ICE JAM SIMULATIONS IN RIVERS WITH ISLANDS

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ABSTRACT

This investigation performed ice jam profile simulations in rectangular channels with islands of different length and channel geometry. The results of the simulations were non-dimensionalized so that they could be applied to channels of different slopes, widths, discharges and island lengths. The investigation used a model called "ICEJAM" developed by Flato and Gerard (1986) at the University of Alberta. This model, like others, does not simulate islands adequately on its own. However, solutions for ice jam profiles with islands were made possible by simulating the single channel segments of a multi channel geometry separately. The separate channels had to be linked together using the appropriate boundary conditions.

The general results from the rectangular channel simulations were then applied to the Yukon River at Dawson to obtain a preliminary estimate of the likely effect of islands on ice jam stages for this community.

INTRODUCTION

Channel width is a major factor in determining ice jam thickness. Traditional one-dimensional ice jam profile models over predict the ice jam thickness in channels with islands. This occurs since they use the combined width of the two channels on either side of the island to calculate the thickness profile. The Yukon River near Dawson contains varying channel geometry with most reaches containing numerous islands. Since ice jam flooding is a concern at this site, it was desirable to develop a model that can simulate ice jam profiles around islands correctly.

This preliminary investigation performs ice jam simulations in rectangular channels with islands of different length and channel geometry. The results of the simulations were non-dimensionalized so that results could be applied to channels of different slopes, widths, discharges and island lengths.

BACKGROUND INFORMATION ON ICE JAMS

Ice jam forces and modelling

Figure 1 shows a typical ice jam profile. The shape of this profile is governed by the balance between the downstream and upstream forces acting on the ice jam. The downstream forces acting on an ice jam are the shear of the water flowing underneath the ice jam and the downstream weight or gravity component of the ice jam. These forces are resisted in the upstream direction by the wall shear near the riverbanks. In general, the larger the downstream forces the thicker the ice jam has to become in order to provide enough contact area at the shear walls to resist these downstream forces. The major work on ice jam profile modelling followed from the work of Uzuner and Kennedy (1976). This work has led to the development of the differential equation describing the variation of the ice jam thickness. Flato and Gerard (1986) showed this equation in the following form:

$$\frac{dt}{dx} = \frac{\rho' g\, S_w}{2\, k_p \gamma_e} + \frac{\tau_i}{2\, t\, k_p \gamma_e} - \frac{k_{xy} \tan\phi\ t}{B} \qquad (1)$$

change in ice jam thickness with distance along channel = gravity component term + shear from water under ice jam term - shear wall resistance term

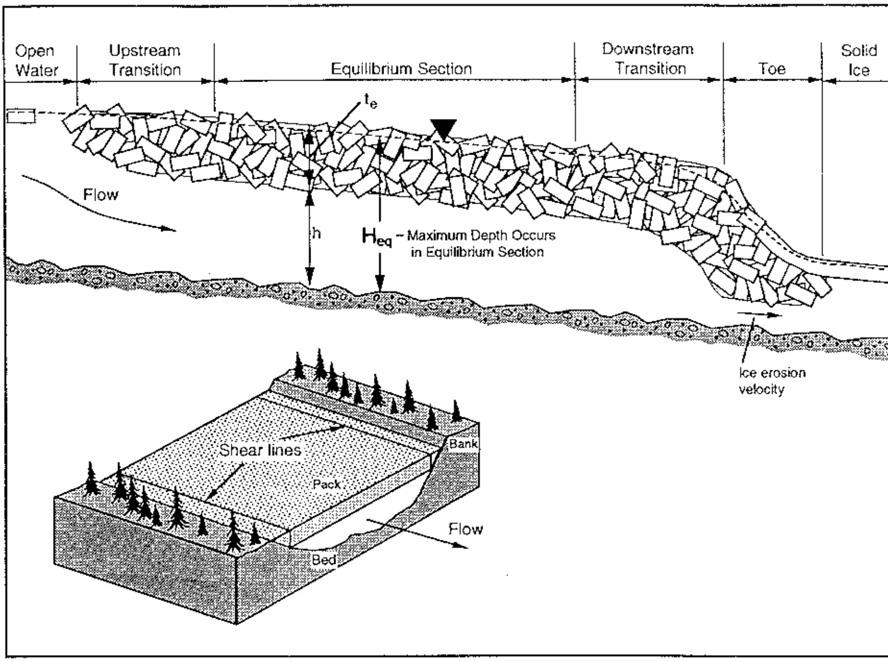

Figure 1. A typical longitudinal profile through an ice jam.

where:

t	=	ice jam thickness at distance x along channel
ρ'	=	density of ice
g	=	acceleration due to gravity
S_w	=	slope of water surface
k_p	=	passive pressure coefficient
γ_e	=	0.5 ρ g (1-ρ'/ρ) (1-e), a measure of average confining stress at a section.
ρ	=	density of water
e	=	ice jam porosity
τ_i	=	shear stress applied to jam underside by flow of water
k_{xy}	=	lateral stress transfer coefficient = σ_y / σ_x
φ	=	angle of shearing resistance
B	=	bottom width of ice jam underside
σ_y	=	thickness-averaged normal stress at bank
σ_x	=	thickness-averaged and width-averaged longitudinal stress
x,y	=	streamwise and transverse co-ordinates respectfully

An important part of the ice jam profile shown in Figure 1 is the equilibrium section. The maximum stage produced by the ice jam occurs in this section. An ice jam has to attain a certain length in order to develop such a section. As a first approximation, Equation 1 was applied to the equilibrium section in a prismatic channel by Beltaos (1983). The ice pack thickness and waterway depth are uniform throughout this section, making its analysis simpler. Under these uniform flow conditions, dt/dx = 0 (ice jam thickness is constant) and S_w (water surface slope) = S_f (friction slope) = S (channel bed slope). Following the Beltaos substitution of these relations into the differential Equation 1 yields a simple quadratic equation for the equilibrium ice jam thickness t_e:

$$t_e = \frac{6.25\ S_f\ B}{\mu}\left(1 + \sqrt{1 + 0.35\ \mu\ (R_i / S_f\ B)}\right) \quad (2)$$

where:

$$\mu = k_{xy}\ k_p \tan\phi\ (1\text{-}e) \quad (3)$$

and R_i is the hydraulic radius of ice influenced part of the waterway area.

Note that the channel width B is a dominant variable that determines the ice jam thickness in Equation 2. Using a relation similar to Equation 2, Calkins (1991) showed that a significant reduction in the equilibrium thickness can occur by splitting a single channel into two or more channels. His work investigated the possibility of using longitudinal structures to reduce ice jam thickness. This potential reduction in thickness has been aluded to in the literature in the 1970's. It has also been put into practice in the 1970's by some hydro companies (Randy Raban at the 8th Workshop on the Hydraulic of Ice Covered Rivers, Aug., 1995). However, the length of a structure or island that is needed to take full advantage of the stage reduction has never been addressed. It seems intuitive that a longer island would produce a stage closer to this potential reduction than a shorter one.

When solving Equation 1 or 2 for ice jam thicknesses, the hydraulic equations must determine the shear on the jam underside. These terms show up as the bottom shear τ_i in Equation 1 and R_i and S_f in Equation 2. The details of the hydraulic formulation can be found in Flato and Gerard (1986) and are based on the logarithmic velocity distribution represented by the dimensionless Chezy relation and hydraulic roughness 'k'. It can be noted that unlike the manning "n" relation, this relation applies to very high roughnesses associated with ice jams as well as medium and small roughnesses associated with river beds and smooth channels respectively.

The ICEJAM model calculates an initial water surface profile in the upstream direction based on a uniform ice thickness. It then uses the resulting shears to calculate a thickness profile in the downstream direction using Equation 1. However, this new thickness profile changes the hydraulics under the jam and new shears and water level elevations have to be calculated in the upstream direction again. This is followed by another thickness calculation in the downstream direction and the process continues until all thicknesses at each cross-section converge to a specified tolerance.

<u>Characterization of "ice jam type" - high, medium, or low thickness ice jams</u>

It was the aim of this investigation to model ice jam thickness profiles around islands for various channel geometries and discharges and to generalise these simulations in a non-dimensional sense. A dimensionless parameter which worked well for this study was the dimensionless discharge ξ, first developed by Beltaos(1983). Gerard(1988) described this dimensionless parameter in this form:

$$\xi = \frac{(q\,k^{\frac{1}{6}} / \sqrt{gS})^{\frac{3}{5}}}{SB} \qquad \textbf{(4)}$$

where:

k = combined roughness of ice jam (k_i) and channel bed (k_b). (Flato and Gerard, 1986)

and q is the discharge per unit width:

$$q = Q/B \qquad \textbf{(5)}$$

where:

Q = total discharge in channel

Beltaos(1983) develops another parameter called the dimensionless equilibrium stage η:

$$\eta = \frac{H_{eq}}{S\,B} \qquad \textbf{(6)}$$

where H_{eq} is the equilibrium stage. Beltaos showed that η is a function of ξ, the ice jam to bed roughness ratio, and the ice jam strength parameter μ. An equivalent relation from Gerard(1988) that is in terms of the roughness "k" rather than the friction factor "f" is:

$$\eta = 0.38\,\xi + \frac{5.75}{\mu}\left(1 + \sqrt{1 + \frac{0.13\mu\xi}{(1 - k_r^{-0.25})}}\right) \quad (7)$$

where $k_r = k_i/k_b$.

Equation 7 is not very sensitive to k_r and assuming μ is a constant, say 1.3, then η is only a function of ξ. The relation between the dimensionless discharge ξ and the dimensionless stage η is plotted in Figure 2. The inset plots in Figure 2 show simulations of ice jam profiles for an approximate range of ξ found in the field. These inset figures indicate that for a small value of ξ around 10, the ice jam thickness is much greater than the waterway depth; for a value of ξ around 50, the ice jam thickness and waterway depth are of about the same magnitude; and for a large value of ξ of around 1000, the ice jam thickness is much thinner than the waterway depth. These proportions of ice jam thickness to waterway depth are defined here as high, medium, and low thickness ice jam types. This definition of ice jam type can provide insight on how islands may effect the stage reduction: since islands reduce the ice jam thickness and not the waterway depth, than it would seem reasonable to assume that a reduction in stage would be greater for smaller values of ξ (high thickness type ice jams). It is therefore important to assess what channel parameters affect the value of ξ most significantly. This can be assessed by substituting Equation 5 into Equation 4 and rearranging to obtain:

$$\xi = \frac{Q^{0.6}\,k^{0.1}}{S^{1.3}\,B^{1.6}\,g^{0.3}} \quad (8)$$

Equation 8 can give an indication on which channel properties most strongly affect ice jam type and hence the possible reduction in stage due to islands. It appears from the exponents that the channel width B and channel slope S are the 1st and 2nd most dominant factors determining ice jam type. The discharge is the next most significant, and the combined roughness k has an almost negligible effect. In general, wider and steeper channels produce the high thickness ice jam types and therefore these channels would exhibit the largest reduction in stage due to islands.

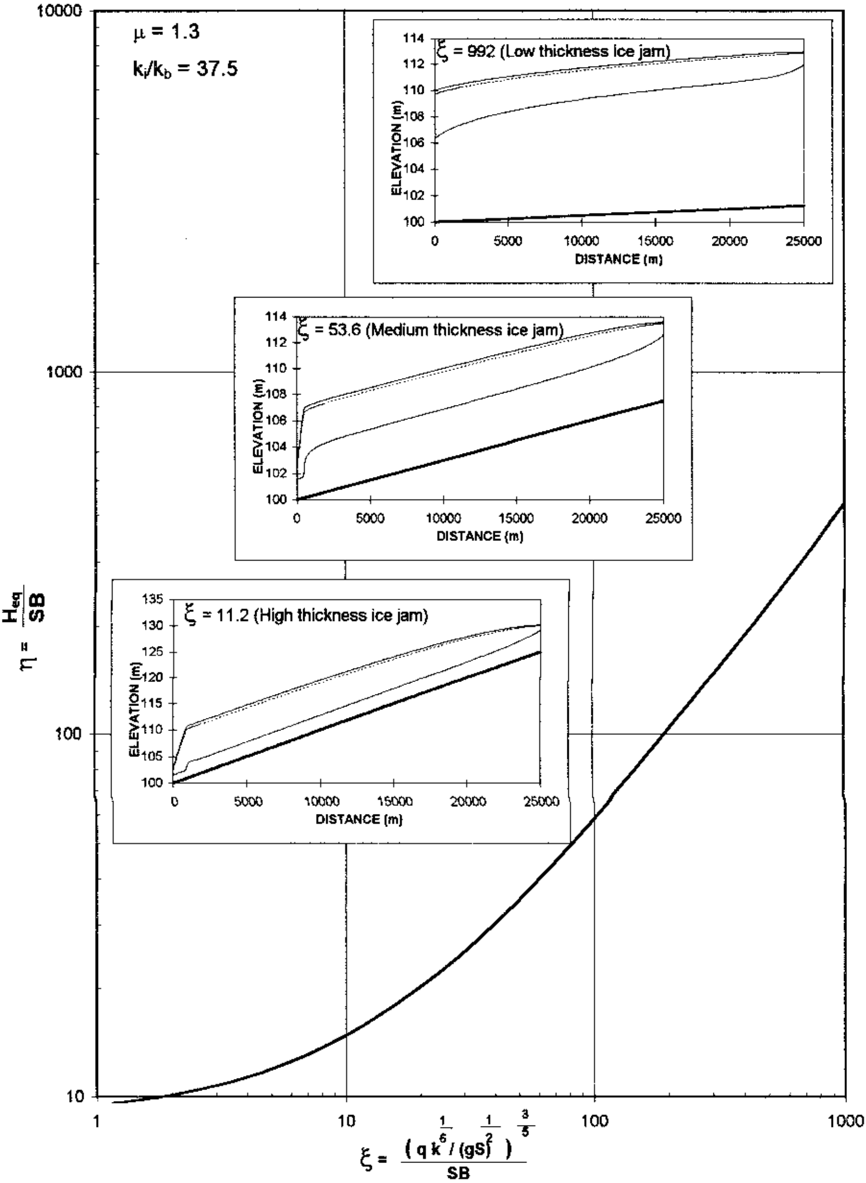

Figure 2. Relation between dimensionless discharge ξ and dimensionless stage η for ice jams (Eqn.7, $\mu = 1.3$, $k_i/k_b = 37.5$). Inset plots show simulated ice jam profiles in rectangular channels spanning the approximate range of ξ found in the field. ξ determines whether an ice jam is a low, medium, or high thickness type.

ICE JAM SIMULATIONS WITH ISLANDS

Parameters and constants used in the ICEJAM model

There are many parameters that have to be specified when using ice jam profile models. Most of these parameters have to do with the geotechnical behavior of the ice pack. The following are some of the constants used in this study. The values of these constants were chosen from past lab and field calibrations and lie within commonly accepted ranges. For further discussion of these parameters see Flato and Gerard(1986) and Gerard and Stanley(1988).

angle of internal friction	ϕ	50°
ice density	ρ'	916 kg/m^3
ice porosity	e	0.40
shear coefficient	k_{xy}	0.240
passive pressure coefficient	k_p	7.55
pack cohesion	C_i	0 (zero for break-up jams)
maximum erosion velocity	V_e	1.6 m/s
jam strength parameter (Equation 3)	μ	1.3

Methodology for choosing simulations

It was the aim of this investigation to model ice jam thickness profiles around islands of different lengths and for various channel geometries and discharges and generalise these simulations in a non-dimensional sense. The effect of the island for each simulation was assessed by taking the minimum stage produced by the island (H_{min}) and comparing it to the equilibrium stage (H_{eq}) for an equivalent single channel. The ratio of H_{min}/H_{eq} was used to non-dimensionalize the stage reduction. The stage reduction ratio H_{min}/H_{eq} was taken as the dependent variable and was tested against the following independent dimensionless variables:

- L_{is}/B - dimensionless island length where L_{is} is the length of the island ($1 < L_{is}/B < 64$).
- ξ - dimensionless discharge ($11.2 < \xi < 992$).
- k_i/k_b - ice jam to bed roughness ratio ($1 < k_i/k_b < 100$).
- S - channel slope ($0.00005 < S < 0.001$).

Table 1 shows a summary of the simulations performed in this investigation. The island length was tested in runs 1 through 17 for three different values of ξ. Runs 1, 8,

Table 1. Simulations conducted in present study.

Run #	Q (m^3/s)	S	B (m)	k_i (m)	k_b (m)	$\frac{k_i}{k_b}$	k (m)	ξ	η (H_{eq}/SB)	H_{eq} (m)	Relative length of island (L_{is}/B)	H_{min} (m)	Stage reduction ratio (H_{min}/H_{eq})
1	1500	0.001	600	3.00	0.08	37.5	0.73	11.2	15.6	9.33	64	6.59	0.706
2										9.33	32	6.60	0.707
3										9.33	16	6.72	0.720
4										9.33	8	7.18	0.770
5										9.33	4	7.87	0.843
6										9.33	2	8.47	0.907
7										9.33	1	8.86	0.950
8	1500	0.0003	600	3.00	0.08	37.5	0.73	53.6	37.7	6.79	64	5.73	0.844
9										6.79	32	5.74	0.844
10										6.79	16	5.80	0.855
11										6.79	8	6.00	0.884
12										6.79	4	6.24	0.919
13										6.79	2	6.45	0.950
14										6.79	1	6.60	0.972
15	4000	0.00005	600	3.00	0.08	37.5	0.73	992	424	12.68	64	12.56	0.990
16										12.67	16	12.63	0.996
17										12.66	1	12.66	1.000
18	1330	0.0003	600	8.00	0.08	100	1.50	53.6	39.8	7.16	64	6.07	0.847
19	1500	0.0003	600	3.00	0.08	37.5	0.73	53.6	37.7	6.79	64	5.73	0.844
20	1500	0.0003	600	0.73	0.73	1	0.73	53.6	36.0	6.49	64	5.51	0.849
21	822	0.001	180	3.00	0.08	37.5	0.73	53.6	37.8	6.80	64	5.75	0.846
22	1500	0.0003	600	3.00	0.08	37.5	0.73	53.6	37.7	6.79	64	5.73	0.844
23	3674	0.00005	3600	3.00	0.08	37.5	0.73	53.6	41.7	7.50	64	6.38	0.851

indicates dimensionless variable being tested

Table 2. Results from Calkins (1991).

Case #	Q (m^3/s)	S	B (m)	* k_i (m)	* k_b (m)	* $\frac{k_i}{k_b}$	* k (m)	ξ	η (H_{eq}/SB)	H_{eq} (m)	Relative length of island (L_{is}/B)	H_{min} (m)	Stage reduction ratio (H_{min}/H_{eq})
1	22.65	0.003	60	0.27	0.27	1.00	0.27	7.8	14.8	2.66	L_{is}>>B	1.77	0.665
2	22.65	0.003	60	1.21	0.16	7.72	0.50	8.3	15.6	2.80	L_{is}>>B	1.90	0.679
3	22.65	0.003	60	2.31	0.30	7.72	0.95	8.9	16.6	2.99	L_{is}>>B	2.08	0.696
4	34	0.003	60	1.60	0.21	7.72	0.66	10.9	16.9	3.05	L_{is}>>B	2.14	0.702
5	34	0.003	60	3.02	0.39	7.72	1.24	11.6	18.6	3.34	L_{is}>>B	2.42	0.725

* friction factor "f" in Calkins(1991) converted to roughness "k".

and 15 were used to test the effect ξ with island length being held constant. Runs 18 through 20 were used to test the effect of the ice jam to bed roughness ratio; all other dimensionless variables were held constant. Runs 21 through 23 tested the effect of channel bed slope; all other dimensionless variables were held constant. Table 2 shows the results from Calkins(1991) for long islands based on equilibrium thickness.

Results

Figure 3 shows simulated ice jam profiles for islands ranging from 1 to 64 channel widths long. The simulations show that as the island gets shorter the stage reduction due to the island decreases. The profiles also indicate that the thinnest part of the jam occurs at the downstream end of the island and thickest part occurs at the upstream end. It can also be noted that the minimum water depth under the ice jam occurs at the upstream end of an island; this increases the chances of grounding at this point and supports the fact that islands can cause ice jams to form. The simulations in this figure are for an ice jam of the medium thickness type.

Figure 4 shows simulations for ice jam profiles around an island for high, medium, and low thickness ice jam types. It is apparent from this figure that the stage reduction is the highest for the high thickness type ice jam, and the lowest for the low thickness type ice jam.

Figure 5a-c are based on simulations for long islands. Figure 5a shows the effect of the ice jam type (dimensionless discharge) on the stage reduction ratio. The results from Calkins (1991) are plotted in Figure 5a and seem to be in excellent agreement. The figure shows that stage reduction ranges from about 0.66 for high thickness type ice jams to almost 1 for low thickness type ice jams. For the low thickness ice jam types, islands lengths of 64 widths were still not long enough to produce the full stage reduction. Figure 5b shows the stage reduction ratio for different values of channel bed slope. The figure shows that the channel bed slope has negligible effect on the stage reduction ratio if the dimensionless discharge ξ is held constant. It is apparent that ξ is able to capture the effect of slope entirely. Figure 5c shows the stage reduction ratio for different values of ice jam to bed roughness ratios. The figure shows that the ice jam to bed roughness ratio also has a negligible effect on the stage reduction ratio if the dimensionless discharge ξ is held constant.

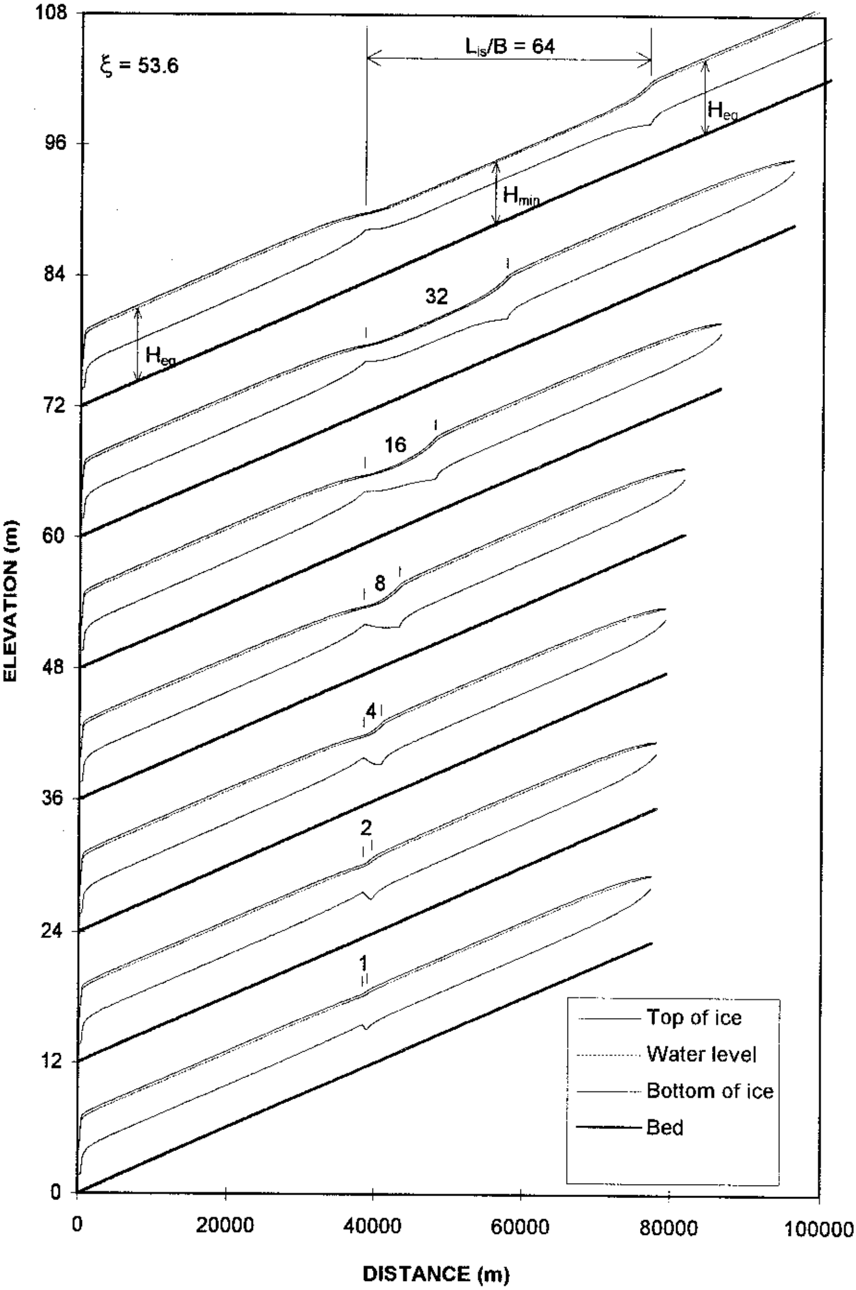

Figure 3. Ice jam simulations for various island lengths (Runs 8 - 14, medium thickness ice jam type).

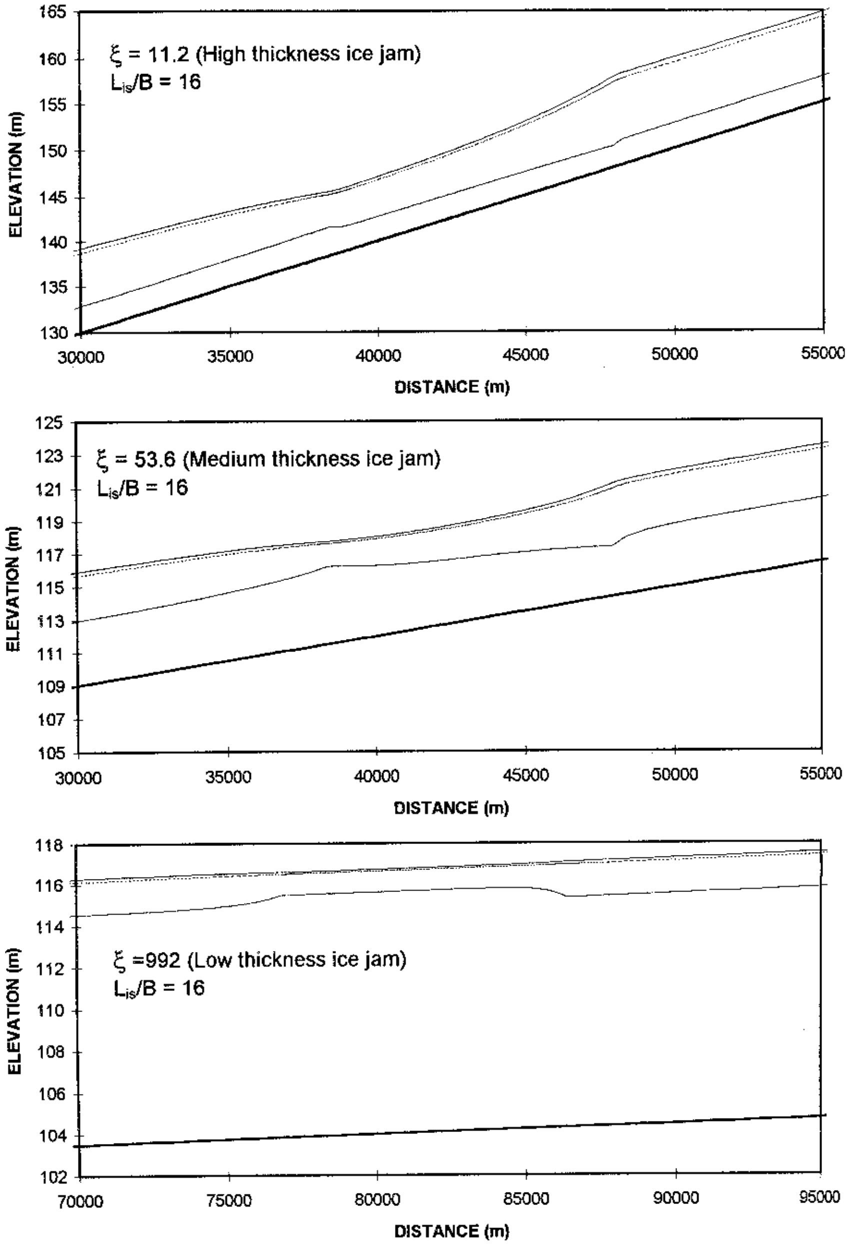

Figure 4. Simulated ice jam profiles with islands for dimensionless discharges of 11.2, 53.6, and 992 (Runs 3, 10, 16).

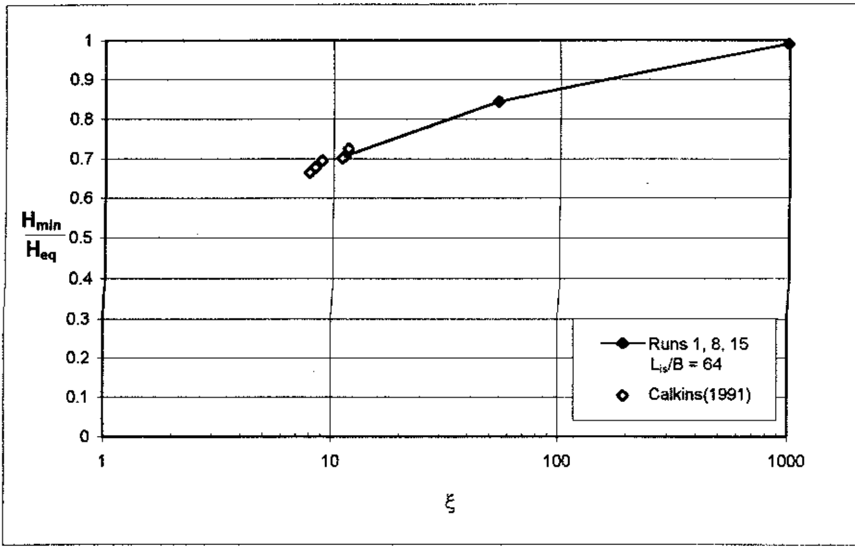

Figure 5a. Reduction in stage as a function of the dimensionless discharge ξ for long islands (L_{is}/B=64, Runs 1 ,8,15). Also shown are results from Calkins (1991).

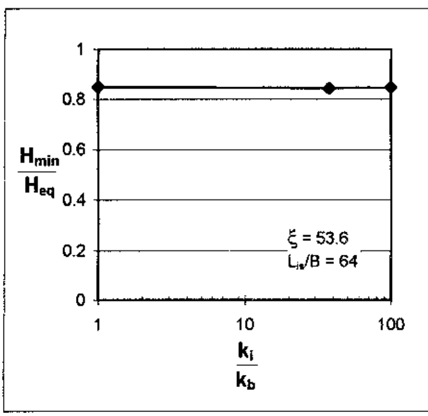

Figure 5b. Reduction in stage as a function of the ice jam to bed roughness ratio. Dimensionless discharge is constant, islands are long (Runs 18 - 20).

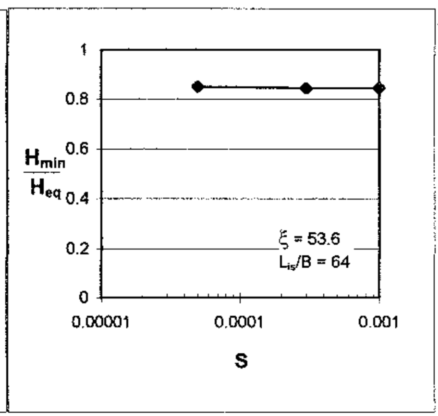

Figure 5c. Reduction in stage as a function of the channel bed slope. Dimensionless discharge is constant, islands are long (Runs 21 - 23).

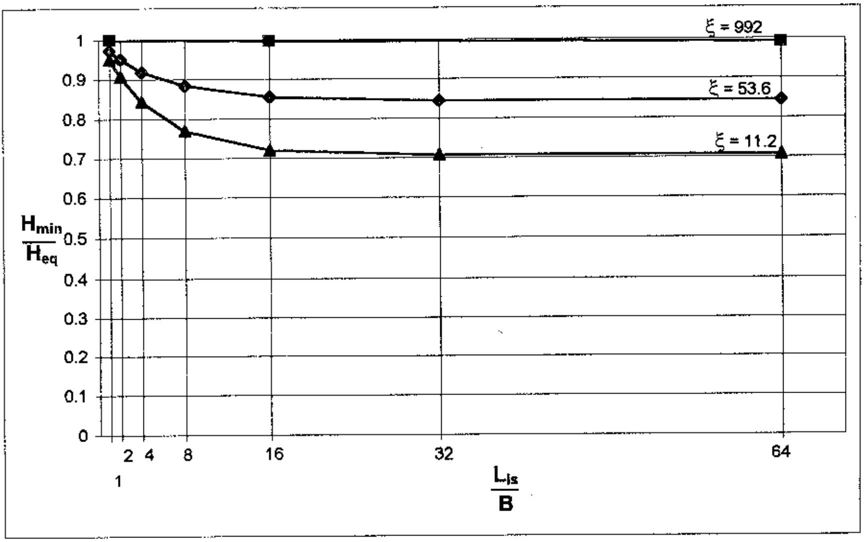

Figure 6. Reduction in stage as a function of the dimensionless discharge ξ and the relative island length L_{is}/B (Runs 1 - 17).

Figure 6 shows the stage reduction ratios for island lengths ranging from 1 to 64 channel widths and ξ ranging from 11.2 to 992. These curves are useful in determining an estimate for the stage reduction if some simple channel parameters (Q,S,B,k,L_{is}) are known. Figures 5a through 6 indicate that the stage reduction due to an island is only a function of the ice jam type (dimensionless discharge) and dimensionless island length:

$$\frac{H_{min}}{H_{eq}} = f\left(\xi, \frac{L_{is}}{B}\right) \tag{9}$$

PRELIMINARY APPLICATION OF RESULTS TO THE YUKON RIVER AT DAWSON

The following is an example application of the results of the island simulations in a rectangular channel applied to a natural situation; the Yukon River at Dawson. This was done to obtain a preliminary estimate of the effect of islands on the ice jam stage in order to determine if further detailed analysis on the Yukon River is required.

Gerard, Jasek, and Hicks(1992) obtained ice jam rating curves for the Yukon River at Dawson using the ICEJAM model. Although this was basically the same model used in this study, it did not model the effect of islands. The following is an example calculation using information from Gerard et al for initial input:

Flood Stage = H_{eq} = 11 m
Q = 4000 m^3/s
S = 0.00032
B = 600 m

k_i = 3.0 m
k_b = 0.08 m
k = 0.73 m

Using Equation 8, a value of dimensionless discharge was obtained:
$\xi = 89$

Using Figures 5a and 6, stage reduction ratios for long and short islands were obtained and the corresponding decrease in stage was calculated. It is possible that long island results apply to some sections of the Yukon River where many shorter islands occur in frequent succession. The calculated stage reduction ranged from 0.44 m for short islands to 1.43 m for long islands. Using the rating curve in Gerard et al, this translates to an increase in channel discharge capacity ranging from 10 to 30%. This indicates that there may be a significant effect of islands on the Yukon River at Dawson which warrants further analysis.

Table 3.
Stage reduction ratios (H_{min}/H_{eq}) obtained in study were applied to the Yukon River at Dawson to obtain initial estimates of the effect of islands on ice jam stage(H_{eq}-H_{min}).

	L_{is}/B	H_{min}/H_{eq} (Fig.5a & 6)	H_{min} (m)	H_{eq}-H_{min} (m)
Long island	64	0.87	9.57	1.43
Short island	2	0.96	10.56	0.44

DETAILS OF NUMERICAL SOLUTION

Figure 7 shows the iterative process used to obtain ice jam profiles around islands. The iterative process used the ICEJAM model to solve for the different channel segments and then linked them together with the appropriate boundary conditions. DS, IS, and US denote the channel segment downstream of the island, the channel

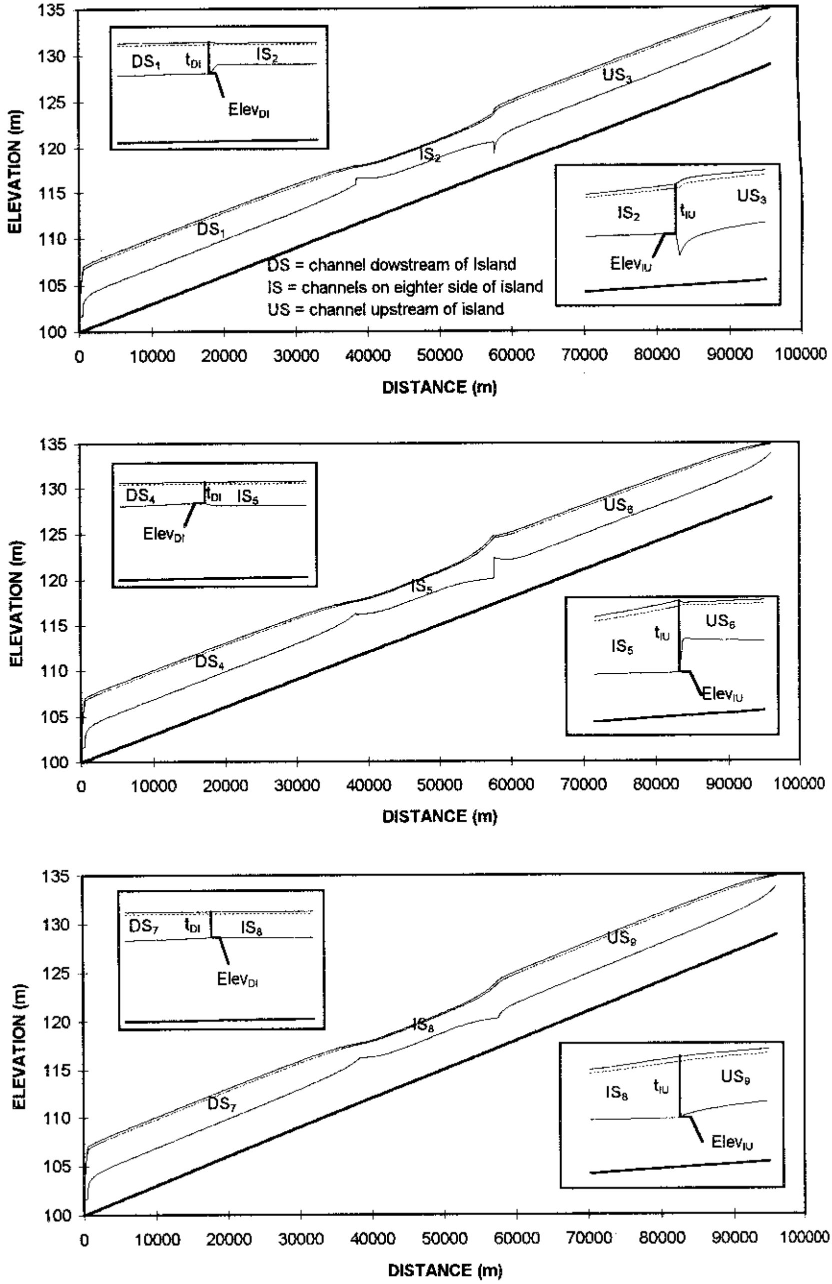

Figure 7. Ice jam profiles showing the iteration process for the boundary conditions of the downstream, island, and upstream ice jam segments (Run 9).

segments on either side of the island, and the channel segment upstream of the island respectively. The subscripts on each denote the order in which the thickness profile segments were solved. The boundary conditions which had to be iterated were the ice jam thicknesses t_{di} and t_{iu} at the downstream and upstream ends of the island respectively. The inset plots show a close-up of the thickness profile near these boundary conditions. The first guess for t_{di} and t_{iu} was the equilibrium jam thickness of the island channel and upstream channel respectively. This gave the DS_1 - IS_2 - US_3 profile shown in the figure. This initial guess for the boundary condition thicknesses produced large discontinuities near the boundary conditions. It is apparent from the profile that t_{di} was overestimated and t_{iu} was underestimated. This discontinuity had a corresponding error in the thickness equation (Eqn. 1). This error always occurred upstream of the boundary condition as the thickness profile is calculated in a downstream direction. The guess for the 2nd iteration for t_{di} and t_{iu} was taken as the thickness at the node immediately upstream of the boundary locations. This iteration, DS_4 - IS_5 - US_6 produced another error in the thickness equation near the boundary conditions. These errors were then used in the Newton-Rhapson method to calculate t_{di} and t_{iu} for the DS_7 - IS_8 - US_9 (3rd iteration) and so on until the thickness equation was satisfied for all channel segments. It would take anywhere from 5 to 20 iterations to arrive at a final solution. Longer iterations would occur for shorter islands. This is because the two boundary conditions were close enough together that they were coupled; both thicknesses had to be solved for using the 2-D form of the Newton-Rhapson method.

Figure 8 shows the values of the terms in the differential thickness equation and the converging errors at one of the upstream boundary conditions. The error always occurs upstream of the boundary condition since the thickness equation is solved in the downstream direction.

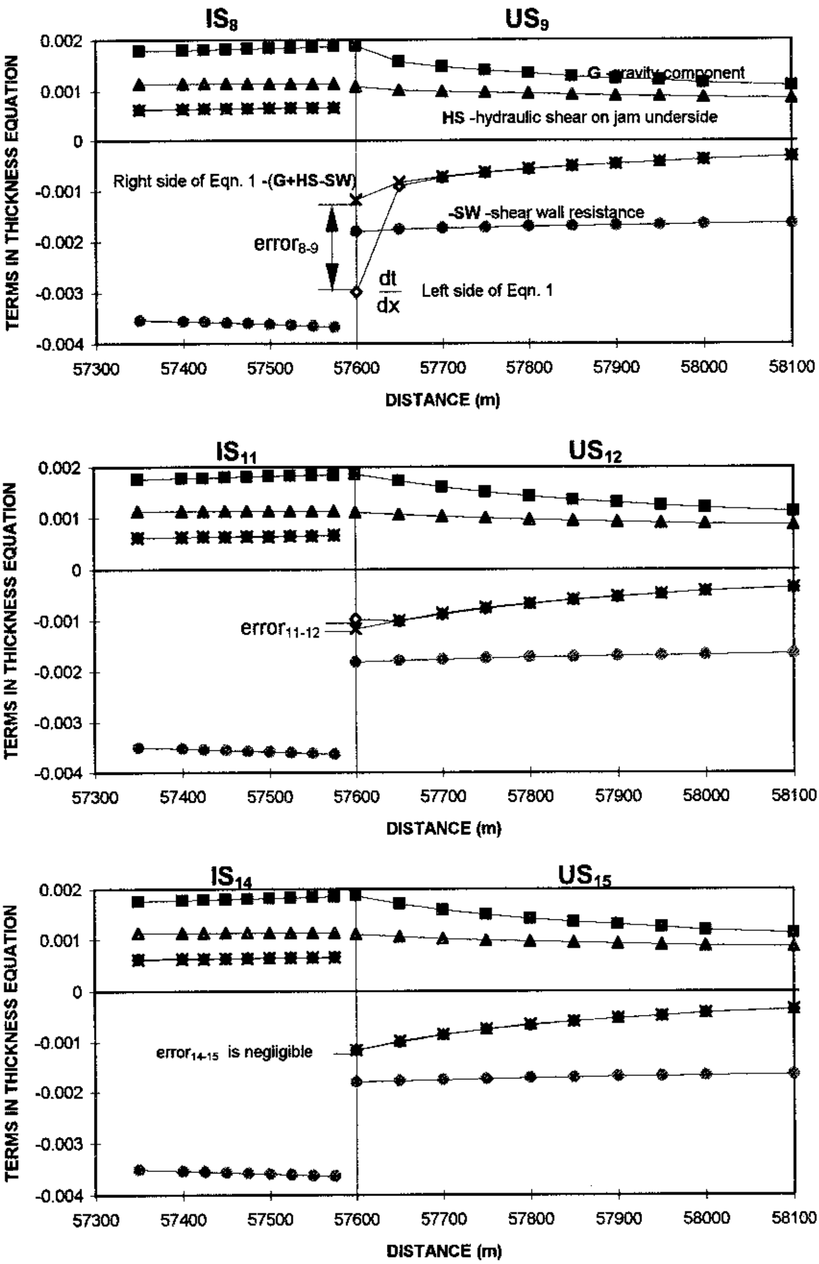

Figure 8. Terms in of the ice jam thickness Equation 1 were used to iterate for the boundary conditions (ice thicknesses t_{DI} and t_{IU}) of the downstream, island, and upstream ice jam segments. Shown here is the iteration for t_{IU} only (Run 9).

CONCLUSIONS

The ICEJAM model developed by Flato and Gerard(1986) was used to simulate ice jam profiles around islands in rectangular channels by splitting up the profile into several channel segments and linking them with the appropriate boundary conditions. The boundary conditions consisted of the ice jam thickness where the ice jam profile segments joined. The value for these thicknesses had to obtained by an iterative process until errors in the thickness equation for all channel segments and nodes were negligible.

Simulations were performed to investigate the effect of island length, channel width, channel slope, discharge and hydraulic roughness of the bed and ice jam. Through dimensional analysis, the dimensionless reduction in stage due to the island was found to be a function of only the dimensionless island length and the dimensionless discharge. The dimensionless discharge was useful in incorporating the effect of channel width, channel slope, channel discharge and hydraulic roughness into one variable. The channel width and slope had the largest effect on the dimensionless discharge (or ice jam type) and thus on the stage reduction due to islands. In general, islands reduce the relative stage in wider and steeper rivers to a higher degree than in narrow and flatter rivers. The definitions of the terms high, medium, and low thickness ice jam types were introduced. The ice jam type was shown to be a function of the dimensionless discharge and helped illustrate the effect of islands on stage reduction on a more intuitive basis.

The investigation found that longer islands produced a larger reduction in stage than shorter islands. However, this reduction approached a limiting value for long islands that was equivalent to the theoretical reduction based on the equilibrium thickness.

A preliminary application of the results was performed for the Yukon River at Dawson. The results showed that there may be a 0.4 to a 1.4 m stage reduction at the flood stage. This translates to an increase in channel capacity of 10 to 30% which is significant and therefore warrants further analysis.

FURTHER STUDY

The next step in the analysis will consist of applying the method conducted in rectangular channels to a natural river. This will be possible with recent survey work conducted on the Yukon River at Dawson. This will involve simulating ice jam profiles with and without the effect of islands and comparing them to ice scar data from the 1979 ice jam flood.

Another possible angle of attack is to develop a 2-D model to simulate ice jam thickness profiles such as presented by H.T.Shen in these proceedings and proposed work by F.E.Hicks at the University of Alberta.

By modeling the porous flow through the ice pack as well as the conduit flow underneath the ice jam (as in the RIVICE model), it may be possible to make further refinements to the stage reduction curves developed in this study. However, this effect is likely only significant in the high thickness ice jam types.

REFERENCES

Beltaos, S., 1983. River Ice Jams: theory, case studies and applications. ASCE J. Hyd. Div., Vol. 109, No. 10, pp 1338-1359.

Calkins, D. J., 1991. Longitudinal floating structures - new concept in river ice control. CSCE Canadian Journal of Civil Engineering, Vol. 18, No.6, pp.933-939.

Flato G. and Gerard R., 1986. Calculation of Ice Jam Thickness Profiles. Fourth Workshop on Hydraulics of River Ice. Montreal, Quebec.

Gerard, R., 1988. Course Material for Ice Engineering, University of Alberta, Edmonton Alberta.

Gerard, R., Jasek M., and Hicks., F., 1992. Ice jam flood assessment - Yukon River at Dawson. Report prepared for Indian and Northern Affairs Canada. Whitehorse, Yukon.

Gerard, R. and Stanley S., 1988. Ice jams and flood forecasting, Hay River, N.W.T. Report prepared for Environment Canada and Indian and Northern Affairs Canada. Yellowknife, N.W.T.

Uzuner, M. S. and Kennedy, J. F., 1976, Theoretical Model of River Ice Jams. ASCE J. Hyd. Div., Vol. 102, No. 9, pp 1365-1383.

DISCUSSION

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First, I would like to express my appreciation for this work because this type of information has been long overdue. On a specific point, could you explain how you determine the absolute roughness of an ice jam? (k_i)

Reply: Thank you for the kind words. On your specific point, the bed roughness (k_b) is calculated from an open water surface profile using HEC-2. Using this k_b in the ICEJAM model, k_i can be calculated if the discharge and a surveyed ice jam profile are known. The relation used in ICEJAM between k_i, k_b and the combined roughness (k) is the following: $k = ((k_i^{1/4}+k_b^{1/4})/2)^4$. This relation is a reworking of the Sabaneev relation which is in terms of the mannings "n" coefficient:
$n = ((n_b^{3/2}+n_i^{3/2})/2)^{2/3}$.

K.S. Davar,
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Has consideration been given to use of the Froude No. for the main channel and island branches, as it characterizes the change in stage(depth); also is it related to the tendency for ice cover formation and progression?

Reply: The Froude No. has not been considered explicitly. However, the ICEJAM model is based on a force balance and therefore simulates the effect of the inertial-gravity ratio (or Froude No.) implicitly. The ice particle Froude No. may come into play when considering whether particles are entrained or juxtaposed during the formation of an ice jam. However, this is dependent on ice particle size and other factors. For simplicity, the model assumes that the particles can always be entrained and therefore a cover of a sufficient thickness to resist the downstream forces is always permitted to develop. It is a good point however, in certain situations where the velocity is not high enough to entrain the particles, islands would have no effect on the thickness.