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Transport of suspended sediment during the breakup of the ice cover, Saint John River, Canada

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ABSTRACT

River concentrations of suspended sediment and particulate contaminants, such as trace metals, increase sharply during ice breakup, with potentially detrimental ecological impacts that may be complicated by changing climatic conditions. To enhance the very limited knowledge on this issue, comprehensive data have been collected on the Saint John River (SJR). During breakup, the suspended sediment concentration (SSC) was found to rise gradually, crest, and decline, roughly in step with the runoff, but occasionally spiked to extremely high peaks. The latter ranged from 4.2 to 6.5 times the runoff-generated peak concentrations (RPCs), which ranged from 35 to 150 mg/L. Peak RPCs and individual-event sediment loads generally increased with flow discharge. The sediment spikes were invariably associated with waves resulting from releases of upstream ice jams and with the ensuing ice runs. Concentration–discharge graphs exhibited pronounced clockwise hysteresis, indicative of sediment supply constraints. This feature is more prominent in high-runoff events and typically associated with a lag of 1–3 days between peak concentration and peak discharge, which arrives later. Prediction of SSC via sediment-rating curves is hopeless, but such curves can be helpful in computing loads associated with individual events using a modified approach that terminates load computation 3 days after the arrival of peak discharge. The bulk of the sediment load is delivered on the rising limb of the hydrograph and is likely to be missed in routine sediment monitoring programs. Practical steps to capture this information are suggested. Increases in SJR spring flows during recent decades are projected to continue under a warming climate, resulting in considerable increases of SSCs and loads by the end of this century.

1. Introduction

Large sediment concentrations in rivers 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 and flood waters over riparian land increases in-stream suspended 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 benefits downstream biotic productivity. However, large sediment concentrations 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 attached to sediment particles, water quality is also affected by suspended sediment concentration. Despite the importance of suspended sediment to river water quality, measurements during the highly dynamic conditions of the breakup period are rare.

As mentioned by Beltaos and Burrell (2016), a five year study of ice breakup and jamming along the upper Saint John River (SJR for short) was initiated in December 1992 as a joint project of the National Water Research Institute (NWRI) of Environment Canada and the New Brunswick Department of the Environment (NBDOE). One of the study goals was to understand and quantify 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 (Beltaos and Prowse, 2009).

Comprehensive sampling and analysis of suspended sediment particles 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, 2016).

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The objective of this paper is to present original data on, and analysis of, suspended sediment concentrations and loads being transported by the Saint John River. The main focus is on runoff-generated quantities. Concentration extremes, or pulses, that are generated by ice jam release waves are noted herein but detailed information and analysis are presented in a companion paper (Beltaos, 2016). Following presentation of background information, the study area and adopted methodology are described. The results of the study are presented next and analytical procedures are developed and tested for predicting sediment loads associated with different runoff-sediment transport events. Knowledge gaps as well as research and monitoring needs are discussed.

2. Background information

2.1. General

Suspended sediment concentrations in rivers vary with location and time. Channel form, particle size, stream velocity, flocculation processes, and sediment sources are factors in the spatial distribution of sediment in rivers. Temporal fluctuations are a function of velocity changes, stream mixing and particle size (Tassone and Lapointe, 1989). Gatto (1995) identified several factors affecting bank erosion during the ice season. Freeze–thaw cycles, and ground ice processes can directly erode bank soils and disrupt bank sediment structure and strength, making banks more susceptible to erosion by other mechanisms in the spring and summer. River ice can abrade in-situ bank soils and shoreline sediments.

2.2. Sediment regime during ice season

Ice cover formation results in changes to flow velocity and shear stress parameters, and thus alterations to mixing processes such as vertical diffusivity and longitudinal dispersion that are important mechanisms for spreading of suspended substances. One of the major consequences is a reduction in sediment transport capability as bed shear stress, velocity and diffusivity decrease (Prowse, 1996). On the other hand, higher stream velocities and ice scouring during breakup result in an increase in suspended sediment concentrations (Milburn and Prowse, 1996). For example, Tywoniuk and Fowler (1972) reported low suspended sediment concentrations and stream flows in Prairie watercourses during the freezeup and winter ice cover periods, with increasing flows and concentrations during the breakup period. The importance of the breakup event has also been stressed in recent comprehensive reviews (Turcotte et al., 2011; Ettema and Kempema, 2013), which discuss the various mechanisms that influence sediment transport in cold-region rivers.

Prowse (1993) found very high SSCs in the Liard River near its confluence with the Mackenzie River during the latter stages of breakup. He attributed this finding to increased exposure of river banks to potential erosion, intensive ice-channel interaction, and large water velocities that prevail during the breakup event. Beltaos et al. (1994) also measured very large concentrations in the SJR, occurring concurrently with the release of an ice jam and the consequent formation of a sharp wave known as "jave" (short for ice jam release wave). This process was fully elucidated in later seasons, as will be discussed later herein and partially reported by Beltaos and Burrell (2000). A limited data set on several pristine Alaska streams indicated that suspended sediment concentration increased in step with discharge during the spring breakup (Toniolo et al., 2013).

2.3. Water quality during breakup

Environment Canada and the New Brunswick Department of the Environment have analyzed water quality samples of the SJR and tributary streams collected during the winter or breakup, as well as open water periods (Beltaos and Burrell, 2016). Cheng and Lockerbie (1994) reported on measurements and modelling of dissolved oxygen levels under ice cover in the SJR. A recent state-of-the-Environment report on the SJR (Kidd et al., 2011) contains no quantitative information pertaining to the breakup period.

Milburn and Prowse (1993) identified rapidly increasing concentrations of some trace metals that tend to parallel the progression of breakup and associated changes in suspended sediment concentrations. Based on data collected during 1993, they concluded that rapid changes in important water quality parameters during river ice breakup have significant potential to alter the freshwater ecosystem. Beltaos and Burrell (1999, 2016) reported on metal sorption onto suspended sediment particles during the period of ice breakup. For most of the 17 metals that were investigated, metal concentrations increased linearly with the concentration of suspended sediment, indicating strong sorptive tendencies.

2.4. Ecosystem effects

Sediment is a major factor in riverine ecosystems. As noted by Waters (1995), suspended sediment can: reduce the light available to photosynthesizing plants thus decreasing primary production; abrade and suffocate periphyton and macrophytes; reduce the respiratory capacity of fish and modify the behaviour of invertebrates. The effects of suspended sediment on fish and fish habitat are discussed in several papers (e.g. Robertson et al., 2006, Waters, 1995). Sediment transportation and deposition can cause changes in channel morphology and the creation or loss of aquatic habitat (Robertson et al., 2006). Milhous (1996) listed the effects sediment has on aquatic animals. The spawning of many fish species will be unsuccessful if the stream bed is covered with sand or fine gravel before spawning, or if the eggs are covered after spawning. Furthermore, some species of amphibians cannot use voids within a cobble/boulder bed if these voids are filled with sediment. From an ecological standpoint, a critical time period often exists during which fine sediment or sand should not be deposited on the stream bed or during which sand and fines should be removed by the flow from the stream bed. Large sediment concentrations at breakup can also have positive effects on aquatic ecology via nutrient and organic inputs that enhance ecosystem productivity (Prowse, 1996).

3. Study area

The SJR 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 stretch of the SJR, in which sediment samples were taken, extends along the SJR from Dickey, Maine, USA to St. Leonard, New Brunswick, Canada (Fig. 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).

During August 1993, thirty bed material samples were obtained in the stretch between Edmundston and St. Leonard. Size analysis showed that this stretch of the river has a predominantly sand-gravel 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 1.1 mm near the banks, while D_{84} was on the average about three times D_{50}. Bimodal grain size distributions for individual samples were rare while most samples were dominated either by gravel or by sand sizes (see also Beltaos and Burrell, 2016). The D_{50} value of 4.8 mm (fine gravel) falls into the gap between sand and medium gravel.