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The transport of sediments by released anchor ice

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A B S T R A C T

The impact of sediment transport by anchor ice release on the annual sediment budgets of rivers is unknown. Sediment transport on regulated rivers could be significant since open water persists throughout the winter season and anchor ice forms and releases often. Studies that quantify the amount of sediment carried or rafted by released anchor ice pans are rare and have been performed on unregulated rivers with significantly different flow regimes, or have few collected samples. In this study, anchor ice samples were collected on three regulated rivers in Alberta: the North Saskatchewan, Peace and Kananaskis River. Previous studies on the amount of sediment contained in anchor ice are discussed and compared. Gravel and cobble sized particles were also sampled from anchor ice pans as they floated by to better understand the largest sediment anchor ice transports. The sampled gravels and cobbles contained in anchor ice showed that 24% of the total sampled mass came from only 1.2% of the particles sampled. The average sediment concentration contained in released, floating anchor ice was found to be 28.2 g/L, with a standard deviation of 33.2 g/L, and a median of 18.4 g/L. This information will allow for more accurate estimations of how transport of sediment by anchor ice releases affects the annual sediment budget on regulated rivers.

1. Introduction

The formation of anchor ice occurs annually on many northern rivers, where turbulent water is exposed to freezing air temperatures. Initially, small frazil crystals are generated and rapidly mixed in the water column as the temperature of the water drops below 0 °C (i.e. the water column becomes supercooled). These frazil crystals are inherently adhesive or "sticky" in nature, and when they come in contact with the bed of a river due to the rapid mixing of the water column, they often freeze in place and begin to form anchor ice through continued frazil accumulation and/or in-situ growth (e.g. Kempema et al., 2008; Qu and Doering, 2007). Anchor ice formation has been observed to alter flow conditions in a river by altering bed roughness and shape (Kerr et al., 2002), and to transport sediment when it is released (Kalke et al., 2015, 2016; Kempema and Ettema, 2011).

Anchor ice formation is common downstream of a hydropower station because the release of warm water (> 0 °C) from the station inhibits ice formation and the river remains open downstream throughout the winter season. This enables frazil and, subsequently, anchor ice to form and release throughout the winter season. This is of interest given that extended periods of anchor ice formation and release alter a rivers winter ice regime. For example, Nafziger et al. (2017) observed different ice regimes between regulated and unregulated streams. It was observed that on regulated streams anchor ice events (formation and release) occurred throughout the winter season, whereas on unregulated streams anchor ice events were limited to before and after the establishment of a solid ice cover (Nafziger et al., 2017). It was also noted that on average the regulated streams experienced more anchor ice events than unregulated streams (Nafziger et al., 2017). Anchor ice formation in the downstream reach can cause local staging at the tailrace that results in large operational losses for the station (e.g. Girling and Groeneveld, 1999). Anchor ice formed in the downstream reach will often release, either due to mechanical or thermal processes, which can impact downstream hydropower stations. For example, Jasek et al. (2015) reported that the release of anchor ice downstream of the W.A.C Bennett and Peace Canyon Dams caused large fluctuations (referred to as anchor ice waves) in water levels and discharge on the Peace River, Alberta. These fluctuations can result in flow restrictions (operational loss) from the dam while the ice cover is developing through the Town of Peace River. This is to ensure a stable ice cover forms and to prevent flooding during freeze-up or break-up (Jasek et al., 2015). Anchor ice releases downstream of the dams can also transport or "raft" sediment. On a regulated river, this could impact the overall sediment budget since anchor ice is formed and released frequently throughout a winter season. However, the overall impact of sediment transported by anchor ice is still unknown, and field studies that attempt to quantify the scale of sediment transported by anchor ice in rivers are rare.

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There have been a few field studies that directly measured the sediment concentration in released anchor ice (Kalke et al., 2015, 2016; Kempema and Ettema, 2011). However, these studies had either small sample quantities (e.g. Kalke et al., 2015, 2016), or were performed on rivers with low winter discharge that may not be comparable to large rivers such as the Peace or North Saskatchewan River (e.g. Kempema and Ettema, 2011). In order to better estimate the impact of anchor ice rafting of sediment to the annual sediment budget downstream of a hydropower station, three regulated rivers were selected for anchor ice sampling in this study: the North Saskatchewan River, the Peace River, and the Kananaskis River. These samples provide data on the size range and concentrations of sediment contained in released anchor ice. This allows for better estimates of sediment transport when used in conjunction with anchor ice surface concentration obtained through digital images. In this study, grab samples of released anchor ice containing sediment were collected during the winters of 2015–2016 and 2016–2017. Additionally, gravels and cobbles contained in released anchor ice were sampled to understand the impact of large bedload materials transported through anchor ice release.

2. Literature review

2.1. Anchor ice formation

Anchor ice formation has been observed to grow in three distinct stages: initial, transitional, and final growth stages (Kerr et al., 2002). The initial stage of anchor ice growth has been observed in laboratory studies between Froude numbers of 0.14 and 0.76 (Doering et al., 2001; Kerr et al., 2002; Qu and Doering, 2007). Field observations of anchor ice growth have shown anchor ice formation to occur when the Froude number is between 0.2 and 1.0 (Hirayama et al., 1997; Terada et al., 1998). Anchor ice formation begins with frazil deposition on the front-face, back-face and contact points between gravel in the river bed substrate (Kerr et al., 1997; Qu and Doering, 2007; Stickler and Alfredsen, 2009). Fig. 1 shows anchor ice formation on the front-face, back-face and contact points on the Kananaskis River. This deposited anchor ice grows quickly upwards towards the free surface with continued frazil deposition (Qu and Doering, 2007). As the anchor ice continues to grow above the crest of the gravel it begins to develop into three distinct forms: tail, scale, or ball-type formations depending on the Froude number (see Kerr et al., 2002). These small formations on individual gravel particles eventually come into contact with one another and form a continuous sheet of anchor ice. During the transitional stage, anchor ice continues to grows vertically towards the free surface, which increases the drag force on the accumulation; this either causes the anchor ice to flatten out or release (Kerr et al., 2002).

Once a sheet of anchor ice is flattened it can continue to grow through frazil accumulation or in-situ ice growth; this is the final growth stage. In-situ anchor ice growth is driven by heat and mass exchange between the anchor ice crystals and the supercooled water (Kempema and Ettema, 2011). Kempema and Ettema (2011) concluded that an anchor ice accumulation could cover large areas of the river bed through continued frazil accumulation, whereas the internal strength of the anchor ice mass and the strength of its bond to the substrate came from its in-situ growth. Although anchor ice grows through both mechanisms, Kerr et al. (1997) observed no in-situ or dendritic growth occurring in the laboratory. This was attributed to the short time duration between successive frazil deposition and the negligible temperature difference between the anchor ice and supercooled water. Qu and Doering (2007) also observed in their laboratory experiments with a Couette flow apparatus that frazil accumulation was the dominant mechanism of growth but noted that in-situ growth was also detected from the analysis of temperature curves but could not be detected in anchor ice images. Conversely, in a field study by Kempema et al. (2008) in-situ thermal growth was found to be the major contributor to the growth of anchor ice and frazil accumulation was not observed.

2.2. Anchor ice release and rafting

Anchor ice release has been observed to occur through two mechanisms in the laboratory and field; mechanical or thermal release. Mechanical release occurs through the application of a mechanical force. This type of release can occur through the action of the shear force exerted by the flow acting against the anchor ice formation that causes it to release from the bed, or by the inherent buoyancy of the formation. Kerr et al. (1997) found in a laboratory study that when an anchor ice accumulation grew sufficiently thick, the increased drag caused the accumulation to either be released or flattened. As the anchor ice was flattened and the thickness was reduced, a sudden release of a section of the accumulation could cause a disturbance that released the entire anchor ice accumulation (Kerr et al., 1997). Doering et al. (2001) found that mechanical anchor ice release only occurred with a flow Reynolds number < 42,000. Jasek et al. (2015) observed the mechanical release of an entire anchor ice formation in the Peace River. Another type of mechanical release occurs if the buoyant force acting on the anchor ice exceeds the weight of the accumulation and the strength of the bond to the river bed.

Thermal release of anchor ice can occur when the water column warms above 0 °C and causes a weakening of the ice-substrate bond (Tsang, 1982). Initially when the water column is supercooled, the

Fig. 1. Digital image showing anchor ice forming around gravel in the Kananaskis River, December 8, 2016.

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