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Field monitoring of secondary consolidation events and ice cover progression during freeze-up on the Lower Dauphin River, Manitoba

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ABSTRACT

Dynamic freeze-up processes on fast moving rivers determine the ultimate thickness of the ice cover and the associated ice-affected water levels. Secondary consolidation events, the shoving and mechanical thickening of a progressing ice cover at freeze-up, can cause rapid water level rises that can flood land unexpectedly. Additionally, they can lead to over-thickening of an ice cover beyond that calculated with a steady discharge. The lack of field data and observations of secondary consolidations in the literature results in a poor understanding of the conditions that affect the timing and severity of these events. In this study, data pertinent to further the understanding of secondary consolidation events were collected over two freeze-up monitoring seasons on the Lower Dauphin River. The high spatial resolution of pressure transducers and trail cameras, along with first-hand observations of consolidation events, provide a dataset that was used to analyze the extent of several secondary consolidation events and their effect on water levels throughout the 12 km reach. The most significant event caused a water level increase of 2.5 m over a span of 8 min when approximately 7.5 km of ice cover consolidated to a length of 4.7 km. An unmanned aerial vehicle was used to obtain aerial imagery of the ice front, which advanced through a series of localized shoves as incoming ice packed against the stationary cover. Other data collected includes top-of-ice elevations, ice thickness estimations, and meteorological data. Collectively, the dataset provides a relatively complete account of two freeze-up seasons on the Lower Dauphin River, including the processes of ice cover advancement and consolidation that play an important role in the peak ice-affected water levels and flooding potential. The dataset can be used by ice researchers to assess the ability of current state-of-the-art numerical models in simulating dynamic freeze-up processes, and highlight areas for future research and model development.

1. Introduction

Freeze-up ice jams in fast moving rivers can cause water levels to rise far beyond open water elevations, which can lead to flooding and socioeconomic concerns. The thickness of a rubble ice jam has historically been modeled using theory derived from soil mechanics; the ice is thought to behave as a granular material with strength resulting largely from frictional interlocking of the ice blocks. The ability of an ice cover to resist mechanical thickening under external forces of gravity and water shear is proportional to the confining pressure due to buoyancy (Beltaos, 1995). Although they are often modeled the same way, freeze-up ice jams differ from breakup jams in that the air temperature is below 0 °C, causing continual heat loss from the river (Michel, 1991), which adds strength as interstitial water freezes near the surface. As an ice cover progresses upstream during freeze-up, a portion of it may unexpectedly shove and consolidate, creating a thicker accumulation with a greater backwater effect. Hereafter, the term "shove" will refer to the mobilization of a stationary ice cover that is in the process of collapsing, and "consolidation" will refer to the mechanical thickening of the collapsing cover. These two processes often occur simultaneously. Factors influencing the magnitude, frequency, and extent of consolidation events are poorly understood.

Several field studies have been conducted to investigate breakup ice processes and dynamics (e.g. Beltaos et al., 1996; Beltaos and Carter, 2009; Beltaos et al., 2011; Beltaos et al., 2012). However, the number of field studies during freeze-up is more limited (e.g. Michel, 1984; Andres, 1999; Robichaud and Hicks, 2001; Andres et al., 2003; Sui et al., 2005). It has been observed in the field that ambient air temperatures during freeze-up are linked to ice dynamics, and can control whether an ice cover is more prone to frontal progression or consolidation events (Andres, 1999; Michel, 1984). Michel (1991) suggested that shoving is much less likely during freeze-up due to freezing effects, unless the stationary front progresses very quickly. Andres et al. (2003) observed ice consolidation events at freeze-up on the Peace

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River. They used the term "primary consolidation" to refer to the small, frequent shoves that occur very early in the formation period, before the freezing of interstitial water. They used the term "secondary consolidation" to refer to the collapse and mechanical thickening of an existing consolidated or juxtaposed ice cover. Secondary consolidations were found to produce the highest freeze-up levels due to the effects of the surge sent downstream, resulting in over-thickening of the ice cover. The conditions that are thought to trigger secondary consolidation events are (i) rapid advancement of the stationary front, (ii) sudden increases in discharge, and (iii) dramatic changes in atmospheric conditions (e.g. air temperature and solar radiation) that can deteriorate or hinder the growth of the solid crust at the surface of the ice cover (Andres et al., 2003).

The Dauphin River in Central Manitoba has been observed to undergo secondary consolidation events during freeze-up in the past that have caused ice-related staging of up to 4–5 m or more (Clark and Wall, 2016). Lindenschmidt et al. (2012) applied the numerical model RIVICE to simulate ice thicknesses and ice-affected water levels for the 2010–2011 freeze-up season on the Dauphin River, but the quantity and completeness of field data with which to compare numerical simulation results was limited. Further, only final ice elevations at the end of freeze-up were used to calibrate model parameters and the ability of the model to simulate time-dependent variations in water levels that are greatly influenced by secondary consolidation events was not shown. More comprehensive field datasets on the timing and magnitude of secondary consolidation events are required to advance the current understanding of freeze-up ice dynamics and the factors that trigger these events.

The objective of this paper is to present data collected during two freeze-up monitoring seasons on the Dauphin River in Central Manitoba, with a specific focus on the processes of ice cover advancement and secondary consolidation events in the steeper, lower reach. Novel to this study is the completeness, quantity, and variety of collected data; the spatial and temporal resolution of measurements captured dynamic conditions of ice cover progression and consolidation events to an unprecedented degree. This dataset sheds light on processes that lead to very thick, consolidated ice jams in fast moving rivers, and implores further study of how atmospheric conditions affect timing and severity of consolidation events at freeze-up. Visual observations of ice conditions before, during, and after secondary consolidation events, paired with quantitative data collected from deployed instrumentation (including water levels and meteorological variables), provide a unique dataset that advances the current state of published freeze-up field data. Collectively, the data also provides other ice researchers with a well-documented case study with which to evaluate the ability of state-of-the-art numerical models in simulating secondary consolidation events and their effects on channel hydraulics.

2. Methodology

2.1. Study site

The Dauphin River is located in Central Manitoba, approximately 250 km north of the City of Winnipeg, and is the final river in the water network connecting Lake Manitoba to Lake Winnipeg (see Fig. 1). The water levels on Lake Manitoba are regulated by the Fairford River Water Control Structure (FRWCS) which has been in operation since 1961. The outflow travels along the Fairford River to Lake Pineimuta, then to Lake St. Martin. The natural outlet to Lake St. Martin is the Dauphin River, which is approximately 52 km long and drains to Lake Winnipeg.

An interesting property of the Dauphin River is the abrupt channel slope change that occurs approximately 11.2 km upstream of the outlet to Lake Winnipeg. The upper reach has a slope of approximately 0.029% over its 40 km length, while the lower reach has a slope of 0.16%; roughly 5.5 times steeper than the upper reach (Clark and Wall, 2016). The upper reach is characterized by numerous channel meanders and a wider top width with shallow banks; conversely, the lower reach is much straighter and has steeper banks. The width of the lower reach typically varies from about 110–160 m. The steeper slope of the lower reach causes the open water velocity in certain areas to exceed 1.5 m/s. The turbulent, fast moving water can generate significant volumes of frazil ice during freeze-up. Historically, this has led to the formation of a hanging dam at the outlet to Lake Winnipeg as the entrained frazil ice is deposited under the thermal lake ice cover (KGS Group and North/South Consultants, 2014). Thick ice jams composed of frazil ice pans form in the steeper reach as the cover advances upstream from Lake Winnipeg; ice-affected water levels in this reach can rise 4–5 m or more above open water conditions (Clark and Wall, 2016).

Environment Canada operates a discharge and water level gauge on the Dauphin River (gauge 05LM006) that is located about 25 km upstream of the outlet (see Fig. 1). A percentile analysis of the recorded flows during the ice-affected season from 1977 to 2017 is presented in Fig. 2, showing that the flows in 2015 and 2016 were generally higher than average. The average discharges in 2015–2016 and 2016–2017 during the period of ice cover advancement up the lower reach in each freeze-up season were approximately 110 m^3/s and 210 m^3/s, respectively.

2.2. Overview of monitoring efforts

A summary of instrument types and deployment locations for the 2015–2016 and 2016–2017 seasons is shown in Table 1. The number of monitoring sites was increased in the second monitoring season due to the apparent success of the 2015–2016 season and need for higher resolution data. Monitoring sites were originally named sequentially as DRLL01 (where "DRLL" indicates "Dauphin River Level Logger"), DRLL02, etc. from Lake St. Martin to Lake Winnipeg (see Fig. 1). Sites added in the second year were appended with a letter to denote their position between original sites. Note that some equipment was not retrievable by the time of publication for the 2016–2017 season due to high water levels.

Two site visits were conducted on December 9, 2016 and December 12–14, 2016 during the 2016–2017 season to coincide with ice cover progression up the Lower Dauphin River. Visual observations of shoving events during these visits aided in comprehending the data collected from the loggers and trail cameras. Surveys of the near-shore top-of-ice profiles were conducted on March 23–24, 2016 and February 21–22, 2017 for the 2015–2016 and 2016–2017 monitoring seasons, respectively.

For the 2016–2017 season, near-shore transect surveys of ice elevations and ground elevations were conducted during site visits on March 15–16, 2017 and May 15–16, 2017 to quantify the thickness of the ice grounded along the channel bank. A schematic illustration of the evolution of the ice cover in the spring is shown in Fig. 3. Warm air temperatures and increased flows caused the ice cover to decay in the middle of the channel. The water level dropped with the increased conveyance and caused the ice cover to rest along the bank. The first transect surveys were conducted during this time to obtain near-shore top-of-ice elevations. The second transect surveys were conducted when the ice cover had fully cleared to obtain ground elevations at the same locations. Shear cracks were often observed near the bank during the first transect survey, but they typically did not extend to the ground and therefore did not provide a good estimate of the ice thickness.

2.3. Equipment specifications and deployment methods

Water levels were recorded using pressure sensors (Levelogger Model 3001, Solinst, USA). These instruments are capable of measuring water level with an accuracy of ± 0.03 m. The loggers were fastened to 75 mm × 75 mm × 315 mm iron angles and the assembly was secured

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