

This report has been submitted to  
IAHS Workshop on River Ice  
Vancouver, August 12, 1987 and  
the contents are subject to change.

This copy is to provide information  
prior to publication.

ICE JAMS

by

S. Beltaos

River Research Branch  
Water Quantity Modelling and Monitoring  
National Water Research Institute  
Canada Centre for Inland Waters  
Burlington, Ontario L7R 4A6, Canada  
NWRI Contribution #87-106

ICE JAMS  
by  
S. Beltaos

Water Quantity Modelling and Monitoring  
River Research Branch  
National Water Research Institute  
Canada Centre for Inland Waters  
Burlington, Ontario L7R 4A6, Canada

## **MANAGEMENT PERSPECTIVE**

To deal with problems posed by ice jams such as predicting flood levels and designing remedial measures, it is necessary that the mechanics of ice jamming be thoroughly understood. This (invited) theme paper reviews current understanding of ice jam processes and mitigation approaches. It is shown that there exist large gaps in ice jam knowledge, particularly with regard to their interaction with sheet ice covers. Development of suitable materials to substitute an ice cover in laboratory experiments is a major research requirement. Remote-sensing instrumentation for rapid jam thickness surveys in the field is also needed for effective design of emergency measures as well as for testing and developing theoretical concepts.

## PERSPECTIVE - GESTION

Il faut très bien connaître les caractéristiques mécaniques des embâcles pour venir à bout des problèmes qu'ils causent, comme la prévision du niveau des crues et l'élaboration de mesures correctrices. Le présent document thématique (d'un conférencier invité) donne un bref aperçu des connaissances actuelles des processus en cause et des mesures d'atténuation. On y explique qu'il existe de grandes lacunes au niveau des connaissances en matière d'embâcles, particulièrement en ce qui a trait à leur interaction avec les couches de glace feuilletées. La mise au point de matériaux appropriés pour tenir lieu de couvert glaciaire dans les expériences en laboratoire est un objectif primordial dans ce domaine. Il faut également perfectionner les instruments de télédétection afin d'obtenir un relevé rapide de l'épaisseur des glaces sur le terrain pour prendre les mesures d'urgence qui s'imposent et pour élaborer et tester des concepts théoriques.

## RÉSUMÉ

Les embâcles sont les plus graves des effets des glaces des cours d'eau. Les problèmes causés par les embâcles comprennent l'endommagement de structures, des interférences avec la navigation, des contraintes pour la production de l'hydro-électricité et des inondations, ces dernières ayant le plus grand impact. Il faut connaître très bien les processus de formation des embâcles pour pouvoir prévoir et atténuer ces problèmes. Le présent document traite de ces processus, c.-à-d. la formation, l'évolution et le dégagement, de façon à identifier les divers types d'embâcles, les facteurs hydroclimatiques importants et les variations régionales du régime des glaces. Étant donné que les connaissances actuelles dans ce domaine sont qualitatives ou empiriques, la solution de divers problèmes dépend non seulement de l'application de principes scientifiques, mais aussi d'observations particulières sur place et de la surveillance des glaces. Ces processus sont parfois si complexes qu'il faut faire appel à la modélisation. Ce document donne un bref aperçu des méthodes d'atténuation et les classe en deux grands groupes, les méthodes structurales et non structurales. Les premières sont généralement fiables mais coûteuses, tandis que les autres sont moins chères mais souvent inefficaces. Il faut réaliser des progrès dans plusieurs domaines pour améliorer nos connaissances, notamment: la recherche de base, l'instrumentation et les techniques de mesure sur le terrain, et la mise au point de matériaux appropriés pour tenir lieu de couverture de glace dans les expériences en laboratoire.

## ABSTRACT

Ice jamming is the most serious effect of river ice. Problems caused by ice jams include damage to structures, interference with navigation, constraints to hydropower production and flooding, the latter having the greatest impact. To anticipate and alleviate such problems, a thorough understanding of ice jam processes is necessary. These processes, i.e. formation, evolution and release, are discussed so as to identify various types of jams, important hydroclimatic factors and regional variations in the ice regime. Because much of the current knowledge is qualitative or empirical, the solution of various problems depends not only on application of scientific principles but also on site-specific observations and ice monitoring. Occasionally, the processes are so complex that physical modelling is necessary. Mitigation methods are reviewed briefly and broadly classified as structural or non-structural. The former are generally reliable but expensive while the latter are much cheaper but often ineffective. To improve the state of the art, advancements in several areas are needed. These include basic research, instrumentation and techniques for field measurements, and development of suitable materials to substitute an ice cover in laboratory experimentation.

## INTRODUCTION

The most serious consequence of ice formation on northern rivers is the jamming that occurs during freeze up and breakup. Flooding, damage to structures, interference with navigation and hydropower production are some of the problems caused by ice jams.

Ice-jam flooding is considered "the greatest hazard of river ice" (Ashton, 1986) and is essentially caused by the large thickness and bottom roughness attainable by ice accumulations. In most ice-forming rivers, the annual peak stages are often produced by ice jams. These high stages are also responsible for damage to structures located on the floodplain or in the river. Avoidance of jamming during the winter period imposes serious constraints to hydropower production while jams in navigable channels can be very costly to shipping. For example, a 1984 jam in the St. Clair River persisted for 24 days and caused an estimated loss of \$40 million to the shipping industry.

In Canada, the annual tangible damage due to ice jams has been estimated at \$35 million. This is the present value of a 1968 figure suggested by Atkinson (1973) but it does not include navigation-related costs or benefits that would be realized through improved technology. Damages are also known to increase with time due to increasing urbanization (Environment Canada, 1986). Moreover, it should be emphasized that monetary figures do not include the less tangible but no less destructive damages resulting from local resident inconvenience, distress and loss of life.

# RIVER ICE REGIMES

On most rivers, the formation of a continuous ice cover is preceded by hydrothermal processes pertaining to frazil production, transport and agglomeration as well as border ice growth (e.g. see Ashton, 1986, for a detailed discussion).

Initiation of an ice cover usually occurs from congestion of slush "pans" at surface constrictions that often form by border ice. The initial cover is thus a freeze up jam and may consist of a single layer of floes or of a thick accumulation. The freezing weather causes vertical and lateral ice growth which leads to formation of a solid ice cover.

At high latitudes, cold weather persists throughout the winter and river flows generally decrease or remain constant. With the approach of spring, runoff begins to increase, mostly due to snowmelt, and the river stage rises while the ice cover deteriorates by melting and heat absorption. Eventually, sections of the cover are set in motion and quickly break down into smaller fragments. These accumulate to form jams when their downstream movement is impeded.

Similar events occur at more moderate latitudes but here the situation is complicated by frequent occurrence of "winter thaws", i.e. brief periods of mild weather usually accompanied by intense rainfall. Such thaws often lead to ice breakup and a new freeze up when cold weather resumes. Clearly, the "premature" type of breakup that is caused by intense runoff with little thermal ice deterioration, is much more frequent at moderate latitudes (see also Table 1 where regional differences in ice regimes are summarized).

Table 1. Regional Differences in Ice Regimes

Stream Region Feature	High Latitude Streams	Moderate Latitude Streams
Number of freeze up-breakup episodes per year	One	Often more than one
Thickness of winter ice cover	Large	Moderate
Variability of ice thickness at breakup	Little	Large
Main "trigger" of breakup	Snowmelt	Rainfall
Occurrence of premature breakup	Infrequent	Frequent

Forecasting the onset of freeze up and breakup are important questions because these events often herald ice jamming. Ice formation begins soon after the stream temperature drops to 0°C. Mathematical models are available for reliable prediction of stream temperature and first ice formation (Ashton, 1986) but the subsequent formation of an ice cover is a more complex process. Its forecasting requires site-specific data on likely locations of ice cover initiation.

Present capabilities to forecast the onset of breakup derive from empirical work combined with qualitative understanding of the relevant processes (Shulyakovskii, 1963; Beltaos, 1984a). The winter ice cover is first set in motion when the river stage exceeds a value  $H_B$ , that depends on: ice cover thickness,  $h_i$ , preceding freeze up stage,  $H_F$ ; and an index of accumulated thermal deterioration,  $S_T$ , of which the simplest version is the accumulated degree-days of thaw. For premature events, i.e.  $S_T \approx 0$ , empirical evidence suggests that

$$H_B = H_F + k h_i \quad (1)$$

in which  $k$  is a site-specific dimensionless coefficient. Values of  $k$  obtained at five sites range from 2.5 to 8.0 (Beltaos, unpublished data). Where the thermal effect is significant, i.e.  $S_T > 0$ , the value of  $H_B$  given by Eq. 1 must be reduced in a manner that is again site-specific.

Recent observations and semi-empirical analysis of early breakup phases have led to increased understanding (Beltaos, 1984b, 1985) but much remains to be learned.

## ICE JAM PROCESSES

### Initiation

A common mechanism of ice jam initiation during freeze up is "congestion". This occurs when the surface flux of ice floes exceeds the local channel capacity to transport them (Fig. 1). Provided the local flow velocity is low enough so that incoming floes do not submerge upon stopping, a surface jam, i.e. a jam consisting of a single layer of ice floes, will form. Congestion has been studied to some extent (Frankenstein and Assur, 1972; Nuttall, 1973; Calkins and Ashton, 1975; Tatinclaux and Lee, 1978; Acherman and Shen, 1983) but its prediction in practice is uncertain and relies on field observation. Congestion also occurs during breakup but infrequently, probably because of higher breakup velocities.



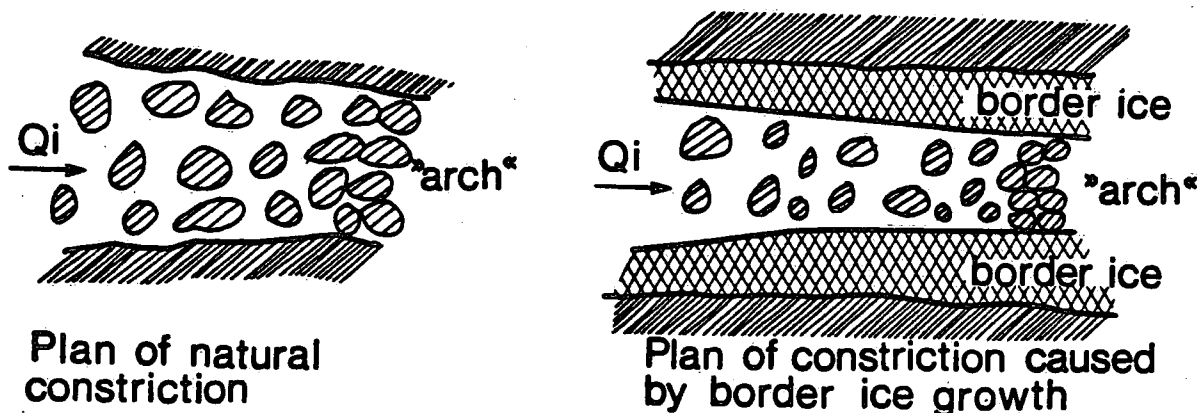


Fig. 1 Illustration of congestion at a constriction.

When ice floes arrive at a floating obstacle, such as an existing ice cover or a surface jam formed by congestion, they may remain on the water surface or they may submerge, depending on local hydraulics and floe properties. This phenomenon has been studied extensively in the laboratory (e.g. Pariset and Hausser, 1961; Uzuner and Kennedy, 1972) while Ashton's simple theory (1974) is known to give good results for floes that are neither too thin or too thick:

$$V_S / \sqrt{(1 - s_i) g h_i} = 2 / \sqrt{5 - 3 \left(1 - \frac{h_i}{H}\right)^2} \quad (2)$$

in which  $g$  = acceleration due to gravity;  $s_i$  = specific gravity of ice;  $h_i$  = ice floe thickness;  $H$  = local water depth; and  $V_S$  = incipient submergence velocity (see also Fig. 2 for a definition of symbols). Equation 2 applies to solid ice floes but can be adapted to porous floes, as shown by Beltaos (1986).

If the velocity  $V_u$  under the block is less than  $V_S$ , a surface jam will start. If, however,  $V_u > V_S$ , the incoming floes will submerge. There are, then, three possibilities:

- (a) Floes are transported under the obstacle until they come to an area of low enough velocity so that buoyancy will cause "deposition" at the lower boundary of the obstacle. Then, a "hanging dam" will form in that area and grow until the flow velocity increases to such a value that floes can no longer deposit, or until their supply is exhausted. Hanging dams usually form during freeze up and can attain extreme thicknesses and lengths (a thickness of 90 m (!) was reported by Gold and Williams, 1963, for a hanging dam in the Ottawa River). Little information exists about incipient erosion and deposition velocities for ice floes (Tatinclaux and Gogus, 1981; Michel, 1984). In practice, these parameters are estimated during calibration of computer models of ice conditions.

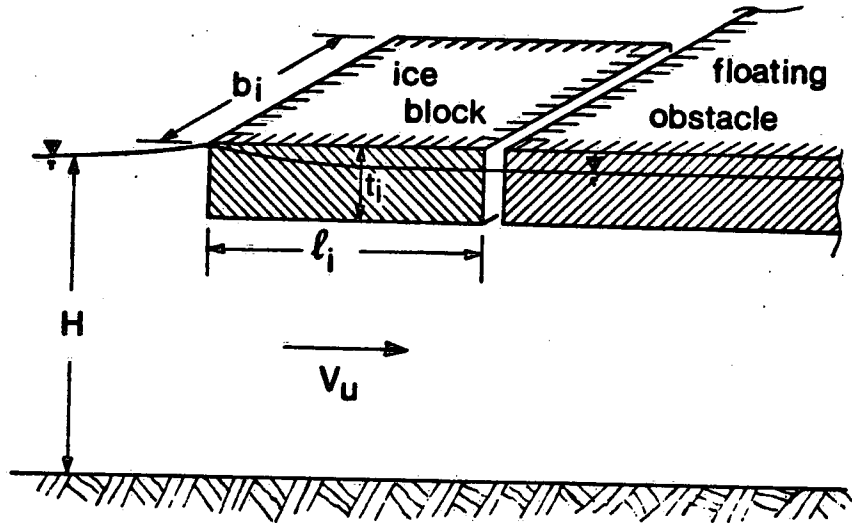


Fig. 2 Stability of a floating ice block - definition sketch.

- (b) Floes deposit just downstream of the obstacle's edge, thus initiating a thickened jam (aggregate thickness exceeds that of an individual floe). The thickness,  $t$ , of such an accumulation is given approximately by (Michel, 1971):

$$F \equiv \frac{V}{\sqrt{gH}} = \sqrt{2(1-s_i)(1-p)} \frac{t}{H} \left(1 - \frac{t}{H}\right) \quad (3)$$

in which  $p$  = jam porosity; and  $V$  = average flow velocity just upstream of the jam. It is noteworthy that Eq. 3 has no solution for  $t/H$  when the Froude number,  $F$ , of the approach flow exceeds the value  $F_m = 0.154 \sqrt{1-p}$  (maximum of RHS, for  $t/H = 1/3$  and  $s_i = 0.92$ ). Pariset et al (1966) suggested that the condition  $F > F_m$  is unstable whereby submerging floes pile up until the increasing head loss raises the water level just enough for  $F$  to decrease to the value  $F_m$ . If  $F < F_m$ , Eq. 3 has two solutions for  $t/H$  but only the lower one is plausible. Eq. 3 is based on the requirement of "no-spill" at the leading edge of the jam. A more complex equation that includes the effect of floe thickness has been developed by Tatinclaux (1977), based on the depth to which floes can be carried by the flow.

- (c) Floes may be solid and large enough relative to the flow depth so as to lodge between the obstacle and the channel bed. Then a grounded jam starts, as first pointed out by Mathieu and Michel (1967) and, more recently, by Beltaos and Wong (1986a). The latter authors also reported that grounding persisted for a short distance, until the upstream water depth increased to a value that incoming floes could no longer submerge (e.g. see Eq. 2).

A third jam initiation mechanism, common during breakup but not well understood, is the "wedging" of a moving ice accumulation between the channel bed and stationary ice cover. Wedging is accompanied by intense local breaking of the ice cover and piling up of the fragments. Recently, this phenomenon was reproduced in the laboratory using plastic blocks for the incoming accumulation and a substitute material for the ice cover, having suitably scaled down strength (Beltaos and Wong, Unpublished data).

From the preceding discussion, it is evident that jams can form anywhere in a stream, if moving floes encounter competent ice cover. At the same time, the probability of occurrence is enhanced at sites exhibiting certain man-made or geomorphic features, e.g. constrictions, sharp bends, islands, bridge piers, shallows, slope reductions, etc. Prediction of where and when an ice jam will form during a freeze up or breakup event, is not possible at present. Only probabilistic statements can be made, based on site configuration and historical data.

#### Development

Once initiated, a jam propagates upstream and the forces applied on it increase as they are generated by flow shear and own weight. Internal stresses then develop; they also increase with jam length but only up to a limit because of resistance to shear near the shores. So long as the internal stresses are less than the jam strength (partly or wholly deriving from vertical, buoyancy-generated, stresses), a jam remains stable. This happens more frequently in small streams (whence the name "narrow" channel jam) or during cold periods, promoting freezing and bonding between ice fragments. Often, however, and particularly at breakup, "narrow" jams remain stable only with very short lengths. The jam's strength is quickly exceeded and the jam collapses (or "shoves") and thickens until it is just able to withstand the applied forces. Beltaos (1983) showed that, during breakup, internal friction is practically the sole source of jam strength and collapse-type jams should be the rule for any but very small streams (this is the so called "wide" channel jam). The above understanding and the "narrow" - "wide" terminology are due to the analysis of Pariset et al (1966) who considered ice jams to be floating granular masses (see also Uzuner and Kennedy, 1976).

#### Steady State and Equilibrium

Truly steady conditions rarely prevail in rivers but temporal gradients are often small enough to be neglected in pertinent equations. This is an implicit assumption in much of the theoretical ice jam literature and, so far, appears realistic when used judiciously. If a steady jam is long enough, it will include an "equilibrium" reach characterized by uniform thickness and flow depth (Fig. 3). It can be shown that the equilibrium water depth is the maximum attainable by a jam whereby its prediction is of prime interest.

Since the flow depth under the jam can be calculated by a resistance formula (e.g. see Beltaos, 1983; 1986), the main difficulty lies in predicting the jam thickness,  $t$ . For a narrow jam, Eq. 3 applies, or the equivalent:

in which  $V_u$  is the average flow velocity under the jam. For a wide jam, Pariset et al (1966) give

in which  $B$  = channel width at the bottom surface of the jam,  $\tau_i$  = flow shear stress applied on the bottom surface of the jam;  $w_i$  = downslope component of jam's own weight per unit area;  $\rho$  = density of water;  $C_i$  = cohesion of jam; and  $\mu$  = coefficient that depends solely on the internal friction of the jam. Field evidence gathered to date indicates that  $\mu$  has fairly consistent values, averaging about 1.2 (Beltaos, 1983; 1986) while the cohesion term on the RHS of Eq. 5 can be neglected at breakup.<sup>1</sup> Using Eq. 5 with  $C_i = 0$  and a resistance equation, it can be shown that the overall equilibrium water depth,  $H$ , is given by (Beltaos, 1983).

<sup>1</sup>For freeze up jams, Pariset et al (1966) found that  $C_{it} = 1200$  N/m. The strength of freeze up jams could also be augmented by formation of a solid ice layer at the water surface (Michel, 1978a).

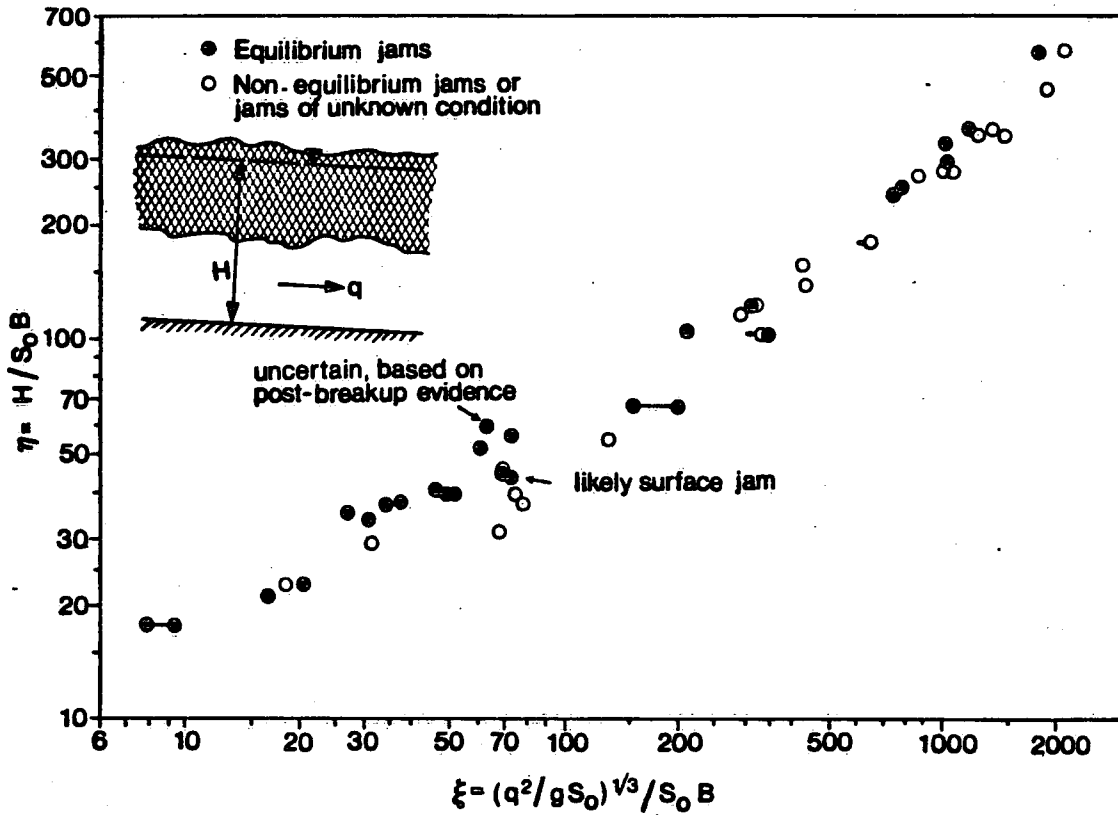


Fig. 4 Field data on breakup jams. Dimensionless depth - discharge relationship.

in which  $S_0$  = channel slope;  $f_1$  = friction factor of jam underside;  $f_0$  = composite friction factor of the flow under the jam; and  $\xi$  is a dimensionless discharge, i.e.

$$\xi \equiv \frac{(q^2/gS_0)^{1/3}}{S_0 B} \quad (10)$$

in which  $q$  = discharge per unit width.

As explained by Beltaos (1983; 1987), the main independent variable in Eq. 9 is  $\xi$  which permits simple assessment of  $H$  by defining  $\eta$  as a function of  $\xi$ . Figure 4 shows this function, as determined by data from Canadian rivers, ranging in width from 40 to 1800 m and in discharge from 10 to 15,000 m³/s.

### Transitions

Figure 3 shows that jam thickness and flow depth vary in the transitional reaches upstream and downstream of the equilibrium reach. Note that if the jam is too short to have an equilibrium reach, its entire configuration will be "transitional".

Prediction here is possible via numerical solution of differential equations describing jam stability and hydraulic principles (e.g. Uzuner and Kennedy, 1976; Beltaos and Wong, 1986b). Of particular interest is the downstream transition of "wide" jams which may be grounded near the toe (Fig. 3). In this instance, the usual neglect of seepage flow through the jam voids is not valid and the continuity of water flow must be expressed differently (Beltaos and Wong, 1986b).

#### Release

A sudden jam release is attended by surge-like phenomena such as high velocities and rapid stage increases. Eye-witness descriptions of the destructive potential of ice jam releases abound in literature (e.g. Gerard, 1979; Le Brun-Salonen, 1985). While it is not generally possible to predict when a jam will release, approximate calculations of the resulting surge characteristics can be made using unsteady flow models (Mercer and Cooper, 1977; Henderson and Gerard, 1981; Beltaos and Krishnappan, 1982). Observations and calculation show that the celerity of the surge can be very large. Values of 10 m/s (!) are possible for major jams. The water speed can also be very large, though always less than the corresponding celerity. As an illustration, suppose the celerity of a surge is 10 m/s while the local water surface slope is 0.003. Then the rate of rise of the water level at a fixed location would be almost 2 m/min (!) which explains why there is often little time for implementing flood emergency measures.

The destructive capacity of a surge is occasionally manifested in the seemingly effortless breaking of an intact ice cover by a released ice jam. Such phenomena are called "breakup fronts" and, on occasion, advance for long distances at high speeds (e.g. 5 m/s, Gerard et al, 1984). In this fashion, ice jam releases may effect the breakup of long reaches downstream. We cannot predict at present how far a released jam will travel or where it might be arrested and reform. Recent work in this direction suggests that the energy slope of the surge is a crucial parameter (Ferrick et al, 1986).

#### Factors Affecting the Severity of Ice Jams

Based on the preceding discussion, the main factors governing the severity of an ice jam can be summarized as follows:

- (a) Discharge: It influences both the flow depth under the jam and the jam thickness, thus having a dominant effect on jam stage. This effect extends to the surge caused by the release of the jam because surge characteristics depend on the initial water level profile.
- (b) Hydraulic Resistance: The roughness of the jam underside and of the river bed influence flow depth and jam thickness.
- (c) Channel Width and Slope: These are important factors, governing the thickness of wide jams.

### Classification

A classification system for ice jams has been developed by Beltaos and Davar (1984) for the IAHR Working Group on Ice Jams. This system is based on four criteria, i.e. season, dominant formation process, spatial extent and state. A brief outline of the system is given below.

Under the first criterion, we have freeze up jams and breakup jams. Important differences include composition (slush ice versus solid ice blocks); strength characteristics (cohesion and possibly shear strength due to freezing versus virtually cohesionless accumulation); and amenability to release (rare versus nearly always).

The main jam formation processes are congestion (resulting in a surface jam); submergence, transport and deposition (hanging dam); submergence and deposition ("narrow" jam); and shoving or collapse ("wide" jam). The latter type has usually the greatest potential for damage, particularly during breakup.

Spatial extent refers to both vertical and horizontal dimensions of a jam. In plan view, a jam can be complete or partial depending on whether it extends fully across the stream or partly, e.g. due to islands. In elevation, a jam may be floating or grounded. Floating jams are further subdivided into surface and thickened. Flow through the voids of a floating jam can be neglected, unless the jam is very thick relative to the flow depth underneath it. A grounded jam extends to the river bed. Grounding is common near the shores and in the toe area of a jam. Flow occurs entirely as seepage.

The state of a jam indicates the presence or absence of significant temporal variations (evolving versus steady). Steady jams can be further subdivided into equilibrium and non-equilibrium ones. The former type is long enough to include an equilibrium reach where approximate downstream uniformity prevails. Maximum ice jam water levels occur under equilibrium conditions.

### MANAGEMENT AND MITIGATION

Various control measures can be implemented to alleviate high water levels or other adverse effects of ice jams, for example, interference with navigation and constraints to hydropower production. Ideally, a mitigation study would be based on a thorough understanding of local ice processes and a capability to predict the beneficial as well as any detrimental consequences of alternative control measures.

From earlier discussion, it is clear that the state of knowledge on ice jams is deficient in many respects. Full understanding of ice jam processes is not at hand and mathematical simulation is only reliable with regard to certain, relatively simple, aspects of ice jam behaviour. To compensate for such deficiencies, mitigation studies take into account all pertinent historical information. However, such

- (d) Strength Characteristics of a Jam: The cohesion and internal friction of a jam influence its thickness. Breakup jams, being practically cohesionless, should be thicker than freeze up ones, other things being equal. Moreover, breakup discharges are usually much larger than freeze up ones which explains why breakup usually governs the peak water levels.
- (e) Ice Volume: The amount of ice available to form a jam can influence the jam stage if it is less than that needed to develop an equilibrium section.
- (f) Water Temperature and Heat Transfer: Apart from possible effects on the strength of a freeze up jam, melting of a breakup jam could be significant (Prowse and Marsh, 1985).
- (g) Strength and Thickness of Ice Cover During Breakup: Competent ice cover will cause more frequent and persistent jams than a highly deteriorated one. This could in the long run, translate to higher water levels (see, for example, Fig. 5).

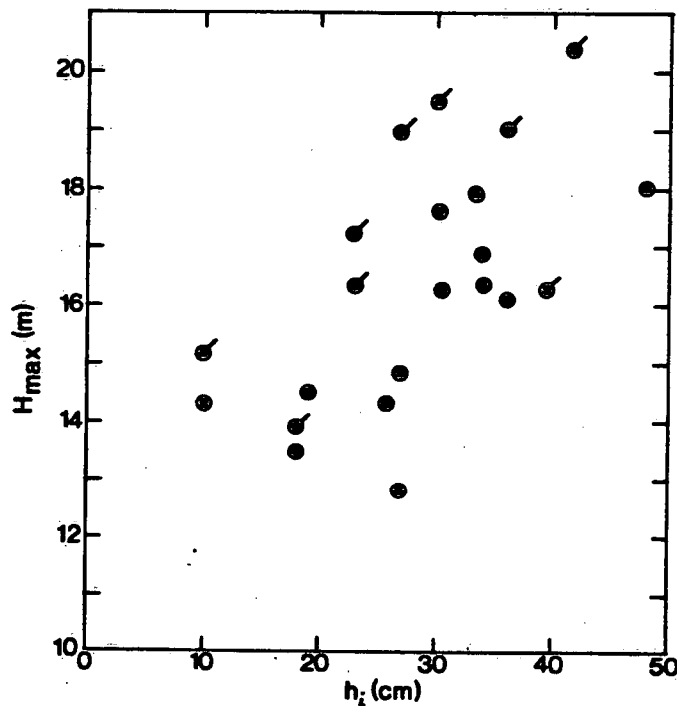


Fig. 5 Maximum stage attained during breakup ( $H_{max}$ ) plotted versus thickness of winter ice cover ( $h_i$ ), Thames River at Thamesville, Ontario, Canada. Note effect of  $h_i$  on  $H_{max}$ , though other effects are also indicated.



information is very often not sufficiently detailed to provide the full "picture" or to serve as a calibration base for the mathematical model to be applied. Consequently, it is essential to monitor the ice regime for at least one season and obtain the required quantitative data. The sophistication of the monitoring program will depend on the nature of the study. Guidelines for relatively simple observations are given by Prowse (1985). In addition, the river bathymetry and slope have to be measured within the reach of interest.

The above information, coupled with a mathematical model<sup>2</sup> of ice conditions should generally provide a fair understanding of the processes at work. Moreover, application of the model would help estimate the average annual damage caused by ice jams. (See, for example, Gerard and Karpuk, 1979 and Gerard and Calkins, 1984). When this is done, the stage is set for consideration of mitigation measures. Often, several possibilities are available (e.g. see Bolsenga, 1968; U.S. Army Corps of Engineers, 1982; Perham, 1983; Cumming-Cockburn, 1986). The latter reference includes an extensive summary of structural and non-structural measures used to control ice jams at freeze up and breakup.

Structural methods (e.g. flow or ice control dams, weirs, booms, flow or ice diversions, ice storage, dykes, flood proofing) are generally reliable and anticipatory but expensive. Non-structural methods (e.g. mechanical ice removal, ice breaking, blasting, surface treatment, forecasting and warning) are relatively cheap but often reactive and uncertain. The final selection of a control measure depends not only on its effectiveness (e.g. benefit/cost ratio) but also on whether it has the potential for creating problems elsewhere in the river. Considerations of this kind are facilitated by numerical, computer-assisted, models of ice jam processes. Only a few models of this type have been developed, however (e.g. Petryk, 1981; Calkins, 1984) and most are proprietary.<sup>3</sup>

Occasionally, the nature of the problem is such that little faith can be placed on existing data or mathematical analysis. Physical modelling might then be an alternative or complementary approach. The main difficulty here lies in the scaling down of the properties of intact ice covers when their behaviour is relevant to the problem at hand. Kotras et al (1977) and Michel (1978b) give comprehensive discussions of scaling requirements. In general, the model "ice" must

---

<sup>2</sup>Models of varying complexity have been used. They range from very simple, analytical expressions of ice jam water levels using reach-average hydraulic parameters, to comprehensive numerical algorithms that compute ice and flow conditions as functions of space and time.

<sup>3</sup>Under the auspices of the National Research Council of Canada, a proposal has been formulated to develop a comprehensive non-proprietary model simulating river ice conditions. The work is to be carried out by a consortium of Canadian Engineering Consulting firms with in-house support by numerous public agencies, including a few from the United States.

be much weaker and more flexible than freshwater ice while having the same density. Where a cold room facility is available, saline or doped ice can be used (Timco, 1981; Hirayama, 1983). Such materials, however, are mainly used for ice-structure interactions. Very limited application to ice-jam related studies has been made, possibly due to incidental problems caused by hydrothermal processes. At room temperature, a synthetic wax-based material has been used (e.g. Michel et al, 1973; Michel and Abelnour, 1975) but its composition is proprietary.

Finally, a study of ice jam mitigation might benefit from previous experience under similar circumstances. Petryk (1985) gives a compilation of past case studies on ice jams in the form of brief summaries, including nature of the problem, relevant publications, if any, and contact persons.

#### MAJOR UNKNOWNNS

The study of ice jams took on a "scientific" flavour some thirty years ago when several researchers and engineers formulated a theoretical basis for equilibrium conditions (e.g. Kivisild, 1959; Kennedy, 1958; Pariset and Hausser, 1961). Much progress has been made since then, despite the enormous complexities associated with ice jamming phenomena. At the same time, it is recognized that much has to be learned in the future before ice jam technology reaches a level comparable to that of other areas in hydraulics.

Gerard (1984) presented a comprehensive discussion of research needs and his conclusions remain valid today. They involve: systematic field observation of ice jam behaviour, development of non-proprietary computer models; study of formation processes; development of non-proprietary model "ice" for physical modelling and laboratory studies of ice jam - ice cover interactions; improved methods for remote measurement of river stage during freeze up and breakup; and continued study of the fundamentals of the behaviour of fragmented ice accumulations.

The importance of developing convenient model "ice" materials for laboratory use cannot be overemphasized. The laboratory route seems to be the only feasible one for quantification of processes related to ice jam - ice cover interaction. Such processes often govern the formation and release of breakup jams and thence dictate the severity of breakup events.

Validation of ice jam theories and design of effective emergency measures often require rapid techniques for the measurement of jam thickness and its spatial distribution. Only manual drilling can provide data of this kind at present (Fig. 6) but this technique is extremely laborious and, as a rule, hazardous for breakup jams (e.g. see Beltaos and Moody, 1987). Impulse radar systems, proven in applications with solid ice sheets, could perhaps be modified and adapted to sense the thickness of a porous ice accumulation. The main difficulty is caused by the multiple ice-water interfaces that are present in a jam.

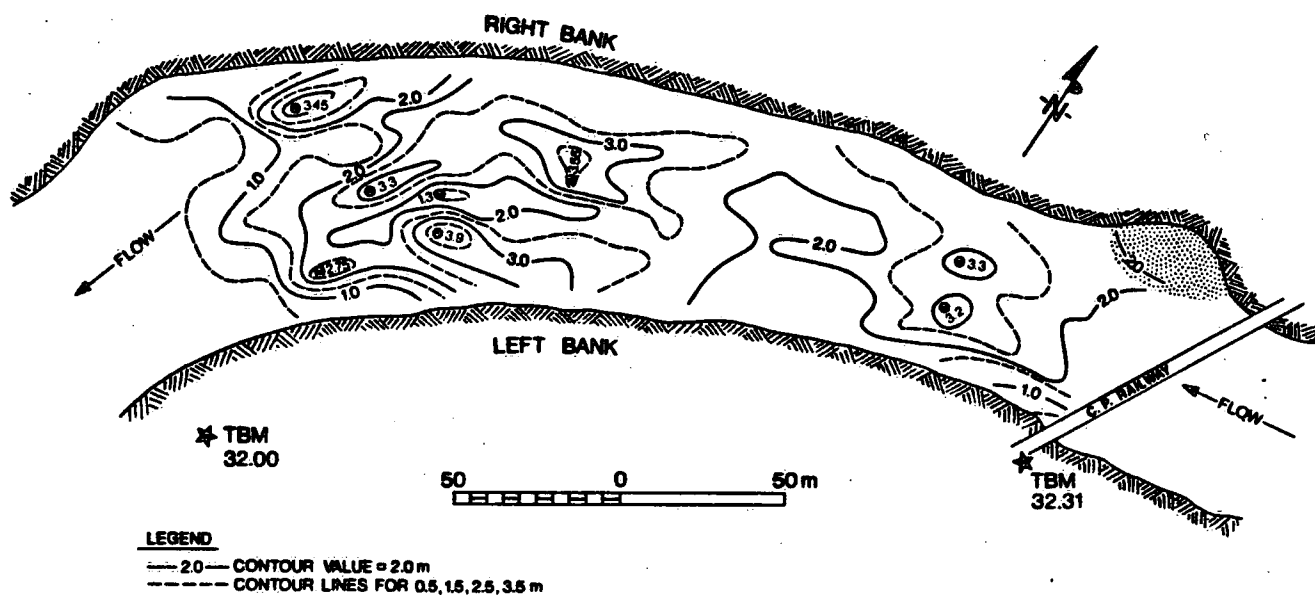


Fig. 6 Contour plot of ice jam thickness measurements, Thames River near Chatham, Ontario, Canada. Toe of jam (end of sheet ice cover) located at section of maximum thickness. Jam "froze" in place due to cold weather, enabling safe access.

#### REFERENCES

- Ackermann, N.L. and H.T. Shen. 1983. Mechanics of Ice Jam Formation in Rivers. U.S. Army CRREL Report 83-31, Hanover, NH.
- Ashton, G.D. 1974. Froude Criterion for Ice Block Stability. Journal of Glaciology, Vol. 13, No. 68, pp. 307-313.
- Ashton, G.D. ed. 1986. River and Lake Ice Engineering. Water Resources Publications, Littleton, Colorado, U.S.A.
- Atkinson, C.H. 1973. Problems and Economic Importance of Ice Jams in Canada. Proceedings Seminar on Ice Jams in Canada, Edmonton, Alberta, NRC Tech. Memo No. 107, pp. 1-16.
- Beltaos, S. 1983. River Ice Jams: Theory, Case Studies and Applications. Journal of Hydraulic Engineering, ASCE, Vol. 109(10), pp. 1338-1359.
- Beltaos, S. 1984a. Study of River Ice Breakup using Hydrometric Station Records. Proceedings Workshop on the Hydraulics of River Ice, Fredericton, N.B., Canada, pp. 41-59.

- Beltaos, S. 1984b. A Conceptual Model of River Ice Breakup. Canadian Journal of Civil Engineering, Vol. 11, No. 3, pp. 516-529.
- Beltaos, S. 1985. Initial Fracture Patterns of River Ice Cover. National Water Research Institute, Burlington, Ontario, Canada, Contribution No. 85-139.
- Beltaos, S. 1986. Monograph on River Ice Jams, Chapter 4: Theory. Submitted to NRCC Working Group on Ice Jams.
- Beltaos, S. 1987. River Ice Jams: Theory, Case Studies and Applications. Closure, ASCE J. of Hydr. Eng., Vol. 113, No. 2, pp. 246-255.
- Beltaos, S. and K. Davar. 1984. Classification of River Ice Jams. Draft submitted to IAHR Working Group on Ice Jams.
- Beltaos, S. and B.G. Krishnappan. 1982. Surges from Ice Ice Jam Releases: A Case Study. Canadian Journal of Civil Engineering, Vol 9 (2), pp. 276-284.
- Beltaos, S. and W.J. Moody. 1986. Measurements of the configuration of a breakup jam. National Water Research Institute, Burlington, Ontario, Canada, Contribution No. 86-123.
- Beltaos, S. and J. Wong. 1986a. Preliminary Studies of Grounded Ice Jams. Proceedings IAHR Symposium on Ice, Iowa City, Iowa, USA, Vol. II, pp. 3-14.
- Beltaos, S. and J. Wong. 1986b. Downstream Transition of River Ice Jams. Journal of Hydraulic Engineering, ASCE, Vol. 112, No. 2, pp. 91-110.
- Bolsenga, S.J. 1968. River Ice Jams. Research Report 5-5, U.S. Lake Survey, Department of the Army, Detroit, Michigan, U.S.A.
- Calkins, D.J. 1984. Numerical Simulation of Freeze Up on the Ottawaquechee River. Proceedings Workshop on Hydraulics of River Ice, Fredericton, N.B., Canada, pp. 247-274.
- Calkins, D.J. and G.D. Ashton. 1975. Arching of Fragmented Ice Covers. Canadian Journal of Civil Engineering, Vol. 2(4), pp. 392-399.
- Cumming-Cockburn & Assoc. Ltd. 1986. Ice Jams on Small Rivers - Remedial Measures and Monitoring. Report to Supply and Services Canada, Environment Canada, Ontario Ministry of Natural Resources, City of Mississauga and Credit Valley Construction Authority, Toronto, Canada.
- Environment Canada. 1986. Flooding in New Brunswick. An Overview: 1696-1984. Water Planning and Management Branch, IWLD, Atlantic Region, Dartmouth, N.S.

- Ferrick, M., G. Lemieux, N. Mulherin and W. Dement. 1986. IAHR Symposium on Ice, Iowa City, Iowa, USA.
- Frankenstein, G.E. and A. Assur. 1972. Israel River Ice Jam. Proceedings IAHR Symposium on Ice and Its Action on Hydraulic Structures, Leningrad, USSR, Vol. 2, pp. 153-157.
- Gerard, R. 1979. River Ice in Hydrotechnical Engineering: A Review of Selected Topics. Proceedings Can. Hydrology Symposium, Vancouver, Canada, pp. 1-29.
- Gerard, R. 1984. Ice Jam Research Needs. (For NRCC Working Group on Ice Jams). Proceedings Workshop on the Hydraulics of River Ice, Fredericton, N.B., Canada, pp. 181-191.
- Gerard, R. and D.J. Calkins. 1984. Ice-Related Flood Frequency Analysis: Application of Analytical Estimates. Proc. Cold Regions Engineering Specialty Conference, Canadian Society for Civil Engineering, Montreal, Canada, pp. 85-101.
- Gerard, R. and E.W. Karpuk. 1979. Probability Analysis of Historical Flood Data. J. of the Hydr. Div., ASCE, Vol. 105, No. HY9, pp. 1153-1165.
- Gerard, R., T.D. Kent, R. Janowicz and R.O. Lyons. 1984. Ice Regime Reconnaissance, Yukon River, Yukon. Proceedings Cold Regions Engineering Specialty Conference, Canadian Society for Civil Engineering, Montreal, Canada, pp. 1059-1073.
- Gold, L.W. and G.P. Williams. 1963. An Unusual Ice Formation on the Ottawa River. Journal of Glaciology, Vol. 4, No. 31, pp. 569-573.
- Henderson, F.M. and R. Gerard. 1981. Flood Waves Caused by Ice Jam Formation and Failure. Proceedings IAHR Symposium on Ice, Quebec, Canada, Vol. 1, pp. 277-287.
- Hirayama, K. 1983. Experience with Urea-Doped Ice in the CRREL Test Basin. Proceedings 7th International Symposium on Port and Ocean Engineering Under Arctic Conditions, Finland, Vol. 2, pp. 788-801.
- Kennedy, R.J. 1958. Forces involved in pulpwood holding grounds - I. Transverse holding grounds with piers. The Engineering Journal (Engineering Institute of Canada), Vol. 41, pp. 58-68.
- Kivisild, H.R. 1959. Hanging Ice Dams. Proceedings 8th Congress of IAHR, Vol. 2, Paper 23-F, pp. 1-30.
- Kotras, T., J. Kewis and R. Etzel. 1977. Hydraulic Modelling of Ice-Covered Waters. Proceedings Conference on Port and Ocean Engineering Under Arctic Conditions, St. John's, Canada, pp. 453-463.
- LeBrun-Salonen, M. 1985. A Historical Review of the March 1902 Ice Jam Floods. Report Prepared under the Canada Works Program, Contract No. 1829-DE6, Fredericton, N.B.

- Mathieu, B. and B. Michel. 1967. Formation des embacles secs. Proceedings 12th IAHR Congress, Fort Collins, Colo., USA, Vol. 4, pp. 283-286.
- Mercer, A.G. and R.H. Cooper. 1977. River Bed Scour Related to the Growth of a Major Ice Jam. Proceedings 3rd Canadian Hydrotechnical Conference, Quebec, Canada, pp. 291-308.
- Michel, B. 1971. Winter Regime of Rivers and Lakes. U.S. Army CRREL Monograph 111-B1a, Hanover, N.H.
- Michel, B. 1978a. Ice Accumulation at Freeze-Up or Breakup. Proceedings IAHR Symposium on Ice Problems, Lulea, Sweden, Part 2, pp. 301-317.
- Michel, B. 1978b. Ice Mechanics. Les Presses de l'Université Laval, Québec, Canada.
- Michel, B. 1984. Comparison of Field Data with Theories on Ice Cover Progression in Large Rivers. Canadian Journal of Civil Engineering, Vol. 11, No. 4, pp. 798-814.
- Michel, B. and R. Abdelnour. 1975. Breakup of a Solid River Ice Cover. Third International Symposium on Ice Problems, Hanover, New Hampshire, USA.
- Michel, B., J. Llamas and J.L. Verrette. 1973. Modèle de la Rivière Becancour. Rapport Technique GCT-73-05-0, Université Laval.
- Nuttall, J.B. 1973. River Modification and Channel Improvements. Proceedings Seminar on Ice Jams in Canada, Published as NRCC Technical Memorandum No. 107, Ottawa, Canada.
- Pariset, E. and R. Hausser. 1961. Formation and Evolution of Ice Covers on Rivers. Transactions of Engineering Institute of Canada, Vol. 5, No. 1, pp. 41-49.
- Pariset, E., R. Hausser and A. Gagnon. 1966. Formation of Ice Covers and Ice Jams in Rivers. Journal of the Hydraulics Division, ASCE, Vol. 92 (HY6), pp. 1-24.
- Perham, R.E. 1983. Ice Sheet Retention Structures. CRREL Report 83-30, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.
- Petryk, S., U.S. Panu, V.C. Kartha and F. Clément. 1981. Numerical Modelling and Predictability of Ice Regime in Rivers. Proceedings IAHR Symposium on Ice, Quebec, Canada, Vol. I, pp. 426-433.
- Petryk, S. 1985. Casebook on Ice Jams. Draft Report, NRCC Working Group on River Ice Jams, Ottawa, Canada.

Prowse, T.D. 1985. Guidelines for River Ice Data Collection Programs. Draft Report, NRCC Working Group on River Ice Jams, Ottawa, Canada.

Prowse, T.D. and P. Marsh. 1985. Hydrothermal Decay of Ice Jams. Proceedings 42nd Eastern Snow Conference, Montreal, Canada, pp. 272-276.

Shulyakovskii, L.G. ed. 1963. Manual of Forecasting Ice Formation for Rivers and Inland Lakes. Israel Program for Scientific Translations, Jerusalem, 1966.

Tatinclaux, J.C. 1977. Equilibrium Thickness of Ice Jams. Journal of the Hydraulics Division, ASCE, Vol. 103, HY9, pp. 959-974.

Tatinclaux, J.C. and M. Gogus. 1981. Stability of Floes Below a Floating Cover. Proceedings of International Symposium on Ice, IAHR, Vol. 1, pp. 298-311.

Tatinclaux, J.C. and C.L. Lee. 1978. Initiation of Ice Jams - A Laboratory Study. Canadian Journal of Civil Engineering, Vol. 5 (2), pp. 202-212.

Timco, G.W. 1981. A Comparison of Several Chemically-Doped Types of Model Ice. Proceedings, IAHR Symposium on Ice, Quebec, Canada, pp. 356-366.

U.S. Army Corps of Engineers. 1982. Ice Engineering. Engineer Manual 110-2-1612, Washington, D.C.

Uzuner, M.S. and J.F. Kennedy. 1972. Stability of Floating Ice Blocks. Journal of the Hydraulics Division, ASCE, Vol. 98, HY12, pp. 2117-2133.

Uzuner, M.S. and J.F. Kennedy. 1976. Theoretical Model of River Ice Jams. Journal of the Hydraulics Division, ASCE, Vol. 102 (HY9), pp. 1365-1383.