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COLD REGIONS HYDROLOGY AND HYDRAULICS MONOGRAPH; CHAPTER I, SECTION 2: BREAKUP JAMS

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ABSTRACT

The river ice breakup and attendant ice jamming is a brief but potentially hazardous period in northern countries. Flooding is the most conspicuous problem caused by ice jams but damage to river structures, interference with navigation and loss of hydro-revenue are also significant consequences. The formation and evolution of ice jams are reviewed and the main jam types defined. Of particular interest is the "wide" river jam that is formed by internal collapse and thickening. The wide jam is by far the most common at breakup and has the greatest flooding potential. Pertinent theories leading to prediction of ice jam water levels are briefly discussed with emphasis on the "equilibrium" condition. The latter is characterized by maximum water depth and longitudinal uniformity which simplifies prediction methods to analytical calculation in terms of river slope, width and discharge. The release of ice jams can be a violent event, owing to surge-like phenomena manifested in extreme water speeds and rates of rise. Approximate prediction of surge characteristics is possible using open-water models of unsteady flow but it is not fully understood how jams release. Management of river ice to mitigate its effects is based on a combination of historical data, field observations and mathematical (and occasionally physical) modelling. Major unknowns are reviewed, and an Appendix discussing the hydraulic resistance of ice jams is included.

RÉSUMÉ

Le dégel des rivières et les embâcles qui en découlent durent peu de temps, mais peuvent constituer une période dangereuse dans les pays du nord. Si le problème le plus fréquent causé par les embâcles est l'inondation, l'endommagement des ouvrages hydrauliques dans les cours d'eau, l'interférence avec la navigation et la perte de revenus hydro-électriques n'en sont pas moins des conséquences importantes. Ce rapport porte sur la formation et l'évolution des embâcles et définit également les principaux types d'embâcles. L'embâcle "large", formé par un effondrement interne et un épaississement des glaces, présente un intérêt particulier. Ce type d'embâcle est en effet de loin le plus fréquent au moment du dégel et celui qui présente les plus grands risques d'inondation. Les théories pertinentes à partir desquelles sont faites les prévisions du niveau des eaux causé par les embâcles sont brièvement examinées, en fonction surtout de l'état d'"équilibre". Ce dernier, caractérisé par une profondeur d'eau maximale et une uniformité longitudinale, réduit les méthodes de prévision à de simples calculs analytiques de pente, de largeur et de débit du cours d'eau. La débâcle est parfois un événement violent à cause du phénomène de surpression qui se manifeste par des vitesses d'écoulement extrêmement élevées et une hausse rapide du niveau des eaux. Il est possible de prévoir à peu près les caractéristiques de la surpression à l'aide de modèles de débit non-permanent en eau libre, mais on ne comprend pas tout à fait de quelle façon l'embâcle

cède. Pour gérer les glaces des cours d'eau en vue d'atténuer leurs effets, on se fonde sur une combinaison de données historiques, d'observations sur le terrain et de modèles mathématiques (et, à l'occasion, physiques). Les grandes inconnues du problème sont examinées et une annexe porte sur la résistance hydraulique des embâcles.

MANAGEMENT PERSPECTIVE

This report has been prepared in response to a request by the ASCE Technical Council on Cold Regions Engineering, and is intended to form a part of "Cold Regions Hydrology and Hydraulics Monograph". Ice jamming in rivers is a major concern in northern countries, particularly with regard to flooding, and this brief state-of-the-art report should be useful to engineers and managers concerned with rivers.

PERSPECTIVE DE GESTION

Ce rapport, préparé à la demande du Technical Council on Cold Regions Engineering de ASCE, doit faire partie d'une monographie sur l'hydrologie et l'hydraulique des régions froides. Les embâcles dans les cours d'eau sont une des grandes préoccupations des pays septentrionaux, notamment en ce qui a trait aux inondations, et ce bref rapport à jour devrait aider les ingénieurs et les gestionnaires qui s'occupent des cours d'eau.

BREAKUP JAMS

1. INTRODUCTION

The most serious consequence of river ice formation is the jamming that occurs during freezeup and breakup. Flooding, damage to structures, interference with navigation and hydropower production are some of the problems caused by ice jams. The flooding aspect is considered the "greatest hazard of river ice" (Ashton, 1986), resulting essentially from the large thickness and underside roughness attainable by ice jams. Peak annual stages in northern rivers are often due to ice jams. Moreover, ice-jam flood events appear to cause several times more damage than open-water floods. A factor of three was found by Humes and Dublin (1988) for the St. John River in New Brunswick.

Ice jams are porous accumulations of ice fragments such as frazil slush or ice pans at freeze up and solid ice blocks at breakup. Because of greater flow discharge, lower internal strength and greater roughness, breakup jams are potentially far more hazardous than freeze up ones. Figure 1 shows photos of breakup jams while Figures 2 and 3 illustrate their configuration. There is considerable variation of thickness in the transverse direction but without any persistent trend. On the other hand, the thickness generally increases in the downstream direction, attaining a maximum at the toe (downstream end) and then quickly decreases under the sheet ice cover. Because the Thames River is relatively narrow and deep, the jam thickness in

Figure 3 is a relatively small fraction of the water depth. In wider rivers the opposite is true and grounding of the jam near the toe is probable.

2. FORMATION

Breakup jams generally form where ice floes encounter competent sheet ice cover. As has already been described in the previous section, local hydraulics and floe size dictate whether a surface jam, a thickened jam or a hanging dam will form when ice floes encounter stationary cover. Letting V represent the average flow velocity under the ice cover and V_S, V_D = critical" submergence and deposition velocities respectively, ($V_S < V_D$) we have the following cases:

(a) $V < V_S$: surface jam, i.e., incoming floes remain on the water surface and a single-layer accumulation grows upstream.

(b) $V_S < V < V_D$: thickened jam. Incoming floes submerge upon arrival at the ice edge and deposit immediately downstream.

(c) $V_D < V$: (possibly) hanging dam. Incoming floes not only submerge upon arrival at the edge but are transported under the cover to deposit at a downstream location where the velocity drops below V_D. Deep river sections are especially prone to such depositional accumulations of ice, commonly called "hanging dams". Hanging dams are known to attain extreme thicknesses and are essentially freeze up phenomena. They do not cause serious backwater because ice merely kepps filling a dead or eddy zone until the flow velocity under the deposit increases to V_D. On the other hand, hanging dams are obstructions to broken ice transport and likely to cause persistent jams during breakup (Beltaos and Dean, 1981).

An additional mechanism of jam formation, common during breakup but not well understood, is the "wedging" of a moving ice accumulation between the ice cover and the channel bed. 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 a synthetic "ice" cover and polyethylene blocks (Wong _et_ _al_., 1988).

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.

3. EVOLUTION

As a surface or thickened jam propagates upstream, the external forces applied on it, being proportional to jam length, increase. This produces internal stresses, resisted by the internal strength of the jam which comprises internal friction and cohesion. Excessive stresses bring about a collapse of the jam and thickening until a balance between stress and strength is attained. These concepts were first given quantitative expression by Kennedy (1958), Kivisild (1959), and Pariset and Hausser (1961) and further developed by Pariset et al. (1966), Uzuner and Kennedy (1976) and Beltaos and Wong (1986b). A brief synthesis of these works is presented next.

As already discussed in the previous section, the thickness, t_N, of a thickened jam (case (b) above) is given by

$$t_N = V^2/2\ (1-s_i)(1-p)g \qquad (1)$$

in which s_i = specific gravity of ice; p = porosity of jam and g = acceleration due to gravity. Beltaos (1986) showed that t_N decreases in the upstream direction, tapering off to an asymptotic value within a distance from the toe equivalent to hundreds of river depths. This configuration is possible provided the jam does not collapse. The longitudinal, vertically averaged, effective stress (total stress minus pore water pressure), σ_x, is given by:

$$\frac{d}{dx}(\sigma_x t) + \frac{2k_0 k_1}{B}(\sigma_x t) = s_i \rho g S_w t + \tau_i - \frac{2tC_i}{B} \tag{2}$$

in which t = thickness of jam; B = channel width at the level of the jam's underside; S_W = water surface slope; ρ = water density; τ_i = flow shear stress applied on the underside of the jam; C_i = cohesion of jam; and k_0, k_1 are dimensionless coefficients defined by the following expressions, describing stress and strength characteristics of granular materials.

$$\sigma_Z = \text{transverse stress} = k_1 \sigma_x \tag{3}$$

$$\tau_R = \text{resistance to shear} = C_i + k_0\, \sigma_Z \tag{4}$$

Figure 4 illustrates the forces acting on an element of the jam (Btdx) whose balance is expressed by Eq. 2. While the latter is difficult to solve analytically, simple numerical techniques can be developed for efficient calculation of σ_x. For stability, σ_x should not exceed the strength of the jam in compression which develops due to the confinement produced by buoyancy forces. The effective vertical stress σ_y has an average value of (see Figure 5).

$$(\sigma_y)_{ave} = \gamma_e t = \{\tfrac{1}{2}\, s_i\ (1-s_i)(1-p)\rho g\}t \tag{5}$$

and the compressive strength of the jam is assumed equal to $K_x \gamma_e t$, with K_x being a dimensionless coefficient in the neighbourhood of

10 (Beltaos, 1988). For breakup jams, field data consistently indicate that cohesion, if any, is a minor part of a jam's resistance to shear (Eq. 4). Using this result in Eq. 2, it can be shown that a jam of thickness t_N (Eq. 1) would be unstable (i.e., $\sigma_x > K_x\gamma_e t_N$) in any but very small streams. Instability implies that the jam has to collapse and re-adjust its thickness until the new stress σ_x is equal to the (new) strength $K_x\gamma_e t$. The latter type of jam has been termed "wide" because its formation is promoted by increasing river width (note in Figure 4 that applied forces are proportional to the width, but resisting forces are limited by the thickness). The term "narrow" jam has been applied to the hydraulically formed jam whose thickness is given by Eq. 1. The focus herein will be on the wide jam because of its relative frequency during breakup.

If we substitute $K_x\gamma_e t$ for σ_x in Eq. 2 and neglect cohesion, we obtain the wide jam stability expression, i.e.,

$$\frac{dt}{dx} = \left(\frac{s_i\gamma}{2\gamma_e K_x}\right) S_w + \frac{\tau_i}{2K_x\gamma_e t} - \frac{k_0 k_1 t}{B} \qquad (6)$$

which together with the momentum and continuity equations for the flow under the jam, forms a numerically integrable set (e.g., see Uzuner and Kennedy, 1976; Beltaos and Wong, 1986b; Flato and Gerard, 1986). The solution of this set is qualitatively illustrated in Figures 6a and 6b. The latter depicts an "equilibrium" jam, that is, a jam long enough to have an "equilibrium" reach where jam thickness and flow depth are uniform*. Of the transitional reaches, the downstream transition is very important because it leads to the toe where the jam is held in place by intact ice cover and by the channel boundaries. Grounding in this area is possible in steep or wide rivers.

In ice jam literature, it is commonly assumed that the entire flow discharge is conveyed under the jam, i.e., seepage through the voids of the jam is negligible. This is likely true of freeze up jams where the sizes of frazil ice grains and spaces between them are small. However, breakup jams consist principally of ice blocks and the void spaces are much greater. Seepage through the jam could now be significant. This is particularly important near the toe where the jam thickness-to-flow depth ratio is maximized. From laboratory experiments with plastic blocks, Beltaos and Wong (1986a) formulated the following equation for the flow discharge, Q_p, through a breakup jam:

$$Q_p = \lambda A_J \sqrt{S_w} \qquad (7)$$

in which A_J = cross-sectional area of submerged portion of the jam; S_W = water surface slope; and λ = a dimensional coefficient that depends on ice block dimensions, jam porosity and acceleration of

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*The water surface slope in the equilibrium reach is equal to that of the channel bed which in natural streams translates to equality with the open water flow slope.

gravity. No field data exist for λ. Extrapolation of laboratory results indicates that $\lambda \sim 1\text{-}2$ m/s but this must, at present, be viewed as a mere guess. Where seepage is suspected to be a significant component of the flow, the equations of momentum and continuity could be adjusted using Eq. 7.

4. EQUILIBRIUM

We have already defined what is an equilibrium jam. Brief reflection suggests that the water depth within the equilibrium reach is greater than or equal to that occurring anywhere else along the jam. Moreover, the equilibrium depth also exceeds water depths attained by the jam prior to its attaining the equilibrium condition. Because uniform conditions prevail in the equilibrium reach, the LHS of Eq. 6 vanishes which permits development of an analytical solution. Beltaos (1983) showed that the jam thickness can be expressed in terms of the depth of flow under the jam, h:

$$\frac{t_e}{S_o B_e} = \frac{1}{2\mu(1-s_i)} \{1 + \sqrt{1 + 2 \frac{f_i}{f_o} \mu \frac{1-s_i}{s_i} (\frac{h_e}{S_o B_e})}\} \qquad (8)$$

in which S_o = uniform flow water surface slope ≈ open water slope under steady conditions; the subscript "e" denotes equilibrium conditions; f_i, f_o are friction factors for the jam undersurface and composite flow, respectively; and μ is a dimensionless coefficient expressing internal strength characteristics of the jam, i.e.,

$$\mu = k_0 k_1 \; K_x \; (1-p) \qquad (9)$$

The derivation of Eq. 8 is straightforward: Put dt/dx = 0 and $\tau_i = (f_i/2f_0)\ \rho g h S_0$ in Eq. 6 and solve the resulting quadratic for t/S_0B (see also Appendix A for hydraulic resistance considerations). Further, we may write

$$h_e = \left(\frac{q}{\sqrt{4gS_0/f_o}}\right)^{2/3} \qquad (10)$$

in which $q = Q/B_e$ = discharge per unit width for the flow under the jam. Since the total depth of water, H, is equal to $h + s_i t$, use of Eqs. 8 and 9 results in (with s_i fixed at 0.92)

$$\eta \equiv \frac{H_e}{S_0 B_e} = 0.63\ f_o^{1/3}\ \xi + \frac{5.75}{\mu}\ \{1 + \sqrt{1 + 0.11\ \mu\ f_o^{1/3}\ (\frac{f_i}{f_o}\ )}\xi \qquad (11)$$

in which

$$\xi \equiv \frac{(q^2/gS_o)^{1/3}}{S_o B_e} \qquad (12)$$

Field data have shown that the coefficient μ can be considered a constant with an average value of 1.2 or 1.3 (Pariset et al., 1966; Beltaos, 1983). In addition, Beltaos (1983) has shown that f_0 is partly related to ξ or, more correctly, to t/h which, in the equilibrium reach, depends on ξ, while f_i/f_o is usually in a fairly narrow range. Thus, Eq. 11 suggests that, as a first approximation, η could be considered a function of ξ alone. This has been verified by numerous case studies (e.g., see Beltaos, 1987) and Figure 7 summarizes the results in the form of a data band and an "average" relationship. It is noteworthy that the data band of Figure 7 includes rivers ranging in width from 36 to 1,750 m and in discharge from 10 to 14,700 m^3/s. Figure 7 is particularly suitable for quick estimates of ice jam water levels because it only requires knowledge of flow discharge, channel width and river slope. More detailed methods calculate h and t separately, using additional information on the hydraulic roughness of the jam and the bed (Appendix A). Beltaos (1983) developed an analytical method of this kind and found that it yielded better predictions than Figure 7.

5. RELEASE

A sudden jam release is attended by surge-like phenomena such as high velocities and rapid stage increases. The witness accounts reproduced next illustrate the destructive potential of ice jam-surges.

- Athabasca River at Fort McMurray, 1875: "In less than an hour the water rose 57 feet, flooding the whole flat and mowing down trees, some 3 ft. diameter, like grass...", quoted by Gerard (1979) from Moberley and Cameron (1929).

- Athabasca River above House River confluence, 1936: "During the night they (three men) awakened to find three feet of water in the room. Scrambling into some clothes they waded out and untied their horses and tried to find higher ground. The water rose so rapidly that all they could do was to climb a tree. Lee and Cinnamon got a safe one and climbed higher as the water rose. They could see Donaldson in difficulties and shouted to him, but he appeared unable to climb or the sapling would not support him and he gradually sank out of sight.." [Athabasca Echo, 24 April 1936, Athabasca, Alberta; quoted from Gerard, 1979].
- Moira River at Belleville, 1981: "The river went up about 5 feet in 30 seconds." (Chatham Daily News, Feb. 21, 1981, Chatham, Ont.)
- Mackenzie River near Point Separation, 1973: "...on release the flow accelerated slowly reaching an estimated peak velocity in excess of 25 fps after 30 minutes..." (Mercer and Cooper 1977).
- Nashwaak River, 1902: "The ice run seemed to gain in power and velocity as it advanced. The force of ice and water carried away three large mill dams before the ice jammed near Stanley...Grounded on gravel deposits, this jam caused

> the Nashwaak River to rise to an unprecedented height and subsequently inundated numerous homes and farms...When this immense jam released, it carried away the 53 metre long Stanley Bridge...The Murray Dam and the Douglas Brothers Dam were destroyed, followed by the destruction of the Red Rock Bridge...It was this incredible release of ice and water that drowned a 30 year old woman at Covered Bridge." (Le Brun - Salonen, 1985).

Such violent and rapid motions of the water and ice can be explained, if it is considered that the release of a large ice jam is similar to a dam-break. The initial condition for ice jam release is not as severe as that of the dam break situation, but the very steep toe slopes that are often encountered and the large water depths further upstream (see Figure 6) can produce destructive surges that are not naturally possible during open-water floods. To calculate the consequences of a surge due to jam release, Mercer and Cooper (1977) applied an open-water unsteady flow model, implicitly assuming that the presence of the ice would not significantly alter flow velocities and depths. This assumption was verified by Beltaos and Krishnappan (1982) via an analysis of the equations of motion for the water-ice system. The unsteady open-water flow model MOBED (Krishnappan, 1981) was then used in rigid-bed mode to reproduce pertinent field and laboratory data (Beltaos and Krishnappan, 1982, Wong et al., 1985). Surging flow prediction generally requires computer applications and detailed input data. A simplified analysis by Henderson and Gerard (1981) simulates the jam release by the sudden removal of a sluice gate in a frictionless rectangular channel of zero slope. The resulting analytical expressions are "crude" but help illustrate the violent nature of surges, in a quick and simple manner. The surge celerity, C_R, and surging water velocity, V_R, resulting from a release are given (after simplifying and reducing to analytical form the results of Henderson and Gerard, 1981).

$$\frac{C_R}{\sqrt{gH_D}} = F_D + \sqrt{(1+0.4\ m\ )(1+0.2m\ )} \qquad (13)$$

$$\frac{V_R}{\sqrt{gH_D}} = F_D + 0.4\ m\ \sqrt{\frac{1+0.2\ m}{1+0.4\ m}} \qquad (14)$$

in which m = relative backwater caused by the jam = $(H_U - H_D)/H_D$; H_U, H_D = water depths upstream and downstream of the jam respectively; and F_D is the Froude number of the flow downstream of the jam. Eq. 13 indicates that C_R exceeds $\sqrt{gH_D}$ which represents a large velocity (e.g., H_D = 4 m, $\sqrt{gH_D}$ = 7 m/s). Where m is large, C_R could attain values of 10 m/s or more. Eq. 14 shows that water velocities are governed by the value of m which in turn is strongly influenced by river width. Thus we would expect that violent surges would usually occur in large rivers which is in accord with experience. Values of V_R exceeding 7 m/s have been reported (see earlier quotation from Mercer and Cooper, 1977).

The release of ice jams is closely related to ice clearing in a reach and thus to maximum possible breakup stages. To date, it has not been possible to understand why and predict when a jam will release, in a general way. Experience suggests that, in at least some river types, ice jams cannot remain stable beyond a certain discharge but are dislodged when this discharge is attained (Beltaos, 1984; Cumming-Cockburn, 1986). The maximum possible stage is then that of an equilibrium jam at the limiting ("ice clearing") discharge value. Of course, such a stage may or may not occur because a jam could release before attaining its full potential, i.e., equilibrium.

The release and downriver movement of an ice jam often results in a phenomenon known as the "breaking front", i.e., a moving sharp transition between relatively intact sheet ice cover and ice rubble. Breaking fronts can "clear" long river reaches and have been observed to advance as rapidly as 5 m/s (e.g., see Gerard et al., 1984; Prowse, 1986). While there is an obvious association between jam releases and breaking fronts, the detailed mechanics of the phenomenon is not understood.

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.

(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, Figure 8).

MANAGEMENT AND MITIGATION

Various measures can be implemented to alleviate flooding or other adverse effects of ice jams such as interference with navigation and constraints to hydropower production. Ideally, a mitigation study should 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 a few, relatively simple aspects of ice jam behaviour. To compensate for such deficiencies, mitigation studies take into account all pertinent historical information but this is rarely detailed enough to furnish the "full picture" or to serve as a calibration base for a mathematical model. Consequently, it is usually necessary to monitor the ice regime for at least one season and obtain the required qualitative and quantitative data. The sophistication of the monitoring program depends on the nature of the study and the type of model to be used. Guidelines for relatively simple observations are given by Prowse (1985) while more detailed programs are discussed by Andres (1988).

The above information, together with a mathematical model* of ice conditions should generally provide a fair understanding of the processes at work and help determine the average annual damages due to ice jams. The stage is then set for consideration of mitigation alternatives. Often several possibilities exist (e.g., see Bolsenga, 1968; U.S. Corps of Engineers, 1982; Perham, 1983; Cumming-Cockburn, 1986; Burrell, 1988). The last two references include comprehensive summaries of structural and non-structural methods 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

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*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.

models of this type have been developed, however (e.g., Petryk, 1981; Calkins, 1984) and most are proprietary.*

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 (1978) give comprehensive discussion of scaling requirements. In general, the model "ice" must 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), but its composition is proprietary. Recently, Wong _et al_. (1988) reported on a non-proprietary synthetic material, SYG-ICE, based on plaster, stucco and PVC resin. SYG-ICE has properties that compare well with those of other materials and is suitable for room-temperature tests on breakup and jamming.

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*At present, a 3-year project is underway in Canada to develop a comprehensive, non-proprietary model of the river ice regime. The work is done by consultants and public departments. Funding is provided by the latter group which includes several non-Canadian agencies as well (U.S., Sweden).

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 UNKNOWNS

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., Kennedy, 1958; Kivisild, 1959; 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 many of his conclusions still apply, i.e., we still need systematic field observation of ice jam behaviour, study of formation processes, 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 laboratory tests cannot be overemphasized. The laboratory route seems to be the only feasible one for quantification of processes related to ice jam - ice cover interaction. These processes often govern the formation and release of breakup jams and hence 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 (Figure 2), 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.

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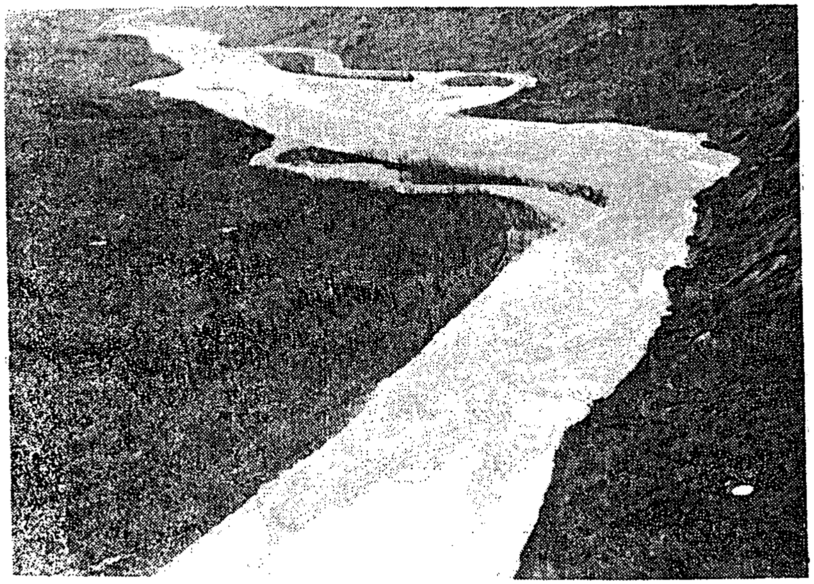


Figure 1a. Ice Jam in Smoky River, Alberta, 1976. Note toe of jam in foreground and open lead in intact ice cover.

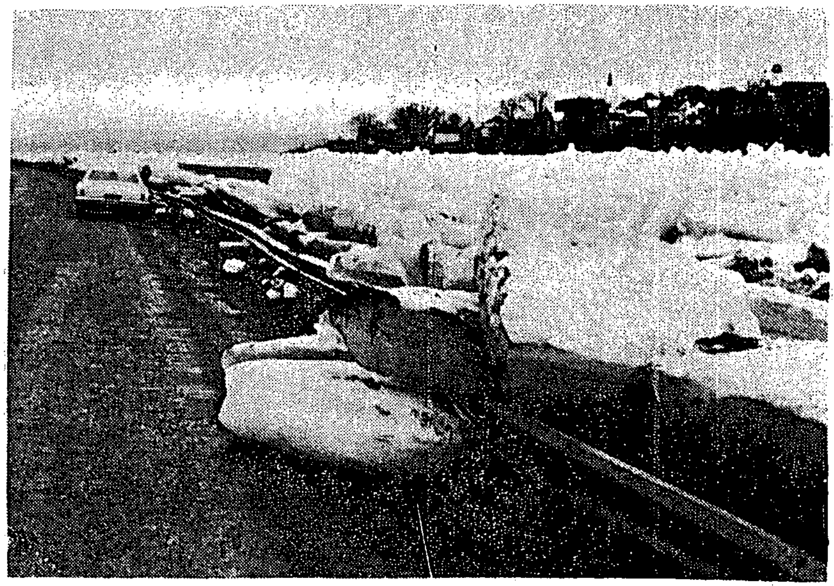


Figure 1b. Ice jam in St. John River, New Brunswick, 1976 (courtesy Dale Bray). Note high stage and "rough" upper surface of jam.

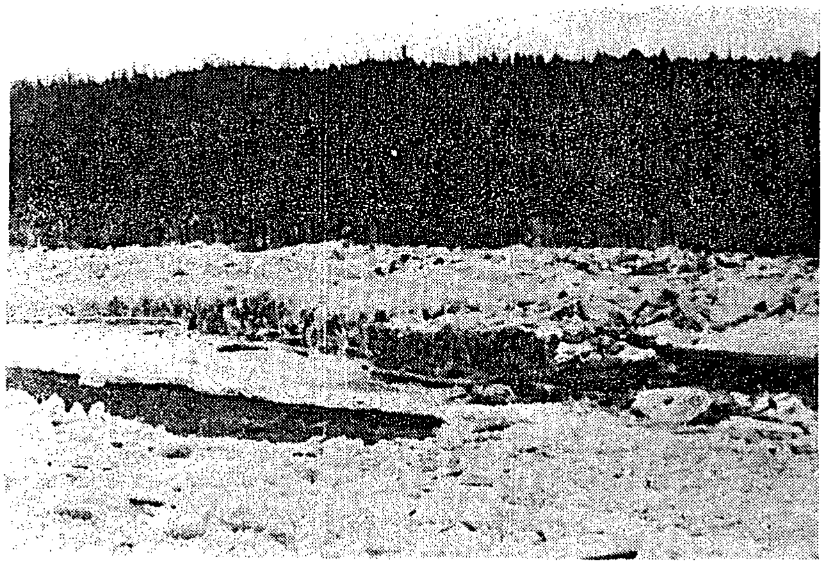


Figure 1c. Shear wall formed by the release of an ice jam in Smoky River, 1976. Height ~5 m.

Figure 1d. Remnants of a jam in Great Rattling Brook, Newfoundland, 1984. Height of shear wall ~3 m. The jam formed due to a winter thaw and breakup. Note new ice cover beginning to form at the water level.

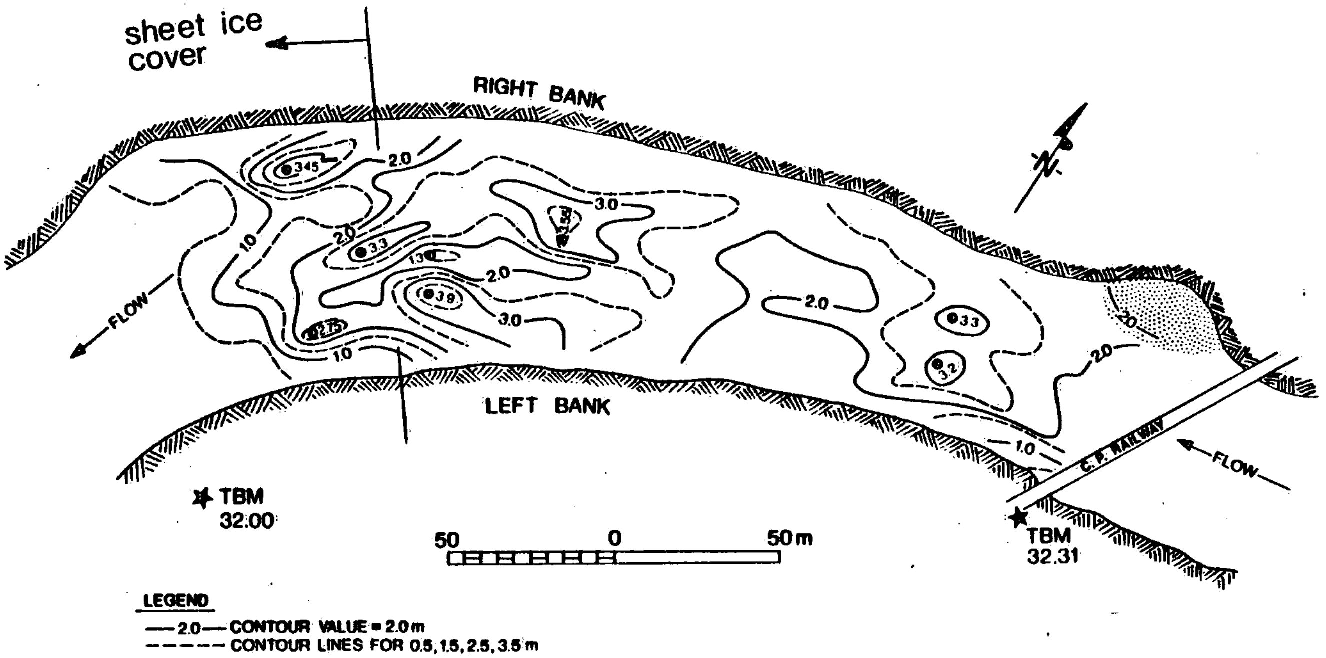


Figure 2. Measured thickness variation near the downstream and (toe) of an ice jam; Thames River near Chatham, Ontario, January 23, 1986.

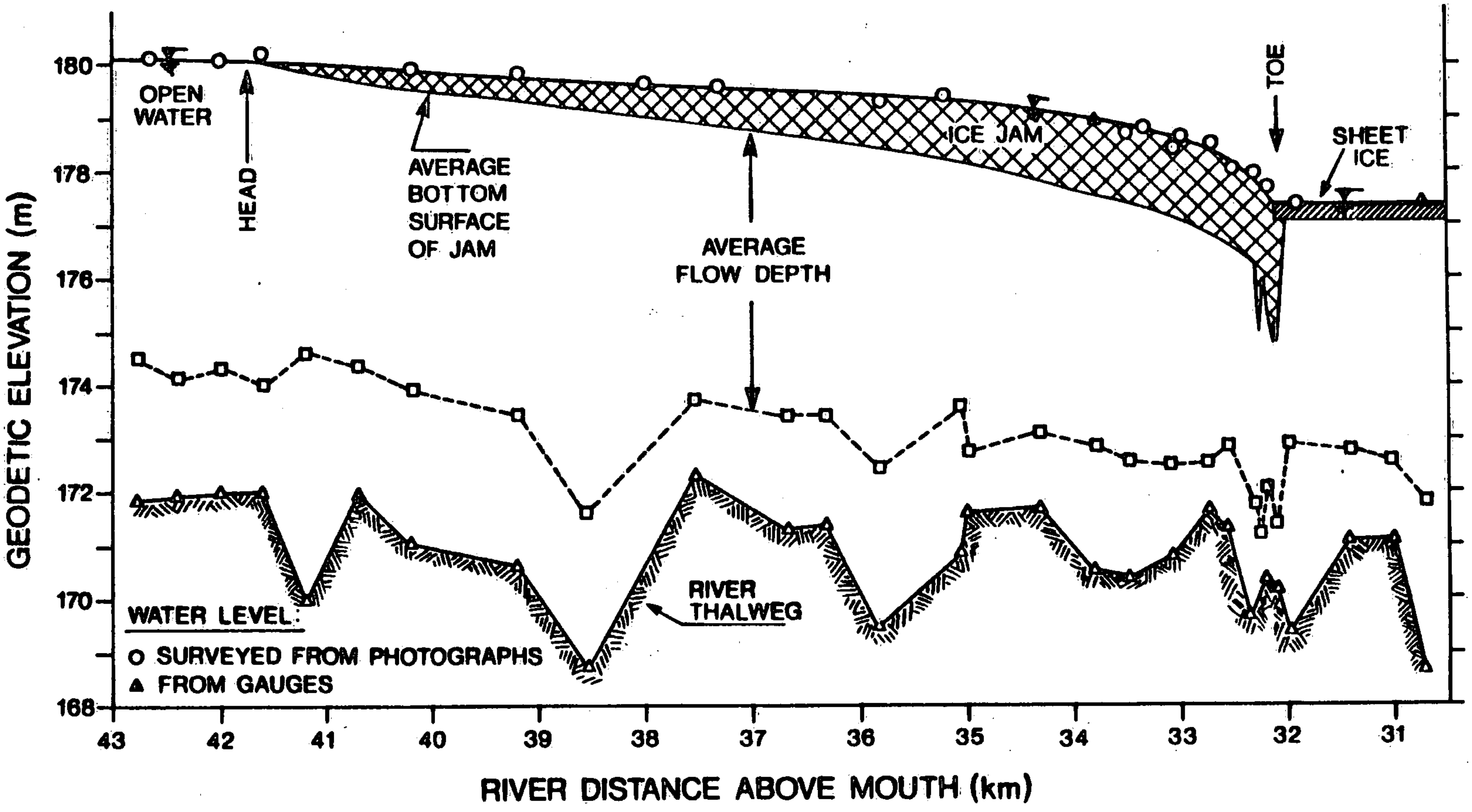
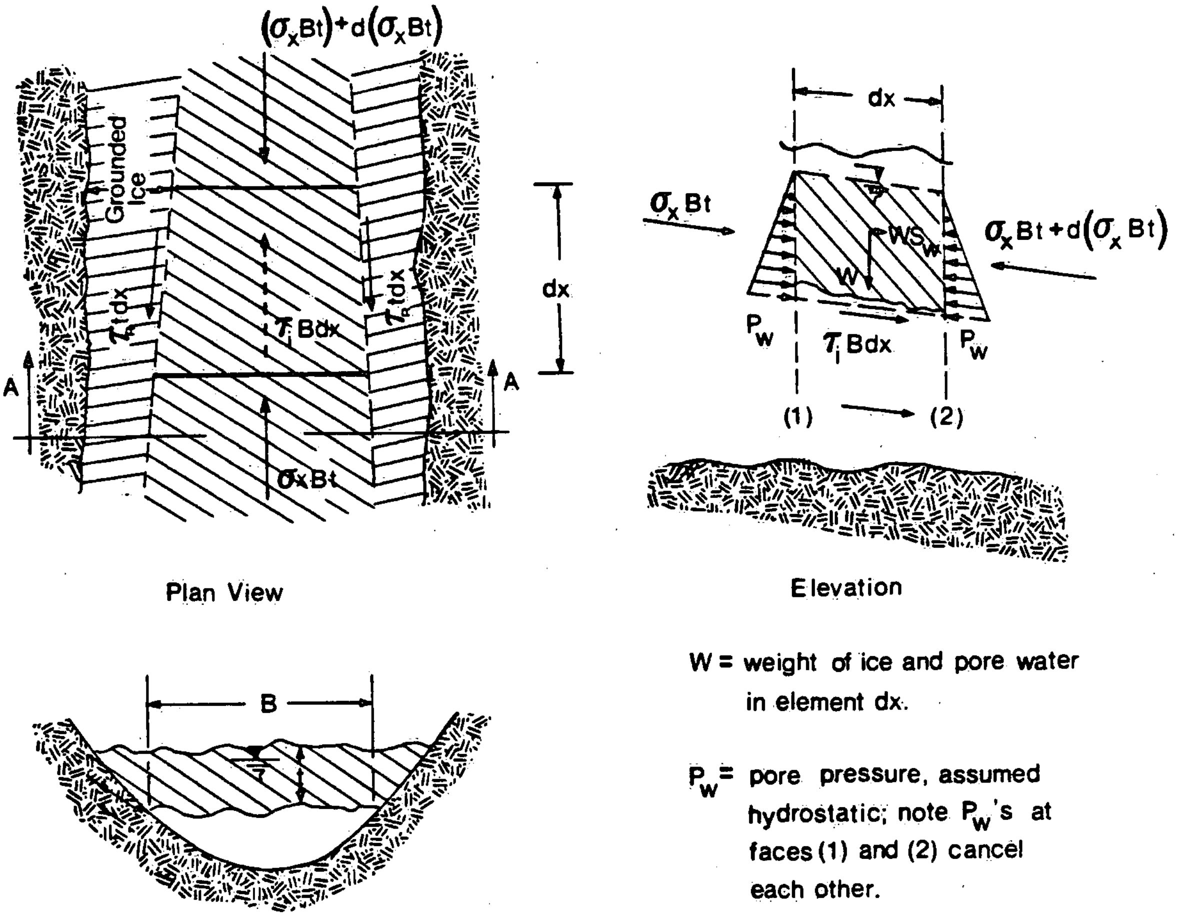


Figure 3. Longitudinal profile of the jam described in previous figure.



Plan View

Elevation

Cross-Section AA

W = weight of ice and pore water in element dx.

P_w = pore pressure, assumed hydrostatic; note P_w's at faces (1) and (2) cancel each other.

Figure 4. Forces acting on an element of a jam (Btdx).

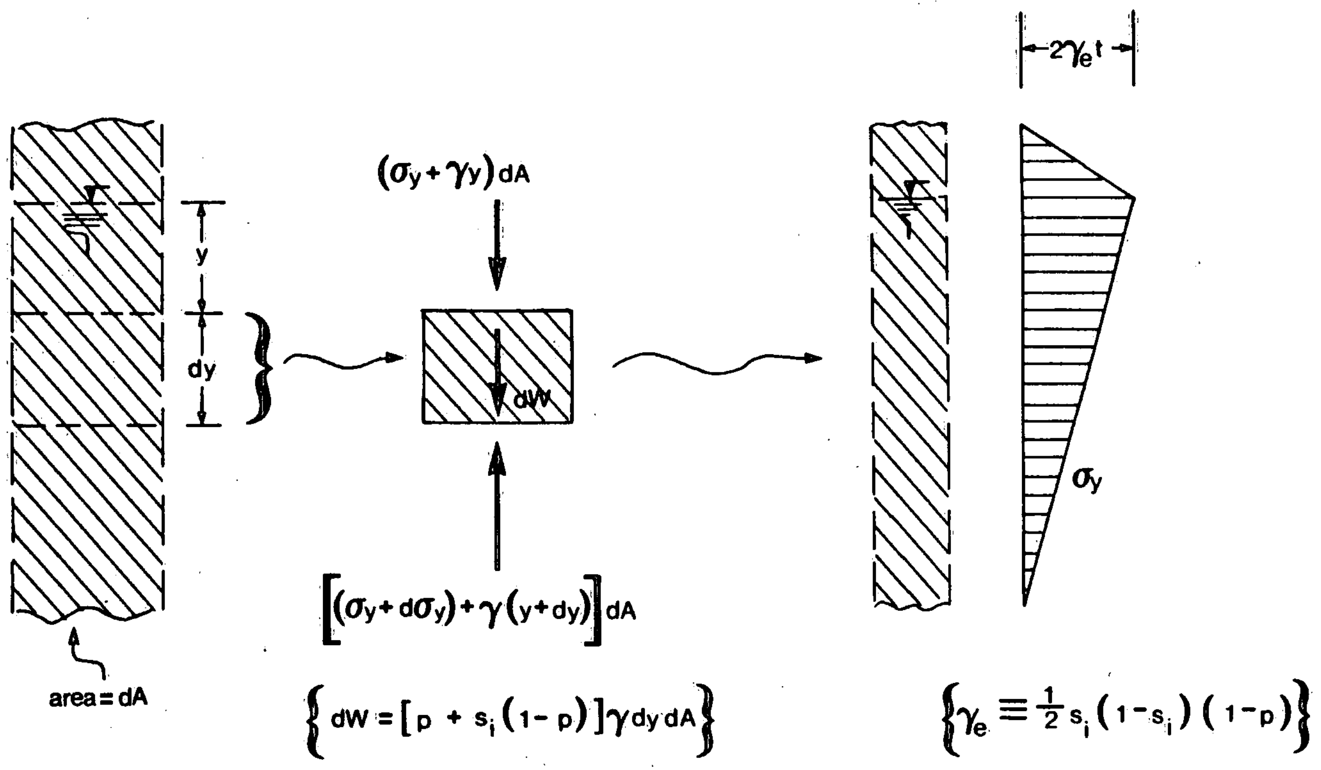
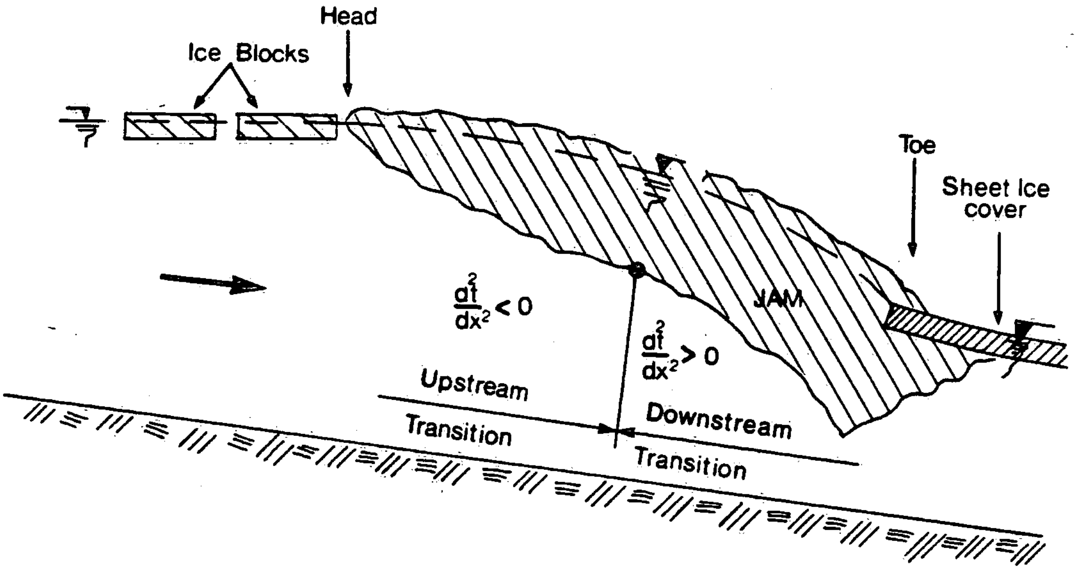


Figure 5. Distribution of vertical effective stress σ_y. Basic derivation steps illustrated for the submerged portion of the jam. Similar reasoning applies for the emerging portion where there is no pore water.



(a) Prior to attaining equilibrium

(b) After attaining equilibrium

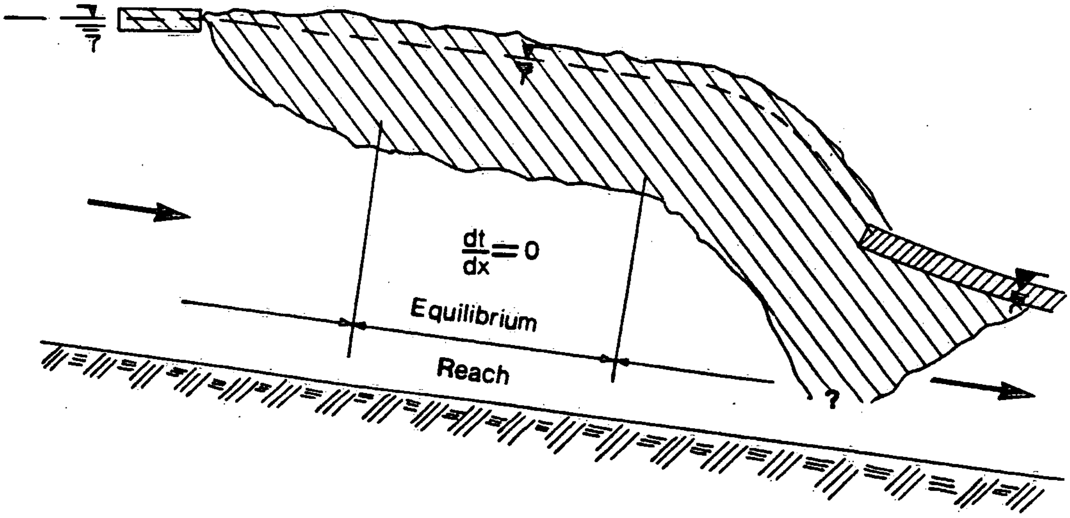


Figure 6. Schematic illustration of a "wide-river" jam.

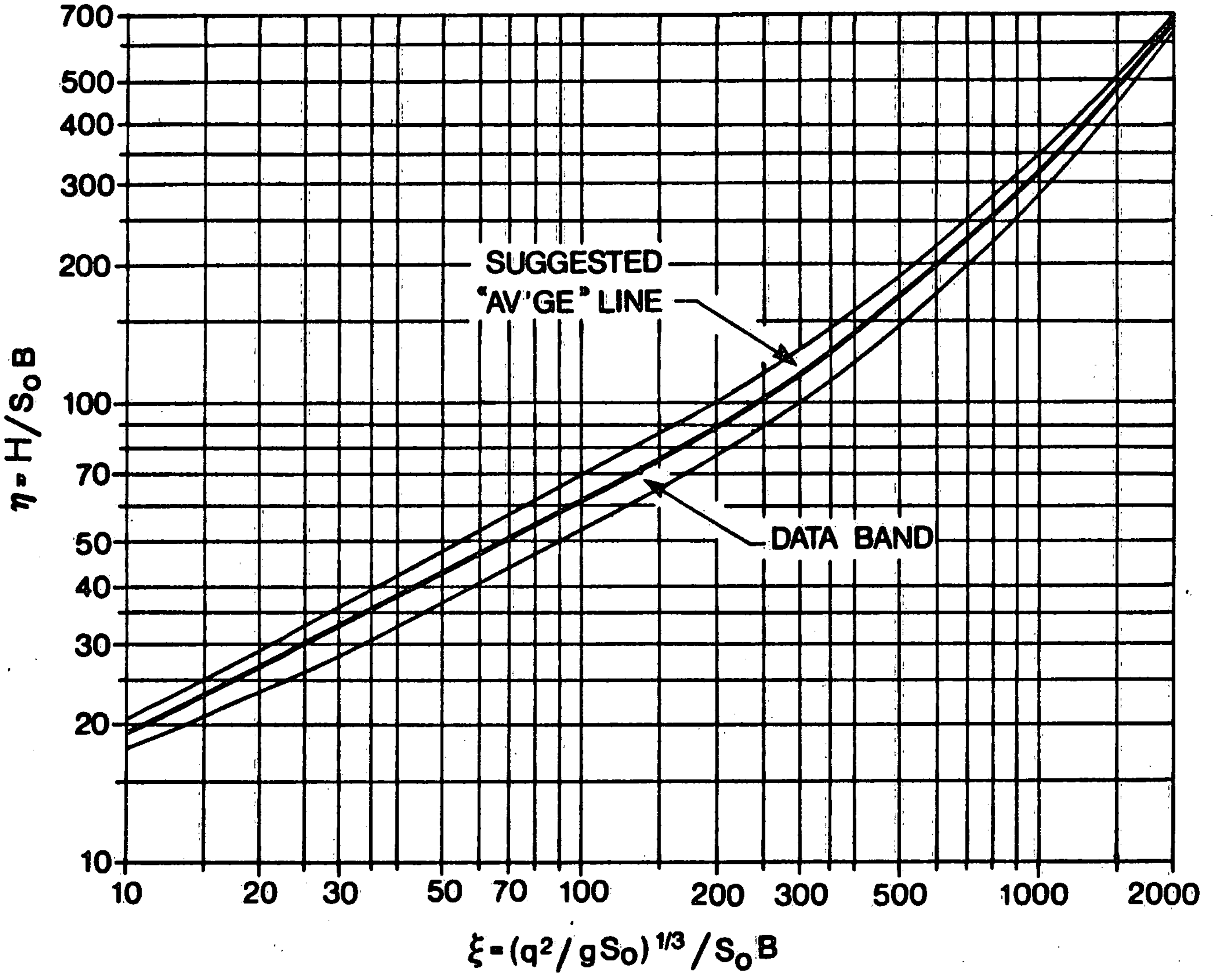


Figure 7. Dimensionless relationship between equilibrium water depth caused by a wide jam and river slope, width and discharge (after Beltaos, 1980).

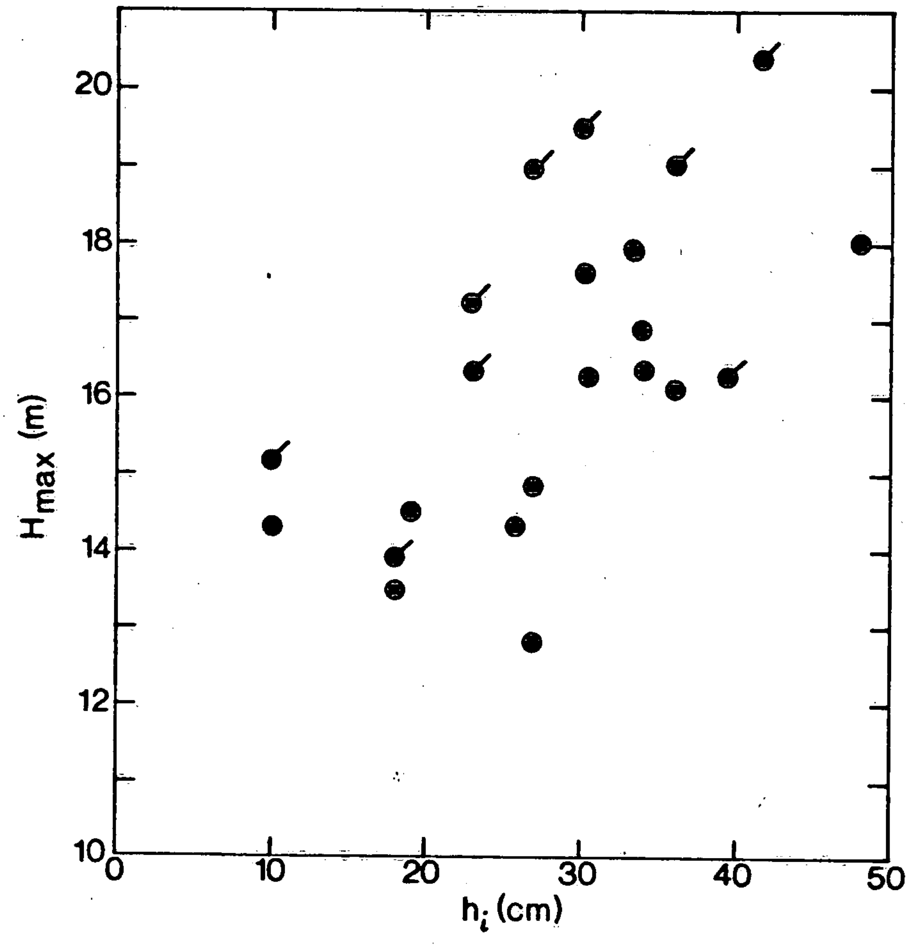


Figure 8. Maximum water stage attained during breakup versus ice cover thickness (h_i). Thames River at Thamesville, Ontario. Note effect of h_i on H_{max} and scatter indicating additional influences.

APPENDIX A: HYDRAULIC RESISTANCE OF BREAKUP JAMS

The two-layer flow concept and composite resistance relationships have already been discussed in the previous section. Nevertheless, breakup jams require special attention owing to the fact that the flow under them is "extremely rough", i.e., the absolute roughness is comparable to the flow depth itself.

For fully rough turbulent flows in natural streams the friction factor diagram (Figure A.1) can be represented by Limerinos' (1970) equation:

$$f = [1.16 + 2\ell og\ (R/d)]^{-2} \tag{A.1}$$

in which R = hydraulic radius and d = statistical measure of absolute roughness of the boundary. For river beds, d represents a diameter that is not exceeded by 84% of the bed particles. The equivalent sand roughness height, K_S is then ~3 d (see Beltaos, 1979, for a more detailed discussion and justification of Eq. A.1).

Eq. A.1 is not easy to work with for calculating composite (two-layer) flow parameters such as friction factor f_o and absolute roughness, d_o. Considerable simplification can be achieved, if we notice that, in the expected range of breakup jams, R/d ~1 to 5, the friction factor varies in inverse proportion to R/d (Fig. A.1). Then, the composite absolute roughness, d_o, works out to:

$$d_o \simeq \left(\frac{\sqrt{d_i} + \sqrt{d_b}}{2} \right)^2 \qquad (A.2)$$

in which d_i, d_b = roughnesses of ice jam and bed respectively. Moreover,

$$f_o = [1.16 + 2\ell og\ (R_o/d_o)]^{-2} \qquad (A.3)$$

in which $R_o \simeq (R_i + R_b)/2$ = hydraulic radius of composite flow. Trial calculations have indicated that Eq. A.2 provides very good approximations to the correct value of d_o. A relationship similar to Eq. A.2 (but with different exponents for d_i and d_b) has been developed by Gerard (in Ashton, 1986) based on the approximation $f \propto (R/d)^{-1/3}$ which, however, applies to the range $20 \leq R/d \leq 1{,}000$, as illustrated in Figure A.1.

We have seen so far how to calculate d_o and f_o, given d_i, d_b and f_i, f_b. It remains to consider how to select the latter set of parameters. For breakup jams, Beltaos (1983) proposed the following relationship, based on re-analysis of Nezhikhovskiy's (1964) Manning coefficient-ice jam thickness relationship

$$d_i = 1.4\ \{1-e^{-0.73(t-0.15)}\} \qquad (A.4)$$

in which both the jam thickness t and roughness, d_i, are expressed in metres. More recently, direct confirmation of Eq. A.4 was obtained in terms of measured absolute roughness (Beltaos and Moody, 1987). Eq. A.4 suggests that for jams thicker than 4 m, $d_i \simeq \text{const} = 1.4$ m while for jams thinner than 1.6 m, $d_i \simeq 0.6$ t. It should be emphasized that Eq. A.5 is semi-empirical and does not take into account such parameters as ice block size and thickness that should obviously be relevant, owing to complete lack of pertinent data.

The river bed roughness, d_b, is normally determined on the basis of open-water bathymetry and hydraulics. Typically, d_b behaves in the manner depicted in Fig. A.2, i.e., it is constant above a certain threshold stage or discharge, but rapidly increases as the stage falls below this value. Clearly, the latter type of behaviour indicates that energy losses are dominated by non-frictional effects, arising from the irregularity of natural streams, such as expansions, contractions, changes in direction, etc. (see also Miller and Wenzel, 1984). Where the bed hydraulic radius, R_b, in flow under a jam, corresponds to an open water stage less than the threshold (Figure A.2), the value of d_b cannot be estimated with confidence. A working hypothesis, adopted by Beltaos (1983), is to simply transpose the open-water variation of d_b with depth (or of f_b with depth) to ice-jam conditions by using R_b in place of open-water depth. While this assumption is difficult to test directly, it has so far provided plausible results.

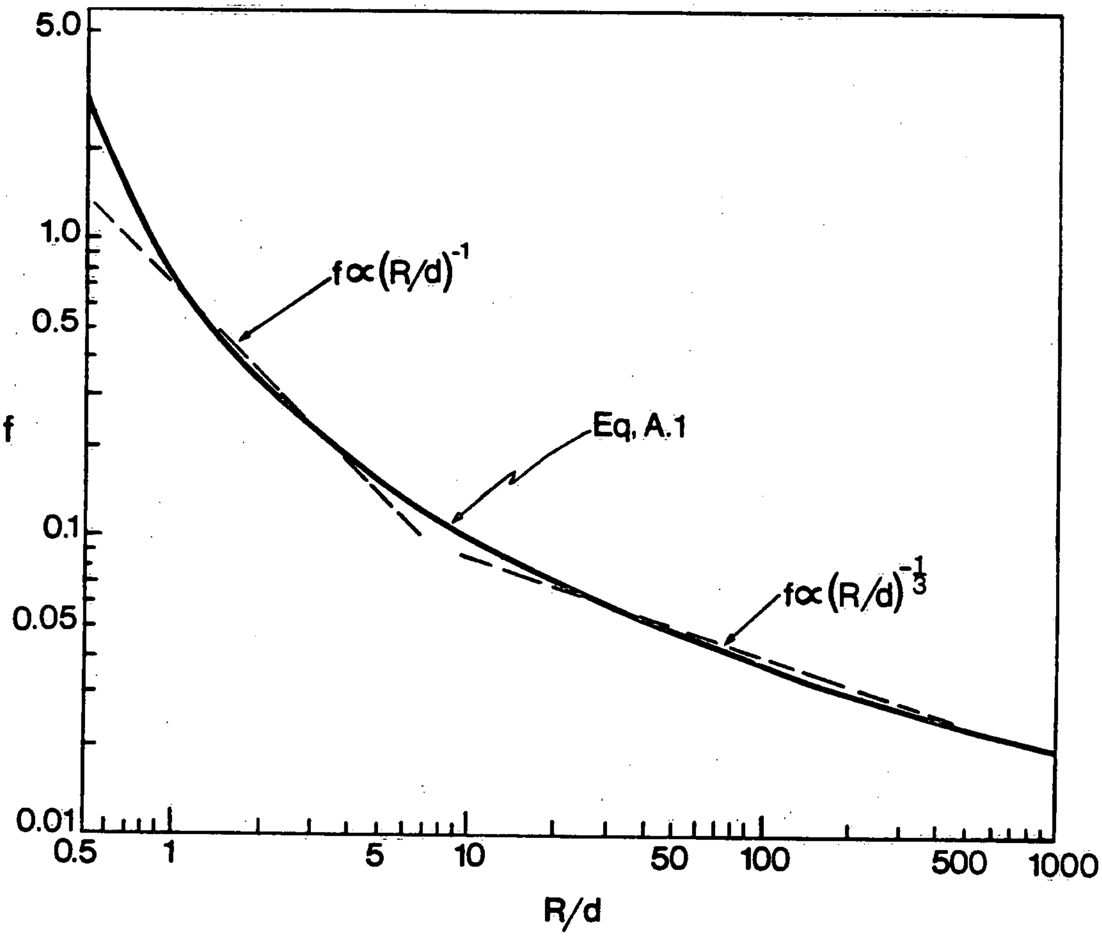


Figure A.1. Friction factor versus relative roughness for fully rough flow. Note different power-law approximations in different ranges of R/d.

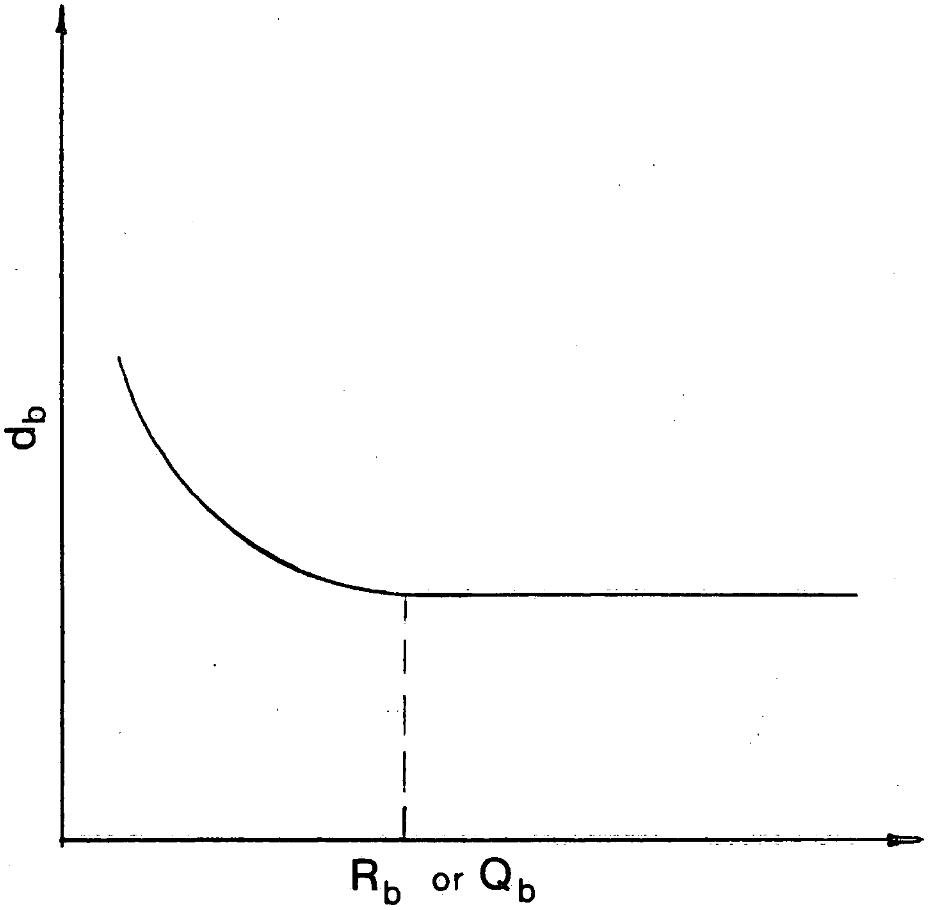


Figure A.2. Variation of bed roughness with flow depth or discharge under open water conditions.