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Multi-day anchor ice cycles and bedload transport in a gravel-bed stream

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SUMMARY

River dynamics in cold regions and the physical processes involving ice formation and release remain relatively understudied topics. Current research suggests that anchor ice forms in diurnal cycles and has the potential to move sediments when released from the bed. Given the importance of river ice dynamics, studies are needed to describe the physical processes of anchor ice and its impact on sediment transport. The study presented in this paper investigated in situ anchor ice formation on the Stoke River in Quebec, Canada. In the fall of 2012, we observed multi-day anchor ice formation cycles and release, which usually ended with a small runoff event. During a cycle, there was little or no release of anchor ice, thus allowing its gradual growth as the air temperature remained cold. Surface and anchor ice layers also often merged, leading to the formation of thick ice masses. Sediment transport was monitored using bed particles individually tagged with passive integrated transponders (PIT-tags). Movement of the experimental particles, measured after each multi-day cycle event, ranged from 0.5 to 4 m. Possible transport mechanisms include: (1) anchor ice rafting, (2) ice jam breakup creating a *jave* with high erosive capacity, (3) flow corridors through anchor ice masses with high erosive capacity, (4) mechanical pushing of particles by drifting ice blocks during ice breakup, and (5) entrainment by flow or drifting ice blocks of anchored ice with strong ice-pebble bonds. Given the coincidental occurrence of anchor ice release and runoff events, it is uncertain which specific mechanism caused the particles to move. This study is a step forward in understanding the behavior of anchor ice processes and ice-related sediment transport.

1. Introduction

Anchor ice formation is a fluvial process common to all cold region rivers during the freeze-up period. Anchor ice is initiated when sticky frazil ice particles, driven downward by water turbulence, adhere to the riverbed. These initial adhesion sites grow through a combination of frazil ice accumulation and *in situ* ice growth (Qu and Doering, 2007) resulting in large continuous, porous, hard sheets of anchor ice on the river bed (Kempema and Ettema, 2010). While Qu and Doering (2007) suggest that anchor ice growth is mainly due to frazil ice attachment, other researchers (Osterkamp and Gosink, 1983; Kempema and Ettema, 2010) suggest that ice crystal growth through heat exchange is a major contributor. Over the last three decades, several studies have contributed to the understanding of anchor ice and its potential impact on engineering structures and natural environments. Marcotte (1984) and Girling and Groeneveld (1999) examined how anchor ice found downstream of a hydropower dam could increase water level, thereby reducing power generation and economic gains. Brown (1999) observed that anchor ice could impact fish populations by forcing them to migrate to ice-free habitats. Prowse (2001) and Huusko et al. (2007) showed that anchor ice can freeze fish eggs and macrophyte stalks. Turcotte and Morse (2011) and Turcotte et al. (2012) discussed how ice-related processes behave differently in steep river basins. They proposed a concept of a watershed cryologic continuum which can lead to a better understanding of different ice processes occurring in a river (Turcotte et al., 2012, 2014). Kempema and Ettema (2013) showed in field study how anchor ice can form on structures like trash racks using wedge-wire screens.

Several studies have attempted to quantify the density of anchor ice (Qu and Doering, 2007; Stickler and Alfredsen, 2009) and model the hydraulic conditions leading to anchor ice formation using dimensionless numbers such as the Froude, **Fr**, and Reynolds, **Re**, numbers (Terada et al., 1999; Doering et al., 2001; Kerr et al., 2002; Qu and Doering, 2007; Bisaillon and Bergeron, 2009; Stickler and Alfredsen, 2009). In most field observations, anchor ice masses formed at night and were released the following day,

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when solar radiation provided sufficient heating for the heat balance of the water temperature to become positive and break the ice-pebble bond (Barnes, 1906; Tsang, 1982; Parkinson, 1984; Daly, 2005; Bisaillon and Bergeron, 2009; Stickler and Alfredsen, 2009; Kempema and Ettema, 2010).

Kempema and Ettema (2010) present a field study where bed particles transported by anchor-ice during winter were larger than those transported hydraulically during the spring flood. The study by Kempema and Ettema (2010) is of particular interest as it provides the first quantitative sediment transport analysis caused by anchor ice processes. However, as mentioned by the authors, further research is required to better understand the contribution of winter sediment transport by ice to the annual sediment transport budget.

Early observations of sediment transport by fluvial anchor ice were made at the beginning of the 20th century. Barnes (1906) was among the first scientists to discuss sediment transport caused by anchor ice: very large boulders were lifted off of the St. Lawrence River bed, at the downstream end of rapids located near Lachine, Quebec, Canada, and were transported in the ship waterways south of Montreal city. Decades later, Osterkamp (1975) suggested that the anchor ice release processes might be important for sediment movement in rivers. Tsang (1982) further suggested the importance of the lifting power (i.e., buoyancy) of anchor ice and its role in total sediment transport in rivers. The study by Kempema and Ettema (2010) is of particular interest as it provides the first quantitative analysis in sediment transport caused by the occurrence of anchor ice processes. They studied, on the Laramie River in Wyoming, anchor-ice rafted sediments ranging from sand to cobbles. They compared particles rafted by anchor ice to those transported by bedload and found that anchor ice transported coarser material than water flow at peak discharges. They also investigated the ability of anchor ice to transport individual pebbles of various sizes. The largest particle rafted by anchor ice had a mean size of 0.20 m and weighed 9.5 kg, while the largest particle collected from the bedload samplers during a spring flood had a mean size of 0.0016 m and weighed 12 g (i.e., two orders of magnitude lower) (Kempema and Ettema, 2010). Using Passive Integrated Transponders (PIT) to monitor particle displacements, Kempema and Ettema (2010) found that 63 particles out of a sample of 128 moved during the winter. To ensure that ice-related processes moved these particles, the authors used larger and heavier particles than those that would be moved by ice-free processes. They concluded from their work that further research is required to better understand the contribution of winter sediment transport by ice to the annual sediment transport budget.

The objective of this study was to analyze the transport of bed particles in relation to cycles of anchor ice formation and release in a coarse gravel-bed river. In this study, the term "sediment" refers to coarse bed material such as gravels and cobbles ranging from 40 mm to 150 mm. Based on our observations and measurements, the formation and release processes for anchor ice were very different from commonly reported diurnal cycles (Tsang, 1982; Bisaillon and Bergeron, 2009; Kempema and Ettema, 2010). This study provides a step forward in our understanding of sediment transport influenced by river ice and provides quantitative observations that are needed to understand anchor ice formation and release.

2. Study site

The study was conducted on a reach of the Stoke River, Québec, Canada (45°34′06″, −71°45′51″). At the study site, the river drains a 51 km^2 watershed composed primarily of woodlands and farmlands. The watershed has a hilly terrain with an average slope of 7%. The study reach is 140 m long and its bankfull width varies from 6 to 12 m. Flow depth can be as low as 0.15 m in winter and late summer and can reach more than 1.5 m during mid-winter and spring thaws. The study reach has several types of morphological units, including a wide and shallow riffle, a narrow riffle, 2 deep pools, and some straight runs with uniform slopes (glide). The average bed slope of the study reach is 0.95%. The reach is lined with forests on each bank, which limits early morning sunlight. However, the river flows in a north–south direction, and it receives a considerable amount of solar radiation during the rest the day. Bed material is composed of gravel particles with a D_{50} of 58 mm (sample size, $n = 202$). This value was determined by measuring the length of the "B" axis for each particle following Wolman's method (1954). Some localized areas with much finer granular material ($D_{50} = 2$ mm) were also present in the reach. The average monthly temperature in this region is −0.2 °C in November, −8.1 °C in December, and −11.9 °C in January (Environment Canada weather station # 7028124).

Within the study reach, 4 sub-reaches of 10 m in length representing homogeneous areas (morphological units) of potential anchor ice formation were identified. Fig. 1 shows the study reach and transects located in the middle of each sub-reach. The characteristics of the 4 sub-reaches are presented in Table 1. Average widths and depths were measured in October 2012 and represent ~90% of bankfull width and ~20% of bankfull depth.

3. Methods

River monitoring was conducted during the winter of 2012–2013. During anchor ice events, the reach was visited once a day early in the morning. Surveys evaluating sediment transport (PIT tag surveys) were conducted after each anchor ice washout event.

Meteorological data were acquired using a weather station located approximately 10 m away from the bank of the river. The weather station had the following instruments: (1) Kipp & Zonen CMP3 pyranometer for measuring solar radiation (*accuracy for daily sums = ±10%*); (2) Campbell Scientific HMP45C temperature and relative humidity probe (*temperature accuracy at 20 °C = ±0.2 °C, relative humidity accuracy at 20 °C = ±2%*); and (3) Campbell Scientific SR50A Sonic Ranging Sensor for water stage measurements (*ultrasonic frequency = 50 kHz, accuracy = ±1 cm or 0.4% of distance to target (whichever is greater)*). The stage sensor was set above the river, 2 m from the shore. The instruments were connected to a datalogger (CR1000, Campbell Scientific) with an acquisition frequency of 720 measurements per hour. A high accuracy temperature logger (Sea-Bird Electronics Inc. SBE56, *accuracy = ±0.002 °C*) was used to record water temperature measurements every minute. Regular maintenance ensured that the probe remained free of plant material and/or ice. The water temperature probe was removed from the river on December 17 to avoid potential loss or damage during mid-winter breakup.

On each visit, photos and observations were used to sketch the distribution of anchor ice and to estimate the relative percentages of surface and anchor ice covers. This subjective evaluation method was applied consistently by the same observer throughout the study. Anchor ice density measurements were obtained on December 13, 2012 ($n = 35$) according to the method described by Qu and Doering (2007) and Stickler and Alfredsen (2009). Anchor ice samples were collected randomly between transects 1 and 2 and weighted on a digital scale. At each sampling location, flow velocities were measured during 2 min at a distance equal to 0.4H from the bed using an electromagnetic current-meter (Marsh-McBirney Flow-Mate 2000, *accuracy = ±2% of reading*).

PIT tags were used to trace particle movements. This method was shown to be very efficient in previous studies given the high