A COMPARISON OF THE ICEJAM AND RIVJAM ICE JAM PROFILE MODELS

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Abstract

This paper presents a review and comparison of two numerical ice jam profile models: RIVJAM, developed at the National Water Research Institute and the ICEJAM model which was developed at the University of Alberta. Both of these models solve an ice jam stability equation in conjunction with one dimensional steady gradually varied flow and both have the capacity to compute profiles for equilibrium and non-equilibrium ice jams.

The focus of the investigation is to compare the analytical equations, the boundary conditions, and the calibration parameters used by the two models. Similarities between the models' governing equations and solution techniques are illustrated through direct comparison of the analytical equations and application to an idealized channel. Relative sensitivity of the models' parameters are also illustrated through application to an idealized channel. Differences between the models' boundary conditions and relative success of calibration are illustrated through the application to two case studies. The first case study selected for investigation describes a documented ice jam event which occurred on the Restigouche River, New Brunswick on April 6, 1988, and the second case study describes a documented ice jam event which occurred on the Thames River, Ontario on February 26, 1986.

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INTRODUCTION

Ice jam related flooding has a tremendous economic impact in Canada. For example, in Alberta alone, 1997 damage claims related to ice jam flooding in Peace River and Ft. McMurray totaled more that \$9M[4]. Numerical models describing ice jam configurations have the potential to be extremely useful tools for determining the flood levels that may be expected under varying ice jam conditions. Also, because of the inherent danger in measuring ice jam properties directly, they can be particularly useful for studying ice jam characteristics indirectly, through calibration of measured water surface profiles and shear wall data. The purpose of this investigation was to examine two such models in terms of their suitability to these two objectives.

This paper presents a review and comparison of the analytical equations, the boundary conditions, solution techniques and the calibration parameters used by two such models. The numerical ice jam profile models considered in this investigation were the RIVJAM model, developed by Beltaos and Wong at the National Water Research Institute, Ontario and the ICEJAM model, which was developed by Flato and Gerard at the University of Alberta. Both of these models solve an ice jam stability equation in conjunction with a one dimensional steady gradually varied flow equation and both have the capacity to compute profiles for equilibrium and non-equilibrium ice jams. The objectives were to provide potential users with information on the relative merits and limitations of models of this type and to provide advice on their efficient use.

Equivalency between the models' governing equations and solution techniques are illustrated through direct comparison of the analytiÿal equations and through an application to an idealized channel shape. Differences between the models' boundary conditions and relative success of calibration are illustrated through the application to two case studies. The first case study selected for investigation was an ice jam event which occurred on the Restigouche River, New Brunswick on April 6, 1988, while the second case study was a documented ice jam event which occurred on the Thames River, Ontario on February 26, 1986. The relative sensitivity of the models' parameters are also illustrated using the latter case study.

COMPARISON OF ICEJAM AND RIVJAM ICE JAM STABILITY EQUATIONS

RIVJAM model - Beltaos and Wong (1986) and Beltaos (1988, 1993)

The RIVJAM model (Beltaos and Wong, 1986; Beltaos, 1988, 1993) computes the longitudinal variation in ice thickness and water surface profile for a cohesionless wide channel ice jam. Based on previous work (Beltaos and Wong, 1986), RIVJAM also accounts for seepage through the fragmented ice cover which allows for flow through grounded accumulations of ice. Through

[4] personal communication, J. Choles, Alberta Environmental Protection, May, 1997

manipulation of the jam stability relationships developed by Uzuner and Kennedy (1976), Beltaos and Wong (1986) derived the following form of the jam stability equation:

$$\frac{dt_s}{dx} = \beta_1\left[\beta_2 \frac{f_o Q^2}{4gh^2 t_s} + S_w\right] - \beta_3 \frac{t_s}{B} \qquad [1]$$

where:

- t_s is the <u>submerged</u> ice thickness;
- f_o is the composite friction factor for the flow under the jam;
- Q is the discharge flowing under the jam;
- S_w is the surface water slope; and
- B is the width of the underside of the ice.

The three dimensionless coefficients, β_1, β_2 and β_3, are defined as:

$$\beta_1 = \frac{s_i^2 \gamma_w}{2K_x \gamma_e}, \qquad \beta_2 = \frac{f_i}{2f_o}, \qquad \text{and} \qquad \beta_3 = \frac{C_o}{K_x} \qquad [2]$$

where:

- s_i is the specific gravity of the ice;
- γ_w is the unit weight of water;
- K_x is a coefficient of proportionality between the compressive "strength" of the jam and the thickness averaged, effective, vertical stress caused by buoyancy.
- C_o is a shear stress coefficient;
- f_i is the friction factor of the underside of the ice jam;
- f_o is the composite friction factor for the total flow beneath the floating cover; and
- γ_e is the effective unit weight of water defined as:

$$\gamma_e = \frac{1}{2}\left(1 - \frac{\rho_i}{\rho}\right)(1-p)\rho_i g \cos\theta \qquad [3]$$

where:

- ρ_i is the density of ice;
- ρ is the density of water;
- p is the porosity of the jam;
- g is the acceleration due to gravity; and
- θ is the angle of the downstream component of the weight of the jam with the horizontal. (This is a relatively small angle, so that $\cos\theta \cong 1$)

ICEJAM model - Flato and Gerard (1986) and Flato (1988)

The ICEJAM model (Flato and Gerard, 1986; Flato, 1988) was developed to calculate the thickness and water surface profiles for a cohesionless, wide channel ice jam with a floating toe (Flato and Gerard, 1986). For a floating toe configuration, the "seepage" through the interstitial spaces in the ice cover is neglected (Flato and Gerard, 1986). The theory behind the development of the jam stability equation in ICEJAM closely follows those theories presented by Pariset, Hausser, and Gagnon (1966) and Uzuner and Kennedy (1976). The shear stress at the banks however is treated in a slightly different manner than Uzuner and Kennedy (1976). Flato and Gerard (1986) defined the shear stress at the banks, τ_o, as,

$$\tau_o = \sigma_y \tan\delta \qquad [4]$$

where σ_y is the thickness averaged transverse stress and δ is the angle of friction between the ice accumulation and the bank. A relationship between the streamwise and transverse stress was presented by Pariset, *et al* (1966) as:

$$\sigma_y = K_{xy}\sigma_x \qquad [5]$$

where K_{xy} is a coefficient that is less than or equal to 1. From Mohr's circle, Flato and Gerard (1986) showed that:

$$K_{xy} = \frac{1-\sin^2\phi}{1+\sin^2\phi} \qquad [6]$$

where ϕ is the shearing angle.

Approximating δ with ϕ, and using Equations [4] and [5], Flato and Gerard (1986) developed the following form of the jam stability equation:

$$\frac{dt}{dx} = \frac{\tau_i}{2K_v\gamma_e t} + \frac{\rho_i g S_w}{2K_v\gamma_e} - \frac{K_{xy} t \tan\phi}{B} \qquad [7]$$

where:

t is the ice thickness;

τ_i is the shear stress on the underside of the ice cover; and

K_v is a passive pressure coefficient.

Similarity between ICEJAM and RIVJAM jam stability equations

The jam stability equation developed by Beltaos and Wong (1986) for the RIVJAM model can be rearranged to:

$$\frac{dt}{dx} = \frac{\tau_i}{2K_x\gamma_e t} + \frac{\rho_i g S_w}{2K_x\gamma_e} - \frac{C_o t}{K_x B} \qquad [8]$$

Coincidence between equations [7] and [8] is found when $\frac{K_x}{K_v} = 1$, $K_v K_{xy} = 1$ and $\tan\phi = C_o$. As it is difficult to measure parameters such as C_o, K_x, K_v, p, and ϕ directly in the field, it has become generally accepted to group such parameters together into one single jam strength parameter. This parameter, generally referred to as μ, was first introduced by Pariset, *et al* (1966), and has often been used to describe the relative strength of ice accumulations. Its value, obtained indirectly from documented ice jams, has been found to range from 0.6 to 3.5, with values between 0.8 and 1.2 considered most realistic (Ashton, 1986; Beltaos, 1983). Flato and Gerard (1986) and Beltaos and Wong (1986) presented their definitions of μ, respectively, as:

$$\mu = K_v K_{xy} \tan\phi(1-p), \qquad [9]$$

and

$$\mu = C_o(1-p). \qquad [10]$$

Again, coincidence between equations [7] and [8] can be found through substitution of the corresponding definitions of μ, provided these definitions of μ are considered equivalent.

BOUNDARY CONDITIONS AND SOLUTION METHODOLOGIES

Both models solve the jam stability equation in conjunction with an energy equation describing steady gradually varied flow. Each model employs a different approach thus requiring slightly different boundary conditions. In addition, each model deals with the issues of the toe configuration and seepage through interstices in a different way.

Solution Methodologies Used in the Two Models

In the ICEJAM model an iterative solution of the gradually varied flow and ice jam stability equations is employed. The initial ice jam thickness is estimated by the user and a gradually varied flow profile analysis progresses in the upstream direction using the estimated ice jam profile. The ice jam stability equation [7] is then solved by stepping from the head of the jam to the toe, using the water surface profile just calculated. This new ice thickness configuration is then used to compute a new gradually varied flow profile and the process is repeated until the solution converges. An under-relaxation approach is used to limit the change in the magnitude of solution variables between iterations in order to ensure stability of the iterative solution.

No interpolation of channel geometry or cross section properties is provided in the ICEJAM model. Therefore, the spatial discretization is dependent upon the location of the input cross sections. This is a very limiting feature in practical applications as the spacing between surveyed cross sections is seldom adequate in terms of the spatial discretization required to resolve the computed profile. Therefore, for this investigation a preprocessing program was developed to calculate interpolated cross sections from the available surveys which could then be used as input to the ICEJAM model.

The RIVJAM model is based on a gradually varied flow approximation which neglects the gradient in the velocity head term. This simplified gradually varied flow equation is coupled with the ice jam stability equation [1] providing a system of two equations for the unknown ice thickness and flow depth which are solved together using a Runge-Kutta solution technique. Cross section properties are interpolated between sections, allowing the spatial discretization to be refined in regions where solution variables are changing rapidly, based on user specified tolerances.

Flow Through Interstices

In the ICEJAM model, seepage through the fragmented ice accumulation is assumed to be negligible. However, this assumption leads to implausibly large or even infinite flow velocities where the jam is so thick that it is partly or fully grounded. As grounded jams are known to occur naturally, especially near the toe, Beltaos sought to describe the flow through the interstitial spaces of the rubble, which now represents the main portion of the discharge. Beltaos and Wong (1986) developed the following relationship to describe the flow through the voids:

$$Q_T = Q + \lambda A_j \sqrt{S_w} \qquad [10]$$

where

Q_T is the total flow;
Q is the flow under the ice cover (as defined earlier);
λ is a coefficient describing the flow through the voids in the ice cover;; and
A_j is the cross sectional area of the jam.

Boundary and Toe Conditions

In considering the application of these models, it is important to note that some of the basic assumptions inherent within the jam stability equation no longer apply within the toe region. More specifically, the downward thrust is no longer absorbed solely by the resistance at the banks. Much of the resistance is supplied by the obstruction (solid intact ice sheet) or by portions of the bed (in particular for grounded accumulations). Also, for a grounded accumulation, where the floes are in direct contact with the bed, the thickness averaged vertical stress is no longer due to buoyancy alone (the usual assumption).

Figure 1 depicts a schematic of the toe region and suggests the existence of a downstream limit for the region in which the jam stability equation applies (interface A-A). The RIVJAM model does not attempt to compute downstream of point A-A, where additional frictional resistance becomes available at the bottom of the ice sheet, leading to a gradual decrease and disappearance of the rubble thickness. Though Figure 1 depicts a "floating toe" condition, grounding is often characterized by a jam thickness that extends to the river bed, at or upstream of A-A. In such cases, RIVJAM will only compute as far downstream as the point of grounding. The ICEJAM model, on the other hand, stipulates that all ice jams have a floating toe, and computes the entire profile by making the following two assumptions: (1) there is a region under the sheet ice where the thickness decreases in such a manner that the flow velocity under the rubble is equal to a user-specified value, the "erosion" velocity as discussed below (the rubble thickness is now less than would be dictated by the stability equations [1, 7, 8],which no longer apply here since ice cover-rubble friction is believed to add to the resistance of the streamwise force in this region); (2) downstream of this section, the rubble drops to zero at a rate dictated by the submerged angle of repose. These assumptions in ICEJAM result in a characteristically linear water surface profile downstream of point A-A, joined rather abruptly to the curved, M-2 type of profile that prevails upstream of A-A.

As the two models handle the toe region differently, their corresponding boundary conditions are physically different. Two boundary conditions must be specified for the ICEJAM model simulation, specifically: the ice thickness at the upstream end of the ice accumulation; and the water level downstream of the toe. If the water level downstream of the toe is unknown, ICEJAM will automatically set the downstream water level to the uniform flow depth. A floating toe configuration is assumed by ICEJAM and the toe configuration is approximated by assuming that the thickness is governed by an "erosion velocity", V_{max}, which is the maximum velocity the accumulation at the toe can withstand before individual floes are swept downstream. This approach assumes that no scour will occur on the bed. When this erosion velocity is exceeded, the flow depth below the cover is increased so as to reduce the velocity to V_{max}. Thus the cover is effectively floated upwards to accommodate the flow. When the velocity determined below the cover is less than V_{max}, the usual form of the jam stability equation, coupled with a gradually varied flow equation, is used to compute the jam profile. The location at which the V_{max} criteria is no longer exceeded corresponds to interface A-A in Figure 1, and can usually be recognized by a kink in the computed water surface profile.

The RIVJAM model also requires two input boundary conditions. These are the flow depth and the thickness of the ice at the starting point of the calculations which is at the downstream end of the modelled accumulation. The downstream starting point does not necessarily have to be located at the furthest downstream point where the jam stability equation applies (interface A-A in Figure 1). However, it should not be downstream of this point, as discussed earlier.

The difference in the required boundary conditions for the two models means that the size (or the length) of the modeled ice jam is controlled differently in each case. Since the ICEJAM model requires a specified water level downstream of the toe and an ice thickness at the head of the accumulation, the length of the jam is essentially predetermined by the user. In the RIVJAM model both boundary conditions are specified at the downstream point in the modeled reach (which may, in fact, be within the ice jam as mentioned earlier).

The volume of ice (and therefore the length of the accumulation) is controlled primarily by the thickness specified at the (downstream) starting point. Therefore, the length of the jam is essentially an "output" in RIVJAM if the this thickness is known. If this point is at the jam toe, then the thickness is generally an estimate which is adjusted to produce a jam of the correct size. The "equilibrium jam" (theoretically infinitely long jam of constant thickness except near the toe and head) profile can be determined by specifying increasing ice thickness values at the toe until the model "blows up", (ie produces a continuously diverging solution). Then the equilibrium jam profile is that produced by the maximum toe thickness which provides a physically realistic ice jam profile.

ESTABLISHING THE EQUIVALENCY OF THE TWO MODELS

Although the equivalency of the two jam stability equation formulations has been established above, it was desirable to determine whether the different solution methodologies and boundary conditions had any significant impact on the results obtained with the two models. To overcome the slight differences that were expected to occur due to the different interpolation techniques used by each model for a natural (irregular) channel, an idealized channel was used. It was based on the Restigouche River case study, as the Restigouche River is considered "representative of northern Canadian conditions, i.e. large streams subjected to a single breakup event each year... The stream size, though moderate by comparison to that of the Mackenzie or the Peace, combines with its considerable slope to produce very thick ice jams and serious flooding" (Beltaos and Burrell, 1990). A trapezoidal channel with a constant base width of 150 m, a 2:1 side slope, and a bed slope of 0.0008 was used. The discharge for these tests was set to 300 m^3/s which was close to the recorded discharge for the 1988 ice jam event on the Restigouche River (Beltaos, and Burrell (1990).

To ensure that only the effects of the solution methodology and boundary conditions were being compared, the ICEJAM model was modified to accept RIVJAM's jam stability equation [1]. As the models handle the toe conditions differently, the downstream boundary for both models had to be adjusted so as to match the furthest downstream point where the jam stability equation governed (interface A-A in Figure 1). This was done by first running the ICEJAM model and examining the computed velocities to determine the most downstream point where the velocity was below V_{max}, and hence the point where the ice jam stability equation took over the calculations. The ice thickness and flow depth computed by the ICEJAM model at this location were then used as the input boundary conditions for the RIVJAM model. Because the ICEJAM simulation requires that the upstream ice thickness be specified as a boundary condition, the upstream ice thickness computed from the RIVJAM simulation then had to be used as an input to the ICEJAM model to determine the final profile for comparison to the RIVJAM model's test results.

Figure 2 presents the toe region of profiles obtained by this method, and it is seen that the results obtained for the two solution methodologies are quite close. The maximum difference in computed ice thickness between the two models was 2.1% and the maximum difference in depth was less that 0.5%. This indicates that the simplification to the gradually varied flow analysis in the RIVJAM model is justified (at least in this case) and that the decoupled solution used in the ICEJAM model is not a disadvantage.

CASE STUDIES

A number of case studies were considered in this investigation (Healy, 1997). Of these, two were selected for presentation in this paper. The first was an ice jam which occurred on the Restigouche River on April 6, 1988. This particular case study was selected because the documented configuration near the toe suggested extensive grounding and, since the ICEJAM model does not consider flow through interstices, it provided a good opportunity to examine the importance of this capability to modelling grounded jams. The second case study selected was an ice jam documented by Beltaos and Moody (1986) which occurred on the Thames River on February 26, 1986. This event was selected because it turned out to be a particularly challenging problem for both models, and in particular, because it turned out to be a case where the two models could be made to produce either very similar, or very different results thus illustrating the importance of obtaining supplementary descriptive data when documenting ice jams. In both cases the friction slope was calculated using Mannings equation.

Restigouche River: April 6, 1988

This ice jam, documented by Beltaos and Burrell (1990), formed initially on April 5, 1988, and was enlarged by incoming ice on April 6, 1988. A water surface profile was measured through the resulting accumulation. This ice jam profile remained relatively stable for the next two days, as confirmed by intermittent water level measurements. Thus steady state conditions could reasonably be assumed. The approximate bottom of the jam was estimated from shear wall data. It was not feasible to measure the discharge during this period. However, Beltaos and Burrell (1990) reported a good match to the measured data using RIVJAM with a discharge of 330 m^3/s and $\lambda = 2.2$ m/s. This discharge was used in the calibration of both models in this investigation.

"Typical" values of the ice jam parameters μ and K_x (1.0 and 10, respectively) were used in the calibration of both models. This event was of the equilibrium type and through simple inspection of the jam stability equation it is evident that K_x has no effect on the equilibrium thickness. A value of $\mu = 1.0$ falls within the expected range of values recorded by Ashton (1986) and Beltaos (1983).

Figure 3(a) illustrates the effect of varying the input toe thickness on the computed jam profile, ice volume and subsequent length, for a value of λ of 1.7 m/s and the calibrated composite Mannings *n* of 0.09. Clearly the initial thickness specified by the user can produce very different jam profiles and, therefore, this boundary condition acts as one of the major calibration parameters for the RIVJAM model when the toe thickness is unknown. Figure 3(b) presents the results obtained with the RIVJAM model for a toe thickness of 5.26 m and values of $\lambda = 0.0$, 1.0, 1.7 and 2.0 m/s. Based on these results, a values of λ of about 2.0 m/s would be expected to provide a reasonable match to the data (with consideration of the shear wall data, and jam length which was known to be about 18 km).

Figure 4(a) presents the results obtained with the ICEJAM model for a calibrated composite Mannings *n* of 0.07, with values of $V_{max} = 1.0$, 1.5 and 2.0 m/s, assuming the ice thickness at the upstream boundary was 1 m. The lower roughness obtained here reflects the fact that flow through the interstices is not considered. Note that, for V_{max} =1 m/s, the kink in the water surface profile is about 0.5 km upstream of where the edge of the sheet ice cover was observed (starting point for RIVJAM model), thus rendering this particular simulation obviously unrealistic. Based on these runs, it appears that values of V_{max} between 1.5 and 2.0 m/s would be expected to provide reasonable results, given also the available shear wall data. These values are relatively high considering the inherent assumption that the bed does not erode under the toe. Figure 4(b) illustrates the effect of varying the upstream boundary ice thickness on the computed jam profile and ice volume. This upstream boundary condition is slightly less sensitive than the toe thickness boundary condition required by the RIVJAM model.

Figure 5 depicts a close-up of the toe region comparing the results of both ICEJAM (V_{max} = 2.0 m/s) and RIVJAM (thickness at the toe = 5.26 m). As the figure illustrates, both models provide a reasonable simulation of the water surface. Although the RIVJAM model appears slightly better at capturing the profile of the underside of the ice cover near the toe it should be remembered that the thickness at the most downstream point is a specified input boundary condition for the RIVJAM model. At the same time it is noted that, to improve ICEJAM's performance in the toe area of this grounded jam, it has been necessary to stipulate a rather high value for V_{max}, (2.0 m/s compared to the value of 1.25 m/s used in the next example, which was not grounded) and to place the edge of the sheet ice cover (interface A-A) about 25 m upstream of where it was actually observed.

Thames River: January 22, 1986

This winter ice jam on the Thames River in Ontario, which was documented by Beltaos and Moody (1986), formed as a result of the release of an upstream ice jam during the evening of January 22, 1986. High water marks in the newly formed jam were photographed during the morning of January 23 after cold weather had returned and conditions had stabilized. Using the Water Survey of Canada gauge record at Thamesville (gauge 02GE003), and estimating the time of travel between the gauge and the jam sites to be 12 hours, Beltaos (1988) estimated the discharge as 290 m^3/s. Subsequently, a solid ice layer formed over the ice jam making it safe to collect thickness measurements. Based on the consistency between ice thickness measurements taken within the same section of the jam on February 4 and February 25, 1986, it was assumed that the jam thickness did not change over the period during which the measurements were taken (January 23 to February 26, 1986). The discharge of 290 m^3/s along with values of μ and K_X of 1.0 and 10, respectively, were used in the calibration of both models.

For the RIVJAM calibration, λ was set to 2.0 m/s and the toe thickness was set to match the measured value of 2.2 m. The roughness was then adjusted to achieve the best possible fit to the measured profile. It was found that the length of the jam increased as roughness was reduced. Figure 6 illustrates the results for a composite Mannings n of 0.0606 which was the limiting value for a physically realistic solution (as illustrated by the solution obtained with a composite Mannings n of 0.0605). As Figure 6 also illustrates, the actual ice jam length computed with the RIVJAM model is short, in that the head of the computed ice jam is at station 34585 m, approximately 8 km downstream of the documented head of the accumulation. It is possible that upstream of station 34585 m the jam may have behaved more like the "narrow" type described by Pariset, *et al* (1966) for which the ice jam stability equation is inapplicable. This deduction is consistent with the qualitative description of the ice jam event provided by Beltaos (1988), and with the very low thickness that was measured in the last few kilometers of the jam.

As mentioned earlier, the length of the ice jam is an input parameter for the ICEJAM simulation. Therefore, given the short jam which was computed by the RIVJAM model, two scenarios were considered for the ICEJAM calibration. In the first case a short jam length, corresponding to the length described by the RIVJAM run (i.e. head at station 34585 m), was assumed. In the second case, it was assumed that the "wide" jam criteria applied up to Beltaos and Moody's (1986) observed location of the head (at station 42000 m). In both cases, the thickness at the head was set to 0.3 m (as Beltaos and Moody (1986) noted the average ice thickness ranged from 0.2m to 0.3m) V_{max} was set to 1.25 m/s, and Mannings roughness was adjusted in an attempt to match the computed profile to the measured data.

Figure 7(a) depicts the computed profiles for both the short and long jam scenarios resulting from a calibration which attempted to match recorded profile data within the downstream portion of the jam. As the figure illustrates, the short jam reproduces the measured profile adequately. However, the computed water levels in the upstream portion of the long jam were well above the measured data. Figure 7(b) depicts the computed profile for the long jam where the calibration attempted to match the recorded profile data within the upstream portion of the jam and, as the figure illustrates, this approach does not adequately capture the jam profile in the vicinity of the toe. Based on these results, it could be concluded that the shorter jam is more consistent with the measured data. However, it is unlikely that this would have been the case had not the RIVJAM model results suggested the possibility. This would indicate that the requirement for the user to input the ice jam length might be considered a significant disadvantage of the ICEJAM model. Alternatively, it could be considered an indication of the importance of supplemental descriptive data and good judgment in the interpretation of field data to the proper use of models of this type.

Through the calibration of this event it was evident that the jam was not of the equilibrium type. This provided a good opportunity to test the sensitivity of K_x and μ. Figure 8 presents the results of this sensitivity analysis which was conducted with the ICEJAM model using Mannings equation to calculate the friction slope. Based on values presented in the literature, K_x was varied from 8 to 12 (Figure 8(a)), and μ from 0.8 to 1.2 (Figure 8(b)). The maximum differences in the computed thickness and water levels for this range of K_x values were 0.23 m (17%) and 0.08 m (1%), respectively. The maximum differences in the computed thickness and water levels for this range of μ were respectively, 1.11 m (36%) and 0.37 m (5%). A similar sensitivity analysis was conducted on the composite roughness using a range of composite Mannings n values from 0.04 to 0.08. In this case, the maximum differences in the computed thickness and water levels were 2.16 m (65%) and 2.19 m (25%), respectively. These results suggest a low sensitivity of ICEJAM to K_X and μ. However, on other occasions RIVJAM has indicated much greater sensitivity to these parameters (eg. see Beltaos, 1997).

ICEJAM simulates the final decrease of jam thickness to zero by assuming a rate dictated by the internal friction angle of the submerged rubble. In the Thames River example, Beltaos (1988) measured this rate to be about 2.3/80 = 0.029, a value that corresponds to an (implausibly low) friction angle of 1.66°. A similar indication arises from the Restigouche River example, where observations indicated significant shear walls persisting well past the site where ICEJAM predicts a zero rubble thickness (location 20.6 km in Figure 5). Therefore, it would thus appear that the assumed toe configuration in this model is not entirely consistent with natural occurrences, though it provides a useful expedient to make the transition to the jam stability equation.

CONCLUSIONS

The purpose of this paper was to review and compare two one-dimensional numerical ice jam profile models: RIVJAM and ICEJAM. The intent was to provide potential users with information on the relative merits and limitations of these models, in terms of their ability to describe ice jam profiles quantitatively and to assess ice jam parameters through calibration of case studies. It was also desirable to provide users with information to assist in the efficient use of the models and to determine whether or not consistent results can be expected when calibrating case studies.

The following specific conclusions have resulted from this investigation.

1. The two models solve an identical form of the one dimensional, cohesionless, ice jam stability equation provided that their definitions of μ are considered equivalent.

2. The different solution techniques used by the two models do not produce significantly different results.

3. The RIVJAM approximation, that the gradient in the velocity head is negligible, was found to be reasonable for the cases tested.

4. The RIVJAM model requires the user to input the toe geometry (thickness) as the boundary condition for the jam stability equation. In contrast, the ICEJAM model estimates the toe geometry using a maximum erosive velocity criteria, and requires the user to input the ice

thickness at the head of the accumulation as the boundary condition for the jam stability equation. In the absence of ice jam toe thickness data, this boundary condition becomes a calibration parameter in the RIVJAM model. The ICEJAM model is less sensitive to estimates of its ice thickness boundary condition (at the head of the accumulation) as gradients in the solution are typically much larger near the toe than near the head.

5. In the RIVJAM model, the length of the jam (and therefore the volume of ice in the accumulation) are primarily controlled by the input toe thickness and the input seepage coefficient, λ. In the ICEJAM model the length of the jam must be predetermined by the user.

6. Model calibration is, in some instances, more sensitive to the ice roughness than to either μ or K_x. Where, in addition, discharge is unknown and must be estimated during the calibration procedure, it may be difficult to determine precise values for μ or K_x using models of this type.

7. Although the assumed toe configuration used in the ICEJAM model provides a useful expedient to make the transition to the jam stability equation, it is important to note that the resulting shape is not entirely consistent with natural occurrences, particularly when the toe is grounded. Also, for grounded jams, the calibrated composite roughness will be lower than that obtained with the RIVJAM model, since ICEJAM does not account for flow through the interstices.

Based on these results, it is concluded that the two models produce very comparable results in the region where the jam stability equations apply, provided they are calibrated independently with adequate information. However, as the case studies illustrate, consistent results (both between models *and* between modellers) require knowledge of both the ice jam thickness and the water surface profile. Also, in cases such as the Thames River, documentation of the mode of accumulation formation is essential for adequate interpretation and validation of calibrated profiles.

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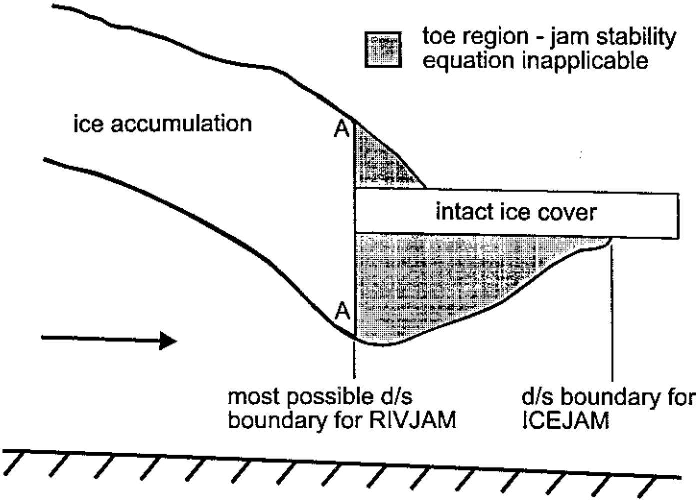

Figure 1. Schematic of ice accumulation in the toe region.

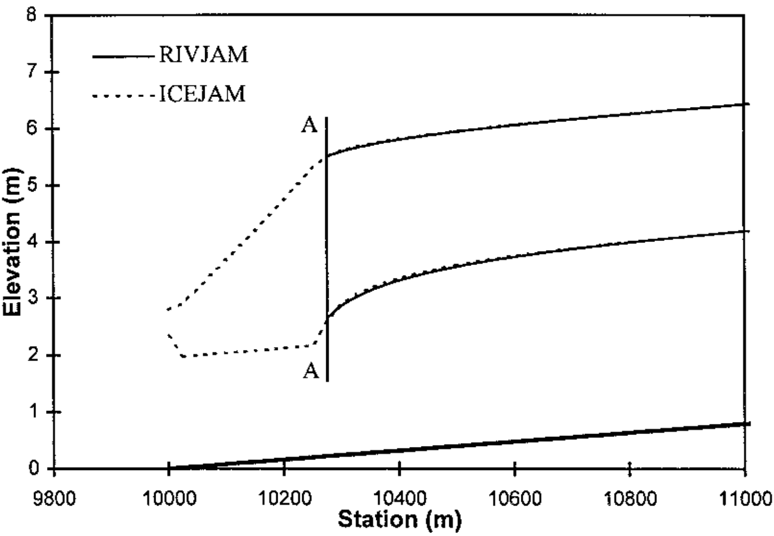

Figure 2. Comparison of ICEJAM and RIVJAM results for the trapezoidal channel.

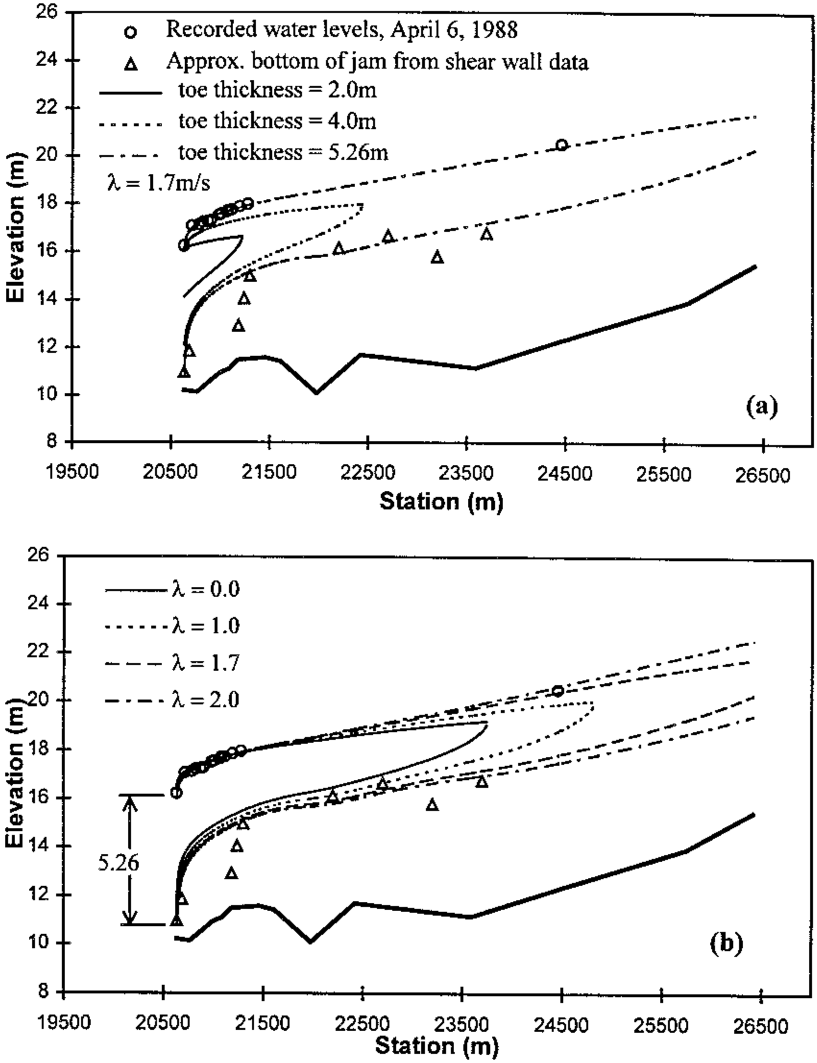

Figure 3. Water surface and bottom of ice profiles for the 1988 Restigouche River ice jam event, as computed by RIVJAM.

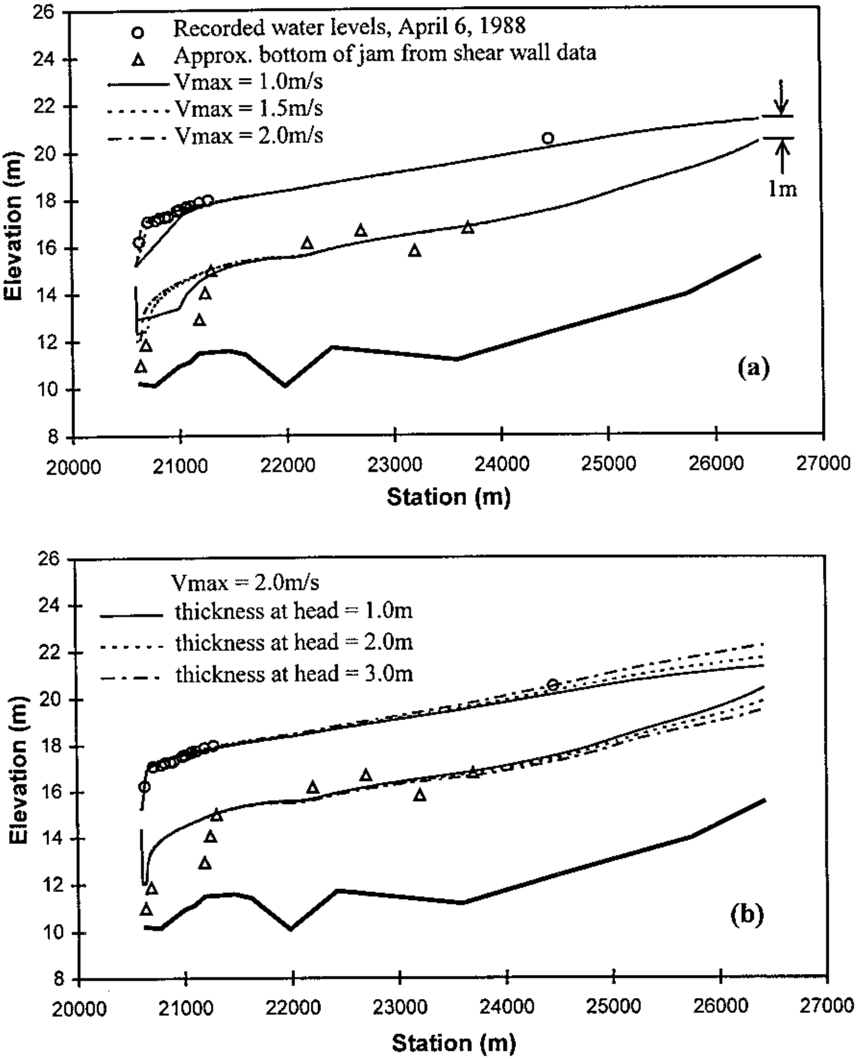

Figure 4. Water surface and bottom of ice profiles for the 1988 Restigouche River ice jam event, as computed by ICEJAM.

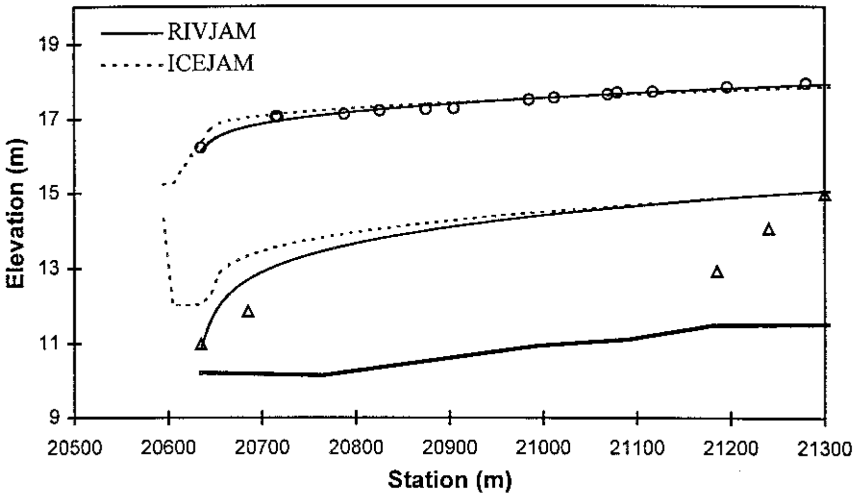

Figure 5. Water surface and bottom of ice profiles near the toe for the 1988 Restigouche River ice jam event, as computed by ICEJAM and RIVJAM.

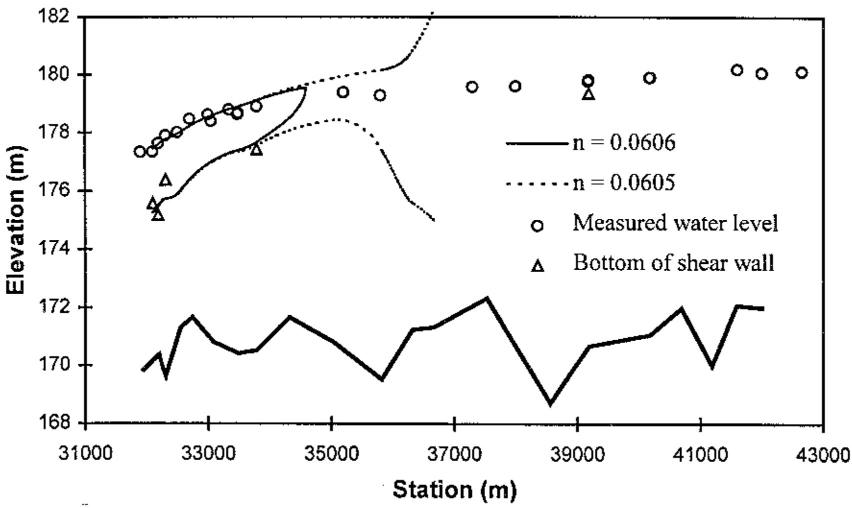

Figure 6. Water surface and bottom of ice profiles for the 1986 Thames River ice jam event as computed by RIVJAM.

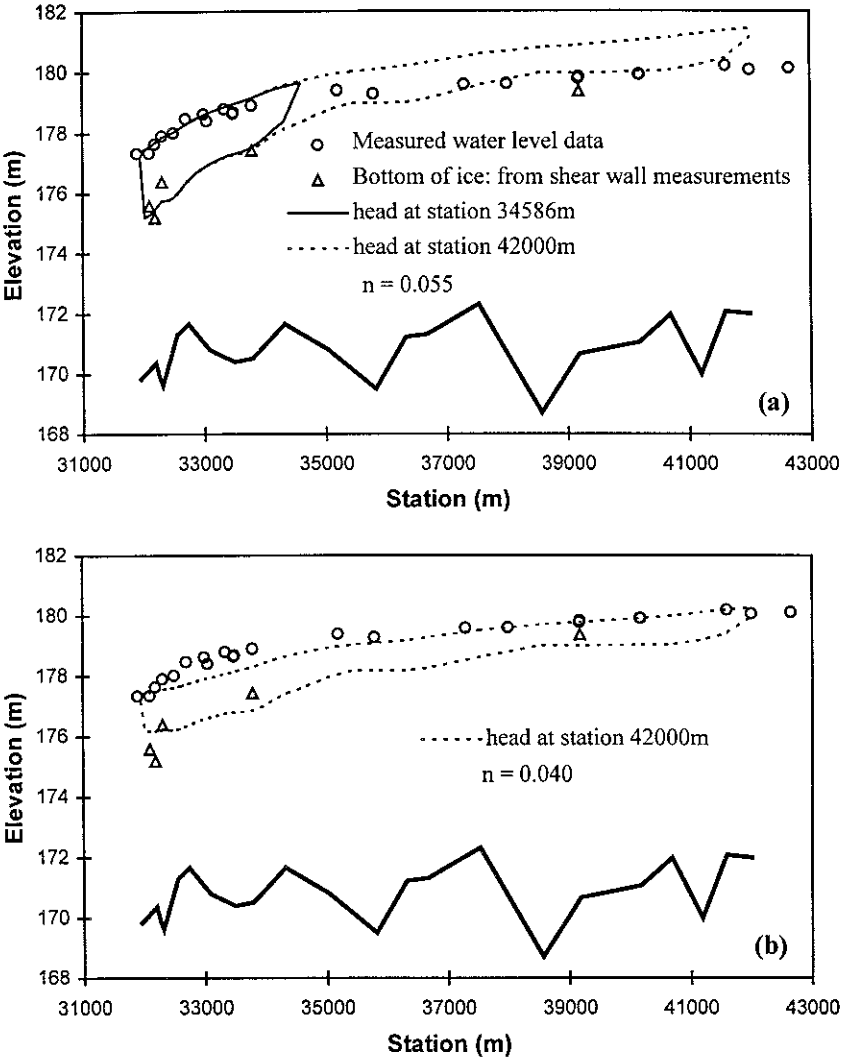

Figure 7. Water surface and bottom of ice profiles for the 1986 Thames River ice jam event, as computed by ICEJAM.

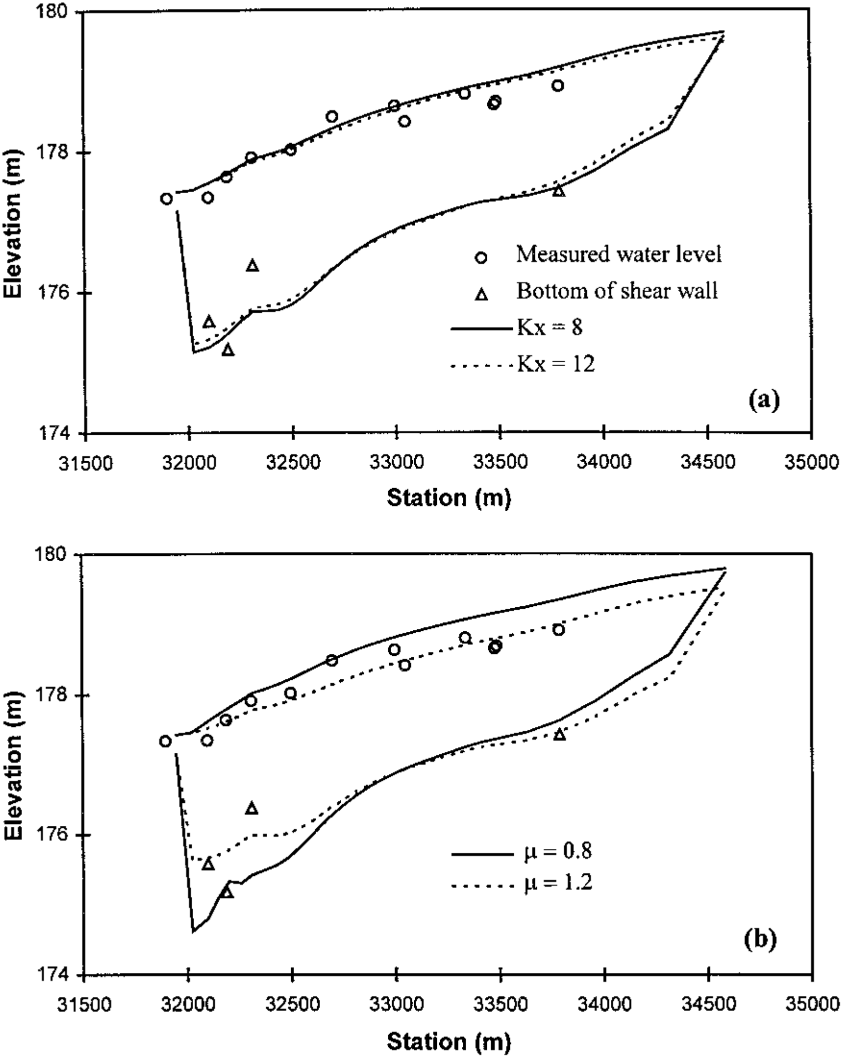

Figure 8. Sensitivity of input parameters for ICEJAM using Mannings roughness.