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ICE JAM CONFIGURATION: SECOND GENERATION MODEL

by

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ABSTRACT

The downstream transition of river ice jams, that is, the region near the toe, has received limited attention despite its significance in understanding how a jam is held in place and whether extensive grounding occurs. A numerical model, developed earlier by the authors for the downstream transition, is simplified and improved so as to enhance "robustness" and scope of application. The new model, called RIVJAM, computes longitudinal variations of jam thickness and water level by (a) using natural stream bathymetry, as opposed to rectangular-channel approximations required by the first model; (b) by moving in both upstream and downstream directions, as opposed to downstream only; and (c) by considering both equilibrium and non-equilibrium jams, as opposed to equilibrium jams only which leads to predicting the upstream transition as well as the downstream one. Test runs are carried out to illustrate model performance in a hypothetical situation, and to study the configuration of non-equilibrium jams and its dependency on the volume of ice in the jam. The model is next applied to a unique set of field data that includes measurements of ice jam thickness, and shown to predict satisfactorily. Future requirements to improve our understanding of modelled processes are outlined.

RÉSUMÉ

La zone de transition, côté aval, des embâcles de glace de rivière a fait l'objet de peu d'études malgré le fait que cette région de la langue soit importante à la compréhension de la façon dont se maintient une embâcle et la mesure dans laquelle il y échouage. Un modèle numérique, mis au point précédemment par les auteurs pour la zone de transition, est simplifié et amélioré pour en accroître la résistance et l'ampleur des applications. Le nouveau modèle, le RIVJAM, permet de calculer les variations longitudinales du niveau de l'eau et l'épaisseur de l'embâcle a) à partir de la bathymétrie du cours d'eau naturel, alors que le premier modèle utilisait des approximations (chenal rectangulaire), b) dans les directions aval et amont, alors que le modèle précédent permettait seulement d'aller dans la direction de l'écoulement et c) en tenant compte à la fois des embâcles en équilibre et non en équilibre, par rapport aux seules embâcles en équilibre, ce qui permet de prédire la transition vers l'amont en plus de celle vers l'aval. Des passages d'essais ont été réalisés afin d'illustrer la performance du modèle en situation hypothétique et d'étudier la configuration des embâcles qui ne sont pas en équilibre et la dépendance de celle-ci sur le volume de glace dans l'embâcle. Le modèle est ensuite appliqué à une série unique de données de terrain, dont des mesures de l'épaisseur des embâcles; le résultat est satisfaisant. Les exigences subséquentes pour améliorer notre compréhension des processus modélisés sont présentées.

MANAGEMENT PERSPECTIVE

A numerical model, designed to compute the configuration of ice jams in natural streams, is described and tested with a unique field data set. This model, called RIVJAM, is a generalized and more robust version of an algorithm developed earlier to study ice jam characteristics near their toe (downstream end). This knowledge is important with respect to how ice jams are held in place and whether extensive grounding is likely. In turn, this is useful in assessing ice jam stability and removal procedures.

PERSPECTIVE GESTION

Les auteurs décrivent et soumettent à des essais avec une série unique de données obtenues sur le terrain un modèle numérique conçu pour déterminer ls configuration d'embâcles dans des cours d'eau naturels. Ce modèle, le RIVJAM, est une version généralisée et plus résistante d'un algorithme mis au point précédemment pour étudier les caractéristiques des embâcles près de la langue (extrémité aval). Cette connaissance permet de comprendre comment les embâcles se maintiennent et la mesure dans laquelle se produit l'échouage. Cela permet alors d'évaluer la stabilité des embâcles et les mesures correctrices à appliquer.

Ice Jam Configuration: Second Generation Model

S. Beltaos[1] and J. Wong[2]

Abstract

An early model of ice jam configuration in wide, prismatic channels, is generalized for applications to natural streams. Test runs are carried out to illustrate model performance and study the configuration of non-equilibrium jams. The model is next applied to a unique field data set that includes measurements of ice jam thickness and satisfactory predictions are obtained. Ideas for future work are outlined.

Introduction

Despite the progress made in the last three decades, our understanding of ice jams and associated phenomena remains limited. One of the major unknowns is the configuration of jams near their toe (downstream end) which is related to the question of how ice jams are held in place. In turn, this pertains to jam formation and release, two important events that are not possible to forecast at present.

Ice jams can be evolving or steady-state (see also IAHR Working Group on River Ice Hydraulics, 1986). The present discussion will be limited to the latter type which can be further subdivided into "equilibrium" and "non-equilibrium" jams. An equilibrium jam contains a reach in which the flow depth and jam thickness are uniform. Ice jams are also classified as "narrow" and, "wide" depending on their formative process (Pariset et al., 1966). The former type has a thickness governed by hydraulic conditions at its leading edge (or "head").

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The wide jam, on the other hand, is as thick as is necessary to withstand the forces applied on it and usually forms after the collapse of a narrow jam that has become too long relative to its strength. For cohesionless jams, such as those formed at breakup, the collapse length is less than a few river widths in all but very small streams.

Limiting the discussion further to breakup jams, known to be more destructive than freeze up ones, we expect their configuration to be as sketched in Fig. 1. A convenient first approximation is to ignore the short narrow-jam portion and assume the jam to be wide throughout. Much of the previous work on ice jams has concentrated on predicting equilibrium thickness and depth which enables assessment of a jam's full potential for flooding. Non-equilibrium analysis was first carried out by Uzuner and Kennedy (1976) who calculated the shape of the jam in the upstream transition (Fig. 1). Flato and Gerard (1986) developed a numerical solution for the entire length of the jam while Beltaos and Wong (1986a) concentrated on the downstream transition and took into account seepage flow through the jam voids. This makes it possible to predict severe thickening and grounding near the toe, in agreement with visual evidence. In the downstream transition, where thickness increases with downriver distance and the water depth decreases, neglect of seepage will produce rapidly increasing velocities, exceeding values known to be capable of "eroding" an ice jam. This limitation can lead to difficulties in predicting ice jam thickness and water level profiles near the toe (e.g. see Flato, 1988).

At the same time, the writers' algorithm (1986a) has several practical limitations since it was intended for gaining insight in very simple, idealized channels. Herein, a more robust model, called RIVJAM, is described and tested against a unique set of field measurements.

<u>Background Information</u>

Beltaos and Wong (1986a) assumed, for simplicity, a very wide, rectangular, prismatic channel and derived a system of three differential equations with three unknowns, based on the principles of continuity, momentum and jam stability, i.e.:

$$\frac{dt_s}{dx}\ ;\ \frac{dh}{dx}\ ;\ \frac{dS_w}{dx} = f_1;\ f_2;\ f_3(t_s,\ h,\ S_w) \qquad (1;2;3)$$

in which t_s = submerged portion of the jam thickness; h = depth of flow under the jam; S_w = slope of the water surface; x = downstream distance; and f_1, f_2, f_3 are functions. The solution of Eqs 1, 2 and 3 proceeds in the downstream direction, starting from the downstream limit of the equilibrium reach. However, for practical applications, the model should accept arbitrary channel bathymetry; compute in the upstream direction as well as downstream; and compute non-equilibrium jam profiles. Work toward a modified model began by noting that the last relationship in Eq. 3 could be eliminated if the momentum equation were simplified to the (often used) form:

$$S_W = (\tau_i + \tau_b)/\rho gh = 0.25\ f_o \rho u^2 \qquad (4)$$

in which τ_i, τ_b = flow shear stresses applied on the ice jam and river bed, respectively; ρ = density of water; g = acceleration due to gravity; u = average flow velocity under the jam; and f_o = composite friction factor. With Eq. 4, S_W can be expressed in terms of t_s and h, hence we would have to solve two differential equations with two unknowns. The two-equation solution was programmed for a wide rectangular channel and the output was compared with that of the three-equation solution. There was little difference, hence Eq. 4 was adopted.

The Second-Generation Model

The ice-jam stability equation for a non-prismatic channel can be written as (Beltaos, 1988)

$$\frac{dt_s}{dx} = \beta_1 \left\{ \beta_2 \frac{A_f}{Bt_s} + 1 \right\} S_W - \beta_3 \frac{t_s}{B} \qquad (5)$$

$$\frac{dh_o}{dx} = S_o - S_W - \frac{dt_s}{dx} \qquad (6)$$

in which A_f = area of flow under the jam; h_o = vertical distance of the underside of the jam from a "datum" line of slope S_o, equal to the open-water slope in the computation reach; and B = channel width at the level of the underside of the jam. In addition:

$$\beta_1 = s_i/K_x(1-p)(1-s_i);\ \beta_2 = f_i/2f_o;\ \beta_3 = \mu/K_x(1-p) \qquad (7)$$

with s_i = specific gravity of ice, herein fixed at 0.92; p = porosity of the jam; K_x = ratio of internal longitudinal stress to the vertical stress (both averaged over the thickness of the jam); f_i = friction factor of the underside of the jam; and μ = ice jam strength characteristic, as originally defined by Pariset et al (1966). Continuity requires that the sum of the flows through and under the jam be a constant, equal to the total discharge. Analysis and experiments (Beltaos and Wong, 1986b) have indicated that the seepage component, Q_p, is given by

$$Q_p = \lambda A_J \sqrt{S_W} \tag{8}$$

in which A_J = "wetted" cross-sectional area of the jam; and λ is a coefficient of seepage, having dimensions of velocity; the average velocity of seepage through the void spaces in the jam is equal to $\lambda\sqrt{S_W}/p$. Use of Eqs. 4 and 8 makes it possible to express S_W in terms of A_f, A_J, B which shows that Eqs. 5 and 6 form a system with two unknowns, t_s and h_o. (Note that A_f, A_J and B are specified if t_s and h_o are given).

Equations 5 and 6 are solved simultaneously by a Runge-Kutta technique and computation may proceed either upstream or downstream starting at a site where t_s and h_o are given. Channel bathymetry is specified by a set of surveyed cross-sections, inputted in the HEC-2 format. Between successive sections, the bathymetry is interpolated linearly.

Coefficients

The composite friction factor, f_o, is herein calculated as

$$f_o = c\ t_s^{m_1} h^{-m_2} \tag{9}$$

in which $h = A_f/B$; and c, m_1, m_2 are constants. Beltaos and Wong (1986a) used c = 0.51, $m_1 = m_2 = 1.17$ which was deduced from data on equilibrium jams. A positive value for m_1 indicates that the hydraulic roughness of a jam increases with its thickness, a trend that has been established by experience (Nezhikhovskiy, 1964; Beltaos, 1988). Near the head and toe of a jam, Eq. 9 may give implausibly low or high f_o and RIVJAM includes a subroutine to impose user-specified limits. The coefficient β_2 is often assumed equal to 0.50 but can vary between 0.3 and 0.8 (Beltaos, 1983).

The coefficients β_1 and β_3 are both inversely proportional to the product $K_x(1-p)$, hence the solution depends on this product but not on each of K_x and p.

We thus fix p at 0.40 (often quoted value but not really known) and compensate by adjusting K_x. Typically $K_x = 10$ (Beltaos, 1988) while $\mu=1.2$. No field values of λ exist. Extrapolation of laboratory test results (Beltaos and Wong, 1986b) suggests that $\lambda=0.6 - 2.0$ m/s, depending mostly on the size of the ice blocks and the porosity of the jam.

Test Runs for Non-Equilibrium Jam

This series of runs was carried out to see how RIVJAM performs in the case of non-equilibrium jams and study their characteristics. A rectangular channel has been assumed, having a slope of 0.36 m/km; width of 560 m; and a discharge per unit width of 2.0 m^2/s. This is an approximation to typical breakup jamming in the Athabasca R. near Fort McMurray. Other parameters were taken as $p=0.40$; $\lambda=0.75$ m/s; $K_x = 4.3$; $c=0.51$, $m_1 = m_2 = 1.17$; and $\mu = 1.20$.

Fig. 2 shows the results as a series of profiles, each having a different value of the grounding depth, Hg. Note that Hg represents a convenient starting condition (e.g. $t_s = H_g$; $h_o=0$) but does not necessarily represent the actual toe situation, as will be explained later. As H_g increases, the jam thickens and lengthens until the "equilibrium" condition is attained (Hg = 7.38 m). If H_g is set higher than 7.38 m, the solution "blows up", that is, the calculated thickness first decreases and then grows as we move upstream, a trend that has no physical meaning. Fig 3 shows how the jam length and maximum water depth, H_m (determined by drawing a tangent to the water surface profile, parallel to the bed) vary with ice volume. The latter is seen to have a strong effect on H_m, particularly for short jams. To attain 95% of the full potential depth (equilibrium value of H_m), the jam would have to contain at least 18,500 m^3 of ice per metre of width or be 14.5 km long (26 river widths).

To assess the actual toe condition, we can compare H_g with H_d, the water depth downstream of the jam. If $H_g > H_d$ a section of grounded ice rubble would form just upstream of the toe. On the other hand, for $H_g < H_d$ grounding does not occur but the toe is located so that $t_s + h = H_d$. In this example, H_d is only about 3.5 m, hence grounding would be expected.

Case Study-Thames River

In mid-January of 1986, a thaw occurred in S.W. Ontario. Much rain fell and several streams, including the lower Thames River, broke up. By January 23, a 10 km

- long jam had formed just upstream of Chatham and, due to cold weather resumption, began to freeze in place. It was thus possible to obtain detailed measurements of the jam thickness, along with other parameters, resulting in a unique data set (Beltaos and Moody, 1987). Note that the thickness of breakup jams is not presently measurable by any other method. Relevant ice-jam and hydraulic parameters were later deduced by analytical and graphical procedures (Beltaos, 1988). The flow disharge was estimated as Q_T=290 m^3/s; while f_0 can be described by C=0.62, m_1=m_2=1.0. The coefficient μ was ≈ 1.2 while $f_i/2f_0$ was ≈ 0.5-0.6. Values of K_x were evaluated at 8.3 (for $f_i/2f_0$=0.50) and 10.4 (for $f_i/2f_0$ = 0.60). To apply RIVJAM, p and μ were fixed at 0.40 and 1.20 respectively while λ was taken as 0.60 m/s. The "free" parameters were K_x and $f_i/2f_0$. Best results were obtained for $f_i/2f_0$ = 0.60 and K_x=9.62 (Fig. 4) which is consistent with earlier findings.

In Fig. 4, the predicted jam profile is seen to end at about 38 km, even though the head of the jam was observed at about 42 km. This is likely caused by the jam reverting to the "narrow" type or even to a single layer of ice floes upstream of kilometre 37 (Beltaos, 1988). Normally, this reach should be much shorter than 4 km but the upper portion of the jam formed under cold weather conditions, hence being more resistant to collapse than a cohesionless accumulation.

Summary and Future Requirements

RIVJAM is a model that computes the configuration of wide jams in natural streams. It is based on a simple algorithm developed earlier to study the downstream transition of equilibrium jams in prismatic channels. Test runs in a hypothetical rectangular channel indicated that RIVJAM performed consistently while illustrating the dependency of maximum water depth on ice volume or ice jam length. Next, the model was applied to a unique set of field data that includes not only the water level profile but the jam thickness as well. Using plausible values for the various coefficients of the model, good agreement was obtained between predictions and measurements.

There is considerable uncertainty in selecting some of the coefficients used in RIVJAM. The seepage parameter, λ, is only known in the laboratory. Good field data on very thick or grounded jams are needed to assess λ reliably. The coefficients β_2(=$f_i/2f_0$) and f_0 are not known very well and are estimated on the basis of empirical and indirect evidence. A major problem here is how to measure flow velocity profiles under breakup jams.

RIVJAM does not compute the "narrow" jam portion that should exist near the head of the jam. This could be done by developing an appropriate subroutine based on existing knowledge. Moreover, a steady-state condition has been assumed even though ice jam evolution can be very dynamic. Basic research is needed to define how fast ice jams collapse and thicken.

Acknowledgments

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FIGURES

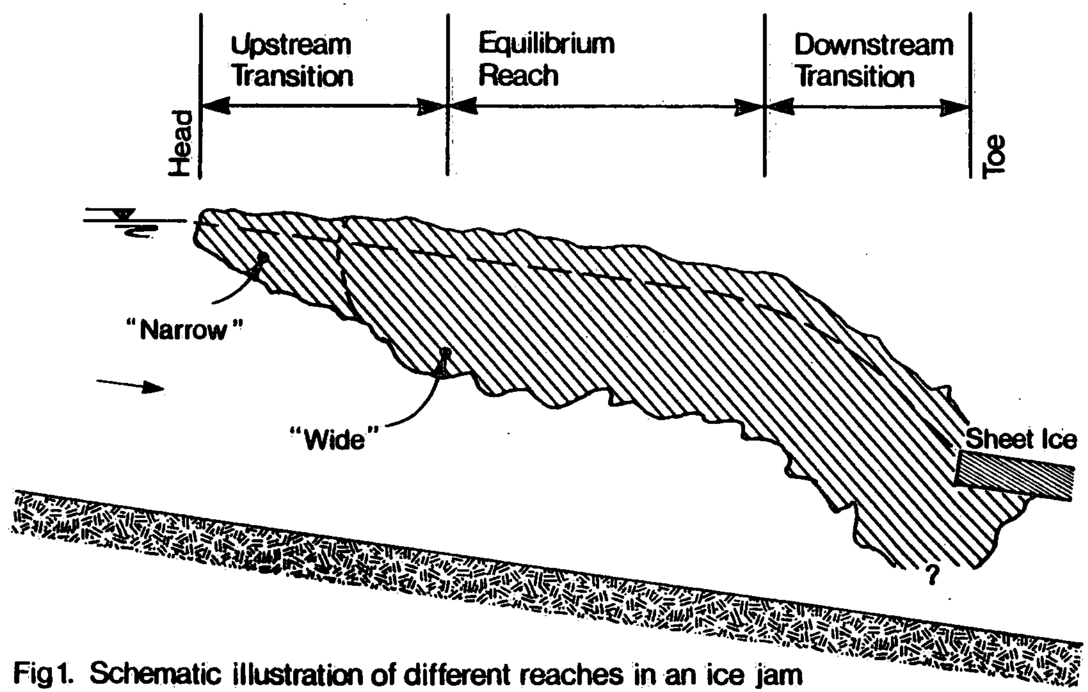

Fig1. Schematic illustration of different reaches in an ice jam

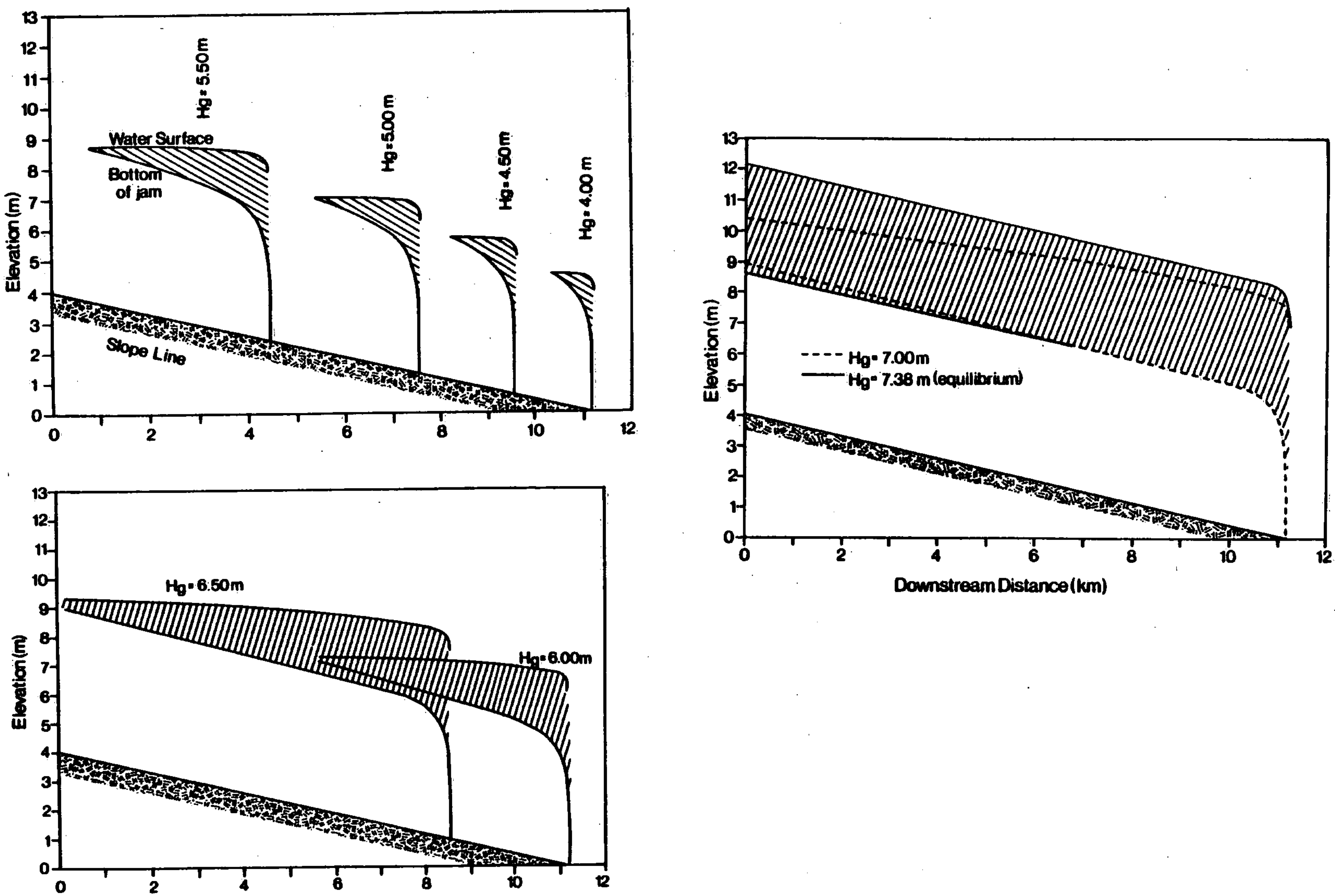

Figure 2. Calculated ice jam profiles for different values of the grounding depth, Hg.

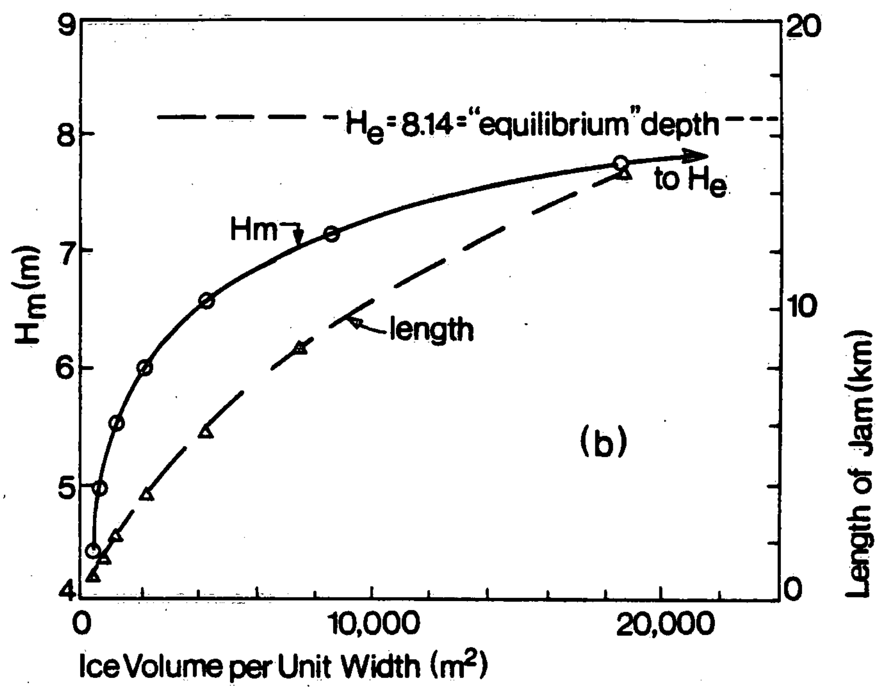

Figure 3. Maximum water depth and length of a jam as functions of ice volume

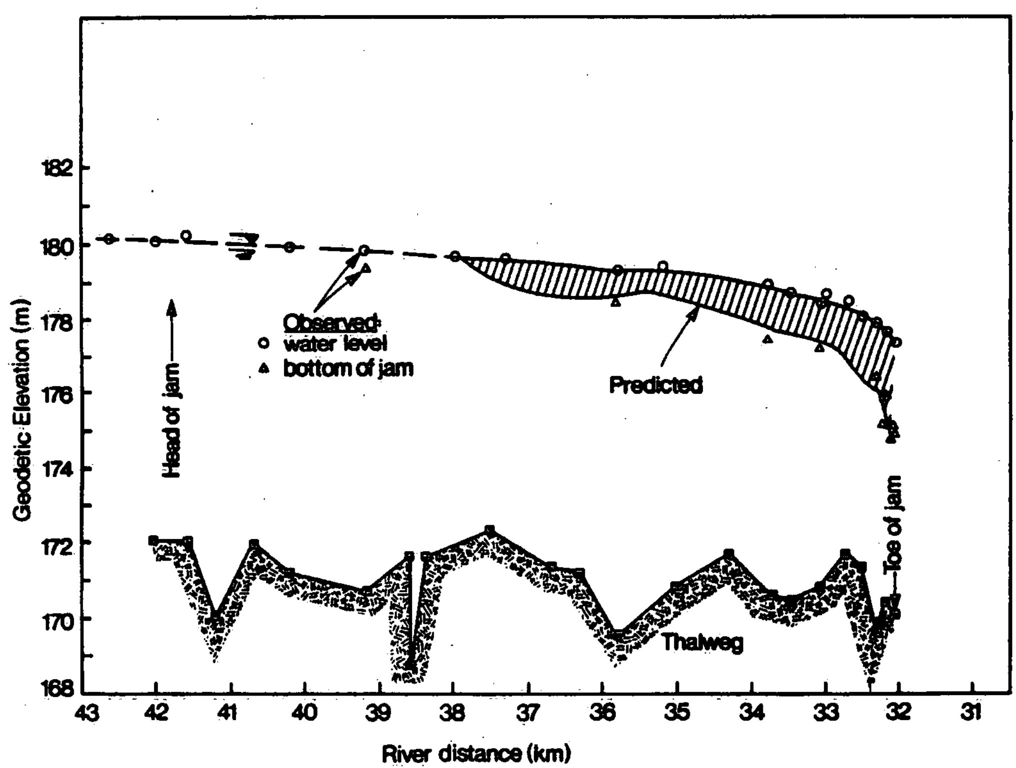

Figure 4. Predicted versus observed profiles for the 1986 jam in the Thames River above Chatham.