Cold Regions Science and Technology 103 (2014) 91–106

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Hydrodynamic properties of ice-jam release waves in the Mackenzie Delta, Canada

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ARTICLE INFO

Article history:
Received 22 November 2013
Accepted 27 March 2014
Available online 8 April 2014

Keywords:
Amplification ratio
Arctic delta
Celerity
Hydrodynamic force
Jave
Rising limb

ABSTRACT

Ice breakup is a controlling factor in the hydrology of arctic Deltas, including the Mackenzie River Delta, which is characterized by numerous channels and lakes. Ice jams that form during dynamic spring breakup events often result in flooding, thus replenishing Delta lakes with essential water, sediment and nutrients. The present study, carried out under the auspices of the International Polar Year, aims to gather and analyze essential quantitative information for improving understanding of Delta ice processes and associated prediction capability. Recent work has shown that dynamic breakup in the flat Delta channels can only be triggered by javes, the sharp waves generated by ice jam releases, which amplify the hydrodynamic forces applied on, and can dislodge, the winter ice cover. First-ever measurements of javes in Delta channels are presented and their hydrodynamic properties quantified via the Rising Limb Analysis Method (RLAM), which enables calculation of the hydrodynamic properties of the measured waveforms. Typical leading edge and crest celerities were 10 and 5 m/s respectively, while a record value of 16.5 m/s was obtained on one occasion and linked to large local depths in Middle Channel. The hydrodynamic forces applied on the riverbed and the ice cover, resulting from various javes, are subdued in Delta channels relative to those in the lower Mackenzie River and in other, previously studied, rivers. This is primarily due to low water surface slope and points to a northward-decrease in the incidence of dynamic breakup and ice jams in Delta channels.

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1. Introduction

The Mackenzie Delta, one of the world's largest Arctic Deltas, contains over 49,000 lakes and covers 13,135 km^2 (Emmerton et al., 2007). This lake-rich environment is one of the most productive ecosystems in northern Canada (Squires et al., 2009), supporting large populations of birds, fish and mammals. River ice breakup is a controlling factor in the hydroecology of the Mackenzie Delta (Marsh et al., 1994). Breakup ice jams can raise water levels to much higher elevations than do open-water floods. The resulting replenishment of Delta lakes with river water, sediment, and nutrients, plays a key role in the maintenance of their aquatic ecosystems. The main concerns addressed by the present study relate to the hydroecology of the Mackenzie Delta ecosystem (Marsh and Lesack, 1996; Prowse et al., 2006) and to potential development resulting from oil and gas exploration and the proposed Mackenzie Valley pipeline. Ice jamming also modifies the temporal and spatial distribution of the flow entering the Delta (Mackenzie, Peel, and Arctic Red Rivers) and therefore has an effect on the fluxes of freshwater, sediment, and nutrients to the Arctic Ocean (Emmerton et al., 2008).

Delta ice processes in general, and breakup processes in particular, have been qualitatively documented in some detail (e.g. Terroux et al., 1981). However, it is quantitative data that are essential for advancing understanding of hydrologic processes and developing mathematical models for environmental impact assessments and predictions of climate impacts on the long-term stability of Delta ecology. Under the auspices of the International Polar Year (IPY), and as a part of SCARF (Study of Canadian Arctic River Delta Fluxes; http://www.sfu.ca/ipy/), this gap is addressed via detailed field observations and measurements, specifically designed to collect quantitative data on Delta ice breakup and jamming processes. This information is not only essential to understanding how the ice breakup helps replenish Delta ecosystems, but can also provide validation data to a parallel study under SCARF that aims to develop a multi-channel hydrodynamic flow model for the Delta (Nafziger et al., 2009).

Beltaos et al. (2012a) introduced the ice breakup field program of IPY-SCARF and presented detailed data and analysis on ice-jam characteristics and effects on the distribution of flow among the main channels of the Delta. Using data from the same field program as well as archived hydrometric information, the conditions under which dynamic breakup and jamming can occur in the flat lower portion of the Mackenzie River were investigated next (Beltaos, 2013a). It was shown that occurrence of such events requires the large hydrodynamic forces associated with sharp waves (also known as "javes") that are generated upon the release of a major jam farther upstream. The jave is a unique river wave, much more dynamic than a runoff wave, produced by snowmelt

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http://dx.doi.org/10.1016/j.coldregions.2014.03.011
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and/or rainfall, but less dynamic than the dambreak. Though javes have been known to river ice observers for several decades (e.g. Beltaos and Krishnappan, 1982; Henderson and Gerard, 1981), it is only in the past decade or so that comprehensive data sets and analytical methods have become available, enabling quantification of the main hydrodynamic variables (e.g. Beltaos, 2013b; Beltaos and Burrell, 2005a, 2005b; Blackburn and Hicks, 2003; She and Hicks, 2006).

The objectives of this paper are to: (a) report measured and deduced properties and effects of javes in Delta channels and in the lowermost reach of the Mackenzie River; and (b) compare these data with previous findings in the steeper, subarctic, rivers that have been examined to date. Of particular interest are jave height and duration, celerity, flow velocity and discharge, as well as hydrodynamic forces that are applied on the ice cover and the channel bed.

Following background information and description of the 2008 field program, jave waveforms (stage-time variations) recorded at various locations along the lower Mackenzie River and major channels of the Delta are presented. Links to triggering events, like ice cover mobilization and ice jam releases, are demonstrated while the rates of propagation of the leading edge and the wave peak are quantified. Analytical methodology to determine non-measurable characteristics such as flow velocity, discharge, and shear stress, is described and subsequently applied to obtain their peak values. These findings are then compared with previous results in steeper rivers using a generalized formulation of dimensionless variables.

2. Background information

Breakup in the Delta usually starts in the second half of May and ends in the first half of June. It is generally driven by the rising flows of the Mackenzie and Peel Rivers (Fig. 1A). The Peel and west-side tributaries rise earlier, and thus breakup develops more rapidly in the southwestern sector of the Delta. However, the breakup in the central and eastern sectors is driven by the much larger flow of the Mackenzie (Terroux et al., 1981). The Mackenzie River hydrograph entering the Delta is captured by the WSC (Water Survey of Canada) gauge located across the mouth of the Arctic Red River (Station No. 10LC014; Latitude 67°27′21″ N, Longitude 133°45′11″ W). This gauging station is named “Mackenzie River at Arctic Red River” (herein abbreviated as MARR) and located some 25 river km upstream of Point Separation (Fig. 1B).

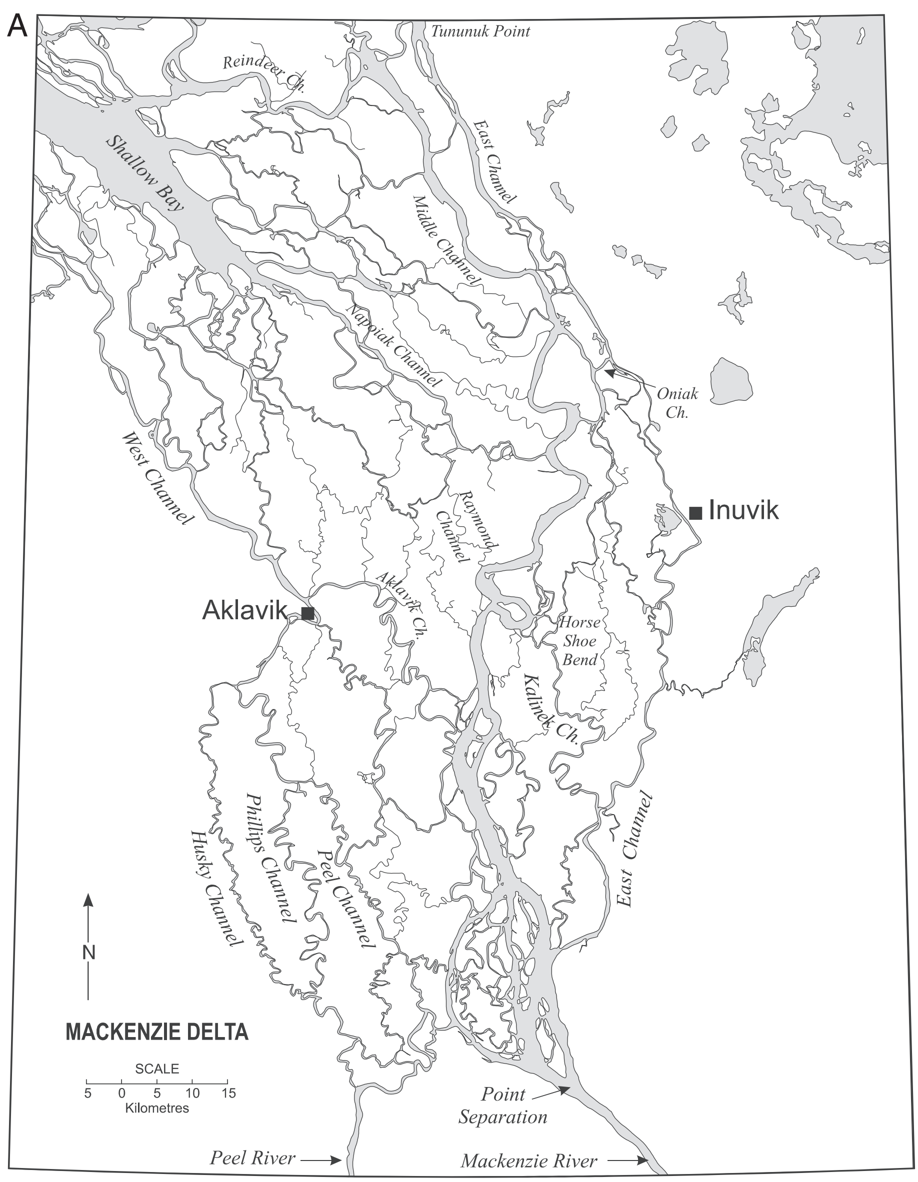

Fig. 1. A. Plan view of Mackenzie River Delta and of main delta channels. The multi-branch reach of Middle Channel within the first 30 km below Point Separation is herein denoted as the “Turtle”. B. Lower Mackenzie River and southern Delta map with location of MARR gauge across from mouth of Arctic Red River.

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