediment pulses on water quality and thence on river ecology. Such impacts can arise from relatively brief but very high concentrations of suspended sediment and/or from enhancements to the runoff-generated sediment load. For instance, suspended sediment can reduce the light available to photosynthesizing plants thus decreasing primary production, abrade and suffocate periphyton and macrophytes, disrupt respiration and modify the behaviour of invertebrates, reduce the respiratory capacity of fish, and cover redds (nests) or fill interstitial spaces in stream beds thus suffocating fish eggs and fry (Waters 1995; Milhous 1996).

Pulse peaks in upper SJR can range from a few to several times the runoff-generated concentrations, approaching the order of 1 g/L. Since the pulses appear to result from the amplified erosive power of javes, and the latter is largely driven by the backwater caused by the parent jam, one would expect a broad relationship between the latter and pulse peak value. However, measurement of ice jam backwater is inhibited by limitations to river access and time available for water level surveys along an ice jam. A surrogate for backwater is the prevailing flow discharge, which largely determines the magnitude of backwater.

Figure 9 suggests that there is indeed a strong relationship between discharge and pulse peak concentration. Of course, there is considerable scatter in this graph, owing to such additional effects as local channel morphology and slope as well as length of parent jam and its distance to the pulse measurement site. Moreover, the discharge at Fort Kent is not necessarily equal to the discharge at the site of the parent jam; it does, however, provide an indication of the prevailing flow magnitude. A more refined correlation might be possible via estimating backwater using a numerical ice jam model and available information on ice jam location and length as well as extensive channel bathymetry data (obtained in past surveys by NB Power Corporation and by Environment Canada). Local discharge could also be estimated with some degree of certainty using data from the hydrometric gauges listed in Table 1.

Beyond ecological concerns, the physical processes that cause sediment pulses need to be elucidated. Prowse (1993) attributed sharp increases in SSC to two factors: (a) elevated water levels due to ice resistance expose additional bank area to potential erosion; and (b) intensive ice-bank and ice-bed interaction that results from high flow velocities during the passage of a jave. In the present study, typical water velocities during javes were ~ 2 m/s, though 3 m/s was estimated for the most dynamic events that were witnessed. Considering that boundary shear stress is roughly proportional to the square of velocity, and that typical open-water velocities in rivers are ~ 1 m/s, one can easily visualize the erosive power of the jave, which is applied to both the bed and the banks of the river. A third factor could be flood-plain erosion because many ice jams cause inundation of extensive flood-plain areas. Upon jam release, local water levels drop precipitously and floodwater returns to the river at considerable speed, potentially carrying significant amounts of sediment with it. Javes are also capable of mobilizing the generally coarse bed material of upper SJR (Beltaos et al. 2011) but it is not clear whether significant amounts of fine particles are available in the river bed for entrainment (Beltaos and Burrell 2015).

In Fig. 8, the SSC pulse is seen to begin and peak at about the same time as, the ice run. This feature is common to all of the documented pulses. For "light" ice runs, such as the one shown in Fig. 8, the sediment pulse ends later than does the ice run. However, for the heavy 1994 run (100% ice concentration, sustained for hours) the pulse ended shortly after (~25 min) the time when 100% ice concentration was attained. This could be due to grounding of rubble near the river banks and forming a shear surface between itself and the moving rubble; this would shield the banks from further erosion by the flow. This phenomenon does not occur where the ice run does not attain full surface coverage. Of course, no firm conclusions can be made on the basis of a single event and more data are needed to confirm or reject this hypothesis.

Though not clearly shown in Fig. 7, the leading edge of the jave arrives before the leading edge of the sediment pulse and the opposite applies to the respective trailing edges. This is plausible because significant erosion would not occur until the jave has attained a height and velocity that can carry away significantly more sediment than under pre-jave conditions. Once the peak jave height is reached, velocities decline rapidly, while any bank erosion that may be occurring would come from surfaces that have already been eroded, thus limiting sediment supply and causing rapid decrease in SSC.

The sediment load, L, delivered during any runoff event or a sediment pulse is given by

$$L = \int_{T1}^{T2} \langle C_s \rangle Q dt \qquad [3]$$

in which T1 and T2 are the beginning and end times of the event, while $<C_s>$ is the flow-weighted average SSC, as defined earlier (Eq. 1); it can be replaced by the dip-sample concentration C_s via the simple relationship of Eq. 2. At first glance, Figs. 5 and 6 might suggest that the loads delivered in sediment pulses are small relative to runoff-generated loads, owing to the brevity of the pulses. However, one must take into account the fact that the discharge values that apply to pulses are likely much larger than the "carrier" or runoff-generated flows, owing to the amplifying effect of javes (Beltaos 2013).

Flow measurement during jave passage is not, however, possible due to the presence of moving ice on the water surface, which prevents deployment of current metering equipment. An alternative would be to apply a hydrodynamic model to compute jave characteristics. This would require knowledge of the location, extent, and pre-release water level profile of the parent jam. The latter is not often available but could be calculated using an ice jam model, provided adequate calibration data are at hand. A more direct approach, which does not require knowledge of antecedent conditions, would involve the Rising Limb Analysis Method (RLAM), which utilizes the St. Venant equations of motion to determine velocity, flow, and shear stress based on measured water level-time variations, such as are routinely recorded by hydrometric gauges.

Depending on jave magnitude, discharge could easily be doubled (Beltaos 2013) and therefore sediment pulses could deliver significant loads relative to the runoff-generated load, especially where multiple pulses are involved.

The present results suggest that breakup sediment pulses can have significant ecological impacts. However, long-term suspended sediment sampling programs such as carried out by WSC are not geared to record pulse concentrations and loads. Nor is it feasible to carry out pulse measurements as part of a national sediment program, owing to logistical constraints and cost. A practical approach might be to rely on focused short-term studies, leading to development of predictive/modelling capability linking jave characteristics to pulse concentrations.

6. Summary and conclusions

Comprehensive measurements of SSC during the spring breakup of the Saint John River ice cover revealed occasional occurrence of sediment pulses or sharp increases in concentration during the passage of javes and ice runs that result from releases of upstream ice jams. Typically, sediment pulses do not last as long as javes but attain peak concentrations amounting to multiples of pre-pulse values. Using prevailing river flow as an index for the backwater of the parent jam, a strong albeit scattered positive correlation was found between discharge and peak pulse concentration.

Possible sources of pulse sediment include the river banks and bed as well as floodplains that may be inundated by the parent jam. The sharp decrease in pulse SSC during on arrival of a heavy ice run in 1994 was postulated to have been caused by grounding of rubble and shielding the river banks from further erosion. If corroborated by future data, this would point to the banks as the primary source of pulse sediment.

Calculation of loads being delivered by sediment pulses requires knowledge of concomitant discharge values, which are expected to be considerably higher than the daily mean values provided by hydrometric agencies. As jave-induced velocities and discharges are difficult to measure, they could be predicted via sophisticated hydrodynamic modelling applications or more directly by use of the Rising Limb Analysis Method.

At present, breakup pulse concentrations and loads cannot be predicted or documented by routine sampling programs. Implementation of focused short-term studies would help develop the understanding and data needed to build predictive capability.

Acknowledgments

Support for this study has been provided by Environment Canada (EC) and New Brunswick Department of the Environment (NBDOE). The author gratefully acknowledges the participation of Brian Burrell, formerly of NBDOE, in the field data collection program. Thanks are expressed to Roy Gardner of Allagash, Maine and C. R. Peter DeMerchant of Perth-Andover, New Brunswick, for river observations and water sampling during mid-winter and spring breakup events. Gratitude is also expressed to EC and NBDOE technical staff for their assistance in field data collection and laboratory analysis of water samples.

References

Beltaos, S. 2002. Effects of climate on mid-winter ice jams. Hydrological Processes, 16(4): 789-804.

Beltaos, S. 2013. Hydrodynamic characteristics and effects of river waves caused by ice jam releases. Cold Regions Science and Technology 85: 42–55.

Beltaos, S. and Burrell, B.C. 1999. Transport of Metals on Sediment During the Spring Breakup of River Ice. Proc., 14th International Ice Symposium, July 1998, Potsdam, NY, USA, Vol. 2, 793-800.

Beltaos, S. and Burrell, B.C. 2000. Suspended sediment concentrations in the Saint John River during ice breakup. Proceedings, 2000 Annual Conference of the Canadian Society for Civil Engineering, London, Ontario, 235-242.

Beltaos, S. and Burrell, B.C. 2003. Climatic change and river ice breakup. - Can. J. of Civ. Eng., Vol. 30, No. 1, pages 145-155.

Beltaos, S. and Burrell, B.C. 2015. Characteristics of suspended sediment and metal transport during ice breakup, Saint John River, Canada. To be submitted to Cold Regions Science and Technology Journal.

Beltaos, S. and Prowse, T. 2001. Climate impacts on extreme ice jam events in Canadian rivers. Hydrological Sciences Journal, 46(1), February, 157-182.

Beltaos, S. and Prowse, T. 2009. River-ice hydrology in a shrinking cryosphere. Hydrological Processes, 23: 122–144.

Beltaos, S., Burrell, B.C., and Ismail, S. 1994. Ice and sedimentation processes in the Saint John River, Canada. Proc., IAHR International Ice Symposium, Trondheim, Norway, August, Vol. 1, 11-21.

Beltaos, S. Ismail, S. and Burrell, B.C. 2003. Mid-winter breakup and jamming on the upper Saint John River: a case study. Can. J. of Civ. Eng., Vol. 30, No. 1, pages 77-88.

Beltaos, S., Rowsell, R. and Tang, P. 2011. Remote data collection on ice breakup dynamics: Saint John River case study. *Cold Regions Science and Technology* **67**(3): 135-145.

Milburn, D. and Prowse, T.D. 1996. The effect of river-ice breakup on suspended sediment and select trace-element fluxes. Nordic Hydrology, 27, 69-84.

Milhous, Robert T. (1996) Modeling of Instream Flow Needs: the Link Between Sediment and Aquatic Habitat, *Proceedings of the 2nd International Symposium on Habitat Hydraulics, Volume A*, Quebec, June 1996, A319-A330.

Prowse, T.D. (1993) Suspended sediment concentration during breakup, Canadian Journal of Civil Engineering, CSCE, 20(5): 872-875.

Prowse, T. and Beltaos, S. 2002. Climatic control of river-ice hydrology: a review. Hydrological Processes, Volume 16, Issue 4, 805-822.

Waters, T.F. 1995. Sediment in streams: sources, biological effects, and control. Am. Fish Soc. Monogr. No. 7, Bethesda, MD.

Table 1. Hydrometric gauges used in the present study

Station location (River)	Station number	Operated by	Drainage area (km^2)	Mean annual flow (m^3/s)	Period reflected in annual flow calculation
Dickey (SJR)	01010500	USGS	6940	138	1947-2012
Fort Kent (SJR)	01014000	USGS(1)	15300	279	1927-2012
Fort Kent (Fish River)	01AE001	USGS(1)	2260	44	1981-2012
Edmundston (SJR)	01AD004	WSC	15500	327	1968-1979
Grand Falls (SJR)	01AF002	WSC	21900	422	1931-2011

(1) Archived data for this station can also be found at the WSC web site, where the drainage area is given as 14700 km^2

Table 2: Suspended sediment concentrations during spring breakup of the SJR

Year	Value	Measured suspended sediment concentrations (mg/L) at four bridge sites within study reach			
		Dickey	Clair	Edmundston	St. Leonard
1993	# Samples	0	56	0	83
	SSC range	NA	5.2-140	NA	34.3-615
1994	# Samples	19	136	5	43
	SSC range	1.2-228	1.5-756	58.6-88.1	10.7-841
1995	# Samples	7	179	18	13
	SSC range	22.0-148	1.2-198	3.0-77.9	2.5-116
1996	# Samples	65	147	58	65
	SSC range	0.2 - 100	0-416.2	17.3-364	6.7-168
1997	# Samples	71	90	64	10
	SSC range	0 -73.8	0.2 - 230	6.2 - 106	13.2 - 61.9

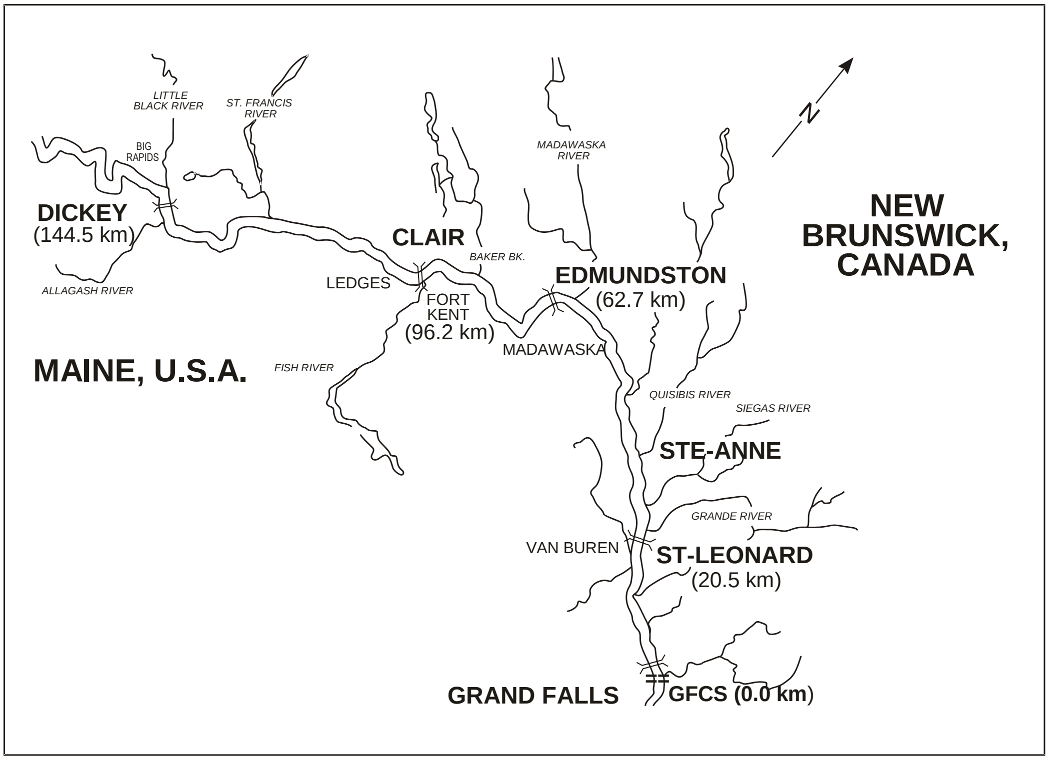

Figure 1. Planview of upper Saint John River between Dickey, Maine and Grand Falls, NB. Channel width has been exaggerated for clarity and is not to scale. Bridge locations are indicated in river kilometres above the Grand Falls Control Structure (GFCS).

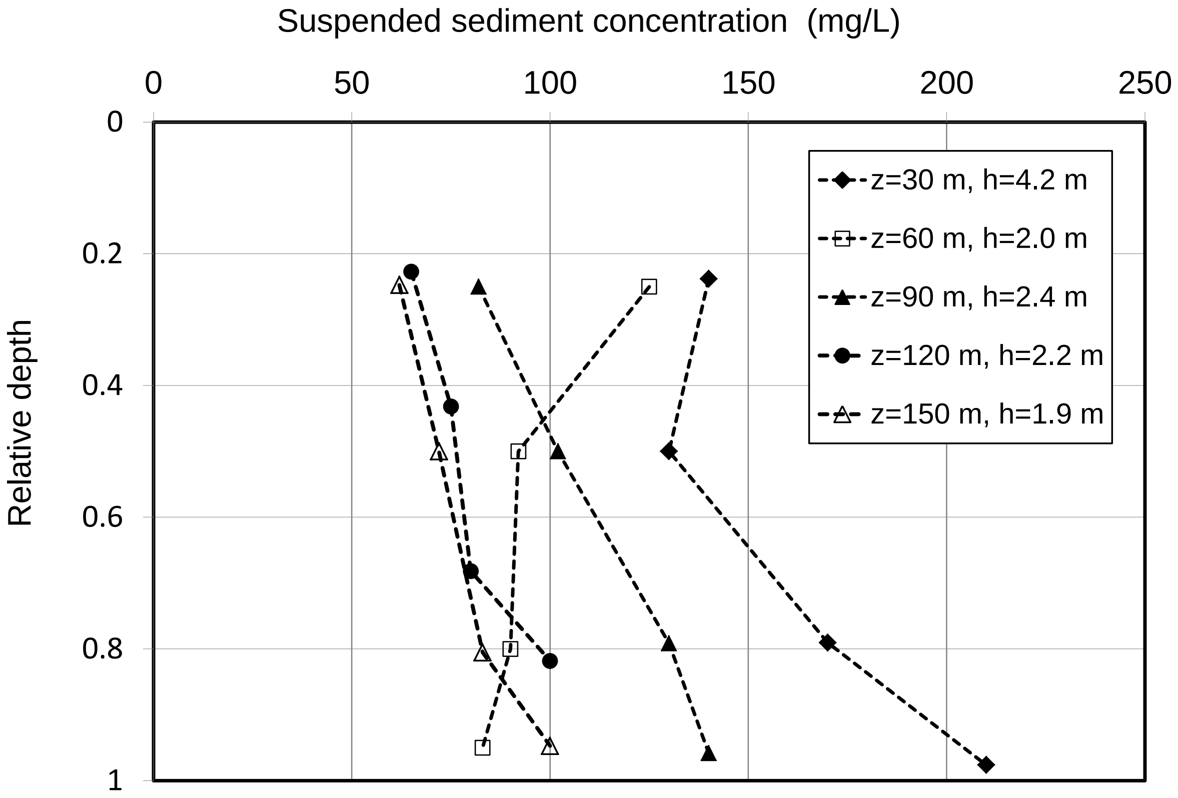

Figure 2. Vertical distributions of suspended sediment concentration near the Clair-Fort Kent bridge, April 11, 1993. z = transverse distance from left water's edge; h = depth of water in vertical; river width = 195 m.

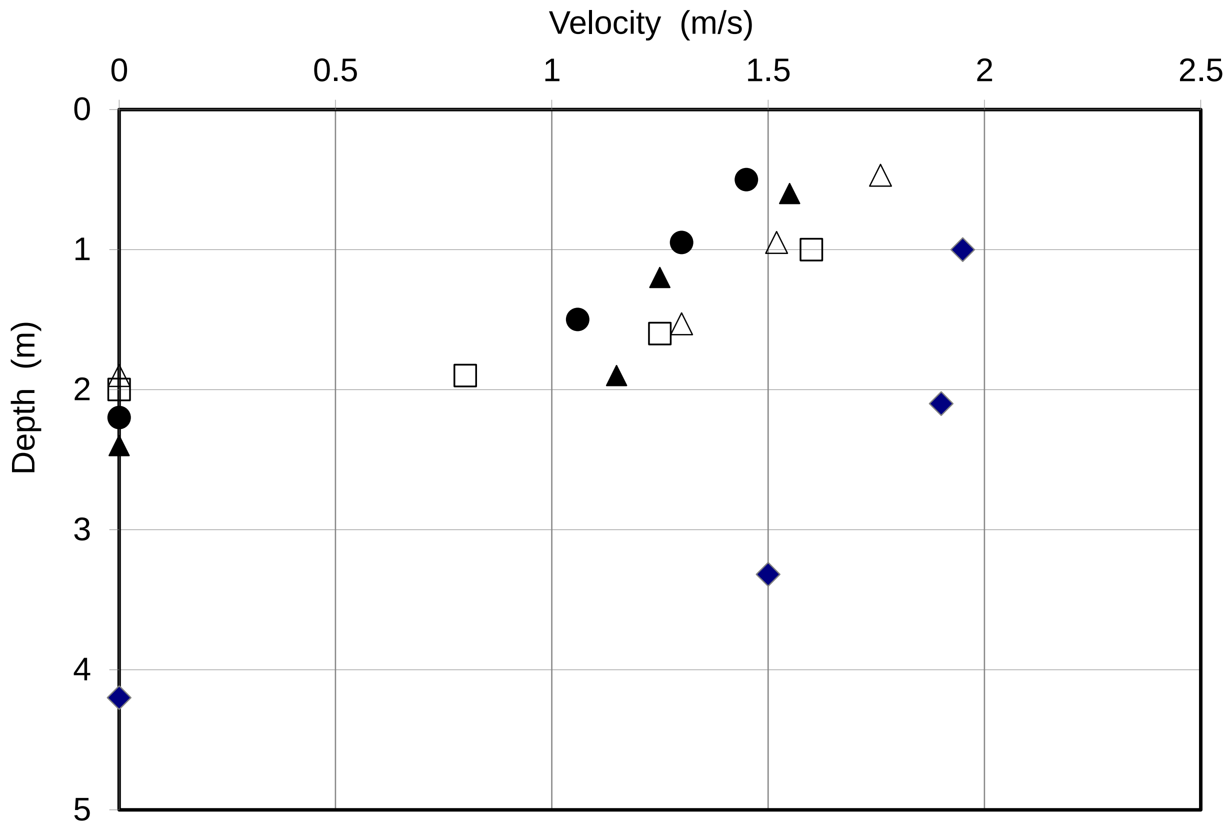

Figure 3. Vertical distributions of velocity near the Clair-Fort Kent bridge, April 11, 1993. Legend same as in previous figure. Zero-velocity points indicate total water depth in each vertical.

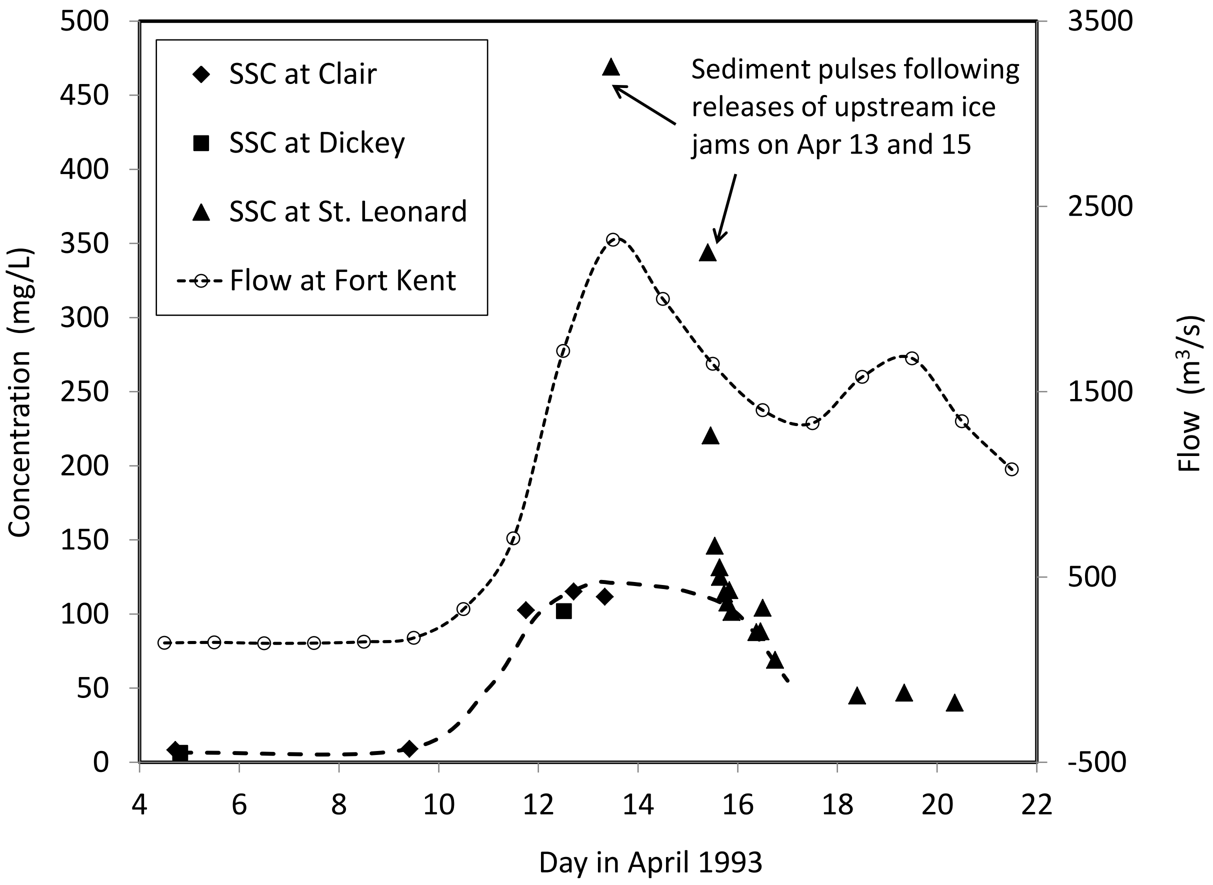

Figure 4. Suspended sediment concentrations and mean daily flows during the 1993 breakup event. SSC values represent dip samples. Abscissa tick marks represent 00:00 h of labelled date. The dashed line approximates the runoff-generated variation of concentration with time. From Beltaos et al 1994, with changes.

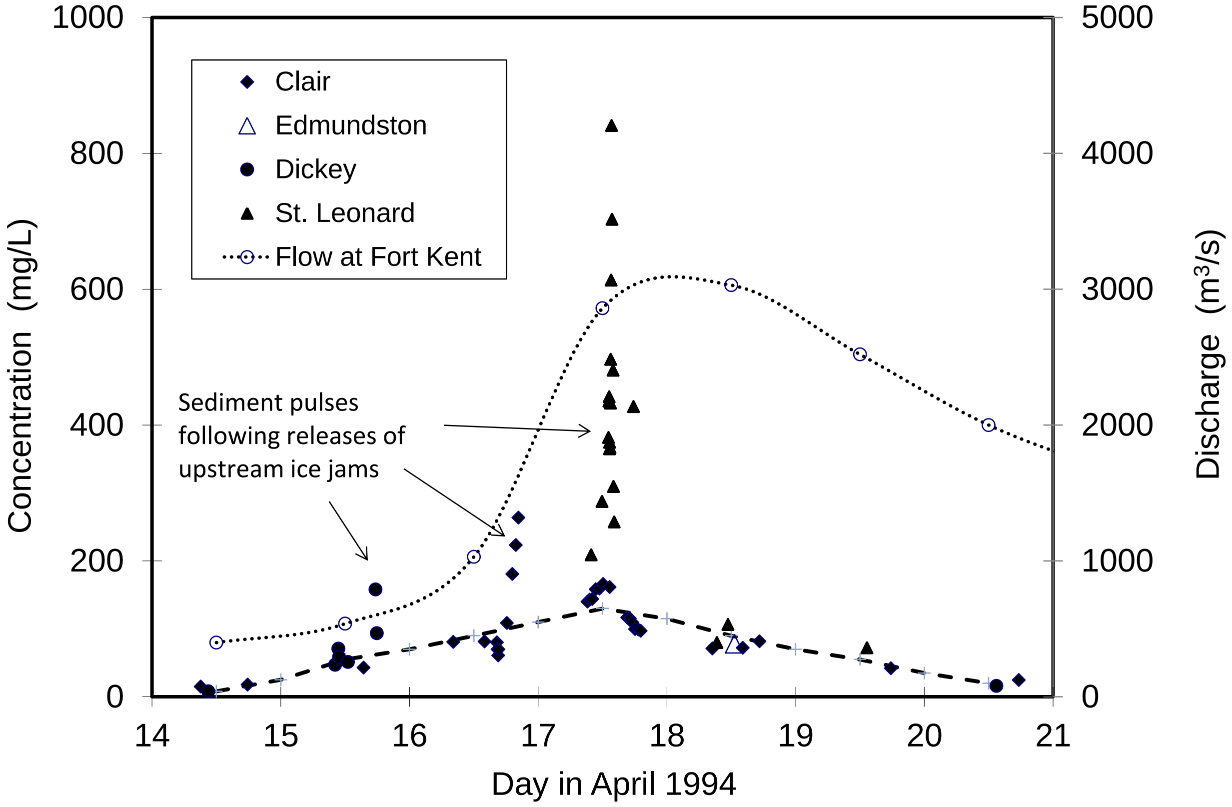

Figure 5. Suspended sediment concentrations and mean daily flows during the 1994 breakup event. SSC values represent dip samples.

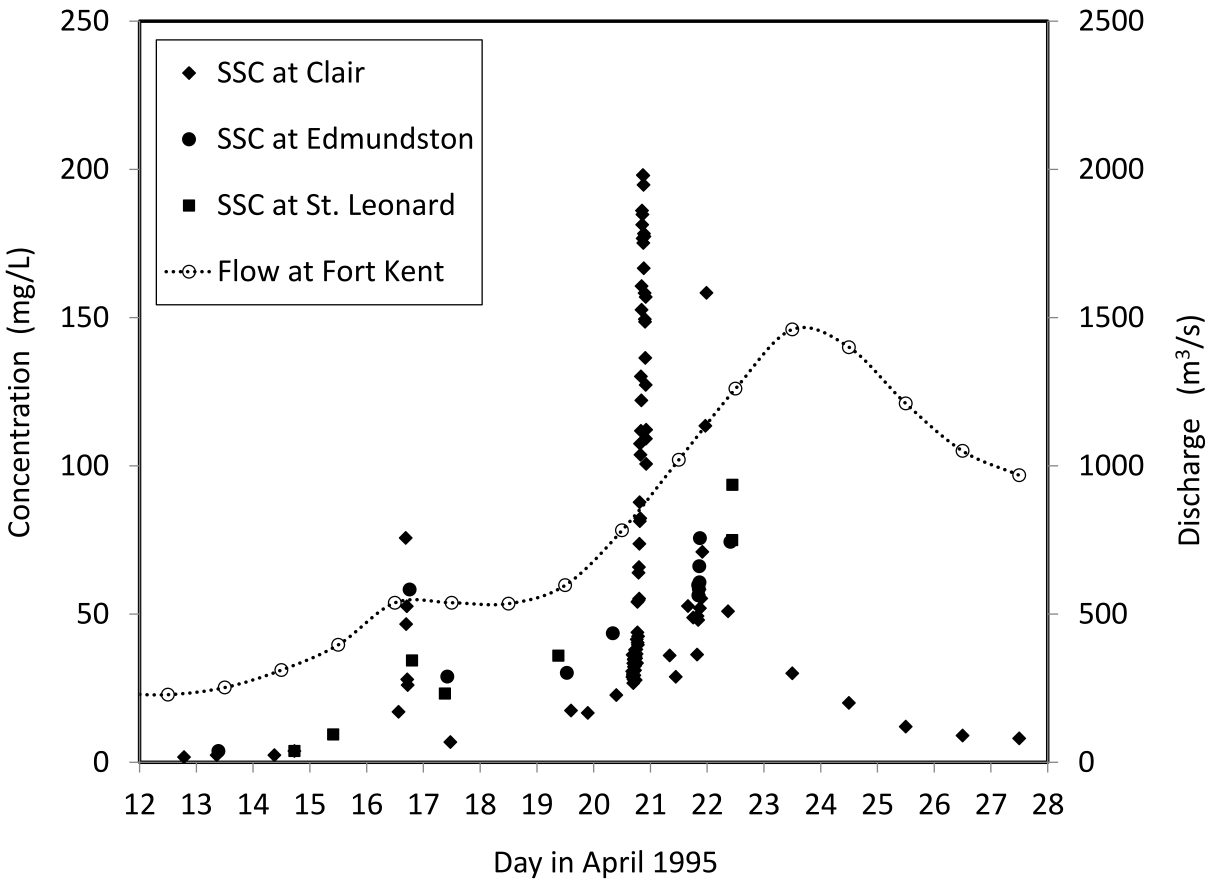

Figure 6. Suspended sediment concentrations and mean daily flows during the 1995 breakup event. SSC values represent dip samples.

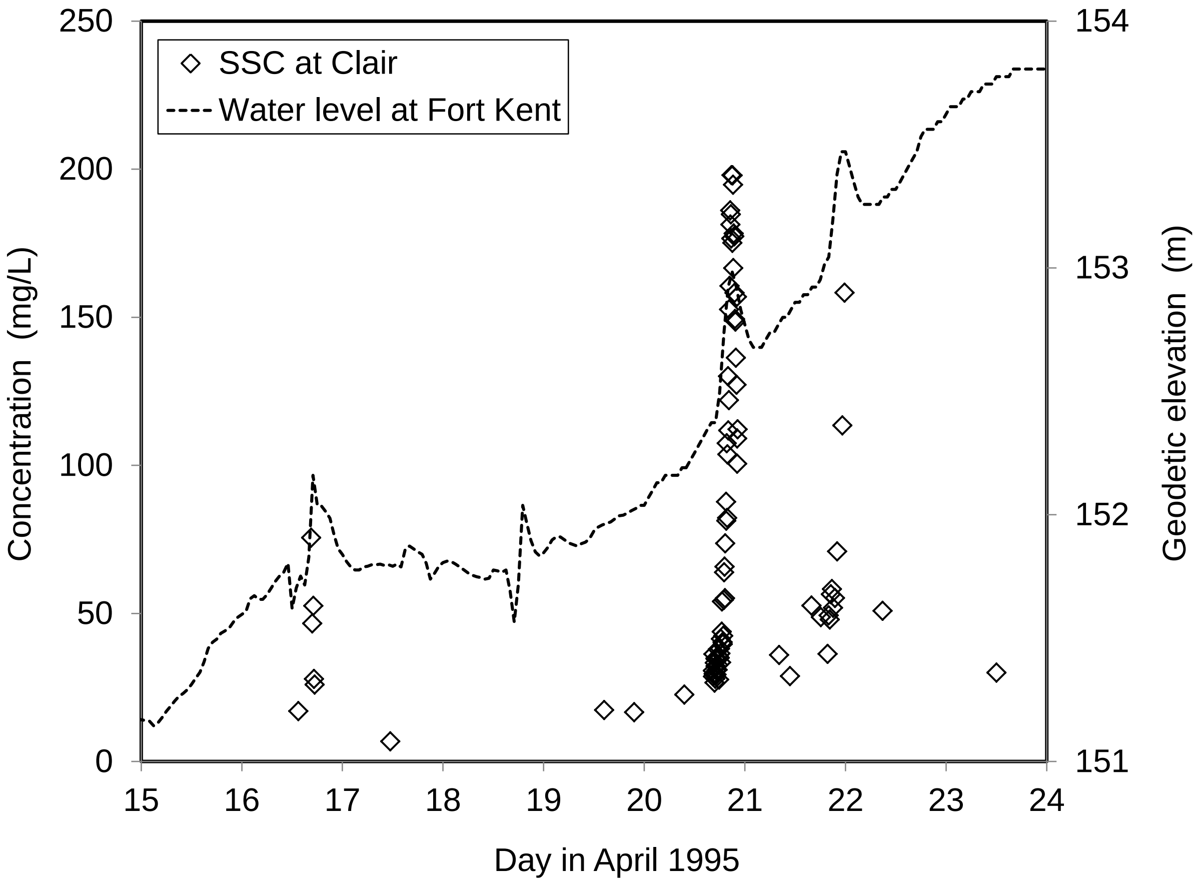

Figure 7. Concurrence of sediment pulses and javes during the 1995 breakup. Fort Kent hydrometric gauge is located 1.3 km downstream of the Clair bridge.

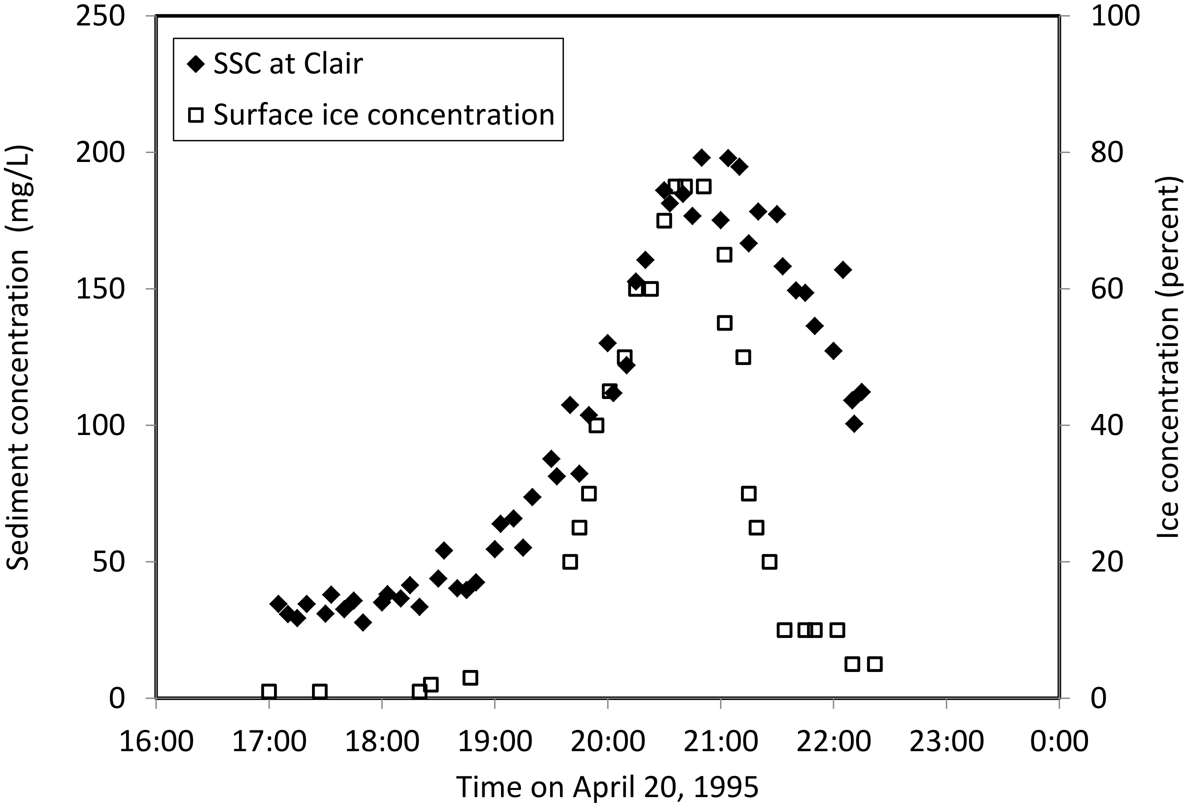

Figure 8. Variations of suspended sediment and surface ice concentrations during the sediment pulse of April 20, 1995. Surface velocity of flow estimated as 2 m/s during the ice run.

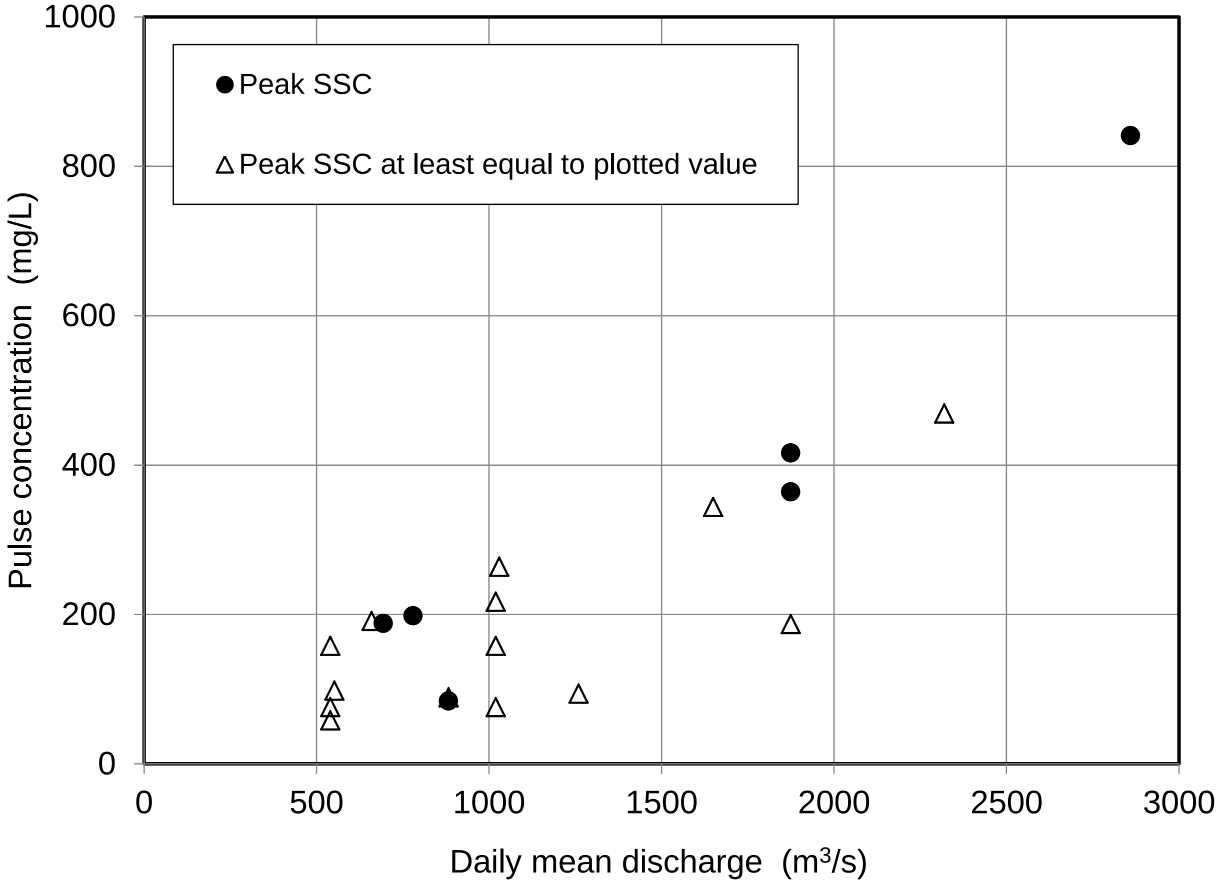

Figure 9. Peak suspended sediment concentrations of breakup pulses in upper SJR plotted versus prevailing daily mean flow at Fort Kent. The triangles describe instances where SSC data are too sparse to allow determination of the peak value.