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Hydrological and thermal controls of ice formation in 25 boreal stream reaches

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ABSTRACT

The Northern Hemisphere has a high density of fluvial freshwater ecosystems, many of which become ice-covered during winter. The development and extent of ice have both ecological and socio-economic implications. For example, ice can cause freezing of riparian vegetation and fish eggs as well as influence hydropower production; however, when, where and why ice develops in small streams is not well known. We used observations from 25 stream reaches to study the factors controlling ice development during two consecutive winters, addressing where in the catchment surface or anchor-ice is most likely to develop, how stream morphology influences ice formation, and how climate influences ice processes. Reaches far downstream from lake outlets, or without any upstream lakes, were most prone to develop anchor-ice, but other factors also influenced ice formation. Anchor-ice was most common where water temperature and groundwater inputs were low and stream power high. Given cold air temperature and water supercooling, the in-stream substrate as well as the current velocity were also important for the development of anchor-ice. Climate and substrate seemed to be important factors for the development of surface ice. This study shows that ice processes are substantial during the hydrological year and may therefore have large implications for the ecology and engineering around boreal streams. The study also demonstrates that ice formation in the studied streams was complex, involving many variables and physical processes. We constructed a conceptual model describing the likelihood for various ice types to develop, based on the large dataset. As such, this model will be useful for practitioners and scientists working in small watercourses in the Northern Hemisphere.

1. Introduction

The ice volume in watercourses constitutes a small part of the cryosphere, but it plays a substantial role for the dynamics of freshwater ecosystems in the Northern Hemisphere (Allard et al., 2011; Lemke et al., 2007; Prowse and Beltaos, 2002). Although most streams and rivers in cold regions are ice-covered every year, the winter period is often ignored in studies of the annual water cycle (Morse and Hicks, 2005). River ice processes in steep streams and rivers are complex, but the understanding of the processes underlying ice development has greatly improved during the last decades (e.g., Beltaos, 2013; Hicks, 2009; Stickler and Alfredsen, 2009; Turcotte and Morse, 2013). River ice is sensitive to changes in climate as well as hydrology and may therefore serve as an indicator of the speed and nature of climate change (Lemke et al., 2007). For example, researchers have already reported a later freeze-up and an earlier breakup of ice in many rivers, resulting in a shorter ice-affected season as a consequence of ongoing climate change (Prowse et al., 2011; Takács et al., 2013). Such changes may have great influence on small watercourses, which have less water volume and are therefore more responsive to variability in weather events, such as changes in temperature and precipitation (Buffin-Bélanger et al., 2013). Furthermore, the total length of small streams far exceeds that of larger rivers (Bishop et al., 2008), implying that the cumulative consequences of changing winter conditions within smaller water bodies may be extensive.

Ice dynamics corresponds to the interactions between the crystallization process, the transport of ice and the resulting ice forms (Buffin-Bélanger and Bergeron, 2011). Dynamic ice development mainly takes place in turbulent waters of high-gradient reaches, and it is especially driven by the build-up of anchor-ice (Hirayama et al., 1997; Kerr et al., 2002; Stickler and Alfredsen,

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2009). Anchor-ice is mainly initiated by accumulation of frazil ice, which is composed of tiny ice particles with adhesive properties in supercooled water. Frazil ice can attach to in-stream vegetation, coarse material and large wood (i.e., anchor-ice is formed by ice particles anchored by the mass of the large object; Stickler and Alfredsen, 2009; Fig. 1A). Accumulation of anchor-ice affects the channel bed morphology and flow regime (Kerr et al., 2002). Depending on the location where frazil ice and anchor-ice accumulate, anchor-ice dams can be created. Anchor-ice dams may cause overbank flooding, altered flow patterns and reduced water velocity. When an anchor-ice dam breaks and is finally drained, the water level drops and suspended ice, i.e., ice that does not rest on water, can develop (Turcotte and Morse, 2013; Fig. 1B). Suspended ice may also develop in shallow channels as water recedes during winter and the ice cover becomes supported by protruding objects such as boulders (Prowse, 1995).

Modelling has for a long time been used in large rivers to gain more insight into river-ice related questions. When expanding currently available ice models, hydrological and morphological differences between small and large watercourses need to be taken into account. For example, in boreal landscapes groundwater (GW) inputs to streams and rivers are more frequent along small than large watercourses (Kuglerová et al., 2014). This implies that the inputs of relatively warm GW can affect the winter thermal regime of small rather than large streams and potentially prevent ice build-up (Dugdale et al., 2013; Turcotte and Morse, 2011; Turcotte et al., 2013, 2014). Second, bed morphology such as channel slope (often larger in smaller streams) may influence ice formation and breakup. Depending on their bed slope, small streams typically have a riffle-pool or step-pool sequence (riffle-pools have slopes <1% and step-pools have 1–10% slopes; Buffin-Bélanger et al., 2013), which makes the thermal regimes of stream water variable across short distances and this promotes ice dynamics.

Ice processes can significantly affect river hydraulics and in just a few days transform a turbulent riffle to a slow-flowing pool (Stickler et al., 2010). Winter floods, caused by the accumulation and release of ice, often reach magnitudes and frequencies higher than those during the ice-free season (Prowse and Beltaos, 2002). This is however rarely accounted for in ecological and hydrogeomorphic research or freshwater management, despite the fact that anchor-ice dams can have both ecological and physical implications. They can cause freezing of riparian vegetation (e.g., Engström et al., 2011; Hu and Pollard, 1997; Lind et al., 2014; Lind and Nilsson, 2015), freezing of fish eggs (e.g., Power, 1993) as well as an obstruction to hydropower production (e.g., Gebre et al., 2013; Girling and Groeneveld, 1999; Stickler et al., 2010). Anchor-ice dams and winter floods influence the diversity of riparian vegetation, for instance by eliminating dominant species and creating colonizable patches for disturbance-adapted species (Lind et al., 2014; Lind and Nilsson, 2015). As winter progresses and a surface ice layer is formed (Fig. 1C), oxygen exchange and light transpiration decline, whereas GW becomes an increased part of the stream flow (Boylen and Sheldon, 1976; Cunjak et al., 1998). This has a direct impact on fish productivity and survival because surface ice and relatively warm GW create sheltered habitats (Prowse et al., 2011). Surface ice covers are also important platforms for seasonal transportation of goods and livestock in arctic and subarctic regions (Engström, 2006; Prowse et al., 2011). Finally, if ice freezes solid to the bottom it can also affect the bed sediment and bottom biota and influence nutrient and material transport by moving substrates (Kempema and Ettema, 2011; Renman, 1993).

So far, most empirical river ice studies have involved one or a few sites, while other studies utilized experiments or numerical modelling (e.g., Allard et al., 2011; Prowse and Conly, 1998; Qu and Doering, 2007; Shen, 2010; Stickler et al., 2010; Turcotte and Morse, 2011). Numerical modelling of ice processes has been done in several cases, but the models have high demands on the data quality (Shen, 2010). Therefore only a few sites, mostly on large rivers have been subjected to such studies. Similarly, the majority of case studies and experiments have been conducted in large (>50 m wide), low-gradient rivers (Buffin-Bélanger et al., 2013). In order to summarize today's knowledge, river ice processes have also been generalized in conceptual models (e.g., Bergeron et al., 2011; Buffin-Bélanger et al., 2013; Turcotte and Morse, 2013) and described in review papers and books (e.g., Beltaos, 2013; Hicks, 2009; Morse and Hicks, 2005; Prowse, 2001). Nevertheless, no previous empirical study has examined ice formation in 25 reaches of relatively small streams (i.e., up to 4th order; Strahler, 1957), encompassing a large variation in hydraulics and geomorphic conditions and thus providing a regional view on ice formation.

The primary goal of this study was to describe how, where and why river ice develops and what specific properties of small boreal streams affect the development of various ice types. To answer these questions, we first surveyed the extent of anchor-ice, surface ice and suspended ice during two consecutive winters in 25 stream reaches and described the current ice processes. We distinguished among anchor, suspended and surface ice types and asked what the primary drivers of their development are and whether similar

Fig. 1. (A) Anchor-ice which is the in-stream formations in lighter color, (B) stream reach with suspended ice, and (C) surface ice in streams in northern Sweden.