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# PRIMER ON HYDRAULICS OF RIVER ICE
# CHAPTER IV. BREAKUP, ICE JAMS AND RELATED FLOODING

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## ABSTRACT

This report will form a part of a Primer on Hydraulics of River Ice, to be used as reference material for teaching river ice aspects of hydraulics to undergraduate and graduate students. Chapter IV of the Primer covers breakup, ice jams and related flooding, a subject of particular importance to river engineering practice in Canada and other northern countries. Ice jams can be classified on the basis of several criteria of which the process and season of formulation largely define their potential for flooding and damage. By and large, the latter is far greater during the breakup period. Predictive methods pertaining to breakup are described and illustrated with examples. They focus on (a) forecasting whether and when breakup might be initiated as a result of an anticipated runoff event; (b) calculating the water levels caused by ice jams; and (c) assessing the effects of surge waves resulting from ice jam releases. Evaluation of flood risks due to ice jams involves considerable uncertainty where good historical records are not available, owing to varying ice jam behaviour from year to year. In such instances, a combination of analysis, empirical estimates and familiarity with local conditions can be helpful in assessing flood risk. Improvements needed in the future in order to advance the state of the art are discussed. A few practice problems, with answers, are included.

## RÉSUMÉ

Ce rapport fait partie d'un manuel d'introduction sur l'hydraulique de la glace fluviale; cet ouvrage servira de référence aux étudiants diplômés ou non qui sont intéressés à l'étude de la partie de l'hydraulique ayant trait aux questions reliées à la glace fluviale. Le chapitre IV de ce manuel examine les mécanismes de la débâcle, des embâcles et des crues subséquentes; c'est un sujet particulièrement important en génie hydraulique au Canada et dans les autres pays nordiques. Les embâcles peuvent être classées selon plusieurs critères dont le processus et la saison définissent largement le potentiel de crues et les risques de dommages. Sommairement, on peut dire que le potentiel des dommages est beaucoup plus élevé durant la débâcle. Des méthodes prédictives des débâcles sont décrites et illustrées par des exemples. Il y est question a) de prévoir s'il peut y avoir une débâcle, et quand, à la suite d'un épisode de ruissellement prévu, b) de calculer les niveaux d'eau qui résultent des embâcles et c) d'évaluer les effets des ondes créées produites par les débâcles. Lorsqu'il n'existe pas de bons relevés antérieurs, il est fort difficile d'évaluer les risques d'inondation attribués à des embâcles car le comportement de ces dernières varie d'une année à l'autre. Lorsque c'est le cas, on peut avoir recours à une combinaison d'analyses, d'évaluations empiriques et de la connaissance des conditions locales pour évaluer les risques d'inondation. Il est question des progrès requis pour faire avancer nos connaissances de la question. Quelques problèmes sont proposés, avec les réponses.

## MANAGEMENT PERSPECTIVE

A Canada-wide survey by the NRCC Subcommittee on Hydraulics of Ice Covered Rivers revealed that only three Universities offer instruction on this subject, despite its obvious importance in a northern country such as Canada. Lack of suitable reference texts was the principal reason. The Primer on Hydraulics of River Ice, now in preparation by members of the Subcommittee, is intended to fill this gap and promote familiarity with the basics of ice hydraulics among engineers, managers and others concerned with river science. NWRI's contribution to the Primer is Chapter IV, Breakup, Ice Jams and Related Flooding.

## PERSPECTIVES DE GESTION

Un relevé pan-canadien du sous-comité sur l'hydraulique des rivières couvertes de glace, CNRC, a indiqué que seulement trois universités offrent des cours dans ce domaine malgré son importance évidente dans les pays nordiques comme le Canada. L'inexistence d'un ouvrage de référence bien adapté constitue la principale raison à cela. L'introduction à l'hydraulique de la glace fluviale, que des membres du sous-comité finissent de rédiger, va répondre à ce besoin et permettra aux ingénieurs, gestionnaires et autres personnes concernées par cette question d'acquérir une certaine familiarité avec ce domaine. L'INRE a rédigé le chapitre 4 de ce manuel, débâcles, embâcles et crues associées.

## 4.1 INTRODUCTION

The breakup of the winter ice cover on northern streams is a brief but potentially very important event of the river regime. Under conditions that occur all too often, the breakup is attended by severe ice jams that cause a variety of problems such as flooding, damage to structures, interference with navigation, and many others. Of these problems, flooding is the most serious. It is basically caused by the extreme undersurface roughness and large thickness that can be attained by an ice jam*. In order to pass the prevailing flow discharge, the river must rise to accommodate not only the very large hydraulic resistance of the jam's underside, but also include some nine-tenths of the jam's aggregate thickness which is below the water level (Fig. 4.1). In Canadian rivers, it is very common to find that the annual peak stage occurs during the ice breakup even though the breakup flow discharge may be much less than the peak value for the year.

Breakup and ice jamming phenomena are very complex, as witnessed by the multitude of processes that are simultaneously at work, e.g., structural processes, thermal, hydraulic, meteorologic, and geomorphic. Partly for this reason, only a few global aspects of ice jams are sufficiently understood to enable associated predictions. Current knowledge is summarized in this chapter with emphasis on capabilities (or lack of) regarding the main practical problems.

## 4.2 CLASSIFICATION AND TYPES OF JAMS

According to the IAHR Working Group on River Ice (1986), ice jams are stationary accumulations of fragmented ice or frazil which restrict flow. Based on this definition, the group proposed a classification scheme that is formulated according to the following criteria:

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*Manning coefficients of up to 0.10 have been reported and thicknesses of several metres are known to form.

- Dominant formation process
- Season of formation
- Spatial extent
- State of Evolution.

The first two criteria, being particularly pertinent to this section, are outlined in Tables 4.1 and 4.2, and illustrated in Figs. 4.2 and 4.3. For more details and descriptions of the various types of jams, the reader is referred to the Working Group's report (1986). Beltaos (1986) describes ice jam processes in detail and presents a summary of the factors influencing the severity of an ice jam. Such factors include river discharge, channel width and slope, jam roughness, jam strength characteristics*, available ice volume, water temperature and heat transfer, and competence of the intact ice cover during breakup.

Inspection of the jam classification tables and figures will show that there are several reasons why breakup jams have a greater flooding potential than freeze up ones, i.e.:

(a) Usually larger discharge at breakup due to runoff from snowmelt or rainfall or both.

(b) The internal strength of breakup jams is generally less than that of freeze up jams. Thus, other things being equal, a freeze up jam need not be as thick as a breakup jam.

(c) Breakup jams are hydraulically rougher because they mostly comprise solid ice blocks as opposed to mainly frazil slush for freeze up jams.

(d) Destructive, surge-like phenomena due to ice jam releases are much more likely to occur during breakup.

The above characteristics combine to render breakup a generally far more troublesome event than freeze up. For this reason, the remainder of this chapter will concentrate on breakup jamming. Some of the ideas described herein can be transferred to freeze up with appropriate modifications. More detailed information may be found in Beltaos (1986).

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*which are partially related to season of formation

## 4.3 PREDICTIVE METHODS

Some important questions pertaining to breakup and jamming relate to forecasting of their occurrence, the stages caused by them and their frequencies. Predictive capabilities that can be applied to answer these questions are reviewed herein.

### 4.3.1 Forecasting

There are two major forecasting problems, i.e., (1) how to forecast whether and when breakup will start, given that the onset of breakup usually heralds the formation of jams; and (2) how to forecast where ice jams will form.

With regard to occurrence of breakup, only empirical or semi-empirical methods are available, based on our limited understanding of the attendant processes. The main factors that tend to trigger breakup are the flow discharge which governs the forces applied on the winter ice cover; and heat input to the ice cover which brings about a reduction of its thickness and strength. The factors resisting breakup are the thickness and strength of the cover as well as its width which has an effect on how high the cover has to rise before it has enough room to move between the banks and past bends or other obstacles. As it has already been discussed in more detail in Chapter 2, the so-called "premature" breakup is the most troublesome, because it involves quick runoff and stage rise (usually due to rain) with little time available for thermal deterioration of the ice. The other extreme is the "mature" or "thermal" breakup, resulting in a gradual deterioration and eventual disintegration of the ice cover without causing any problems.

For non-thermal breakup events, an index for initiation* is the water stage $H_B$ (H = elevation above any fixed datum), expressed as a function of the preceding freeze up stage $H_F$, ice cover thickness, $h_i$, and an index of accumulated thermal effects, $S_T$**

*defined as the time when the winter ice cover is set in motion
**of which the simplest version is the accumulated degree-days of thaw

(Shulyakovskii, 1963; Beltaos 1983a, 1984a). For premature events, i.e., $S_T \approx 0$, empirical evidence indicates that

$$H_B = H_F + Kh_i \qquad (4.1)$$

in which K is a site-specific, dimensionless coefficient, incorporating such variables as river curvature and slope, flow shear stress, ice strength, and steepness of the river banks (Beltaos, 1988). Values of K obtained from data at six sites are summarized in Table 4.3 and generally range between 2.2 and 3.5. The large value for the Thames River (K = 8.0) is due to that stream's low water surface slope and very steep banks. Where the thermal effect is significant, i.e., $S_T > 0$, the value of $H_B$ obtained from Eq. 4.1 is reduced in a manner that is again site-specific. Observation and semi-empirical analysis of breakup initiation have led to increased understanding of the mechanisms involved (Beltaos, 1984b, 1985, 1988) but much remains to be learned.

Considering the matter of whether and where ice jams will form once breakup has started, we may note that there exists very little concrete guidance in the literature. Breakup jams are, nearly always, held in place by unbroken sections of the winter ice cover and can occur practically anywhere. There are, however, preferred sites of formation where favourable geomorphic or other features combine with the presence of intact sheet ice. Such features include sharp bends, bridge piers, constrictions, shallows and areas of abrupt slope and velocity reductions.

In summary, forecasting procedures have not yet attained a satisfactory degree of generality. Much depends on experience and familiarity with local conditions. Field observations at a particular site over one or more ice seasons are an invaluable aid to forecasting.

### 4.3.2 Stages Caused by Ice Jams

The commonest and potentially most dangerous type of breakup jam is the so-called "wide-channel" jam (see Table 1). This type of jam is formed by "shoving" or "collapse" and its thickness is such that the jam is just able to withstand the internal stresses that are produced by gravitational and frictional* forces. Maximum stages occur along the "wide" jam when it has attained its full potential for flooding, i.e., when it is long enough to have an "equilibrium" reach characterized by uniform jam thickness and flow depth (Fig. 4.4). For the equilibrium reach, a simple analysis is possible, relating the jam's thickness to flow characteristics. Taking about 9/10 of the equilibrium thickness and adding the depth of flow under the jam needed to convey the prevailing discharge, gives the overall depth of water, Y.

Using theories by Pariset _et al_. (1966) and Uzuner and Kennedy (1976), Beltaos (1983b) showed that Y can be obtained from

$$\frac{Y}{S_o B} \equiv \eta = f(\xi) \qquad (4.2)$$

with $\xi$ being a dimensionless discharge parameter:

$$\xi \equiv \frac{(q^2/gS_o)^{1/3}}{S_o B} \qquad (4.3)$$

In Eqs. 4.2 and 4.3, q = discharge per unit width; g = acceleration due to gravity; $S_o$ = open-water slope in the jammed reach**, and B = channel width at the average level of the jam's underside.

The form of the function f has been determined using data from numerous case studies (e.g., Beltaos 1983b, 1986). While the data points scatter, a quick calculation of the approximate jam stage is possible via Fig. 4.5 where the "average" $\eta$-$\xi$ relationship is depicted along with the band that includes the observational data. For large values of $\xi$, i.e., low slope or small width, it is possible that the "narrow" type of jam produces a higher water level than the wide one.

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*i.e., friction due to water flow and, conceivably, wind
**assumed equal to jam slope under equilibrium conditions

This can be checked by first calculating the depth and velocity of flow under the jam via a hydraulic resistance formula and then obtaining the "narrow" jam thickness from*:

$$t' = 10.4\ V_u^2/g \tag{4.4}$$

in which $V_u$ = average velocity of flow under the jam. The "narrow" jam water depth Y' is then equal to the flow depth under the jam plus 0.92 t'. For design purposes, the largest of Y or Y' should be selected.

<u>Example</u>

An example of applying the above results can be worked out in terms of the following problem. We are given that a particular river reach has an average width of 200 m, an open-water slope of $0.4 \times 10^{-3}$ and is subject to breakup discharges of 200-1,000 $m^3/s$. We are asked to determine the water levels that can be caused by equilibrium ice jams that might form in the reach.

Solution: We have: $S_oB = 0.4 \times 10^{-3} \times 200 = 0.08$ m

$\xi$ (from Eq. 4.3) = $2.32\ Q^{2/3}$; Q = discharge in $m^3/s$

For Q = 200 $m^3/s$, $\xi$ = 79. From Fig. 4.5, $\eta$ = 54, hence Y = 54 (0.08) = 4.3 m. This can be repeated for additional values of Q to prepare the following table.

| Q $m^3/s$ | $\xi$ | $\eta$ | Y (m) |
|---|---|---|---|
| 200 | 79 | 54 | 4.3 |
| 400 | 125 | 69 | 5.5 |
| 600 | 165 | 80 | 6.4 |
| 800 | 200 | 90 | 7.2 |
| 1,000 | 232 | 98 | 7.8 |

*The numerical coefficient in Eq. 4.4 is derived using a jam porosity of 0.4 and ice specific gravity of 0.92, see Eq. 2.5

To check Y', the narrow jam depth, let us assume that $n_o$, the composite Manning coefficient for the flow under the jam does not change with depth or discharge*, being equal to 0.05. Then:

$$h' = \text{flow depth under jam in metres} = 2\left(\frac{n_o Q}{2B\sqrt{S_o}}\right)^{0.60} = 0.095Q^{0.60}$$

and

$$t' \text{ in metres} = \frac{10.4\, S_o^{3/5}\, Q^{4/5}}{n_o^{6/5}\, g(2B)^{4/5}} = 0.0029\, Q^{0.80}$$

For example, when Q = 1,000 $m^3/s$, we have h' = 6.0 m and t' = 0.7 m so that Y' = 6.6 m which is less than the corresponding value of Y(=7.8 m). Hence, the "wide" type of jam governs in this instance.

One should keep in mind that the stages predicted above represent upper envelopes for actually occurring stages because many assumptions made to derive the above equations may not be fulfilled in practice, i.e.,

(a) the jam may not be fully developed; or it may not fully affect the site of interest,

(b) upon reaching the elevation of the floodplain, water and ice may spread laterally so that the jam cannot attain its full potential for flooding.

It should be noted here that more elaborate methods to calculate ice jam water levels in more detail are available, both analytical (Beltaos, 1983b) and numerical (Petryk, 1988).

### 4.3.3 Surges from Ice Jam Releases

When an ice jam suddenly "lets go" a large disturbance on the water surface profile is free to move downstream (see, for example,

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*This assumption is not correct and only used for simplicity. For more details see Beltaos (1983b, 1986).

Fig. 4.4). The resulting water wave motion exhibits surge-like characteristics and can be destructive as is often reported by eye-witnesses (e.g., see Beltaos, 1986). Water levels downstream can rise very rapidly, allowing little time for evacuations while water and ice speeds of several metres per second are possible.

Though the conditions leading to the release of an ice jam are poorly understood, a fair amount of work has been done on predicting surge celerities, stages and accompanying water velocities (Mercer and Cooper, 1977; Henderson and Gerard, 1981; Beltaos and Krishnappan, 1982). The surge problem is complex and, ordinarily, requires numerical solution techniques and computer use. Quick but crude estimates are possible via the simple analysis of Henderson and Gerard (1981) who neglected bed friction and slope and assumed the initial profile of the jam to be step-like. Beltaos (1986) re-worked some of the analytical expressions resulting from this theory and suggested the following explicit approximations for the surge celerity, C, and the water velocity, V:

$$\frac{C}{\sqrt{gH_D}} = F_D + \sqrt{(1 + 0.4\ m_o)(1 + 0.2\ m_o)} \qquad (4.5)$$

$$\frac{V}{\sqrt{gH_D}} = \frac{C}{\sqrt{gH_D}} - \sqrt{\frac{1 + 0.2\ m_o}{1 + 0.4\ m_o}} \qquad (4.6)$$

in which $H_D$ and $F_D$ = depth and Froude number of the flow downstream of the jam prior to releasing; and $m_o$ = relative backwater of the jam = $(Y - H_D)/H_D$. Eqs. 4.5 and 4.6 should not be applied beyond $m_o$ = 4 and $F_D$ = 0.25. In such cases, it is better to consult the original paper by Henderson and Gerard (1981).

Example

As an illustration, consider a stream 600 m wide, with a slope of $0.3 \times 10^{-3}$, an ice cover 1 m thick, and q = 3.0 $m^2/s$. With

$n_o$ = 0.025, we obtain $H_D$ = 4.1 m and, from Fig. 4.5, Y = 9.7 m. Hence, $m_o$ = 1.4 and $F_D$ = 0.17. Using Eqs. 4.5 and 4.6, we then obtain V = 3.7 m/s and C = 8.8 m/s (!). The destructive potential of large ice floes moving at 3.7 m/s on the water surface is high. Using the celerity of the surge and an estimate of the water surface slope needed to produce the calculated velocity, we could further calculate that the rate of rise of the water level is of the order of 50 cm per minute!

## 4.4 STAGE FREQUENCIES AND FLOOD RISK MAPPING

A major incentive for understanding and predicting ice jam behaviour arises from the need for determining recurrence frequencies of breakup water levels for engineering design purposes. Considering the two types of peak stages that occur in northern rivers, i.e., ice-related and open-water peaks, we may define

$P_I(H)$ = probability that an ice-related peak will equal or exceed the stage H in any one year

$P_o(H)$ = likewise for open-water peaks

Assuming that $P_I$ and $P_o$ are independent, we could calculate the overall probability, P(H), that the stage H will be equalled or exceeded once or twice in any given year:

$$P = P_I + P_o - P_I P_o \qquad (4.7)$$

which shows that P is greater than either $P_I$ or $P_o$. Since $P_o(H)$ can be determined by well-established hydrologic methods, the main question is how to determine $P_I$ (H).

### 4.4.1 Empirical Estimates

It should be kept in mind that breakup stages can be strongly site-specific. Therefore, existing data should pertain to the site of interest or to its immediate vicinity. Transpositions and extrapolations should, as a rule, be avoided. Historical water level data may be available from various sources, e.g., hydrometric gauging stations, local residents, archives, photos, etc. Ice scars on nearby trees also provide an indication of stages that occurred in the past and the year of occurrence (see for example, Gerard, 1981; and Smith and Reynolds, 1983).

A method for performing a probability analysis on data deriving from such diverse sources as above, is described by Gerard and Karpuk (1979). It is based on the "perception stage" concept, i.e., the stage below which any particular source would not have perceived (and recorded) the peak water level.

### 4.4.2 Analytical Estimates

Crude indications of ice-caused flood frequencies can be obtained by a simple analysis based on the frequencies of various discharges occurring during the breakup period. A lower bound is obtained for the situation where no jams form near the site of interest. Then the peak stage can be calculated as a function of discharge using estimated values of ice cover thickness and hydraulic roughness. Similarly an upper bound may be established using the equilibrium jam relationships that were presented earlier. In either case, the frequency of a given stage is that of the discharge associated with that stage. The desired frequency distribution will be somewhere between the two bounding distributions. Better frequency estimates can be obtained if the probability of ice jam formation near the site of interest is known.

An example of applying such techniques in practice is given by Gerard and Calkins (1984). While this example involves many assumptions and simplifications, it is instructive because it shows how to utilize various site-specific "clues" such as the discharge needed to initiate breakup, floodplain spillage, and the discharge which clears all the ice from the reach (see also Beltaos, 1984b).

## 4.5 FUTURE IMPROVEMENTS

Current knowledge of breakup and ice jams is limited relative to other areas of hydraulic engineering. To raise the state-of-the-art many improvements are needed, and a detailed discussion of this matter is beyond the scope of this text. However, it is instructive to consider the most serious gaps, as follows:

(1) Improved capability to forecast the onset of breakup is needed. In the past few years some progress has been made in developing physical concepts and identifying breakup mechanisms. This must be followed by systematic acquisition of fundamental field data. Particularly useful would be data on ice strength and thickness reductions during the pre-breakup period and how they could be predicted using weather forecasts and stream hydraulics.

(2) How ice jams are held in place by intact ice covers is not clear at present, particularly where the jam is grounded over large areas near its downstream end. This question is related to the conditions of ice jam formation and release, both very important issues in practice. Laboratory experiments designed to simulate the interaction between a jam and the intact ice cover downstream, would be most fruitful in this context.

(3) Surges from ice jam releases, have considerable destructive potential which is often manifested in the breaking of the ice cover downstream for tens or even hundreds of kilometres. This phenomenon has not yet been investigated in an engineering sense. Some basic theoretical work is needed here to formulate plausible hypotheses on whose basis laboratory and field programs could be designed.

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Table 4.1. Dominant formation process (from IAHR, 1986, with changes).

| CRITERION 1. FORMATION PROCESS | CONGESTION AND NON-SUBMERGENCE | SUBMERGENCE AND TRANSPORT | SUBMERGENCE AND DEPOSITION | SHOVING OR COLLAPSE |
|---|---|---|---|---|
| CONFIGURATION | Single layer of ice floes and pans, initiated at constrictions or at transverse obstacles. | Ice floes or pans arriving at the edge of an existing cover submerge and are transported by the flow under the cover; they eventually deposit in a low velocity area where they accumulate until the local velocity increases to a "critical" value. | As in previous case but submerging floes deposit immediately downstream of edge; they accumulate in a layer whose thickness exceeds that of individual ice floes. | A surface jam or a narrow jam collapses due to excessive external forces relative to jam strength (internal friction and cohesion); it thickens until it is just able to withstand the applied forces. |
| HYDRAULIC AND CHANNEL CONDITIONS | Low velocity, less than ~0.5-0.7 m/s. | High velocity at ice edge, more than ~1 m/s; low velocity at deposition area, less than ~1 m/s. Accumulation is typically located at channel sections of unusual depth where it "fills" the cavity and follows bed topography. | Moderate flow velocity, sufficient to submerge ice floes but not to transport them under the cover. | Internal friction of jams is generated by vertical internal stresses caused by buoyancy. Origin of cohesion of jams is unclear at present; cold weather seems to promote it. External forces are proportional to river width. The wider the river the more likely is collapse, hence the "wide", "narrow" jam terms. |
| SEASON OF OCCURRENCE | Mostly freezup. Important factor in ice cover formation. Rare at breakup. | Freeze up | Mostly freeze up | Mostly breakup |
| COMMON TERM | Surface jam | Hanging dam | Narrow channel jam | Wide channel jam |

Table 4.2. Season of ice jam formation (from IAHR, 1986).

| CRITERION 2. SEASON | FREEZE UP | BREAK UP |
|---|---|---|
| WEATHER CONDITIONS | Forms with low air temperature. May exhibit cohesion and even shear strength due to formation of solid ice layer on top. | Forms with positive or slightly negative air temperature. Cohesion seems to be negligible relative to internal friction. |
| FLOW CONDITIONS | Forms with relatively steady flow and ice discharge. | May form with intensely unsteady flow and ice discharge. |
| AMENABILITY TO RELEASE | Unlikely to release. Usually freezes in place and may cause locally thick ice cover. | Releases eventually, unless cold weather resumes and freezes it in place. Sudden release may cause surgelike phenomena attended by violent ice runs. |

Table 4.3. K-values at six Canadian river sites.

| Site and Latitude (N) | Source | Long-term Mean Discharge ($m^3/s$) | Water Surface Slope (m/km) | Average Ice Thickness before Breakup (cm) | K |
|---|---|---|---|---|---|
| Thames River at Thamesville 42°32'42" | Beltaos (1988) | 51 | 0.23 | 21 | 8.0 |
| Grand River near Marsville 43°51'43" | Beltaos (1988) | 7.7 | 2.3 | 35 | 2.2 |
| Ganaraska River near Dale 43°59'07" | Beltaos (1988) | 3.4 | 1.8 | 29 | 3.5 |
| Nashwaak River at Durham Bridge 46°07'33" | Beltaos (1984a) | 36 | 0.73 | 60 | 2.5 |
| Meduxnekeag River at Belleville 46°12'58" | Tang et al. (1986) | 26 | 1.8 | 51 | 3.1 |
| Moose River at Moose River 50°48'50" | Beltaos (1988) | 780 | 0.38 | 69 | 2.8 |

## PROBLEMS - CHAPTER IV

### Problem 4.1

At a gauged river site, the river froze in at a water level of 171.50 m. On February 2, a winter thaw is forecast. The river, with its 0.5 m thick ice cover is expected to rise from its present level of 171.00 m by 0.8 m per day for the next three days and then drop. Past experience indicates that the K-value at this site is about 3.0, while winter thaws result in negligible thermal effects on the ice cover. Forecast whether a breakup will take place and, if yes, when. (Answer: Yes; February 5, about noon).

### Problem 4.2

After initiation of breakup in the case of the previous problem, the water level gauge registered several peaks and "spikes" caused by the formation and release of ice jams nearby. The highest peak was at 175.20 m corresponding to a water depth of 6.2 m. Assuming an equilibrium ice jam, estimate the flow discharge applicable to this peak. The channel slope and width are 0.8 m/km and 150 m respectively. (Answer: ~350 $m^3/s$)

### Problem 4.3

The jam of the previous problem released at 1400 hours, on February 6. When would the resulting surge be expected to arrive at a town located 100 km downstream? Assume that (a) the flow discharge on February 2 was 100 $m^3/s$; (b) the river banks are fairly steep so the channel cross-section is nearly rectangular; and (c) the channel and sheet ice Manning roughness coefficients did not change during February 2 to 6. (Answer: about 1730 hours, February 6. Hint: assume sheet ice cover downstream of the jam and calculate $H_D$ = 3.7 m).

Problem 4.4

Near the town of the previous problem the banks have been stabilized with rip-rap that can withstand average flow velocities of up to 2.5 m/s. Determine whether the passage of the surge would be of concern with regard to the rip-rap. (Answer: No)

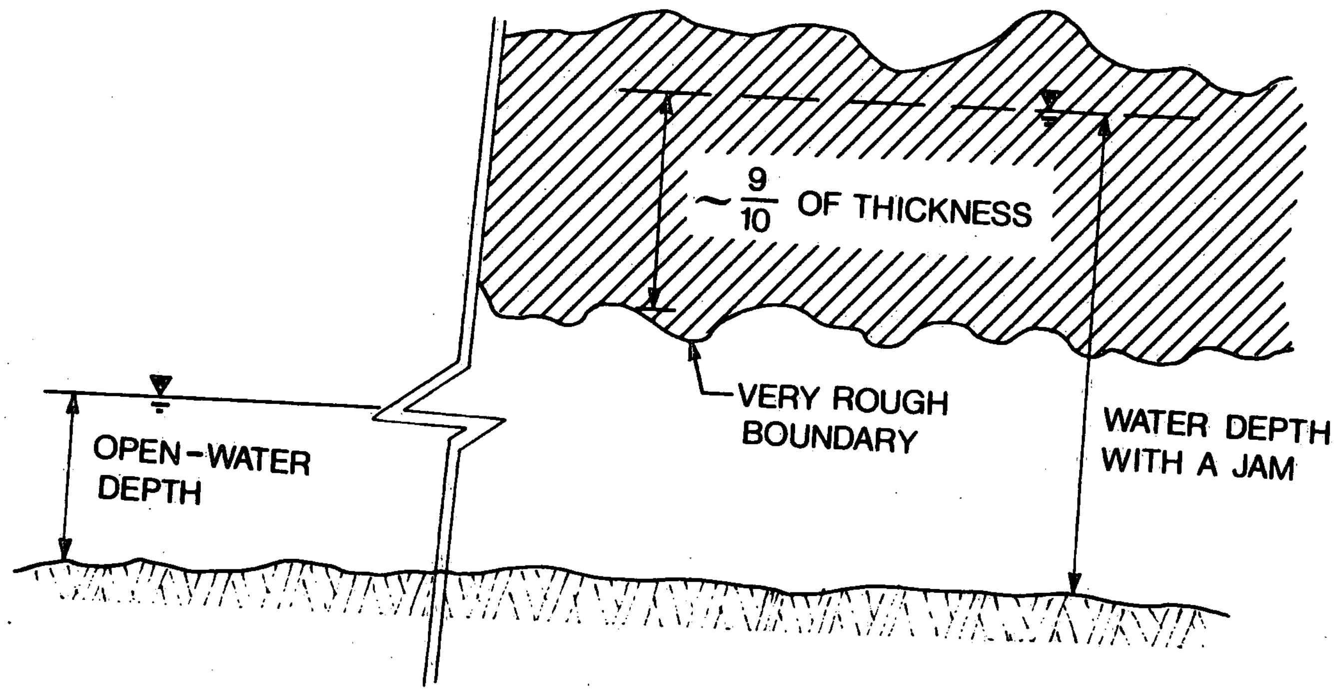



Fig. 4.1. Schematic illustration of large water depths caused by ice jams.

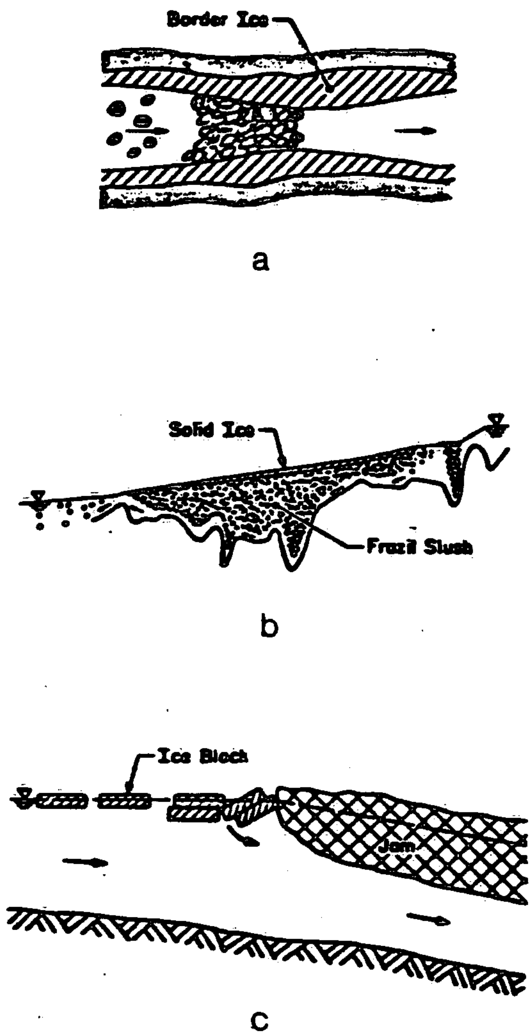
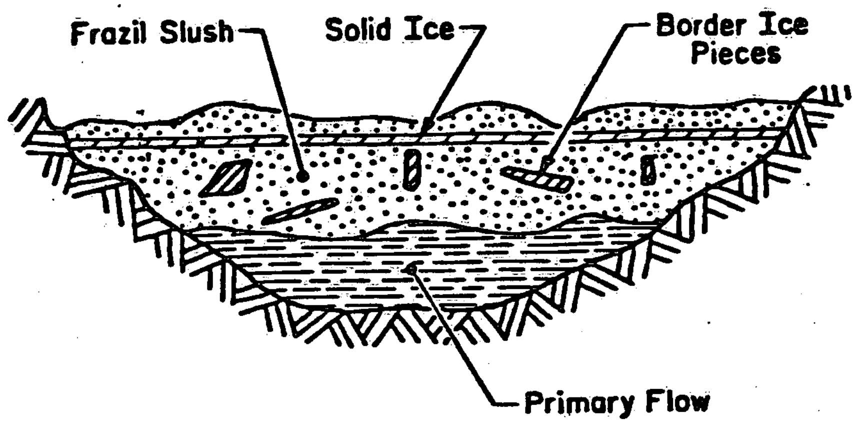
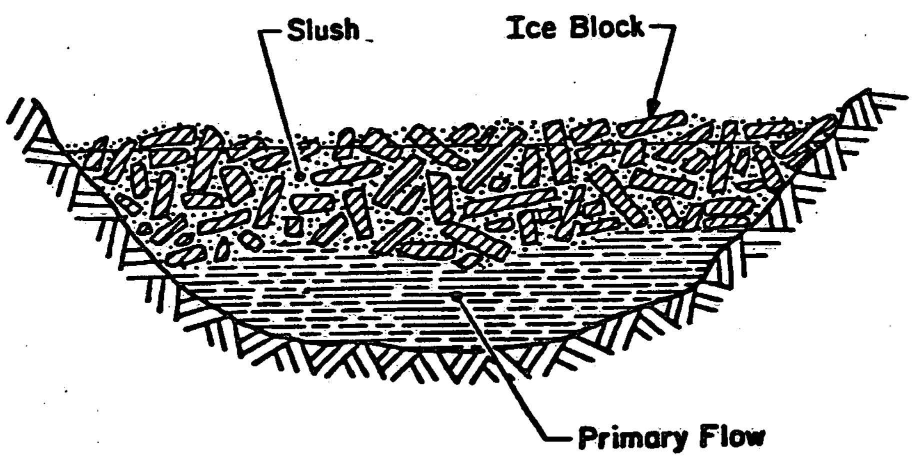



Fig. 4.2. Ice jam formation processes. (a) congestion and non-submergence plan view; (b) submergence and transport-hanging dam; (c) submergence and deposition or shoving-narrow or wide jam.




a. Freeze-up Jam Cross Section




b. Break-up Jam Cross Section

Fig. 4.3. Freeze-up and breakup jams (slush may or may not be present in a breakup jam).

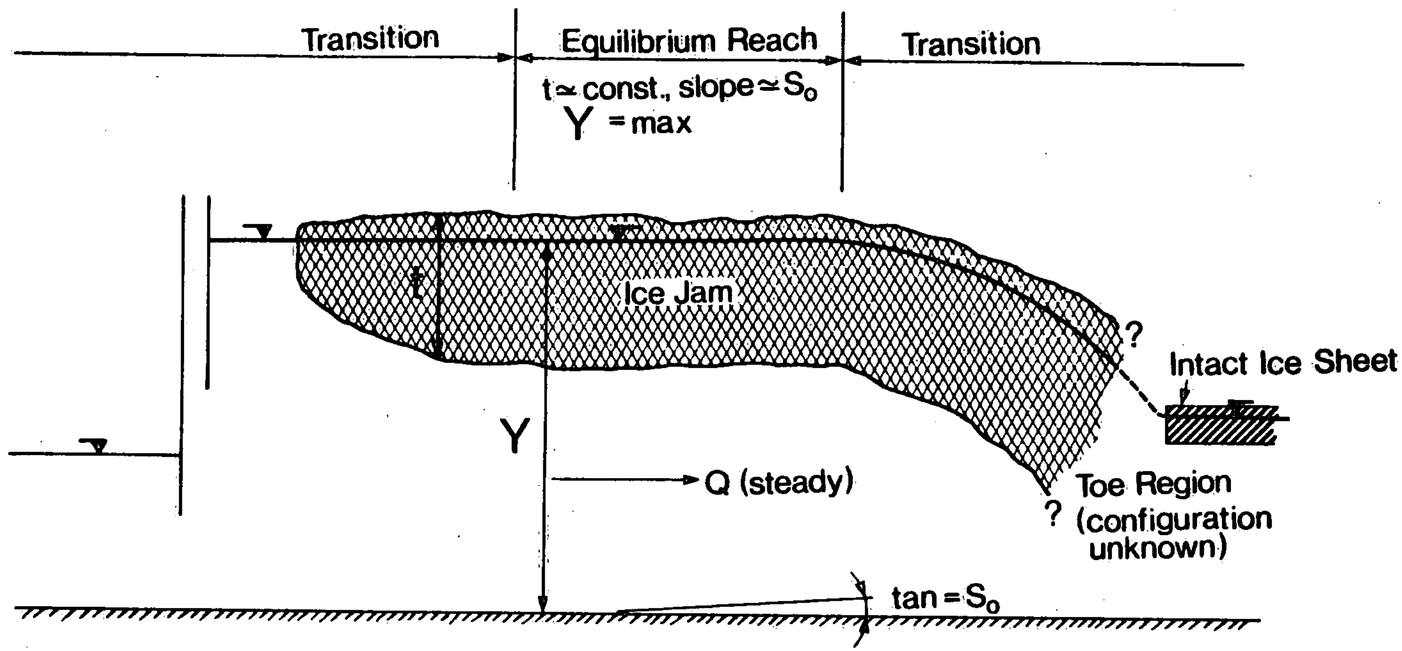



Fig. 4.4. Profile of a jam with an equilibrium reach.

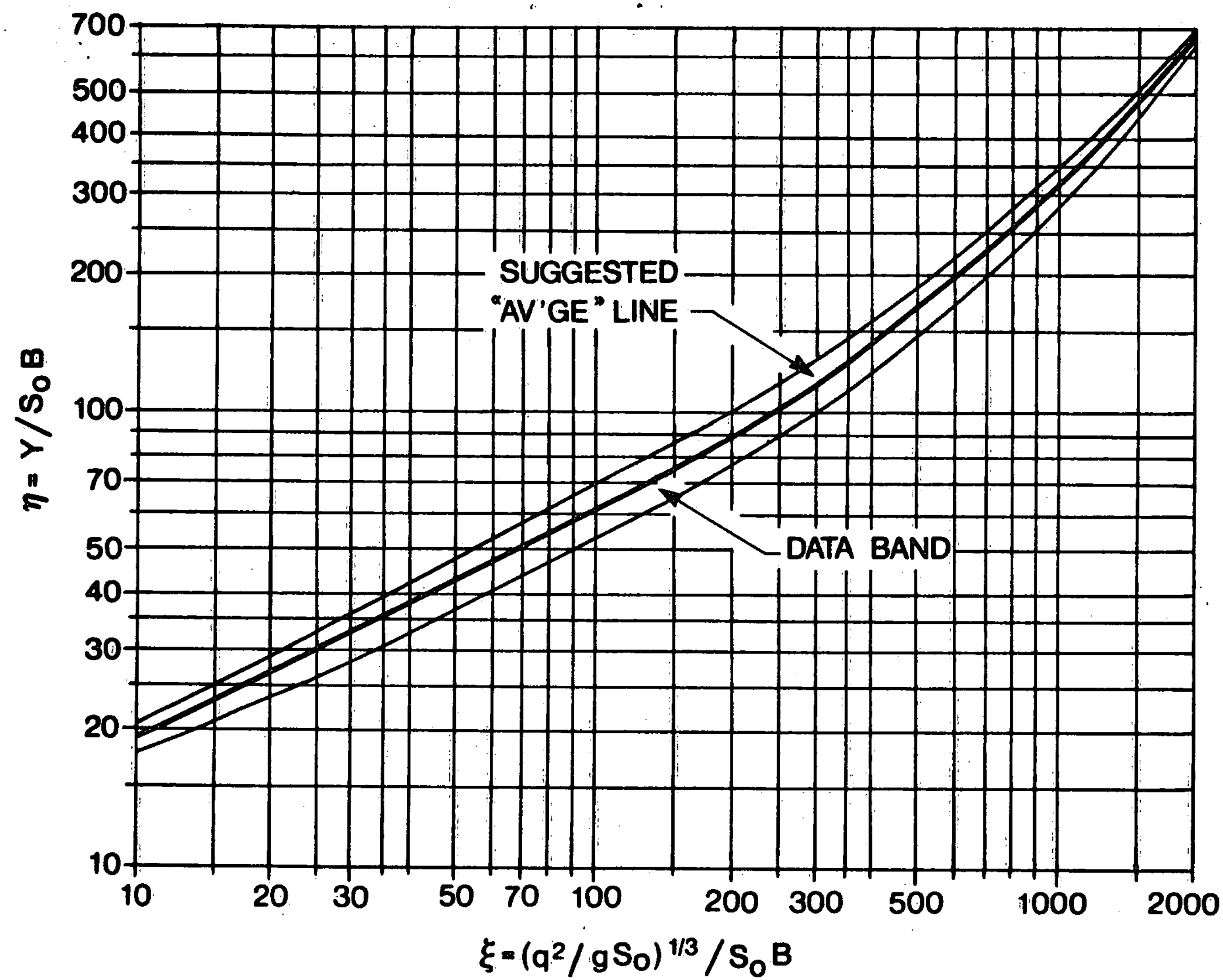



Fig. 4.5. Generalized diagram relating the equilibrium water depth of wide jams to river discharge, slope and width (from Beltaos, 1986, with modifications).