Cold Regions Science and Technology 123 (2016) 71–80

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Celerities of waves and ice runs from ice jam releases

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A R T I C L E I N F O

Article history:
Received 11 May 2015
Received in revised form 5 November 2015
Accepted 15 November 2015
Available online 9 December 2015

Keywords:
River ice
Breakup
Ice jam release
Ice run
Wave
Celerity

A B S T R A C T

The release of a river ice jam can lead to rapidly rising water levels and a fast-moving torrent of water and ice that can threaten riverside communities. Two phases are released when an ice jam fails: a water wave and a moving ice accumulation (called an "ice run"). The propagation of the water component of an ice jam release wave is relatively well understood. However, a dearth of simultaneous observations of both the water and ice components of an ice jam release has hampered the development of tools to predict of the effects of these releases. This paper presents a field experiment on the Hay River in the Northwest Territories where both water level and ice condition were observed simultaneously at several locations over a distance of more than ten thousand flow depths. This research shows that the water wave and the ice run travel at different celerities resulting in two distinct, but initially overlapping, features. The celerity of the leading edge of the water wave was found to be higher than the ice components, making the water wave move out in front of the ice after 4 to 8 ice jam lengths of travel.

1. Introduction

The sudden release of impounded ice and water from an ice jam can be very dangerous for northern riverside communities. Rises in water level exceeding 0.8 m/min and wave celerities of 10.9 m/s resulting from ice jam releases have been measured (Beltaos, 2014; Hutchison and Hicks, 2007). The flooding that results can damage property and threaten lives. Two phases are released when an ice jam fails: a water wave and a moving ice accumulation (called an "ice run"). The water wave is characterized by faster water velocities at the peak and front of the wave, and slower water velocities at the tail of the wave. The ability to predict both the magnitude and the arrival time of ice jam releases is important for the emergency management of breakup floods.

To correctly forecast the consequences of an ice jam release event in terms of its flooding potential, it is essential to be able to predict the celerity and shape of the water wave as well as the celerity and size of the ice run. The water wave provides the volume and height of water that can itself cause flooding; it can also instigate breakup of downstream ice covers or bring about the release or consolidation of existing downstream ice jams. The ice run can likewise interact with an existing ice jam: it may add momentum and volume to the ice accumulation, causing thickening of the ice jam, raising water levels and causing flooding. Ice runs can also cause the release of an ice jam, sending a water wave and ice run downstream with renewed amplitude and celerity. Furthermore, whenever the local ice velocity is slower than the surface water velocity, the ice run has the potential to attenuate the water wave's peak and/or impede its velocity. It has been hypothesized that this is why ice jam release models that neglect ice-water interactions tend to underestimate water levels in the falling limb of stage hydrographs (e.g. Blackburn and Hicks, 2003). Further, She and Hicks (2006) found that the addition of side friction for a limited time after release may improve the prediction of the falling limb.

Currently available ice jam release models have proven quite effective at predicting the arrival time and size of the water wave (e.g. Liu and Shen, 2004; She and Hicks, 2006). However, correctly predicting the propagation speed of the concurrent ice run movements has been more elusive. This is, in part, due to the scarcity of field observations with which to validate numerical models aimed at predicting ice jam release and the propagation of the water wave and ice run. In particular, there have been numerous field studies of ice jam release events (e.g. Beltaos and Burrell, 2005; Hutchison and Hicks, 2007; Jasek, 2003; She et al., 2009) but none present simultaneous data detailing the sizes and relative velocities of both the water waves and their associated ice runs and how these change with distance travelled. Some laboratory studies of ice jam release or wave-ice interactions have also been conducted (e.g. Khan et al., 2000; Wong et al., 1985). However, laboratory flumes do not capture the attenuation of the water wave and ice run that occur in a natural river because the distances travelled in a river, D, are thousands to tens of thousands times the undisturbed flow depth, y_0, and cannot be accommodated at laboratory scales.

The purpose of this study was to take the first step in addressing this knowledge gap by simultaneously documenting the celerities of both water waves and associated ice runs as they propagate downstream. This was achieved by establishing a field experiment on the Hay River

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http://dx.doi.org/10.1016/j.coldregions.2015.11.014

where both the water wave and ice run components of ice jam release events were observed at several locations over a channel length exceeding 10,000 undisturbed flow depths.

2. Study reach and methods

Figs. 1 and 2 illustrate the Hay River and the reach instrumented for this study. The Hay River drains 51,700 km^2 and flows into Great Slave Lake in the Northwest Territories. The Town of Hay River and the K'atl'odeeche First Nation are located where the Hay River flows into Great Slave Lake. These settlements have often experienced severe flooding caused by ice jams.

The study reach is situated just upstream of Alexandra Falls. In this reach, the Hay River meanders through alluvial plains and contains occasional islands. This reach was chosen because of its consistent slope, relatively simple geometry, and the fact that ice jams normally form and release at consistent locations during spring breakup. In addition, Alexandra Falls opens sufficiently early in the breakup period to enable discharge estimation using an open water rating curve. Discharge estimates were also available at the Water Survey of Canada (WSC) station 07OB008 located at km 945.6, upstream of the study reach. The average channel width in the study reach is 114 m (min: 70 m, max: 210 m) with an average slope of 0.0002. Ice conditions and water levels were observed at six stations in 2011 and seven stations in 2013. The subreaches between the stations are numbered Reach 1 to 6. Each observation station is identified with a river kilometer number referenced to the origin of the Hay River (modified from Hicks et al., 1992).

The observation station at km 1032.0 (2.2 km upstream of Alexandra Falls) was operated as a near-real-time communicating station by the Town of Hay River Emergency Measures Organization as part of their spring flood monitoring operations. Water levels were measured at 5 minute intervals with an Omni Controls Inc. DCU-1104 ultrasonic sensor suspended over the river on a cantilever boom (estimated accuracy $+/-$ 0.1 m, due to wind movement in the boom). Ice conditions were observed during daylight hours with a Campbell Scientific CC640 digital camera at 5 to 15 minute intervals. A geodetic benchmark was not established here; therefore, the water levels at this station are reported in terms of stage.

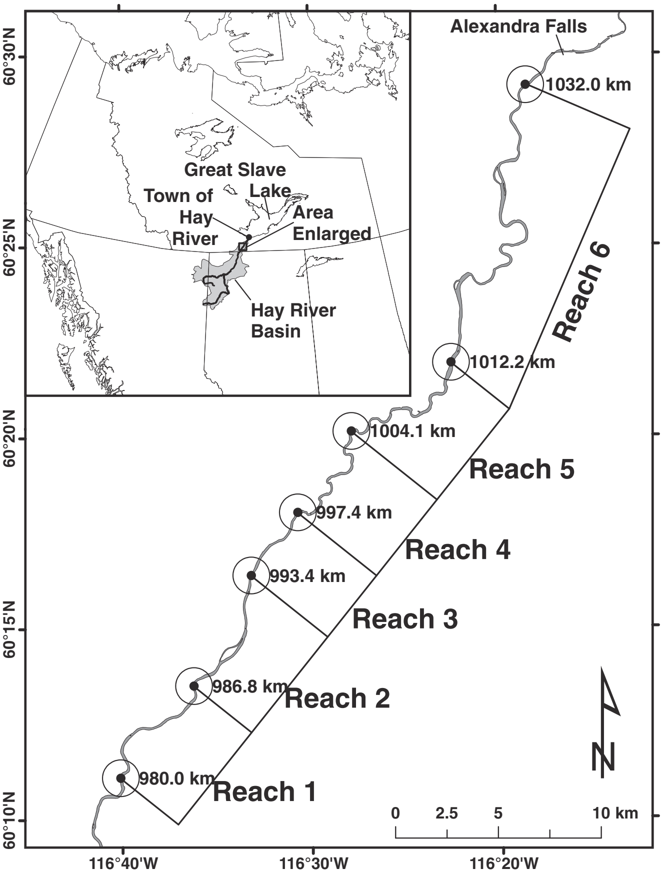

Fig. 1. Location of the Hay River basin and study reaches.

The remaining stations were installed by the University of Alberta's River Ice Research Group at river km 1012.2, 1004.1, 997.4, 993.4, 986.8 (2013 only), and 980.0. Each station consisted of a self-contained submersible pressure transducer and datalogger (Schlumberger Diver models 501 and 601, accuracy: 1.0 and 0.5 cmH_2O, measurement interval: 1 and 2 min) and a tree-mounted game camera (various models used: Reconyx PC800, Moultrie PlotStalker, and Moultrie I-65; photo interval: 5 min, 10 min, or 1 h). Because remote lighting was not installed, ice condition data was typically not available at night (~23:00–04:30). The pressure transducers' clocks were synchronized and the instruments were installed in silt socks and fixed inside perforated heavy steel cases, which were driven flush with the river bed before the onset of breakup. The case elevations were measured with respect to control points established with a GPS static survey and processed with Natural Resources Canada's precise point positioning tool (vertical 95% error: 0.074 to 0.185 m). The pressure data was corrected to eliminate the effects of atmospheric pressure changes using data from a barometric pressure datalogger (Schlumberger Diver model DI500, accuracy: 0.5 cmH_2O) located along the river within 15.5 km of the observation stations. The cameras were retrieved directly after breakup. The pressure transducers were retrieved in late June to early September, after remnant shear walls had melted and high water levels had subsided, when the riverbed was again accessible

Ice conditions were also observed from fixed-wing aircraft, allowing for periodic documentation of ice conditions between ground-based observation stations, as well as upstream and downstream of the study reach from the Alberta-Northwest Territories border to Great Slave Lake (km 942 to 1114). Observational flights were typically conducted daily during breakup, weather and equipment permitting, and more often if ice was moving. The ice jams and ice runs described in this paper were observed from the air at the following times: the afternoons of May 5 and 6, 2011, and the morning and evening on May 11, 2013.

The oblique photographs taken by the cameras at each observation station were used to observe ice condition (presence of intact ice, ice jams, floating ice debris, or open water) and to estimate the surface concentration of floating ice debris. This approach for estimating surface ice concentration is susceptible to an error of approximately 10%, based on comparison with estimated surface ice concentrations observed from aircraft. However, it is believed to be accurate enough to delineate important features of individual ice runs such as the start and end of the ice run and the identification of the peak concentration. A similar approach has been employed by other researchers (e.g. Jasek, 2003).

To identify the ice runs, it was necessary to devise a consistent means of distinguishing ice runs from "background ice"—that is, the remnant ice from along the river banks that was refloated by the passing wave and/or ice associated with the tail end of an ice run. The fronts and backs of the ice runs were taken to be the points at each end where the surface ice concentration was 20%. Alternative approaches for delineating the start and end of an ice run include using the 100% surface ice concentration or using the peak concentration. The 100% concentration was not employed in this study to delineate the start and end of the ice runs because not all ice runs had a peak concentration of 100% at each observation station. The peak concentration was not used because for many ice runs (i.e. Ice Runs I, II, III, Fig. 4) the peak concentration was typically observed in three or fewer photographs, thus making it unrepresentative of the entire ice run. Therefore, for consistency, the 20% surface ice concentration was chosen to delineate the ice runs, as it