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Threshold condition between mechanical and thermal breakup

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Extreme ice-jam flood events in rivers occur during a type of breakup that is partly governed by the mechanical properties of the ice cover, and known as “mechanical”. By contrast, “thermal” breakups are preceded by advanced thermal decay of the ice and can only produce insignificant, if any, jamming. Quantitative conditions that demarcate these two types of breakup events can find application in a variety of issues, such as interaction between river ice processes and the aquatic ecosystem, socio-economic impacts of river ice, and effects of climatic change on river ice regimes. Using recent advances on the onset of mechanical breakup, a simple threshold criterion is postulated and its quantitative consequences are worked out. At a given river site, there is a site-specific rise in water level above the freeze-up elevation, which delineates mechanical from thermal events. This rise is approximately proportional to ice thickness but also depends on local river morphology and hydraulics. Data from case studies on three very different rivers are used to test this prediction and show encouraging results. Respective site-site specific coefficients are determined and environmental implications of the present findings are discussed.

1. Introduction

Ice is present in nearly every Canadian river, for a period that ranges from days to many months. Whether moving or stationary, it interacts with the river flow in various ways, resulting in multiple impacts on the economy and ecosystem, and often posing a major threat to riverside communities. Extreme events resulting from breakup ice jamming are responsible for a large part of such impacts. They include flooding, damage to property and infrastructure, interference with navigation, and inhibition of hydropower generation. Equally important are the many ecological impacts of river ice, which arise from the intimate relationship between ice processes and riverine ecosystems. Extreme ice-jam events have various ecological impacts that can be both beneficial and detrimental. For instance, ice-jam flooding provides essential replenishment to the multitude of lakes and ponds characteristic of the northern Canadian deltas, which are havens for wildlife, especially waterfowl and aquatic animals. (Peace-Athabasca Delta Project, 1973; Marsh and Hey, 1989). On the other hand, flooding caused by ice jams and the surges produced by their release can result in severe fish mortality and loss of spawning grounds (Brown et al, 2001).

The breakup of river ice is triggered by mild weather and encompasses a variety of processes associated with thermal deterioration, initial fracture, movement, fragmentation, transport, jamming, and final clearance of the ice. Though several or all of these processes may be occurring simultaneously within a given reach, it is convenient to visualize the breakup period as a succession of distinct phases such as *pre-breakup, onset, drive, wash.* During the pre-breakup phase, the ice cover becomes more susceptible to fracture and dislodgement via thermally induced reductions in thickness and strength (excepting *premature* breakup events, as discussed later). At the same time, the warming weather brings about increased flow discharges, due to snowmelt or rainfall or both. The increasing hydrodynamic forces and rising water levels fracture the ice cover and reduce its attachment to the riverbanks while the increased flow velocities cause it to move and break down into relatively small blocks. This is the onset of breakup, and is followed by the drive, that is, the transport of ice blocks and slabs by the current.

Depending on hydro-meteorological conditions, the severity of a breakup event can vary between two extremes, those of the *thermal* or *overmature* breakup and the *premature* breakup. The former type occurs when mild weather is accompanied by low runoff, due to gradual slow melt and lack of rain. The ice cover deteriorates in place and eventually disintegrates under the limited forces applied by the modest current. Ice jamming is minimal, if any, and water levels remain low. Premature breakup on the other hand, is associated with rapid runoff, usually due to a combination of rapid melt and heavy rain. The hydrodynamic forces are sufficient to lift and break segments of the ice cover before significant thermal deterioration can occur. Ice jams are now the most persistent because they are held in place by sheet ice that retains its strength and thickness. This is aggravated by the high river flows caused by the intense runoff, rendering premature events the most severe in terms of flooding and damages. Usually, a breakup event falls somewhere between these two extremes, and involves a combination of thermal effects and mechanical fracture of the ice. The term *mechanical* breakup is used herein to denote all non-thermal events because they are at least partly governed by the mechanical properties of the ice cover.

The conditions that determine whether a breakup event will be thermal or mechanical have never been examined or quantified, despite their practical significance in flood forecasting and warning, and in hydroclimatic studies of river ice processes. Using current understanding of breakup initiation mechanisms, a first attempt to develop physics-based criteria for this threshold has been carried out and is presented herein. The resulting relationships are tested with case studies in three different rivers, and their practical implications are discussed.

2. Onset of mechanical breakup

Defining the onset of the breakup event at any particular location along a river as the time when the winter ice cover is set in sustained motion, a number of onset criteria have been formulated in the past few decades (e.g. see Beltaos, 1995). Most are completely empirical, relying on various combinations of water level, ice thickness, freeze-up conditions, and air temperature indices such as degree-days of thaw. A common criterion that incorporates past empirical findings (e.g. see Shulyakovskii, 1966, 1972; Beltaos, 1984, 1987) is:

$$H_B - H_F = kh_o - F(S) \qquad [1]$$

in which H_B = water surface elevation at which the ice cover starts to move; H_F = water surface elevation at which the ice cover formed during the preceding freeze-up event = *freeze-up level*; h_o = ice cover thickness prior to the start of melt, or "initial" thickness for the pre-breakup period; F = a site-specific function of S, the latter being an index of thermal effects on the ice cover, often taken as the cumulative heat flux to the ice or simply the accumulated degree-days of thaw; and k = site-specific coefficient, so far known to take on values between 2 and 10. Note that this type of criterion does not apply to thermal breakup events.

Equation 1 and others like it do not explicitly account for hydrodynamic or morphological effects; hence, they can only be applied to the particular river site at which they have been calibrated, i.e. they are *site-specific*. Application to another site on the same river, or to a different river, can only be made if adequate local data are available. This limitation can, in principle, be overcome with criteria that are based on a physical-process hypothesis. A number of these have been proposed in the literature and were recently reviewed and evaluated (Beltaos, 1997). The following equation, based on the simple requirement that ice plates formed by transverse cracking are set in motion when there is adequate water surface width, was found to describe all six data sets:

$$\frac{W_{BM} - W_i}{h_o} = \frac{\beta(m - 0.50)\sigma_{fo}}{8m^2\tau}\left(\frac{\sigma_f h}{\sigma_{fo} h_o}\right) \qquad [2]$$

in which W_{BM} = water surface width at the stage at which a mechanical breakup is initiated; W_i = width of ice cover = river width at the freeze-up stage minus side strips caused by hinge cracking prior to breakup; h, σ_f = ice cover thickness and flexural strength at the time when breakup starts, while the suffix "o" denotes initial values, just before thermal deterioration begins; m = radius of channel curvature divided by ice cover width; τ = downslope force per unit area applied on the ice cover due to its own weight and to flow shear stress; and ß = dimensionless coefficient, whose exact value cannot be determined by theory beyond upper and lower bounds of 0.3 and 1.5.

The ratio $\sigma_f h/\sigma_{fo} h_o$ quantifies the loss of ice "competence" due to thermal deterioration during the pre-breakup period. This process involves reductions in both ice thickness via top and bottom melt, and in strength, due to penetrating solar radiation and preferential melting at crystal boundaries (Bulatov, 1972; Ashton, 1985; Prowse et al, 1990). It is difficult to predict such effects, however, owing to complexities introduced by the snow cover and its changing reflective/absorptive properties as melt progresses (Prowse and Marsh, 1989). Consequently, the competence ratio has been expressed as an empirical function of accumulated degree-days of thaw, S_5, above a base of -5°C (Bilello, 1980).

With this background, Eq. 2 can be re-written as:

$$\Phi_B \equiv \frac{8(W_{BM} - W_i)\tau m^2}{(m - 0.50)h_o} = \beta\sigma_{fo}\left(\frac{\sigma_f h}{\sigma_{fo} h_o}\right) = \beta\sigma_{fo} f(S_5) \qquad [3]$$

The LHS of Eq. 3 can be calculated from water-level and bathymetric data for any one breakup event and plotted versus degree-days of thaw (base of -5°C), as shown in Fig. 1. The relative collapse of the data points in Fig. 1 supports the structure of Eq. 3 (or Eq. 2), while the scatter is likely caused by three factors:

(a) Uncertainties in hydrometric station data interpretation, where applicable
(b) Use of the degree-day index, S_5, as a surrogate for complex melt and radiation absorption phenomena that cannot be quantified at present
(c) Variations in the initial ice strength, and thence in the quantity $\beta\sigma_{fo}$. As discussed by Beltaos (1997, 1998), flexural ice strength is subject to scale effects and known to decrease with specimen size; in the present context, the size is represented by ice cover width.

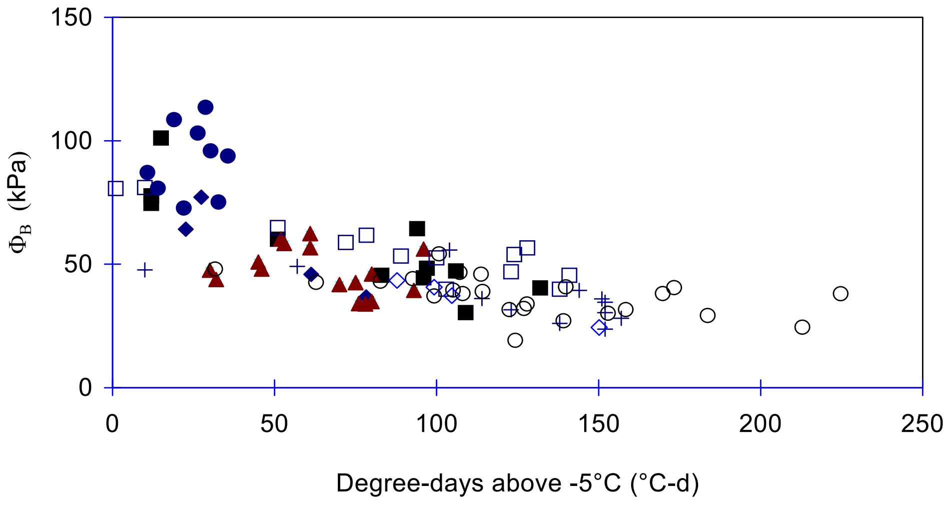

Fig. 1. Onset of breakup criterion (after Beltaos, 1997, with changes). Crosses: Restigouche River; diamonds: Grand R; squares: Nashwaak R; triangles: Moose R; circles: Thames R; hollow squares: St John R (Beltaos, 1999); hollow diamonds: Mackenzie R (using data from Hicks et al, 1995); hollow circles: Southwest Miramichi R (Beltaos, 2002)

Though the physical concept expressed by Eqs. 2 and 3 is rather simple and not fully rigorous, it explains several trends known by experience. [Note that the difference in widths, W_B-W_i, is roughly proportional to the water level rise, H_B-H_F, since W_i is usually close to the freeze-up width, W_F, and the cross sectional shape of a river is close to trapezoidal]. For example, the predicted effect of the freeze-up level, expressed by W_i, is intuitively plausible and has been known empirically for several decades (e.g. Shulyakovsky, 1966; Beltaos, 1987; Beltaos and Burrell, 1992). The effect of river planform is expressed by the dimensionless radius of curvature, m. For relatively straight reaches, m is in the ballpark of 10 or more, and the quantity $(m-0.50)/m^2$ is about 0.1 or less; for a sharp bend, with m = 3 or less, it increases to 0.3 or more . Therefore, relatively straight reaches are expected to break up first and jamming is very likely to occur at sharp bends, as is also known by experience. Similarly, ice jamming is known to occur where river slope and velocity decrease abruptly, which is explained by low τ - values in Eqs 2 and 3.

Of particular interest to the present discussion is the decreasing trend in the quantity Φ_B as thermal inputs increase. This is in accord with expectation, however, the data points do not continuously approach the horizontal axis, but seem to remain above a value of 20 kPa.

3. **Threshold condition for thermal breakup events**

So far, the discussion has exclusively referred to mechanical breakup events, characterized by the fracture and dislodgment of a still-competent ice cover. When the strength and thickness of the cover are reduced to the point where it begins to disintegrate in place, a thermal breakup takes place. A simple quantitative expression of this condition would require the competence ratio, $\sigma_f h/\sigma_{fo} h_o$, to drop below a threshold value:

$$\frac{\sigma_f h}{\sigma_{fo} h_o} \leq \varepsilon \qquad [4]$$

in which ε = a "critical" or threshold value, to be determined empirically. This condition, not only appeals to intuition, but is also consistent with the mechanical-breakup data that are plotted in Fig. 1. Over a rather extensive range of thermal inputs to the ice cover, as indexed by S_5, no data point lies below Φ_B = 20 kPa. By virtue of Eq. 3, this suggests that no thermal events occur for $\beta\sigma_{fo}(\sigma_f h/\sigma_{fo} h_o) > 20$ kPa. Using Fig. 1, it can be determined that the latter condition translates to $\sigma_f h/\sigma_{fo} h_o$ values in excess of 0.17-0.30 (the value of $\beta\sigma_{fo}$ represents the vertical-axis intercept in Fig. 1, and is approximately between 70 and 120 kPa).

Substitution of Eq. 4 in Eq. 3, and use of the symbol W_{BT} to denote channel width when a thermal event is initiated, results in:

$$W_{BT} - W_i \leq \left\{ \frac{\varepsilon\beta\sigma_{fo}\,(m-0.50)}{8m^2\tau} \right\} h_o \qquad [5]$$

which indicates that, at a given site, the threshold value of the width difference should be proportional to the winter ice thickness. The quantity within the brackets on the RHS of Eq. 5 will change from year to year, owing to variations in the unit force, τ. However, the range of such variation is expected to be small because thermal breakups occur under low-flow conditions. Therefore, the bracketed quantity in Eq. 5 can be roughly considered a site-specific constant.

The width of the ice cover, W_i, can be calculated from (Beltaos, 1997):

$$W_i = W_F - 2w_s \qquad [6]$$

in which W_F = water surface width at the stage of the preceding freeze-up; and w_s = hinge crack offset = width of ice strip that remains attached to the river bank when the hinge crack forms. As outlined in Beltaos (1997), hinge cracking develops shortly after the start of runoff. The offset depends on ice cover properties, and, in relatively narrow streams, on river width. The offset value can be estimated from Fig. 2.

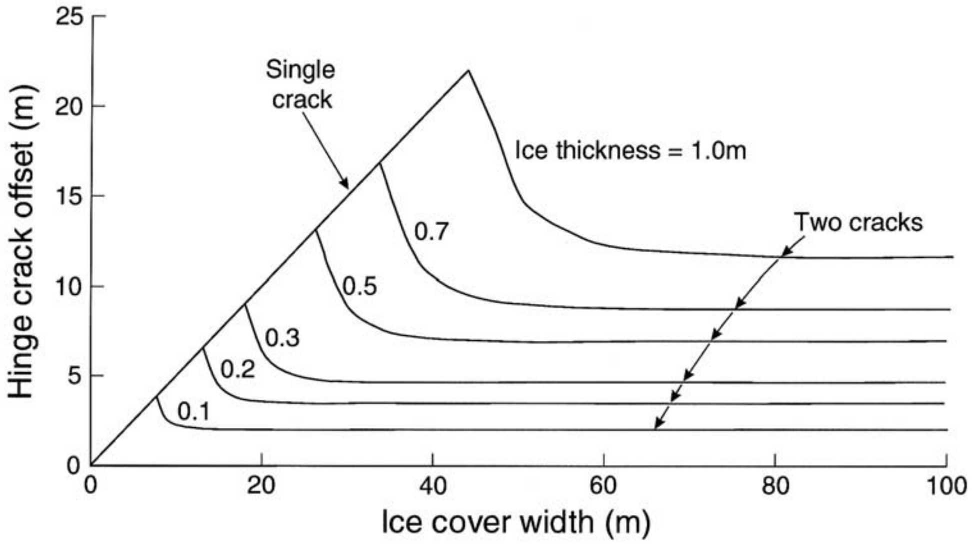

Fig. 2. Distance of hinge crack from river edge, as a function of channel width and ice cover thickness for a fixed value of the modulus of elasticity (E = 1.4 GPa); from Beltaos, 1995.

For typical river width and ice cover thickness, Fig. 2 indicates that the offset only depends on thickness. This dependency is described by:

$$w_s = 11.5 h_o^{0.75} \qquad [7]$$

which applies to the constant-offset range with w_s and h_o expressed in metres. In principle, Eqs 5-7 fully determine the threshold value of channel width that separates thermal from mechanical breakup events. In practice, however, channel width is not available, unless a comprehensive survey of channel bathymetry in the reach of interest is carried out. Assuming that the channel cross section is roughly trapezoidal, with an average side slope of n, Eq. 5 transforms to:

$$H_{BT} - H_F \leq n\left\{\frac{\varepsilon\beta\sigma_{fo}(m-0.5)h_o}{16m^2\tau} - w_s\right\} \approx n\delta h_o \qquad [8]$$

This equation is expressed in terms of the water surface elevation, H, a quantity that is much easier to obtain than surface width, and routinely available at gauged sites. Because the hinge offset, w_s, is proportional to a power of h_o that is close to 1 (Eq. 7) while the latter does not vary excessively from year to year, the quantity within the brackets in Eq. 8 is approximately proportional to thickness, with a coefficient represented by δ.

It is important to stress that, according to Eq. 8, a thermal breakup can only occur when the onset stage is less than $H_F + n\delta h_o$. Similarly, a mechanical breakup can only occur when the onset stage exceeds $H_F + n\delta h_o$. However, the converse is not true. A stage in excess of $H_F + n\delta h_o$ does not necessarily imply that a mechanical breakup will be initiated. The stage must also exceed the value that corresponds to W_{BM} in Eqs. 2 and 3. The interaction among the various factors associated with these conditions leads to two different scenarios that can result in a thermal event, as is further discussed in Section 5.

4. Case studies

4.1. Data Sources

The main sources of field data that can be used to test Eqs. 5 and 8, are hydrometric station records kept by appropriate water agencies in different countries. In Canada, historical daily flow data and chart-recordings of river stage can be obtained from the Environmental Monitoring section of Environment Canada (formerly known as Water Survey of Canada, or WSC). Ice thickness can be gleaned from discharge-measurement notes taken during the winter. As explained by Beltaos et al (1990), such information can be analyzed for each season of record to determine important freeze-up and breakup characteristics such as H_F, H_B and H_m (maximum ice-influenced stage). A number of river-gauging sites have already been examined in order to develop predictive methods for breakup occurrence and severity.

It is often possible to identify thermal breakup events by the relatively smooth and "uneventful" appearance of the stage – time variation. Where thermal events are relatively frequent, it may be possible to test the threshold conditions (Eqs. 5 and 8) in terms of the differences H_B-H_F, or W_B-W_i where channel bathymetry is known. Of the sites represented in Fig. 1, few experience frequent thermal breakups: they were selected for the opposite feature, i.e. frequent mechanical and severe events.

For the present purposes, the gauge site on the SW Miramichi River at Blackville is the best source: thermal events are easily identifiable and occur relatively frequently (Beltaos, 2002). The gauge site on the Restigouche River at Rafting Ground Brook is also a useful source, while a third case study was obtained from Peace River at Peace Point, Alberta. Here, published data (Prowse et al. 1996) to 1993 were supplemented by the writer for the years following 1993. At that particular location, the question of thermal vs. mechanical events is a major issue because of the drying trend being experienced by the Peace-Athabasca Delta wetlands as a result of less frequent jamming in the past three decades.

4.2. SW Miramichi River at Blackville

This hydrometric station is located on the lower portion of the Miramichi River basin. In the vicinity of the gauge site the river consists of a single, mildly curved, channel 100 - 150 m wide, depending on stage. The local water surface slope was surveyed on July 13, 1999, and was found to be 0.36 m/km. Using also bathymetric data from nearby cross sections and gauge rating tables, the variation of average channel width with stage was determined. Detailed flow and stage data are available since the 1961-1962 ice season, though there are occasional gaps in the record.

From gauge records and insitu observations (Beltaos et al, 2001), it has been determined that freeze-up occurs in late fall or early winter; after freeze-up, the stage drops with the decreasing flow. Typically, it attains a relatively steady value until mid- or late March, when it again begins to rise in response to snowmelt that is often accompanied by rainfall. Breakup is usually initiated in April and lasts for several days. In some years, the initial rise in flow and stage does not lead to breakup but is followed by a sustained "plateau" or relatively constant-stage phase, before there is additional runoff that leads to breakup. This feature has also been encountered on the Restigouche River (Beltaos and Burrell, 1992), and probably results from persistent but modest runoff, largely due to snowmelt, which is not quite capable of dislodging the ice cover. If the final runoff event does not materialize quickly, the ice cover continues to decay and a thermal event occurs. Thermal breakups are easily identifiable on the recorder charts by a phase of steady or slowly changing stage, terminated by an abrupt drop that signifies the movement of the ice cover.

As a direct check on the present hypothesis (Eq. 4), values of the quantity Φ_B were calculated for all available events, using the above-mentioned bathymetric information and river slope. From a topographic map, the local radius of curvature was determined (1250 m), and the corresponding value of m calculated (13.6), using the average value of the ice cover width. Values of $\Phi_{B,}$ which by Eq. 3 is equal to the competence ratio $\sigma_f h/\sigma_{fo} h_o$ times the constant $\beta\sigma_{fo}$, were compared between mechanical-and thermal-breakup data sets. The thermal-event range (1.8-21.5 kPa) is clearly separated from the mechanical-event range (19.2 to 68.2), despite the slight overlap. The threshold value is taken as the middle of the overlap range, or 20.4 kPa. With a backward-extrapolated value of 70 kPa for $\beta\sigma_{fo}$, this threshold translates to $\varepsilon \approx 0.29$. Where a data set does not include points with very small S_5-values, as in the present case, backward extrapolation in Fig. 1 is based on a negative exponential relationship that describes normalized plots (Beltaos, 1997). Of course, this is an approximation: visual inspection of Fig. 1 suggests that the value of $\beta\sigma_{fo}$ would be in the range 60-80 kPa, implying a range of 0.26-0.34 for ε.

Table 1 summarizes data needed to test the simpler relationships, Eqs. 5 and 8, and suggests that thermal events comprise about a quarter of the total number of events. Equation 5 is tested in Fig. 3 by plotting the width difference, $W_B - W_i$, against ice thickness, h_o. The two sets of data points can be easily separated by a straight line through the origin. However, the slope of the line is not uniquely defined because of the relatively wide gap between the two sets.

To test the less rigorous, but more practical Eq. 8, the difference H_B-H_F is plotted against ice thickness in Fig. 4 for both mechanical and thermal breakups. The two data sets are satisfactorily delineated by a straight line through the origin, in accord with Eq. 8. Unless detailed bathymetric and hydraulic data are available, the slope of the line can only be determined via historical site-specific data. This finding also explains an empirical threshold that was identified by Beltaos (2002), based on the same data points. This was simply that $(H_B\text{-}H_F)_{th}$ = 0.45 m, which also separates the two data sets in Fig. 7 (the suffix "th" denotes threshold values). Because the range of ice thickness is narrow, relative to the slope of the linear fit, a constant threshold value of H_B-H_F "works" just as well.

Table 1. Summary of results, SW Miramichi River At Blackville

Breakup Year	h_o (m)	H_F (1) (m)	H_B (1) (m)	W_B (m)	W_i (m)
Mechanical Events					
1962	0.66	1.59	2.94	114.5	88.5
1963	0.90	1.43	2.46	111.0	83.1
1964	0.76	3.31	4.56	124.3	98.1
1969	0.60	1.98	2.67	112.6	91.2
1971	0.70	1.52	2.87	114.5	87.2
1972	0.82	1.31	2.80	113.0	84.0
1974	0.58	2.50	3.29	117.3	95.9
1976	0.70	2.59	4.39	123.3	94.2
1979	0.75	1.07	3.38	117.5	85.3
1980	0.56	1.52	3.60	118.5	90.0
1983	0.51	1.90	3.65	119.0	92.5
1984	0.69	3.20	4.45	123.0	98.4
1985	0.49	0.95	1.75	106.0	89.8
1986	0.65	1.22	3.53	118.0	87.2
1987	0.75	1.60	3.65	119.0	86.8
1988	0.60	1.70	3.55	118.5	90.2
1989	0.52	1.50	3.02	115.0	90.8
1990	0.55	2.15	3.10	116.0	93.2
1991	0.56	3.30	3.80	120.5	102.5
1993	0.64	1.50	3.30	117.5	88.4
1994	0.72	2.40	3.84	120.0	91.9
1996	0.45	1.70	3.47	118.0	92.8
1997	0.72	2.75	4.20	122.5	94.4
1998	0.72	1.20	4.41	123.3	86.9
Thermal Events					
1965	0.37	2.80	1.07	103.5	102.0
1966	0.70	1.95	2.35	110.0	89.2
1967	0.72	1.75	1.95	107.0	87.9
1968	0.70	2.59	2.55	111.5	94.2
1981	0.68	2.20	1.30	104.0	90.6
1992	0.64	1.55	1.35	104.0	88.4

(1) Indicated stages represent "gauge height"; add 8.169 m to convert gauge height to geodetic elevation

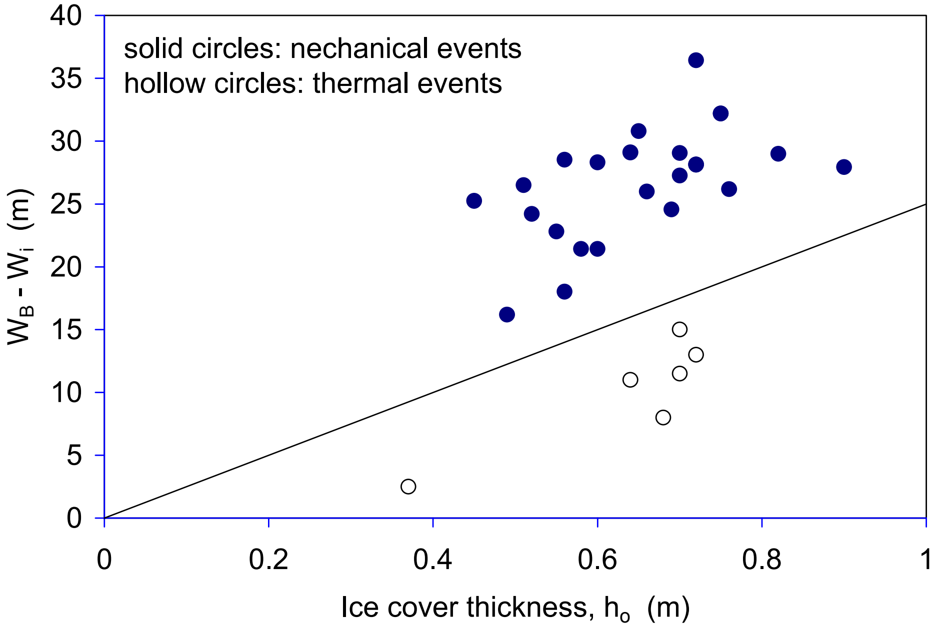

Fig. 3. Distinction between mechanical and thermal breakup events in terms of channel width (Eq. 5). Southwest Miramichi River, NB

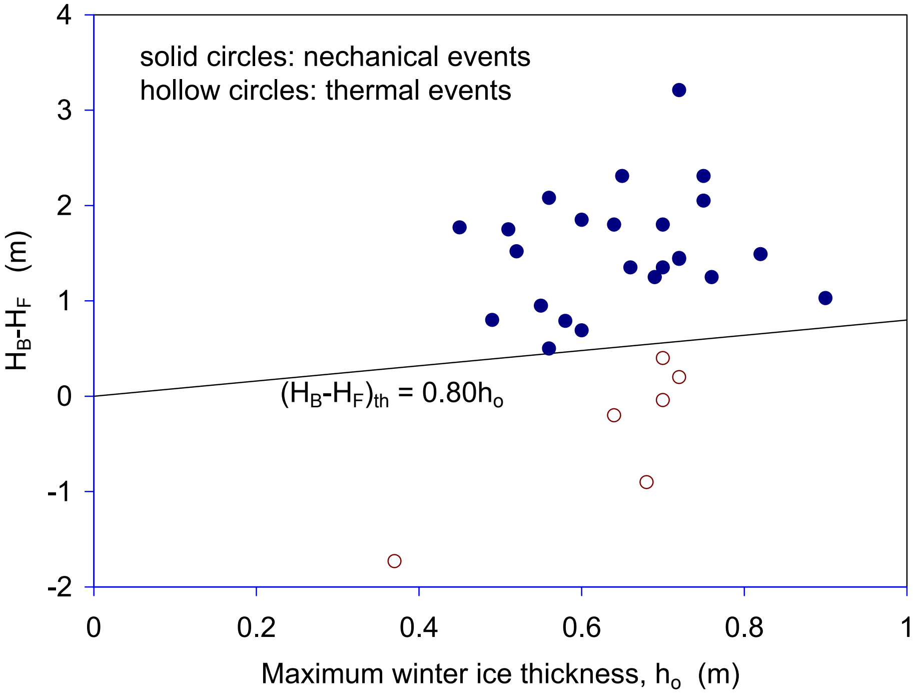

Fig. 4. Distinction between mechanical and thermal breakup events in terms of stage (Eq. 8). Southwest Miramichi River, NB

4.3. Restigouche River at Rafting Ground Brook

Analysis of gauge records at this site was first carried out with the main purpose of studying mechanical events (Beltaos and Burrell, 1992). There were several thermal events in the record (1970-1992) but only three have adequate information to determine values of the quantity Φ_B. The range defined by these three events is 10.5 – 19.6 kPa while the range defined by the mechanical events is 23.7 – 55.7 kPa. The threshold value is estimated as 21.6 kPa, which corresponds to $\varepsilon \approx 0.29$ (with $\beta\sigma_{fo} \approx 75$ kPa). This value is the same as that found for the Southwest Miramichi River. However, $\beta\sigma_{fo}$ was again obtained by backward extrapolation; the visually-assessed range is 60-90 kPa, implying a range of 0.24-0.36 for ε.

In terms of stage, the threshold appears to be expressed simply as $(H_B\text{-}H_F)_{th} = 0$ (Fig. 5), suggesting that the two terms within the brackets in Eq. 8 balance each other.

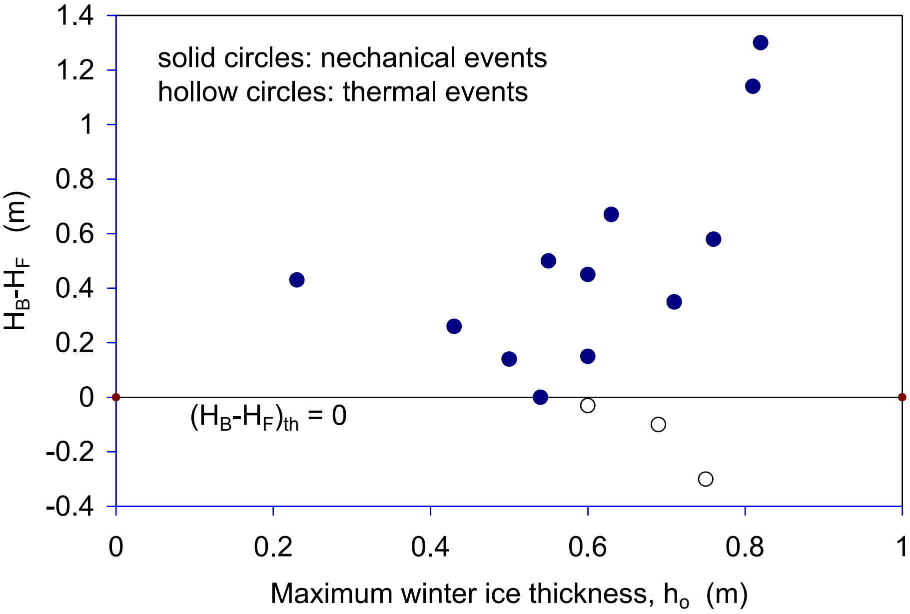

Fig. 5. Distinction between mechanical and thermal breakup events in terms of Eq. 8. Restigouche River, NB

4.4. Peace River at Peace Point

Analysis of gauge records at this site was first carried out by Prowse et al (1996) as part of a study intended to elucidate ice-jam flooding frequency in the Peace-Athabasca Delta. Prowse et al (1996) examined the years 1962-1993 and provided preliminary assessments of which events were of the thermal or the mechanical type. This information was further analyzed by the author who also added more recent years (1994-2001). Event designation is not an easy task in this case because there is virtually no observational information on the local breakup process. Three criteria were adopted as possible indicators of thermal breakup:

a. Closeness of peak breakup stage, H_m, to corresponding stage for flow under sheet ice cover, H_i. Small values of H_m-H_i indicate lack of jamming near the gauge and may thus suggest a thermal event.
b. Large values of accumulated degree-days of thaw at the onset of breakup may indicate a prolonged period of ice decay.
c. Small values of the snowpack index (= total snowfall at Grande Prairie during the period November 1 to March 31) may indicate low spring breakup flows, and again pointing to a protracted pre-breakup period

Use of these criteria resulted in unambiguous designation of most events; however, there were nine events where the designation could only be considered "probable", as indicated in Table 2, where the relevant data are summarized. It was not possible to arrive at any designation in three instances, marked as "unknown". Ice thickness is not available in some of the years of record and the average value (0.90 m) has been inserted as an approximation, given the relatively narrow range of h_o.

There are no detailed data to enable calculation of Φ_B values, and thence determine the threshold ratio, ε. However, Eq. 8 can still be tested, using H_B, H_F and h_o. This is shown in Fig. 6, where a linear threshold is again seen to separate the data points into mechanical and thermal data sets. A few data points from each set plot on the "wrong" side of the dividing line, possibly as a result of uncertainties in event designation. An independent designation, based on mean daily flows and stages, has been carried out by Ashton (2002, pers. comm.). The two sets differ quite a bit on seven occasions, but are otherwise very similar. Ashton's set exhibits a slightly improved separation of data points while the line of separation has the same equation in both cases.

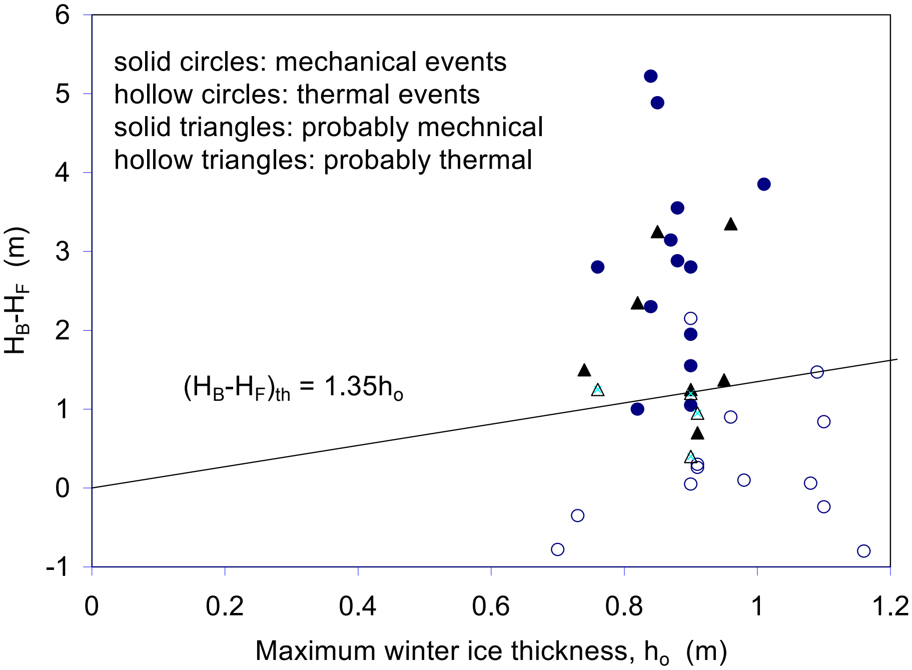

Fig. 6. Distinction between mechanical and thermal breakup events in terms of Eq. 8. Peace River, Alberta

Table 2. Summary of results, Peace River at Peace Point

Breakup Year	h_o (m)	H_F (m)	H_B (m)	Event designation
1962	1.01	212.40	216.25	mechanical
1963	0.76	213.10	215.90	Mechanical (ice-jam flood)
1964	0.85	210.50	213.75	probably mechanical
1965	0.88	211.90	215.45	Mechanical (ice-jam flood)
1966	0.91	214.70	215.00	thermal
1967	0.91	212.60	213.30	probably mechanical
1968	0.91	211.80	212.70	unknown
1969	0.90*	210.95	212.90	mechanical
1970	0.90*	213.20	213.60	probably thermal
1971	0.90*	212.45	213.50	mechanical
1972	0.90*	213.00	215.80	Mechanical (ice-jam flood)
1973	0.98	213.50	213.60	thermal
1974	0.82	212.70	213.70	Mechanical (ice-jam flood)
1975	0.79	213.20	214.20	unknown
1976	0.82	213.55	215.90	probably mechanical
1977	0.76	214.80	216.05	probably thermal
1978	0.91	214.10	215.05	probably thermal
1979	0.95	213.33	214.70	probably mechanical
1980	0.7	212.90	212.12	thermal
1981	0.84	212.13	217.35	mechanical
1982	0.96	212.50	215.85	probably mechanical
1983	0.74	213.25	214.75	probably mechanical
1984	0.90*	212.92	214.60	unknown
1985	0.96	215.15	216.05	thermal
1986	1.09	214.10	215.57	thermal
1987	0.90*	213.40	215.55	thermal
1988	0.90*	214.75	216.30	mechanical
1989	0.90*	214.50	215.75	probably mechanical
1990	0.90*	213.10	214.30	probably thermal
1991	0.90*	214.25	214.30	thermal
1992	0.84	215.20	217.50	mechanical
1993	1.16	214.80	214.00	thermal
1994	0.88	213.57	216.45	mechanical
1995	0.91	214.42	214.68	thermal
1996	0.87	212.38	215.52	Mechanical (ice-jam flood)
1997	0.85	214.32	219.20	Mechanical (ice-jam flood)
1998	1.08	215.92	216.98	thermal
1999	1.1	214.62	214.37	thermal
2000	0.73	213.12	212.77	thermal
2001	1.1	215.12	215.96	thermal

*Thickness not available; average value is used as an approximation

5. Discussion

The postulated threshold condition that is based on a delimiting value of the competence ratio (Eq. 3) is directly supported by data sets from two case studies, the Southwest Miramichi River at Blackville and the Restigouche River at Rafting Ground Brook. These case studies resulted in $\varepsilon \approx 0.29$ (expected range: 0.24 - 0.36). Simplified equations that result from Eq. 3 are also supported by these case studies, and by a less detailed one, describing Peace River at Peace Point.

The present results suggest that river ice covers are subject to thermal breakup when their competence (product of flexural strength and thickness) drops below some 30% of its initial, undeteriorated value. At first glance, this finding does not appear to physically explain the disintegration of the cover that is characteristic of thermal events. One must take into account, however, the spatial variability of strength and thickness because the 30% figure is an "average" for the entire reach of interest. Both thickness and strength are likely to vary randomly along and across the river, as is often observed in the field. Though it is not safe to venture on decaying river ice for thickness and strength measurements, ice blocks that are left stranded on the river banks after breakup has begun, can be examined in some detail. It is not uncommon to encounter blocks that are relatively thick and strong next to blocks that are thin or almost candled. It seems plausible that an ice cover whose average competence has decreased by 70%, contains parts where the competence is approaching zero. These portions will disintegrate first, and create open-water areas on the river surface. The open areas act as heat sinks, elevating the water temperature, which in turn, results in more ice melt and leads to an accelerating process of "opening-up" of the river (Andres, 1988).

Several practical implications result from the present findings, especially the simple threshold expressed by Eq. 8. The threshold rise above freeze-up level varies primarily in proportion to ice cover thickness. Since thermal breakups are unlikely to happen during mid-winter thaws, the applicable thickness is that which is attained at the end of the winter, just before the start of thermal decay. At a fixed location, this thickness does not vary greatly from year to year, so that the threshold rise can usually be regarded as a site-specific constant. This quantity takes the approximate values 0, 0.45 and 1.3 m in the Restigouche, Southwest Miramichi and Peace rivers, respectively. The order of magnitude is comparable to that of the thickness of the ice cover.

It is important to stress that stage rise above the threshold value is a necessary but *not sufficient* condition for a mechanical breakup, because Eq. 1 (or Eq. 2) must also be satisfied. A typical thermal event involves a slow river-stage rise and decline, that never attains the threshold value implied by Eq. 8. This is illustrated by the line labeled "thermal-1" in Fig. 7, where three different hydrographs are considered for the pre-breakup phase that begins at time t_o. The threshold value, H_{th}, does not change with time because it is fixed by antecedent conditions (from Eq. 8, $H_{th} = H_F + n\delta h_o$). On the other hand, the mechanical-breakup onset stage, H_{BM}, as predicted by Eq.1 or Eq. 2, decreases continuously as a result of cumulative thermal deterioration, although it is initially much higher than both H_{th} and the prevailing river stage. Less frequent, but more interesting, is the case where there is significant runoff and the river stage rises above H_{th} but remains below H_{BM} ('thermal-2" in Fig. 7). A mechanical breakup cannot occur and the only possible outcome is a thermal event, occurring after the river stage has

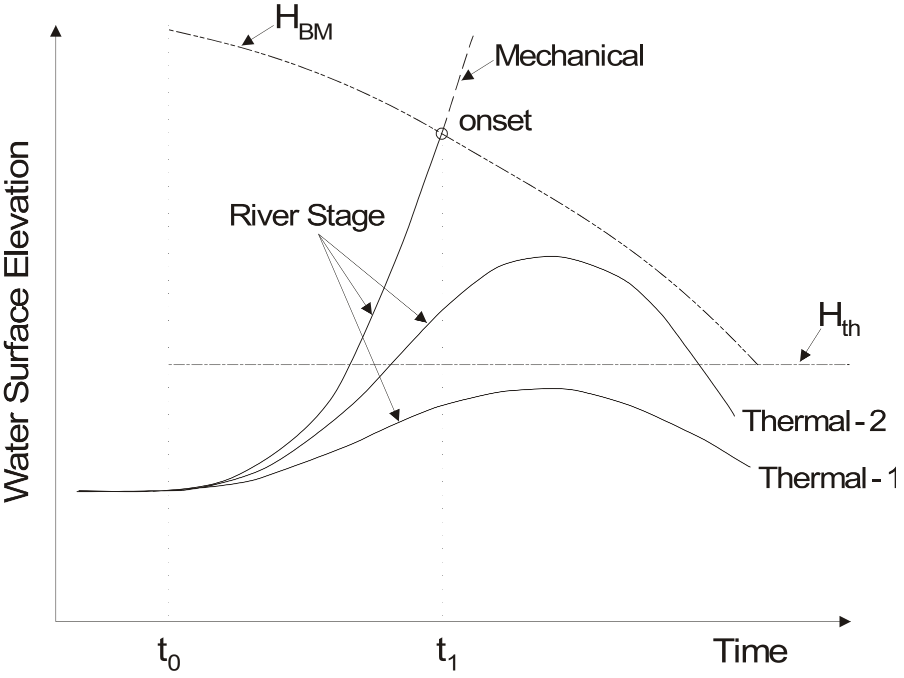

Fig. 7. Illustration of different types of breakup events that may result from different river stage hydrographs

peaked and dropped below H_{th}. While the river stage remains above H_{th}, there is potential for a mechanical breakup and significant ice jams. Once the stage drops below H_{th}, ice jamming is no longer a threat. This scenario may result from unusually high freeze-up levels and/or very slow thermal decay of the ice cover. The writer has observed this type of thermal event on two occasions: 1991 breakup in the Restigouche River near Rafting Ground Brook (Beltaos and Burrell, 1992); and 2002 event in the Peace River near Peace Point (Beltaos, unpublished data).

The present results are of particular interest to ecological and hydrologic implications of climate change. Such variables as freeze-up level, ice cover thickness, pre-breakup ice decay, and spring flow, can change in Canadian rivers and alter the threshold conditions for mechanical/thermal breakups. In turn, this will result in more frequent, or less frequent, ice jams and floods, depending on local circumstances. Similar changes may occur as a result of regulation projects or construction of river structures, and would have to be evaluated during the environmental impact assessment of the project.

6. Summary and conclusions

Theoretical analysis and case studies suggest that the threshold between mechanical and thermal breakup events is quantified by the degree to which the competence of the ice cover (product of strength and thickness) is reduced at the time when breakup is initiated. A 70% loss of competence signals a thermal event, but strength and thickness are difficult to measure or assess during the decay period that leads to breakup.

Therefore, the quantitative consequences of this criterion were worked out and a less rigorous but more practical threshold was derived. The latter is expressed in terms of the rise above the freeze-up level, and is shown to vary roughly in proportion to ice thickness. This criterion is supported by the results of three case studies, and has various practical implications, including issues related to climate change and environmental impact assessment.

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