HYDROTHERMAL DECAY OF ICE JAMS

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Over the last three decades, the Geographical Branch, Department of Mines and Technical Surveys and the more recent National Hydrology Research Institute (NHRI) of Environment Canada have been conducting research on river ice processes in northern Canada, particularly in the basins of the Mackenzie and Liard Rivers (Prowse 1985a). Over this time, a considerable amount of information has accumulated concerning ice jamming. One particular location, at the confluence of the Liard and Mackenzie Rivers, has been identified (Henoch 1973; MacKay and Mackay 1973; Sherstone 1981 and Anderson 1982) as a site of recurrent and often spectacular ice jamming. The formation and release of ice jams at this site have special significance because it is the spring flow from the Liard which normally triggers breakup of the Mackenzie. In 1983, NHRI began intensive studies of ice jam processes at this site. Prowse (1984, 1985b) provides accounts of 1983 and 1984 breakup in this area and Marsh (1985) describes the water temperature regime. Part of the impetus for this later work came from the Canada-Northwest Territories Flood Damage Reduction Program and the need to define the role of ice jams in producing high water levels on northern rivers. As noted by Kriwoken (1982), flooding of communities along the Liard and Mackenzie Rivers has almost invariably been caused by backwater from ice jams.

The morphological setting of the Liard River mouth, while clear of any sharp bends, is highly conducive to ice jamming. Within approximately 20 km of the river mouth, the water slope decreases from .00039 to only .00005, and over the last 10 km the river expands from a width of some 700 m to almost 2800 m. A number of islands and shoals occupy the centre of the river mouth, and only one deep channel, running along the right bank, opens into the Mackenzie River. The chances of jamming are further enhanced by the downstream barrier created by the intact Mackenzie River ice cover.

On the basis of the conditions of formation, the ice jams at the Liard River mouth fall into Popov's (1968; see Chizhov 1975) category of 'estuary ice jams' which form "in the branches of deltas and on estuary reaches on rivers, flowing into lakes, or into rivers breaking up later". Unlike ice jams which tend to form randomly, for example, at channel restrictions or in low velocity reaches, estuary jams regularly develop at the same location. Jams have been observed to form at this site every year since at least 1972 (Sherstone 1981), when reconnaissance observations began. Using eight years of aerial photography, Prowse (1985c) found that, regardless of the type of breakup, large accumulations of ice, up to 8 m thick (Fig. 1) and ranging in length from 10 to 22 km and in area from 9.5 to 22 km^2, have jammed at the Liard River mouth. Moreover, backwater from these jams has raised the stage 6 to 9 m above normal, and increased flow depth up to 4 times that which would occur under open water conditions with equivalent discharge.

The residence time of ice jams at the Liard River mouth varies markedly from year to year, from as little as a few hours to over 10 days. During these periods, jams can undergo a number of dimensional and structural changes. Photographic records obtained of the 1983 jam permit an examination of some of these evolutionary changes and provide insight into the ice jam decay process. Fig. 2 illustrates the length of the 1983 ice jam at different intervals between the time of arrival of the breakup front until the ice jam was destroyed and river ice breakup continued into the Mackenzie River. The ice jam is separated by a debris line into a downstream portion, containing the original jam, and an upstream section comprised of sediment-laden brash ice. Maximum jam length was attained on May 4,

Figure 1. Shear walls remaining after ice jam release. Walls are approximately 8 m high and are a good indicator of ice jam thickness.

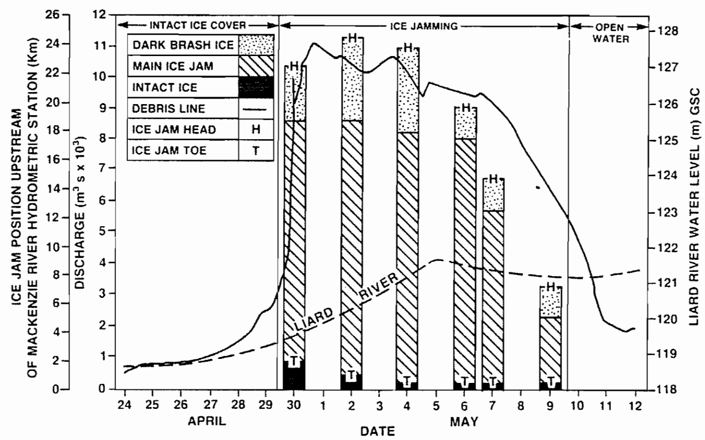

Figure 2. Changes in ice jam length, water levels and discharge. Bar graph indicates ice jam length and components, solid line represents water level and dashed line, discharge.

four days after initial formation. A majority of the ice jam increase can be ascribed to the accumulation of dirty brash ice from the release of upstream tributaries or from the calving of upstream shear walls. The remainder of the jam remained relatively stationary, apart from additional fracturing of the downstream ice cover which accounts for the slight downstream movement of the toe. During this initial 4 day period, discharge of the Liard continued to rise, although water levels at the Liard gauging site remained relatively constant (Fig. 2).

After May 4, discharge began to decrease yet the head of the ice jam began to move downstream and the toe remained relatively stationary. Between May 4 and May 9, the length of the jam decreased from 22.8 km to 6.3 km (Table 1). Such large and rapid changes in jam length could, in some cases, be attributed to the processes of compaction and thickening in response to increasing upstream forces. In this case, compaction does not offer a plausible explanation for the decrease in jam length, largely because the upstream forces, as reflected in water levels and discharge, were decreasing over much of this period (Fig. 2). A more logical explanation is that ice within the ice jam was either entrained underneath the jam or was melted in situ. Much greater rates of melt can be expected for an ice jam surface in comparison to a stable ice cover because: (a) greater surface roughness enhances the convective transfer of sensible and latent heat, and (b) the low albedo of the dirtier ice increases radiation absorption. Here, however, the hydrothermal transfer to the ice jam bottom also accounted for considerable melt, probably greater than that due to surface melt from atmospheric sources.

Date May	T_w (°C)	Q ($m^3\ s^{-1}$)	q_w (MJ dy^{-1})	V_m ($m^3\ dy^{-1}$)	D_c (km dy^{-1})	D_o (km dy^{-1})
6	1.5	4000	2.17×10^9	7.08×10^6	2.09	2.05
7	4.0	3850	5.57×10^9	1.82×10^7	5.37	4.90
8	4.0	3700	5.35×10^9	1.75×10^7	5.16	3.75
9	4.0	3600	5.21×10^9	1.70×10^7	5.02	3.75
10	5.5	3500	6.96×10^9	2.27×10^7	N.A.	N.A.

Table 1. Observed and calculated hydrothermal melt of the 1983 ice jam. All terms defined in the text.

Beginning May 6, temperature measurements were made of the river water entering the ice jam and in holes throughout the jam (Fig. 3). Temperatures were reasonably constant in the vertical and across a section. The temperature on May 6, at the upstream edge of the jam head, was ca. 1.5°C but increased to 4°C on May 7 and then to 5.5°C when the jam finally broke on May 10 (Table 1).

Figure 3. Temperature measurements made from helicopter through holes within the ice jam.

Using these temperatures and daily discharge figures, an estimate can be made of the hydrothermal heat flow, volume of ice melt, and the expected change in ice jam dimensions. Firstly, the total daily heat flow of the river (q_w) can be expressed by:

(1) $q_w = C_w\ p_w\ Q\ T_w$

where C_w is the specific heat of water, p_w the density of water, Q the daily discharge, and T_w the water temperature. Second, assuming that the ice within the jam is 0°C isothermal, the potential volume of ice melted per day (V_m) is:

(2) $V_m = q_w/p_i\ L_i$

where p_i is the density of ice (assumed to be 920 kg/m³) and L_i the latent heat of fusion. Table 1 lists the daily heat flow and potential ice melt for May 6 to 9 calculated from (1) and (2).

Measurements made within the ice jam revealed that the water temperature decreased dramatically within a few hundred metres of the jam head and reached near 0°C after several kilometres. Although insufficient data were collected during the 1983 event to completely define the temperature decay curve, more detailed measurements made during the 1984 event (Fig. 4), show the rapid decrease in water temperature after entering a jam.

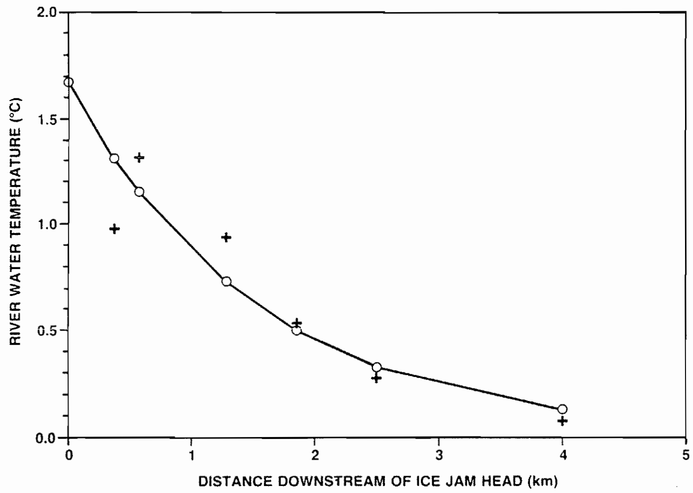

Figure 4. Temperature decay beneath Liard River ice jam, May 3, 1984. '+' indicates measurement point. Line is fitted through data.

In consideration of the above, it is reasonable to assume that most of q_w was expended within the jam reach and that V_m represents the volume of ice melted within the ice jam. The daily change in jam length D_m resulting from ice melt is then:

$$(3) \qquad D_c = \frac{V_m/W\ t_j}{(1 - p_j)}$$

where W is mean channel width, t_j jam thickness and p_j jam porosity. Employing the dimensions for the 1983 jam (Prowse 1985c) of t_j = 7.8 m, W = 723 m and p_j = 0.4, the calculated daily decrease in jam length (D_c) ranges from 2.1 to 5.4 km - greater than those actually observed (D_o) (Table 1). This discrepancy can partly be explained by the implicit assumption in (3) that all hydrothermal melt occurs directly at the ice jam head. In reality, because temperatures did not reach 0°C until well within the jam, heat must have also been consumed in the process of thinning the ice jam; the effects of which would not be entirely reflected in changes in jam length. Furthermore, as melt smoothed the jam subsurface (reduced roughness), velocity would increase and warm water would therefore penetrate further into the jam.

A more thorough analysis of heat transfer to the ice jam would require additional information, such as changes in jam thickness and subsurface roughness, and is beyond the intended scope of this paper. As a first approximation however, this example does indicate that hydrothermal melt must have played a significant role in the decay of the 1983 ice jam and probably in others with similar hydro-meteorological conditions. Although, the authors are unaware of any detailed analytical treatment of the hydrothermal melt of ice jams, other investigators, including for example Parkinson (1982) and Andres and Doyle (1984), have also pointed to its importance in ice jam decay.

Large and rapid increases in river water temperature can be expected to occur only when there is appreciable atmospheric warming of the upstream river water. The greatest warming occurs where the river upstream of the jam is effectively ice clear; a situation produced by sequential, mechanical breakup events. Quite a different situation exists for thermal breakups in which a series of alternating open and ice covered reaches are found upstream of the jam. In such cases, not only is less water surface exposed to atmospheric warming, but the zones of intact ice scattered along the channel keep the water temperature from rising appreciably above 0°C. For example, during the non-sequential, thermal break-up of 1984, water temperatures entering the jam never rose above 1.7°C (as shown in Fig. 4), despite the fact that air temperatures were higher and discharge lower than in the 1983 event. In general, therefore, hydrothermal melt is likely to play a more important role in ice jam decay during mechanical rather than thermal breakup events.

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