Review
Progress in the study and management of river ice jams
Spyros Beltaos *
Research Scientist, Aquatic Ecosystem Impacts Research Division, National Water Research Institute, Environment Canada, 867 Lakeshore Rd., Burlington, ON, Canada L7R 4A6
Received 31 July 2007; accepted 4 September 2007

Abstract
River ice jams can cause extreme flood events with major consequences to infrastructure, riverside communities, and aquatic life. Yet, it is only in the last few decades that concerted efforts have been made to understand and predict ice-jam occurrence and severity. Building on a 1990s state of the art review, new physical knowledge, prediction capabilities, and management methods are discussed herein. The thickness and hydraulic roughness of ice jams have been elucidated, and flow through ice-jam voids quantified. Under-ice transport of frazil ice, which can lead to enormous freezeup accumulations, has been placed on a more rigorous footing, while heat exchange with the water flowing under a jam can be predicted with some confidence. Systematic field measurements have produced new understanding of the waves that are generated by ice-jam releases. Increased understanding of the physical processes has enhanced confidence in older numerical models and motivated development of more sophisticated ones, leading to two-dimensional dynamic algorithms based on continuum as well as discrete element approaches. Ice-jam management and control continue to be difficult tasks, but new structural and non-structural techniques offer promising avenues, at least in the case of relatively small rivers. The emerging issue of climate change and the growing appreciation of related ecological linkages have led to important, but still few, insights on how ice jamming regimes can be modified by altered climatic conditions and what the repercussions might be on river ecology. Despite the progress, there are still major unknowns, particularly related to the conditions of formation and release of ice jams.

Keywords: Breakup; Freezeup; Mitigation; Numerical modeling; Physical characteristics; Prediction; Release waves

Contents
1. Introduction ........................................................ 2
2. Types of ice jams .................................................. 4
3. Physical characteristics of ice jams ................................. 5
   3.1. Measurements of ice-jam water levels and thicknesses .......... 5
   3.2. Hydraulic characteristics of ice jams. ............................ 6
       3.2.1. Roughness (breakup jams) .................................. 6
       3.2.2. Flow through ice-jam voids (breakup jams) ................. 6

* Tel.: +905 336 4898; fax: +905 336 4420.
E-mail address: spyros.beltaos@ec.gc.ca.

0165-232X/$ - see front matter. Crown Copyright © 2007 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2007.09.001
1. Introduction

Ice jams occur during the transitional periods of freezeup and breakup, which mark the beginning and end of an ice cover season, and may also occur in mid-winter in temperate regions during so-called “mid-winter thaws”. Jams often extend for many kilometres along a river and can attain aggregate thickness of several metres. To pass the incoming flow, the river has to rise considerably so as to accommodate both the keel of the jam and the extremely large hydraulic resistance of its underside. Flooding can be the result, even if the prevailing river flow is moderate relative to what is characteristic of open-water floods. It is noted in Ashton (1986) that “ice jam floods are the greatest hazard of river ice”. Prowse and Beltaos (2002) cite several examples of extreme ice-jam flood events that have been documented around the world (e.g. Canada and the United States: Petryk, 1990; White and Eames, 1999; China: Li, 1996; Finland: Kuusisto, 1994a; Iceland: Eliasson, 1994; Norway: Killingtveit, 1994; Russia: Grigoriev and Sokolov, 1994; and Sweden: Bengtsson, 1994). Studies like those of Gerard and Karpuk (1979), Tuthill et al. (1996), Beltaos and Burrell (2002), and de Rham et al. (2007), which compare open-water versus ice-induced floods, indicate that the latter often have far lower recurrence intervals for the higher-order events (Fig. 1).

Ice-jam damage to property and infrastructure can be severe, while the impacts on people range from inconvenience to dislocation, and even to loss of life. Navigation and hydro-power generation are also adversely affected by ice jamming.

Extreme ice-jam events have major ecological impacts, 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. On the other hand, flooding caused by ice jams and the waves produced by their release can result in severe fish mortality and loss of spawning grounds. Details on the socio-economic and ecological impacts of ice jams can be found in such publications as Beltaos (1995), Prowse (2000), and Morse and Hicks (2005).

The issue of climate change underscores the need for reliable prediction tools to assess the future ice jamming regime of a river, as may result from modified hydro-climatic conditions. Long-term stability of aquatic ecosystems as well as security of local residents and infrastructure could be adversely influenced by changed ice regimes, depending on site specific conditions. Design of suitable mitigation or adaptation measures should be based on a good understanding of the risks posed by the anticipated changes. The same applies to the design of new infrastructure that may be subject to ice related risks.

Ice jamming is the net result of complex interactions among highly dynamic hydraulic, thermodynamic, and structural processes. The variability and irregularity of natural streams amplifies the complexity of ice jams, which have only been studied systematically in the past fifty years or so. The state of knowledge up to the mid-

![Fig. 1. Comparison of stage-frequency curves for ice-jam and open-water floods. Saint John River at Perth-Andover, New Brunswick (from Beltaos and Burrell, 2002, with changes).](image-url)
1990s has already been summarized (Beltaos, 1995). Consequently, the objective of this article is to highlight new information and data as well as new prediction and mitigation capabilities. Following descriptions of the different kinds of ice jams, new knowledge on their physical characteristics is discussed, including field and laboratory measurements, hydraulic aspects, as well as mechanical and thermal properties. Ice runs and the waves generated by ice-jam releases are described in a separate section. Advances in numerical modelling and mitigation techniques are discussed next. The findings of the few studies that have been carried out on climatic aspects of ice jams and potential future threats are outlined, followed by a brief discussion touching on additional topics pertaining to engineering practice.

2. Types of ice jams

The IAHR (International Association for Hydraulic Research) Working Group on River Ice Hydraulics (1986) defined an ice jam as “... a stationary accumulation of fragmented ice or frazil that restricts flow”. In the same report, a jam classification scheme was developed, based on four criteria (formation mode, season, spatial extent, and state of evolution). In this section, the various types of ice jams are reviewed briefly, while much more detail can be found in Beltaos (1995). The IAHR definition includes the so-called “ice dam”, a bottom accumulation of anchor ice which, being radically different from other jams, is not included in the present discussion.

At freezeup, cold weather cools the river water to produce frazil slush and pans; while at breakup, warm weather and increased runoff lead to fracture of the winter ice cover. In both cases ice slush, ice pans, and ice blocks are being transported on or near the water surface. If this flux is arrested for any reason (e.g. an existing ice cover) or the ice transport capacity of the river is reduced locally (congestion), an ice jam may form. Once initiated, jams propagate upstream in ways that are dictated by flow and channel conditions as well as by internal strength of the accumulation of ice slush and floes. Depending on the manner of their subsequent evolution, jams can be of the surface or thickened kind. The former has minimal potential for damage, but is a common means of winter ice cover formation via freezing of the interstitial water.

Thickened jams include the narrow/wide channel variety (Pariset et al., 1966) as well as the hanging dam. The most common type of jam, almost exclusively forming during breakup and frequently encountered at freezeup, is the wide-channel jam, which forms by collapse and shoving of ice floe accumulations and is just thick enough to withstand the longitudinal external forces applied on it. These forces arise from the flow shear stress and the jam’s own weight and are resisted by the internal strength of the granular accumulation of ice floes that comprise the jam. The internal strength is mobilized by the net buoyancy of the ice accumulation, which is a vertical external force. In contrast to wide-channel jams, narrow-channel jams (rare during breakup) have a thickness that is controlled by the hydraulic conditions at their head (or upstream end). The thickness is just sufficient for the net buoyancy of the ice to withstand submergence by the hydrodynamic forces and overturning moments that develop at the head of the jam.

A hanging dam is an accumulation of frazil slush and occasional ice pans that forms by transport and deposition under an existing ice cover. Hanging dams form typically at freezeup and are too thick to shove, sometimes attaining extreme dimensions in very deep river sections. Owing to larger flows, breakup jams have typically greater flooding potential than freezeup ones, but freezeup jams can also cause problems (e.g. Weyrick et al., 2007; Beltaos et al., 2007a,b).

Ice jams have also been classified according to whether they are evolving or have attained a near-steady state (Beltaos, 1995). Truly steady-state conditions rarely occur in rivers but the temporal changes of various parameters are often small enough to permit the assumption of steady state for prediction purposes. For steady-state jams, an equilibrium reach may be established if there is sufficient ice supply. Here, jam thickness and water depth remain more or less constant, apart from fluctuations due to natural stream irregularities (Beltaos, 1995). The water surface slope becomes equal to the open-water surface slope, provided the flow is free to assume a relatively uniform condition, i.e. there are no significant flow control influences. Once an equilibrium reach has formed, further supply of ice to the jam results in a mere lengthening of the equilibrium reach without changing the maximum water depth or the lengths of the transitional reaches leading to the head and toe (downstream end) of the jam, respectively.

The season of occurrence is also an important element in ice-jam classification. Intuitively, one may be inclined to assume that freezeup jams occur in the fall and breakup ones in the spring. This is true in many cases, but there is also the possibility of mid-winter jamming, resulting from brief thaws accompanied by rainfall. The resulting runoff is often large enough to initiate breakup, followed by renewed freezeup when the cold weather resumes. In certain regions, mid-winter jams can be even more extreme than spring jams (Beltaos et al., 2003; Prowse and Bonsal, 2004).
3. Physical characteristics of ice jams

3.1. Measurements of ice-jam water levels and thicknesses

The measurement of ice-jam characteristics has always been a difficult task, owing to access limitations, river scale, and transient ice conditions. Freezeup jams are more amenable to measurement because they permit safe access for drilling once a layer of solid ice has formed at the water surface. The same applies to breakup jams caused by mid-winter thaws, as they freeze in place upon resumption of the cold weather (Beltaos et al., 2003). For spring breakup jams, which can release at any time and are thus unsafe for access, use of aircraft and oblique air photography can furnish approximate water level profiles in inaccessible reaches (e.g. Beltaos 1983; Andres and Doyle 1984) while road access enables much more accurate water level surveys (e.g. Beltaos et al., 1996a).

Measurement of the thickness of spring jams is a daunting prospect, and no fully satisfactory measurement method exists at present. One possibility is to use flow-propelled devices, which are designed to trace the bottom of the jam, and equipped with radio tags and pressure transducers to remotely report the hydrostatic head above the transducer. The latter is equal to the submerged thickness or keel of the jam. A probe of this type was developed in the early 1990s (Ford et al., 1991). Named the “Ice Jam Profiler” (IJP), this instrument has been utilized on various rivers. Limitations include the lack of control over the trajectory of the probe and lack of information about the transverse variability of the thickness at any given longitudinal location. Moreover, the resulting profiles are usually incomplete because the probe is eventually arrested at extreme ice protrusions or slack-water zones (Beltaos et al., 1996b). Fig. 2 shows typical IJP results, coupled with local data on channel bathymetry and water level. As discussed by Beltaos (2001), thickness information is essential for credible calibration of ice-jam models or testing of related theoretical concepts.

More recently, comprehensive data sets on the thickness of brash ice were obtained by Morse et al. (2003b) on the Saint Lawrence River, by deployment of an upward looking ADCP (Acoustic Doppler Current Profiler). Apart from furnishing the velocity profile, this instrument uses additional algorithms to detect the elevations of the water–ice and water–air interfaces, as well as the velocity of ice drift. This approach is essentially Eulerian as it produces time series of thickness at a fixed point in the river. In the case of an ice jam, the time series could be transformed to an approximate longitudinal variation, following the release of the jam.

Eulerian detection of ice-jam thickness has also been achieved with a similar set up, the Shallow Water Ice Profiling Sonar (SWIPS) unit, which has been deployed in the Peace River near the town of Peace River during the 2004–05, 2005–06, and 2006–07 ice seasons (Jasek et al., 2005b; Jasek and Marko, 2007); This instrumentation provides a wealth of information, including a continuous record of ice draft, and illustrating a number of consolidation movements prior to stable ice cover formation, as well as furnishing thermal erosion rates during the winter (Fig. 3).

Unlike field measurement, laboratory experimentation affords a controlled environment for studying aspects of ice-jam development that cannot possibly be examined in nature. For example, Hara et al. (1996) carried out a laboratory investigation on the arching of ice sheets to explain ice jamming and associated damages at the Choei Bridge over the Hassamu River in Sapporo, Japan in February of 1994. Wang et al. (2006) reported a detailed investigation into the configuration of ice jams in a curved laboratory channel, while Healy and Hicks (2006) examined dynamic effects on the formation and final configuration of ice jams in a straight laboratory flume.
3.2. Hydraulic characteristics of ice jams

3.2.1. Roughness (breakup jams)

A seminal hydraulic property of a jam is its roughness, which controls resistance to flow and thence plays a major role in flooding potential. Early work on freezeup accumulations (Nezhikhovskii, 1964) provided very useful data for jams comprising loose slush, dense (frozen) slush, and solid-ice blocks. In all three cases, the Manning roughness coefficient increased with increasing jam thickness (average value), being largest for ice block accumulations. Lack of comparable information for breakup jams resulted in adoption of the ice-block values as a working hypothesis, which was recently corroborated by data obtained with the aforementioned IJP probes (Beltaos, 2001). The absolute jam roughness, calculated as a statistical measure of thickness deviation from the mean, increased linearly with average jam thickness for the tested range of thickness (up to 3 m). Application of this finding to the hydraulic conditions pertaining to Nezhikhovskii’s data on ice block accumulations resulted in similar Manning coefficients. Moreover, combining the absolute roughness results with practical experience, Beltaos (2001) obtained the following equations for the composite-flow resistance coefficients under breakup jams:

\[ f_o \approx (0.39 \text{ to } 0.56) \frac{h}{y} \]  
\[ n_o \approx (0.063 \text{ to } 0.076)h^{1/2}y^{-1/3} \]  

in which \( f \) and \( n \) respectively denote friction factor and Manning roughness coefficient, while the suffix “o” denotes composite-flow values. The variables \( h \) and \( y \) represent (laterally averaged) jam thickness and flow depth, respectively. Eqs. (1a) and (1b) apply when \( h/y \) is in the common range of 0.3 to 1.0; for unusually thin or thick jams, composite roughness calculation is far more complex.

3.2.2. Flow through ice-jam voids (breakup jams)

Early papers on ice jams, and some of the models currently in use, assume that no flow occurs within the body of the jam itself. Though this assumption works very well within most of the length of an ice jam, it is incompatible with the empirically-known phenomenon of grounding that typically occurs at breakup and near the toe of a jam. As pointed out by Beltaos and Wong (1986), the entire river discharge would then have to flow as seepage through the voids of the jam. Even where grounding is only partial, a large portion of the flow must occur as seepage; else the velocity under the rubble would have to be impossibly high. Because of the relatively large size of voids in breakup jams, the seepage flow through the jam, \( Q_p \), should vary as the square-root of the water surface slope, rather than in simple proportion to it. This understanding was built into the RIVJAM model (Beltaos, 1996) according to the relationship

\[ Q_p = \lambda A_J \sqrt{S_w} \]  

in which \( A_J \) = cross-sectional area occupied by the wetted portion of the jam; \( S_w \) = slope of the water surface; and \( \lambda \) = “seepage coefficient” (m/s) that is
expected to depend on ice block shape and thickness as well as on ice-jam porosity, \( p_j \) (Ergun formula, as quoted by Bear, 1972). Values of \( \lambda \) that have been found to “work” in numerical ice-jam modelling range from 1.0 to 2.5 m/s (Beltaos, 1993). Direct determinations of \( \lambda \), based on measurements of water surface elevations along grounded reaches created by ice retention structures (Beltaos, 1999; Lever and Gooch, 2007) indicated similar values (1.2 to 2.1 m/s). Lever and Gooch (2007) also found that the seepage coefficient increased with time, and showed that this increase was likely caused by melting in the toe region, which would enhance the porosity.

3.3. Under-ice transport — hanging dams

As already mentioned, hanging dams can be much thicker than even wide-channel jams, owing to under-ice transport and deposition of frazil ice particles and flocs. Since the 1950s, prediction has largely been based on the concept of a critical frazil deposition velocity (e.g. Michel and Drouin, 1981). Though widely used, this premise leads to a broad range of critical deposition velocity values, without any guidance as to how they might vary with local flow and ice conditions. Noting this deficiency, Shen and Wang (1995) suggested that it is more correct to examine the evolution of hanging dams in terms of the ice transport capacity, assumed to be analogous to bed material load. This assumption is justified by observations indicating that frazil particles that are swept under the leading edge of an ice cover are mostly coarse granules, formed from frazil flocs, and often attaining gravel sizes (Chacho et al., 1986). The conservation of frazil ice mass is then expressed by:

\[
(1 - p_t) \frac{\partial A_i}{\partial t} + \frac{\partial Q_i}{\partial x} = 0
\]

in which \( A_i \) = cross-sectional area of the frazil accumulation; \( Q_i \) = ice discharge; \( x, t \) = distance and time variables, respectively; and \( p_t \) = porosity of the frazil accumulation. Where there is frazil ice in suspension, an additional term may appear on the Right-Hand-Side (RHS) of Eq. (3), to express deposition due to the rise velocity of the suspended frazil.

Using repeated frazil thickness measurements in the Yellow River (China), Shen and Wang calculated implied rates of ice transport and compared suitably non-dimensionalized ice discharges with various bed load equations. Despite large scatter, the mean line defined by the data points was very close to Bagnold’s bed load function (Bagnold, 1956, as quoted by Shen and Wang).

Using also the results of laboratory experiments, Shen and Wang proposed the following simple relationship:

\[
\phi_i = 5.5(\Theta_i - 0.041)^{1.5}
\]

in which \( \phi_i \) = dimensionless ice transport capacity = \( Q_i / B_i F d_n (1 - s_i) g d_n \); and \( \Theta_i \) = dimensionless flow strength = \( \tau_i / \rho F^2 (1 - s_i) g d_n \). Here, \( \tau_i \) = flow shear stress applied on the bottom surface of the hanging dam; \( \rho \) = density of water; \( B_i \) = ice cover width; \( F \) = frazil rise-velocity velocity coefficient, approximately equal to 1 for spherical granules; \( d_n \) = nominal diameter of frazil granules; \( g \) = gravitational acceleration; and \( s_i \) = specific gravity of ice \( \approx 0.92 \).

Ice discharge capacity, \( Q_i \), can thus be calculated in terms of the shear stress applied on the bottom of the cover. Frazil deposition occurs where \( Q_i \) decreases in the downstream direction, and will not cease unless the supply of frazil is discontinued or the gradient of \( Q_i \) becomes positive or zero. A zero gradient implies a condition of unchanging hanging dam configuration. Where the frazil supply is maintained, the latter condition can only be fulfilled when the under-ice flow is just capable of transporting the incoming ice discharge. This may lead to extremely thick deposits in deep river sections without significant increases in local water levels, by simply filling the cavity and modifying the flow pattern.

More dangerous are hanging dams that are not as thick but form in reaches of ordinary depth: as the deposit grows, the water level has to rise in order to provide sufficient floatation for the hanging dam and to maintain sufficient under-ice depth to pass the river flow. Two recent examples include the Moira and Kaministiquia Rivers in Ontario (Beltaos et al., 2007a,b). The thickness of the frazil deposit in either case was not excessive (3 to 4 m), but sufficient to cause flooding at the town of Belleville (Moira R., 2004) and at the Fort William Historical Park (Kaministiquia R. near Thunder Bay, 2006). On both occasions, early winter rainfall and subsequent cold weather were major factors. Frazil generation was also promoted by the relatively large slope of both rivers.

3.4. Mechanical properties (wide-channel jams)

In the very common case of the wide-channel jam, the fundamental assumption in predicting thickness and flooding potential is that the jam is a submerged granular mass that can resist external forces through internal friction and, possibly, cohesion. Ice-jam stability theory utilizes the Mohr–Coulomb criteria of failure and often
invokes additional assumptions as to the directions of the principal stresses. Such assumptions are arbitrary and often incorrect (Beltaos 1995), resulting in large discrepancies among reported values of the angle of internal friction ($\phi$). Beltaos’ analysis (1995; appendix A) suggests that $\phi$ should range from 54° to 58° in order to be consistent with empirical findings from ice-jam model calibrations.

Despite a plethora of laboratory test data on the internal strength of ice rubble, it is difficult to find reliable evidence in support of, or against, the field-deduced range of $\phi$. Laboratory determinations exhibit extreme variability, likely arising from deficiencies in testing methods and data interpretation (Ettema and Urroz-Aguirre, 1991; Timco and Cornett, 1999). The testing approach used by Timco and Cornett (1999) is perhaps the least susceptible to such errors. Fig. 4 shows that for dry freshwater rubble subjected to plane-strain deformation with constant strain rates in two directions, the angle $\phi$ decreased from 66° to 38° as the absolute ratio of strain rates ($=\frac{\varepsilon_l}{\varepsilon_t}$) increased from 1.2 to 3.5. If porosity does not change during the collapse and thickening process of an ice jam, a strain ratio of 1 should apply. However, a strict comparison between laboratory and field results can only be made when the experiments involve floating (rather than dry) rubble, which is allowed to thicken against the vertical stresses created by net buoyancy. This condition was fulfilled in a study by Hopkins and Tuhkuri (1999), who calibrated a discrete element model (DEM) against the results of model-ice tests simulating the compression of floating ice fields in rectangular channels. The DEM tracks the forces acting on each one of the “ice floes” that comprise the rubble field and computes its position at different times, as the field is compressed by a moving vertical plate. Numerical experiments with frictionless channel sides showed that longitudinal force increased in proportion to the square of rubble thickness, consistent with the Mohr–Coulomb criterion, which is used in the granular continuum approach. The corresponding values of $\phi$ would be in the range of 55.2°–56.4°, which is in accord with the field deduced range (54°–58°).

3.5. Thermal characteristics (breakup jams)

Heat transfer processes can play a significant role in the evolution of breakup ice jams, which are typically located at the end of long open-water stretches. At the jam head, the water temperature is typically in the neighborhood of a few degrees Celsius, but values of up to 9.5 °C have been reported (Parkinson, 1982; Marsh and Prowse, 1987). As the water plunges under the head of the jam and travels downstream, it gives up heat to the ice cover and its temperature decreases until it attains 0 °C. Measurements (Marsh and Prowse, 1987; Gerard and Jasek 1990; Jasek et al., 1993; Beltaos and Burrell, 2006) indicate a roughly negative exponential decrease in the water temperature with distance from the head of the jam. In turn, this finding suggests that local heat loss by the water to the ice can be described in terms of a bulk heat-transfer coefficient ($h$), which can be nondimensionalized to obtain the Stanton number, $St$ (expressed as $h/UC_V$; $U =$ average flow velocity under the jam; $C_V =$ specific heat of water by volume =4.22 MJ/m$^3$ °C at 0 °C).

Beltaos and Burrell (2006) analyzed all available data and found very high heat transfer coefficients (order of 10 kW/m$^2$ °C), while corresponding Stanton numbers varied from 0.0027 to 0.0081. Such values are much higher than what would be expected from turbulent boundary layer heat transfer literature. It was suggested by the authors that the very rough and porous underside of an ice jam may enhance heat transfer rates via increased flow through the ice accumulation and enhanced contact area between ice and water. Large heat transfer coefficients further imply that the temperature extinction length (distance required for the water temperature to drop to near 0 °C) is relatively short.

4. Ice-jam release: “javes” and ice runs

Release of freezeup jams is rare but not unknown (Beltaos, 1995). On the other hand, many breakup jams release, given enough time. Consequently, this section is primarily about breakup jams, which can last from a few minutes to many days. Most jam releases are abrupt, producing potentially violent events. Positive and negative waves travel downstream and upstream respectively. The downstream-propagating water wave can be
metres high and travels well ahead of the released rubble, even though water speeds far exceed those attained during extreme open-water floods. [A common term for the downstream wave has been “surge”, but it is now known that it is nowhere near as steep as a true surge. Instead, the composite term “jave” has been coined (Beltaos, 2007), short for “jam release wave”]. The potential for flooding, for bed and bank scour, as well as for damage to river structures by moving ice floes, is very high, especially near the point of release where jave attenuation is still minimal. There are many witness accounts of the destructive power of the jave and the perils it poses to local residents (e.g. see Beltaos, 1995). At the same time, the abrupt drop in water level, which is associated with the negative wave moving upstream of where the toe had been, can cause bank slides via suddenly unbalanced pore water pressures. In cases where the jam had been causing floodplain inundation, extensive fish stranding on the river banks may also be the result.

Jasek (2003) described javes and associated ice runs, based on his observations and insights over several years in Northern Canada. He distinguished between “unimpeded” and “impeded” ice runs, respectively describing situations where the reach downstream of the jam was open or covered with intact ice. Unimpeded runs typically occur when an ice-jam releases as a result of the dislodgement of an ice sheet of limited length. In the case of impeded runs, the increased stage and shear stress that accompany a jave can dislodge and set in motion extensive lengths of the winter cover. This is known as a “sheet-ice front”, which is often observed far downstream of the rubble ice run. Where the sheet-ice front is arrested by intact ice cover, it may eventually be joined by the advancing rubble, forming a new jam. On the other hand, the rubble may keep plunging through the sheet-ice cover, forming a “rubble front”. It is not known at present how to quantify the three-way interaction of flow, moving ice blocks and plates, and stationary ice cover. A major study in this direction, motivated by the need to predict dambreak effects in ice covered rivers, is presently being conducted by two Universities (Alberta, Laval) and Hydro Quebec. Progress has been recently reported at the 14th River Ice Workshop, held June 19–22, 2007 at Quebec City (Proceedings DVD available from Prof. Faye Hicks at the University of Alberta, Edmonton).

It has been postulated that sheet-ice fronts can be self-sustaining via sequential release of water from storage. A rudimentary attempt to quantify this phenomenon was included in the model by Ferrick and Mulherin (1989). These authors assumed that the sheet-ice cover is dislodged when a certain “critical” parameter is exceeded, and instantaneously becomes a part of the open-water reach upstream of the ice edge. Using an advanced numerical model, Jasek et al. (2005a) also explored this question, assuming that the ice cover is dislodged when a threshold value of the discharge is exceeded. The dislodged ice is assumed to become a part of the flow, but a higher local Manning coefficient can be specified to account for impediments to free motion due to ice–water and ice–ice interactions. These simulations showed that a non-attenuating jave develops, sustaining, and being sustained by, the breaking front. So far, we have no real-life data to test this theoretical finding. Searching for corroborating field evidence could be an exciting new area of study.

Kowalczyk and Hicks (2003; see also Kowalczyk Hutchison and Hicks, 2007) and Beltaos and Burrell (2005a) presented detailed measurements of waveforms, starting very near the point of release so as to elucidate wave characteristics at their steepest configuration. Both data sets indicate that the wave attenuates and slows down with time from release, while its celerity is greatest at the leading edge, intermediate at the crest and least at the trailing edge. At sites very near the toe, jave amplitudes and rates of rise were up to 4.07 m high and 0.81 m/min, respectively. On one occasion (Restigouche River, New Brunswick), the power of the jave was such that it fractured and dislodged the ice cover well ahead of the ice run, forming a sheet-ice front. Visual observations indicated that the average celerity of this front during the first 20 min from release was no less than 5 m/s (Beltaos and Burrell, 2005a). During a particularly dynamic release on the Athabasca River near Fort McMurray (Alberta), She et al. (2007) were able to observe and track the movement of the breaking front for about 30 min. Initially (3 min after release), the celerity of the front was over 9 m/s (!) but quickly dropped to ~4 m/s (5 min after release) and then gradually decreased to ~2 m/s (27 min after release). Simultaneous water level recordings indicated that the front may have temporarily stalled after this time, causing brief jamming and increase in the local water surface gradient, followed by resumption of motion with renewed momentum.

An important question pertaining to javes relates to their capacity to amplify flow velocity, discharge and shear stress, which define the severity of the wave and its capacity to dislodge the downstream ice cover. However, the presence of moving ice precludes deployment of current metres or other suitable instruments. At the same time, use of a numerical model to deduce such parameters requires detailed pre-release data that are not normally available. To help bridge this
gap, an approximate analytical method has been developed to assess important hydraulic characteristics, based on the variation of stage with time during the rising limb of the wave (Beltaos and Burrell, 2005b; Beltaos, 2005). This approach has been applied to several measured waveforms, and again shows that javes are most dynamic near the toe of the released jam. In the case of a jave in the Restigouche River, peak amplification factors of \( \sim 3, 10, \) and 6 were calculated for velocity, discharge, and shear stress, respectively, relative to unperturbed-flow conditions. The rising limb analysis and associated data indicate that the initial celerity of the jave is very close to, but no more than, that of a gravity wave \((=U+\sqrt{gy}; \ U, \ y = \) average velocity and depth of unperturbed flow, respectively). This value can approach or even exceed 10 m/s in deep rivers.

Casual observers and ice reconnaissance personnel often report that “rivers turn brown at breakup”. This suggests high concentrations of fine suspended sediment which may have a number of ecological implications, due to erosion, deposition, contaminant adsorption, or direct interference with the health of certain species of fish (Prowse and Culp 2003). It is only recently that data on sediment transport during breakup have been obtained, quantifying the relatively large loads being delivered during this brief time period (Walker 1969; Prowse 1993; Milburn and Prowse 2002; Beltaos et al., 1994; Beltaos and Burrell, 1999, 2000). Of particular interest here is that the concentration of suspended sediment is greatly amplified during the passage of a jave, sometimes by a factor of 10, relative to the pre-jave value. Such sediment “pulses” are likely caused by channel and floodplain erosion, and typically peak shortly after the arrival of the peak surface concentration of ice.

A common, and often exceeded, value of flow velocity during a jave is \( \sim 3 \) m/s, which can move bed material 6 cm in diameter (Neill, 1973). However, accessibility is particularly problematic during such events, and there are no measurements to quantify the amount of bed material that is being transported. Nevertheless, the potential for general and local scour of the river bed should be taken into account when designing river structures or assessing the effects of natural or anthropogenic hydro-climatic changes on aquatic habitat. Toxic substances attached to scoured bed sediments in deposition areas, such as reservoirs (Tuthill et al., 2007), can pose threats to aquatic life and human health.

5. Predicting ice-jam thickness and water levels

An analytical solution to the wide-jam stability equation (Pariset et al., 1966; Uzuner and Kennedy 1976) has long been established for the case of “equilibrium” jams. This analysis, which results in closed-form expressions for thickness and water depth (Beltaos 1983), provides an upper envelope to observed ice-influenced stages (excepting hanging dams whose thickness is governed by under-ice transport considerations rather than internal stability). For breakup jams, there is a question as to the flow value that should be used to describe the equilibrium condition. Many breakup jams form when an ice run is arrested, hence it is not obvious whether the formative discharge is equal to the “carrier” (or unperturbed) river flow or to a jave-modified value. Use of the carrier flow was justified on the basis of physical arguments and supported by the available field data (Beltaos, 1983). Direct verification of this working hypothesis emerged recently via laboratory experiments, under both steady and dynamic carrier-flow conditions (Healy and Hicks, 2006; Healy and Hicks, 2007).

Jams do not always attain the equilibrium condition, owing usually to limited supply of ice blocks. This can be an important design factor in many practical situations. Early models of non-equilibrium jams assumed one-dimensional, steady-state conditions and provided useful and robust design/research tools [e.g. ICEJAM (Flato and Gerard, 1986); RIVJAM (Beltaos, 1993, 1996); HEC-RAS, with ice-cover/ice-jam routine (http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html); ICEPRO and ICESIM (Carson et al., 2001, 2003)]. Nevertheless, it has long been recognized that dynamic and two-dimensional effects can be important under certain conditions. A one-dimensional dynamic model was developed by Zufelt and Ettema (2000) and used to explore the effects of unsteady inflow hydrographs in hypothetical situations. The DYNARICE model on the other hand, is both dynamic and two-dimensional (Shen et al., 2000; Liu and Shen, 2000), and has been applied to field conditions (Shen and Liu, 2003). To handle the response of jam thickness to time-dependent forces and stresses, DYNARICE utilizes the Mohr–Coulomb criterion in conjunction with the “viscous-plastic” constitutive law. This law is used extensively in sea ice models to relate internal stresses to strain rates and confining pressures. Flow through the voids of the jam is also accounted for (see Eq. (2)), enabling the model to function where partial or complete grounding occurs. DYNARICE is now a part of CRISSP (Comprehensive river ice simulation system), which includes thermal processes, and has both one- and two-dimensional components (CRISSP1D and CRISSP2D; Shen, 2002; Liu et al., 2006). CRISSP2D is a highly sophisticated model that can simulate thermal and mechanical processes during
both freezeup and breakup, including the evolution of ice jams under highly unsteady flow conditions. This model also allows the user to input locations and properties of ice booms in order to predict ice cover or ice-jam formation as well as boom load and cable tension.

A parallel development is the DEM (discrete element model), which does not need to invoke the concept of a granular continuum. The motion and eventual arrest of each block within a jam is predicted during small time steps by computing the forces applied on each block by the water and by the surrounding blocks. Flow through the voids of the accumulation is taken into account, in addition to the flow under the jam. This approach provides important insights as to both the evolution and the final configuration of an ice jam and enables prediction of the forces exerted by jams on structures (Daly and Hopkins, 1998, 2001; Hopkins and Tuhkuri, 1999; Hopkins et al., 2002; Hopkins and Daly, 2003).

In addition to new model development, extensive model comparisons and evaluations have been undertaken using laboratory channels, hypothetical rivers, and real-life case studies (Healy and Hicks, 1999; Carson et al., 2001, 2003, 2007). Carson et al. (2003) applied several models against a comprehensive case study on the Thames River, Ontario (Beltaos, 1988). All applications indicated that agreement with measurements was only attained where ice-jam resistance coefficients increased with thickness, either in a user-specified fashion or via equations that were already incorporated in the model subroutines. This finding is consistent with the results of the previously described roughness data (see also Eqs. (1a) and (1b)). The case study reported by Carson et al. (2007) was an extreme test of model capability, comprising “blind” applications. Modelers were only given river bathymetry, flow, and jam location and asked to determine the water level variation in the jammed reach. Considering that there was no prior calibration, the results (Fig. 5) suggest good model performance for maximum water levels and fair overall performance near the jam toe.

Numerical simulation of flow and ice conditions when a jam releases to generate a jave is also very important for practical applications, but more difficult to achieve than for jams that are forming or have attained a steady state. The highly dynamic conditions of a jave and the interactions between the water flow and the ice (moving and stationary) add considerable complexity to the modelling task. Common simplifying assumptions include: no effect of moving ice on water motion (ice mass simply being a part of the flow); and extent and thickness of any ice cover that may be present downstream of the jam remain unchanged (e.g. Joliffe and Gerard, 1982; Beltaos and Krishnappan, 1982; Wong et al., 1985; Hicks et al., 1997; Blackburn and Hicks, 2003). Though it does provide useful results under certain conditions, this approach does not account for two other effects that are believed, or known, to occur.

The first such effect involves the possibility that significant frictional resistance develops at interfaces between moving and grounded rubble, typically located near the sides of the river. This effect would tend to inhibit the movement of the water underneath the rubble.

---

**Fig. 5.** Comparison of model-generated ice-jam water levels with measurements, in a “blind” test case. All models were applied without prior calibration. After Carson et al. (2007), with permission from the authors.
and retard wave propagation, as shown by Liu and Shen (2000) who applied the two-dimensional DynaRICE model to explore the effects of side friction in a hypothetical test case. She and Hicks (2006) applied an enhanced version of the public domain “River1-D” software (one-dimensional) to two recently obtained data sets. For one of these sets (Athabasca River above Fort McMurray), model agreement with measurements was optimized when the side friction was set equal to zero; for the other set (upper Saint John River), inclusion of the side friction term for the first 2.8 h of simulation, and neglect for the remaining time, gave the best results. Significantly, the predictive improvement over the no-friction case consisted in better “matching” of the falling limb of the measured jave. Side friction did not appear to influence the rising limb prediction, most likely because the early portion of the jave advances faster than, and ahead of, the rubble.

A second, and more complex, question involves the formation of sheet-ice or rubble fronts and their interaction with the jave. As mentioned earlier, such processes are not quantifiable at present, but concerted research efforts are under way to develop suitable numerical modelling capability.

Before closing this section, it is noted that a review article on numerical modelling of river ice processes (Shen, in press) will appear in this journal shortly. Simulation of ice jamming characteristics is a key element of river ice models, and readers will be able to find much more detailed information on ice-jam modelling in that article.

6. Mitigation

There are both structural and non-structural methods to prevent ice-jam formation in sensitive reaches and to minimize their impacts when they do form. These methods have been reviewed in considerable detail, e.g. Belore et al. (1990), Burrell (1995), Tuthill (1995, 1999, 2005a,b); Tuthill and Lever, 2006; White and Kay (1997a,b); Haehnel (1998). Only a few recent successes are highlighted herein.

On regulated – usually large – rivers, effective ice-jam control can be attained by suitable operation of reservoirs (Ke and Lu, 1996; Jasek et al., 2007). Such structures are primarily built as a means of power generation, but flood control is a secondary objective that enhances the benefit–cost ratio. On small rivers, a relatively inexpensive and ecology-friendly ice control structure (ICS) has gained popularity in recent years. It consists of in-stream piers or other obstacles designed to arrest incoming ice floes while allowing water to pass through. In this manner, a jam forms upstream of a vulnerable reach, in an area where it can do little damage. Nearby floodplains can provide ice storage areas, while allowing excess water to bypass the structure at high flows (Fig. 6).

This concept was first implemented on the Credit River, SW Ontario, using piers spaced at 2 m, centre-to-centre (Cumming-Cockburn & Associates, 1986). Three similar low-cost structures have since been built in the United States (Cazenovia Creek, Lamoille River, Salmon River; Lever and Gooch, 2001, 2007; Lever

![Fig. 6. Conceptual drawing of an ice control structure which retains incoming ice blocks behind boulders in the main channel while relief flow bypasses the structure over the floodplain. From Tuthill and Lever (2006). Digital version was kindly supplied by the authors.](image-url)
and Daly, 2003; Lever et al., 2000; Tuthill and White, 1997). Cost is reduced by relying on extensive physical model testing to establish design parameters and determine the maximum distance between obstacles that will retain ice blocks and hold the resulting jam for sufficiently high flows. An excellent practice that has been established in the US is to systematically monitor and assess the performance of ice control structures (e.g. Lever and Gooch, 2007; Vuyovich and White, 2006). Based on extensive laboratory tests, Morse et al. (2003a) explored two new varieties of ICSs, using either widely-spaced piers supporting steel nets, or cylindrical steel ice booms supporting steel nets.

Dykes have been used frequently as a protection measure for both open-water and ice-jam floods. Commonly, dykes are located on or near the river banks and thus eliminate the natural flow- and ice-relief that is afforded by the floodplain at high river stages. This is particularly significant in the case of ice jams, because large volumes of ice that would normally spread out onto the floodplain are confined by the dykes within the main channel. Thus, they contribute to formation of longer and thicker jams, with higher water stages as a result. Beltaos and Doyle (1996) quantified the potential benefits of setback dykes in a case study pertaining to the Coldwater River at Merritt, British Columbia. This is a relatively small and steep river (width ∼35 m; slope ∼0.003) that can produce a limited volume of ice at the site of interest (upper limit = 63,000 m$^3$). Using the RIVJAM model, calibrated with data from a 1991 ice jam, it was shown that setback dykes can considerably reduce water levels and jam lengths relative to river-bank dykes. The authors noted that this approach is more effective in smaller rivers because larger ice volumes relative to channel width, can be stored for the same setback distance. A few additional advantages were also cited, i.e. reduced construction and maintenance costs, maintenance of natural ice-clearing flows, ecological and recreational potential.

During breakup, the interaction between bridge piers and sheet-ice cover may lead to ice jamming (Kawai et al., 1997). Based on experience, Shattuck (1988) made several design recommendations for avoiding ice-jam instigation by bridges at vulnerable sites. More recently, Beltaos et al. (2006a) quantified the jamming potential of in-stream piers, by comparing driving forces that are acting on an ice cover at the time of breakup initiation to resisting forces generated by the piers and the strength of the ice cover. The resulting design guidelines incorporate features that respectively minimize and maximize resisting and driving forces.

On the non-structural side, an “amphibious excavator” (or “amphibex”) has been successfully deployed to partially or entirely dislodge threatening ice jams. This is an amphibious vehicle that can break sheet-ice and dredge accumulations of ice blocks or frazil slush, as a preventive or emergency measure. Unlike ice breakers, the amphibex can be deployed in rivers of ordinary depth, while the dredging capability provides an advantage over hovercraft, which are also used for ice breaking. An amphibex was successfully deployed on the Red River near Winnipeg in 2005 to dislodge a

![Fig. 7. An amphibex unit operating in the Kaministiquia River. Looking downstream, March 22, 2006. Note open lane behind vessel and slush being carried away by the current (from Beltaos et al., 2007a).](image-url)
breakup jam, held in place by an ice sheet of limited length (300–400 m) and thickness of 0.5 m (Rick Carson, pers. comm. 2005). In a much more challenging application (~10 km of 0.5 to 1 m sheet ice, underlain by up to 4 m of slush), another unit (Fig. 7) was able to cut a lane of open water along a freezeup hanging dam, resulting in much lower water levels. This jam was causing extensive and persistent flooding (for ~3 months during the 2005–06 winter season) of the Fort William Historical Park on the Kaministiquia River near Thunder Bay, Ontario (Beltaos et al., 2007a). One limitation of the amphibex is that there are few such units and deployment lead time can be considerable. In the case of a hanging dam on the Moira River at Belleville, Ontario (2004), it was difficult to assess amphibex effectiveness, owing to late deployment. Though the unit did cut open lanes in the ice cover, water levels were already receding due to earlier ice removal with shore-based construction equipment (Beltaos et al., 2007b).

7. Climatic impacts

The timing and severity of river ice jams are determined by channel morphology, weather conditions, ice cover thickness and strength, and by the flow hydrograph. To a large extent, these factors are controlled by climate, and thence the ice jamming regime could be very sensitive to changes in climatic conditions. The issue of climate change underscores the need for improved understanding of the physical mechanisms that govern ice jamming processes. This is particularly true in northern parts of the globe, which are likely to experience more pronounced climatic changes than regions closer to the equator. However, very little work has been done on how ice-jam processes may change in a warmer world, as outlined next.

Early studies have shown that the general warming experienced in northern parts of the globe during the last 50 to 100 years is in step with changes to freezeup/breakup times and with a general reduction in the duration of the winter ice cover (e.g., see review articles by Beltaos and Prowse, 2001; Prowse and Beltaos, 2002; Beltaos and Burrell, 2003). More recently, Vuglinsky (2006) reported similar trends on Russian rivers, including a trend toward thinner ice covers. The converse is true in isolated instances where the change involves cooling (Brimley and Freeman, 1997). There is also some evidence of increasing frequency of mid-winter thaws and breakups in Atlantic Canada (Beltaos, 2002, 2004; Beltaos et al., 2003).

Future changes to river ice regimes will vary depending on local conditions. For example, Borshch et al. (2001) predicted changes to freezeup and breakup dates of Russian rivers that would result from a uniform climatic warming of 2 °C, based on empirical, temperature-based, relationships. The computed changes vary from a few to many (but under 20) days, pointing to later freezeup and earlier breakup. Prediction of changes to freezeup and breakup jamming events is far more complex than changes to corresponding times. It would have to be based on a case-by-case analysis of current conditions in conjunction with output from scenarios generated by GCMs (General Circulation Models).

A wide-ranging change that can be anticipated at present is an increased incidence of mid-winter breakups and ice jams in parts of Atlantic Canada, Quebec, Ontario and British Columbia (Beltaos, 1997; Beltaos and Prowse, 2001). Mid-winter breakups are also expected to appear in certain regions that do not presently experience such events, such as the Prairies and northern Ontario and Quebec. These potential trends are further corroborated by Prowse and Bonsal (2004) who applied simple but quantitative criteria to delineate present and future zones of mid-winter breakup in Canada and the United States.

White et al. (2007) discussed observed impacts of climate variability on river ice processes in the United States as a first step toward understanding what the effects might be on the ice-jam regime. Numerous studies, mostly pertaining to rivers in New England and Alaska, indicate expected trends, that is, later freezeup, earlier breakup, and thence shorter ice cover seasons. However, only isolated data exist about recent changes in the occurrence and severity of ice jams. A frequent observation is that freezeup jams now form (since the mid-1990s) on rivers where they were not known before, despite long historical records.

In certain rivers, mid-winter thaws can deplete the snowpack that is available for spring runoff, and thence reduce the severity of ice jamming during the spring breakup. This eventuality has been identified as the root cause of a predicted severe reduction of ice-jam flooding in the lower Peace River under two IPCC (Intergovernmental Panel on Climate Change) climate scenarios for the 2080s (Beltaos et al., 2006c). Because ice-jam flooding is a necessary agent of replenishment of the lakes and ponds of the Peace-Athabasca Delta (Beltaos et al., 2006b), this unique ecosystem may be at increasing risk as the local climate changes.

The recently developed ice-jam data base (White and Eames, 1999; Weyrick et al., 2007) is already proving to be a particularly useful reference for exploring trends in ice-jam occurrence and severity at various locations and in different regions of the United States. As the record length increases, so will its value to research into climatic aspects of ice jams.
8. Discussion

The preceding sections cover most of the progress that has been achieved since the 1990s, yet it is not exhaustive. For instance, even though physically-based analysis and numerical modelling have advanced considerably, they cannot yet provide the necessary tools for anticipating and forecasting the occurrence of major ice jams. To fill this gap, river ice researchers and engineers have used site specific, empirical approaches (e.g. Liu et al., 1996; Yang, 1996) that are becoming increasingly sophisticated from the statistical point of view. Emphasis has been on breakup jams because of their greater potential for damages. As a comprehensive review of ice-jam forecasting methods has been produced recently (White 2003), it will suffice here to only give a flavour of current work. Massie et al. (2001) explored the potential use of neural networks, that is, black-box models that can be ‘trained’ to accurately represent complex non-linear cause–effect relationships. McDonald et al. (2002) presented an application that successfully predicted ice jams at a confluence. Mahabir et al. (2006a,b) used fuzzy logic and multiple linear regression to forecast the risk of ice jams near the vulnerable city of Fort McMurray, Alberta. Daly (2002) used a data modelling approach that incorporated real-time observations for forecasting purposes.

Another topic of great practical interest is how to develop ice-jam flood frequency curves in cases where there is little historical information. There is no standardized methodology for this task, other than to combine local understanding of the physical setting with established jam stage formulae and numerical algorithms, along with engineering judgment (e.g. Gerard and Karpuk, 1979; Tuthill et al., 1996; Grover et al., 1999; Daly et al., 2000).

With the gradually growing appreciation of the ecological impacts of river ice, a small number of studies have looked at the linkages between aquatic life and ice jamming. Comprehensive reviews by Prowse (2000) and Prowse and Culp (2003) discuss ice effects on aquatic life in general, including potential effects of ice jams, while Cunjak et al. (1998), and Brown et al. (2000, 2001) studied how fish are affected by freezeup and breakup jams.

9. Concluding remarks

Having worked on this topic since 1974, the writer can look back at the scope of information that was available in the early 1970s with mixed feelings of satisfaction and impatience. Satisfaction, because what is presently known about the physical processes that govern ice jamming phenomena, and what can be mathematically simulated, or measured, far surpass the capabilities of 30–some years ago. Impatience results from a keen awareness of the many important questions that remain unanswered. For example, we still cannot quantify and predict such crucial phenomena as ice-jam formation and release, or motion and arrest of sheet-ice fronts and rubble fronts. Apart from inhibiting our ability to address the many impacts of ice jams, the lack of such understanding also limits our options in anticipating future ice jamming regimes under altered climatic conditions.

Acknowledgments

Helpful discussion with, and input from, James Lever and Andrew Tuthill of the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, and Hung Tao Shen of Clarkson University, are gratefully acknowledged.

References


Daly, S.F., White, K.D., Zufelt, J.E., Lever, J.H., Gagnon, J.J., 2000. Ice-affected flooding, Oahe Dam to Lake Sharpe, S.D., Contract report prepared by the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory for the U.S. Army Engineer District. Omaha, UEA, Hanover, NH.


Jasek, M., Marko, J., Fissel, D., Clarke, M., Buermans, J., Paslawski, K., 2005b. Instrument for detecting freeze-up, mid-winter and break-up ice processes in rivers. Proceedings (CD-ROM) of 13th Workshop on the Hydraulics of Ice Covered Rivers, Hanover, NH,


She, Y., Hicks, F., 2006. Modeling ice jam release waves with consideration for ice effects. Cold Regions Science and Technology 20 (3), 137–147.


White, K.D., Eames, H.J., 1999. CRREL ice jam data base. US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Report 99-2, Hanover, NH, USA.


