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Quantifying frazil production, transport and deposition in a gravel-bed river: Case study of the St. Raymond hanging dam

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ABSTRACT

The study of frazil is often triggered by the problems that it causes. Frazil ice is known to block water intakes leading to shutdown of power and pumping stations and to form large accumulations in rivers, obstructing the flow and inducing flooding. In the downtown St. Raymond reach of the St. Anne River (Quebec, Canada), frazil accumulates yearly in the form of a grounded frazil jam or hanging dam. To adequately investigate ice-induced flood mitigation measures, knowledge is needed on the quantity of frazil produced by the river and deposited in town. Therefore, an intensive field campaign was conducted during the winter of 2014–2015 to evaluate the amount of frazil ice transported by the river and deposited in the hanging dam. This paper presents a method to quantify transported frazil ice, combining field samples and a complete heat budget. This method is compared to the theoretical ice production calculated from the heat budget only and to the spatial and vertical quantification of the hanging dam. Resulting from those methods, the 9.2 km-long hanging dam of 610,000 m^3 and 432 kt (kilotons), was estimated to contain about 237 kt of frazil ice, while it was estimated that the river had produced 350 kt (based on the heat budget alone) and transported 66 kt (based on field samples and heat budget) of frazil before mid-winter. Considering the uncertainties inherent to sampling moving frazil and evaluating the spatial river ice coverage, directly measuring frazil in the hanging dam appears to represent the most reliable quantification approach, although very labor-intensive.

1. Introduction

The town of St. Raymond (QC, Canada) has been repeatedly flooded by the St. Anne River since its foundation in the 1890s. To attenuate flood risks, several engineering structures were constructed along the river and various channel modifications were made over the past decades, but their (respective or global) efficiency is difficult to confirm. Most of these interventions were performed in a context of poor (or only partial) understanding of the river's ice regime even though it was known (e.g., Leclerc, 1966) that about 40% of the floods in St. Raymond had occurred in the presence of ice. For example, an ice control structure (ICS) built in 1976 at the upstream edge of the downtown area has only sporadically intercepted ice runs since its completion. Furthermore, the ICS may be partially responsible for increasing the mass of a hanging dam that forms in the downtown area every year, causing serious flooding at and after freezeup (e.g. 2003 and 2005). Another example is a dyke, built in 2009 and designed to protect the downtown area against the 100-year open water (no ice) runoff events, that was overtopped in 2012 and 2014 during breakup ice jam events (ice jams form within and against the downtown hanging dam).

The St. Anne is a gravel-bed river flowing south-westward from the Laurentian hills to the St. Lawrence River. Upstream of St. Raymond (watershed area of about 750 km^2), the River channel alternates from riffle-pool geomorphology (0.2% slope) to rapids (0.6% slope) over several tens of kilometers (Turcotte and Morse, 2015). These reaches produce important amounts of frazil slush that generally make their way down the river. The St. Raymond reach of the St. Anne River is located at the head of a 4.5 km-long reservoir initiated by a 105 m-long concrete overflow dam (spillway) constructed on a rock sill at Chute-Panet (km 0.0). The dam, initially constructed to support a mill (no longer in operation), is equipped with a 3.66 m-wide gate that has a maximum capacity of 40 m^3/s but that is almost never operated for technical reasons. At the beginning of each winter, an ice cover quickly forms in the reservoir by frazil (or snow) slush interception, consolidation and freezing. Subsequent frazil ice then deposits under the ice sheet to form a large hanging dam that eventually extends up to the ICS located at 6.1 km. After a few cold days, the 3 m-high ICS's weir becomes submerged from ever-increasing backwater formed by the hanging dam. Then the grounded frazil jam progresses

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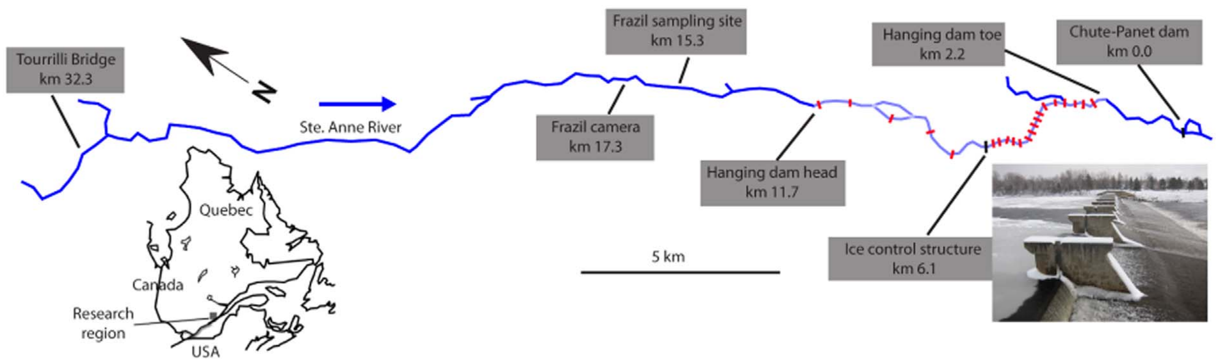

Fig. 1. Map of the study area in St. Raymond (QC, Canada). The St. Anne River and some tributaries are indicated in blue (not actual width), the hanging dam is in lighter blue. The red lines approximately locate the surveyed cross-sections. Downtown Saint-Raymond is located between km 3 to 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

upstream by frazil slush interception and secondary consolidation events along multichannel riffle-pools (km 6.1 to 13.5), a dynamic freezeup process that can last a few days to many weeks depending on hydro-meteorological conditions.

In order to develop adequate ice-induced flooding mitigation measures for St. Raymond (as introduced by Turcotte and Morse (2015)), the objective of this study was to quantify frazil and snow slush fluxes, volumes and masses traveling towards St. Raymond. To respond to this need, an intensive field campaign was conducted during the winter of 2014–2015.

2. Background

A hanging dam is an accumulation of ice (frazil, snow slush, ice floes, released anchor ice, etc.) under an existing ice cover. This accumulation process often takes place in a flat river section that is located downstream of a significant source of frazil generation such as rapids that remain open and exposed to cold air during prolonged periods of time (Beltaos, 2013). Hanging dams can grow to tremendous dimensions: Beltaos and Dean (1981) reported a 300 m-long and 13 m-thick hanging dam in the Smoky river; Gold and Williams (1963) reported a 1200 m-long and 10 m-thick hanging dam in the Ottawa River; Michel and Drouin (1975) measured a 16 km-long 10 m-thick dam in the La Grande River (see Fig. 3.8b, Beltaos, 1995) and more recently Thériault and Taha (2013) reported a hanging dam that generated a 5 m water level increase on the Romaine River.

The ice particle deposition mechanism under the ice cover can be considered analogous to sediment deposition on a river bed, but caused by buoyancy forces instead of gravitational forces (Shen and Wang, 1995). However, sedimentation forms such as dunes, antidunes and ripples have not been found in this inverse sedimentation case (Daly, 1994), possibly because they are difficult to see or possibly because cohesion, mechanical links and freezing between frazil crystals prevent such forms from developing. Beltaos and Dean (1981) quantified hanging dam properties, including shear strength, density and porosity. They constructed an empirical relationship between shear strength and density, both of which increased with height (measured from the bottom up). The measured dry densities varied between 450 and 600 kg/m^3. In the Tanana River in Alaska, White and Lawson (1992) observed a frazil deposition in homogeneous, isotropic layers, suggesting that deposition occurred during discrete events. Horizontal layers varied in thickness between 1 cm and 1.5 m.

Osterkamp (1978) had mentioned: “the most critical need is for instrumentation that can be used to measure the frazil ice concentration in a cross section of a river”. Nowadays, direct measurements of the frazil ice concentration in the flow are still rare. Ford (1984) measured the frazil ice mass concentration in a river by use of a calorimetric frazil ice recorder. Lever et al. (1992) developed another calorimeter in which a known volume of water-frazil mixture was pumped in a chamber, where a screen collected the frazil particles. Pegau et al. (1996) developed an optical instrument to measure frazil but its use has been very limited. The latest tools used to measure suspended frazil concentration in the water column are acoustic. The sonic backscattering data can be related to particle size distribution by laboratory calibration (e.g. Ghobrial et al., 2012; Ghobrial et al., 2013) or by theoretical or empirical scattering models (e.g. Marko and Jasek, 2010; Richard et al., 2011). Richard et al. (2009) and Marko and Jasek (2009) showed that the use of multiple acoustic frequencies improves the estimation of the particle size distribution. Morse and Richard (2009) applied the Rouse suspended sediment model (Rouse, 1937) to previously measured concentration profiles and Richard et al. (2015) compared acoustic measurements to heat transfer calculations. Although acoustic approaches are promising, they are very difficult to perform in shallow gravel-bed rivers and the presence of high turbulence and air content can cause signal interference. Therefore, for this study, frazil concentrations were measured directly using a grab sampling technique and they were complemented by various additional methods.

3. Methodology

3.1. Study area

Study sites along the St. Anne River extended from the Chute-Panet dam (km 0.0) through the downtown St. Raymond area (km 4.5 to km 6.1), across the ICS (km 6.1), and up to the Tourilli River Bridge (km 32.3). Fig. 1 presents an overview of the hanging dam position and extent with some landmarks along the river. Upstream of the reservoir, the downtown reach presents a few riffles with a slope of about 0.05%. Upstream of the ICS, the river channel is characterized by sequences of riffles and pools (gradient of 0.2%) with secondary channels and wide floodplains. From km 13.5 to km 23.5, the river presents a morphology consisting of rapids (0.6% slope) upstream of which the river flattens out (0.2%) and becomes dominated again by riffles and pools. The river width generally varies between 40 and 70 m and its depth during winter is most often limited to less than 0.5 m (with a few 2 m-deep pools along concave banks). As winter progresses, the river's base flow at km 0.0 typically declines from 25 to 10 m^3/s.

While observations were made throughout winter over 32 km and along tributaries, most research efforts were deployed at km 15.3 and between km 0.0 and 12.0. From Nov. 28th, 2014 through Jan. 8th, 2015, riffle-pools and rapids reaches produced different types of ice (border ice, anchor ice, frazil ice) while frazil and snow slush transited downstream and accumulated between km 2.5 and 11.7.