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Extreme sediment pulses during ice breakup, Saint John River, Canada

Spyros Beltaos

Watershed Hydrology and Ecology Research Division, National Water Research Institute, Environment Canada, Burlington, Ontario, Canada

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ABSTRACT

Highly dynamic flow conditions that often occur during the river ice breakup can cause greatly increased instream sediment concentrations and loads, with significant impacts on aquatic ecology and the environment. Sharp waves accompanying the releases of ice jams cause transient but very high flow velocities and shear stresses. However, very limited quantitative information is available on how such ice jam-generated waves (or "javes" for short) influence the transport of suspended sediment even though their effects on it are visually apparent. 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 are concurrent with javes and ice runs. Documented cases of sediment pulses during river ice breakup events in the Saint John River form a unique data set demonstrating temporal and spatial characteristics. Peak SSC values approach 1 g/L and approximately coincide with peak jave stages and surface ice concentrations. Pulse durations amount to several hours, and are shorter than those of the concomitant javes. Despite their brevity, pulses can deliver sediment loads that are significant fractions of the total load for the entire breakup event. Measurement of breakup sediment pulses is not feasible under existing monitoring programs. Instead, focused short-term studies could lead to development of predictive capability, linking pulse properties to hydro-climatic variables that drive the breakup event. A strong influence of river discharge has been detected, leading to projected increases in pulse sediment amounts under a changing climate.

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; Toniolo et al., 2013). The importance of the breakup event was further stressed in comprehensive reviews (Turcotte et al., 2011; Ettema and Kempema, 2013), which discuss the various mechanisms that influence sediment transport in cold-region rivers. High instream sediment concentrations and loads are known to have significant effects on aquatic ecology and the environment. They can, for instance, reduce the light available to photosynthesizing plants thus decreasing primary production; they may abrade and suffocate periphyton and macrophytes or disrupt respiration and modify the behaviour of invertebrates; they could also 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). The need for improved understanding of ice-sediment interactions in rivers is underscored by the changing climatic conditions and the sensitivity of river ice processes to meteorological factors (Beltaos and Burrell, 2003; Beltaos and Prowse, 2009).

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). Extensive suspended sediment sampling was a key component of the field program, as described in the companion paper by Beltaos and Burrell (2016a). The resulting data sets revealed occasional occurrence of sediment pulses, which appear as brief but very sharp sediment "waves" in sedigraphs (graphs of SSC versus time) during any particular breakup event. These pulses are concurrent with javes (sharp water waves generated by the releases of ice jams). A causal relationship can be deduced from the fact that javes greatly amplify hydrodynamic and erosional properties of the flow such as velocity, discharge and boundary shear stress (Beltaos, 2013a).

The objectives of this paper are to: (a) present unique data sets on breakup sediment pulses and their relationships to various javes and associated ice runs; and (b) assess the magnitudes of pulse concentrations and loads, which are primary controls of potentially adverse impacts on habitat and aquatic life. Following brief descriptions of the study area and methodology, various sedigraphs are presented and discussed in

E-mail address: spyros.beltaos@canada.ca.

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conjunction with concomitant water level hydrographs and approximate surface ice concentration values. Temporal relationships among pulses, ice runs, and javes are identified and explained in terms of jave erosion capacity and hydrodynamic flow characteristics. Computation of pulse load, i.e. the amount of sediment delivered by any one pulse is considered next and shown to be possible via application of the Rising Limb Analysis Method (Beltaos and Burrell, 2005b), which enables calculation of the amplified flows that prevail during the passage of a jave. Monitoring gaps are identified next and future research needs are discussed.

2. Background information

A detailed description of the study area, typical river ice conditions, and study methodology is presented in the companion paper by Beltaos and Burrell (2016a); a few key aspects are repeated herein for convenience. The study reach of the SJR extends from Dickey, Maine, USA to St. Leonard, New Brunswick, Canada (Fig. 1). Sediment sampling was carried out from the four highway bridges crossing the river in the study reach, namely at Dickey, Clair–Fort Kent, Edmundston–Madawaska and St. Leonard–Van Buren.

There are three hydrometric stations on the SJR within the study area (at Dickey, Fort Kent, and Edmundston) while a fourth is located at Grand Falls, some 20 km downstream of St. Leonard. Station details are tabulated in Beltaos and Burrell (2016a). 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, which enters the Saint John 0.8 km downstream of the bridge and 0.5 km upstream of the Fort Kent SJR gauge. The river bed consists largely of sand and gravel while the suspended sediment particles (median size ~10 μm) carry significant amounts of trace metals that can far exceed dissolved amounts (Beltaos and Burrell, 2016b).

Suspended sediment concentrations during breakup were principally determined from dip samples since moving ice precluded deployment of a P72 point-integrating fish-type sampler, which is the preferred manner of sediment sampling. The P72 was used under open-water conditions, immediately after the breakup and in summer trips, for detailed measurements of vertical and lateral distributions of concentration at the four bridge sites. Coupled with similar measurements of current velocity and with dip sampling, the point-integrating concentration data enabled development of satisfactory relationships between dip-sample and flow-weighted-average concentrations (Beltaos and Burrell, 2016a).

The highly dynamic conditions that occur during the passage of javes result in amplified velocities, flows and shear stresses, which eventually return to the values they would have if the jave had not occurred. Non-jave breakup conditions comprise variables that are generated by runoff. The term “carrier flow” has been used in the past to denote runoff-generated river discharge, and this practice is also adopted herein. By extension, one may also refer to “carrier velocities” and “carrier concentrations”. The latter usage is particularly convenient as it succinctly describes SSC values that are not affected by javes.

3. Measurements of pulse concentrations and attendant javes and ice runs

Ranges of SSC values determined during the study at different locations are tabulated in Beltaos and Burrell (2016a). Typically, the highest values were obtained from analysis of dip samples taken during ice runs and javes. The first year's (1993) measurements indicated that ice jam releases are followed by large sediment pulses, but were not sufficiently detailed to define complete concentration–time variations. More comprehensive sampling schedules that were adopted in subsequent years resulted in the capture of several pulse sedigraphs, which conclusively demonstrated and quantified the amplification of SSC resulting from ice jam releases. Such increases in sediment concentration are visible to local observers as the colour of the water changes, first to light brown with the rising runoff, and becoming much darker during ice runs.

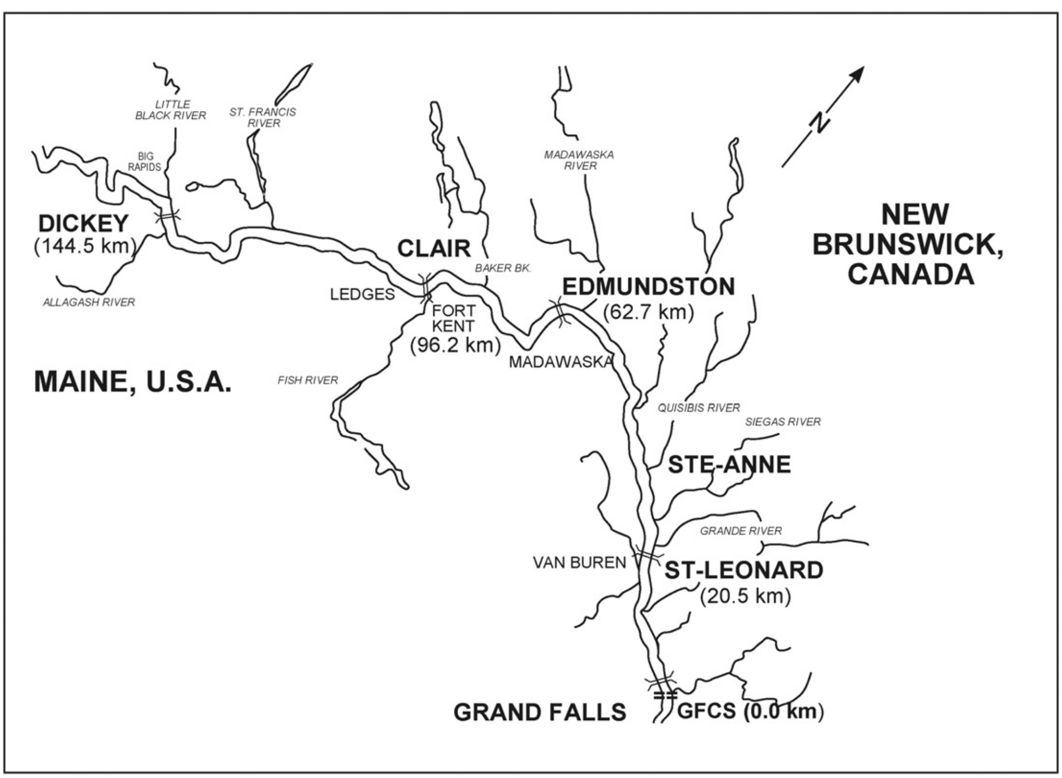

Fig. 1. Planview of upper Saint John River between Dickey, Maine and Grand Falls, New Brunswick. Channel width has been exaggerated for clarity and is not to scale. Bridge locations are indicated in river kilometres above the Grand Falls Control Structure (GFCS).