HEADPOND ICE JAMS - WHERE WILL THEY OCCUR?

D. G. Judge[1], S. T. Lavender[2], R. W. Carson[3], and S. Ismail[4]

Abstract

A "one-dimensional quasi-steady state" numerical model has been developed to assist river engineers in identifying locations along a river channel where moving ice melee are likely to lodge and form ice jams. The model (JAMSIM) is a modified version of an earlier model (ICESIM) which is based on the force balance considerations of Pariset and Hausser (1961). Both models have the capability to simulate the evolution of stable ice jams and to calculate the resulting ice and water surface profiles. JAMSIM has additional capabilities which permit evaluation of likely lodgment locations.

The results of the numerical model can be used to evaluate the propensity for a moving ice melee to lodge due to changes in the geometric characteristics and hydraulic conditions in the reach of the river near the downstream end of the moving ice. These evaluations are useful for planning pipeline crossings, bridge crossings and other infrastructure projects. As well, the evaluation permits examination of alternative operating strategies for managing hydropower dams during ice breakup periods. A specific application of the numerical model to the Saint John River in New Brunswick, Canada, is presented and discussed.

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[1] Senior Hydrotechnical Engineer, Acres International Limited, Niagara Falls , Ontario, Canada.
[2] Manager, Special Projects, Acres International Limited, Niagara Falls , Ontario, Canada.
[3] Manager of Engineering, Acres International Limited, Winnipeg, Manitoba, Canada.
[4] Senior Engineer - Hydraulics, New Brunswick Power Corporation, Fredericton, New Brunswick, Canada.

INTRODUCTION

An analytic numerical model (JAMSIM) has been developed to assist river engineers in predicting locations along river reaches where released ice jams are most likely to re-lodge. JAMSIM calculates the stable cross-sectional ice area of a broken ice melee at each river section using the force balance considerations of Pariset and Hausser (1961) and taking into account both the prevailing river discharge and the downstream water levels which could be either natural or controlled by a dam. Using the results of JAMSIM it is possible to evaluate the propensity for ice jam lodgment due to geometric changes of the river in a particular reach for various combinations of river discharge and downstream water levels. Consequently, the model is a useful tool for examining alternative operating strategies for control dams and for predicting jam locations which assist in the selection of pipeline and bridge crossing locations, and planning other infrastructure projects.

The JAMSIM model is a modified version of an earlier model (ICESIM) originally developed by Acres in the 1970s. The concepts, structure, capabilities and limitations of the ICESIM and JAMSIM models are provided in this paper followed by a specific application to the Saint John River in New Brunswick, Canada.

ICESIM MODEL

ICESIM is a river ice simulation model originally conceived as a tool for analyzing the numerous ice problems in the construction of the Limestone generating station on the Nelson River in Manitoba, Canada. It has since been continually developed and used by Acres for over 20 years on a number of studies for ice management during both freeze-up and breakup periods. The model has also been used to develop inundation maps for ice jam flooding. The model has been applied successfully to many Canadian rivers which vary dramatically in size, climate, and geography. The model has the following general characteristics.

- It is a one-dimensional model, suitable for treating channels of uniform or slowly varying shape. It can provide practical solutions to analysis of processes in rivers where the process can be simplified and reasonably represented by a one-dimensional approximation.

- It simulates steady state flow conditions where a river's discharges can vary along the length of the river and are constant with time. In reality, however, many nonsteady situations can be approximated by a series of steady state conditions. This extends the application of the ICESIM model to limited unsteady state conditions.

- ICESIM is capable of simulating most of the ice processes in a fragmented river ice cover during the formation/freeze-up or the breakup periods. The model is based on a number of empirical and physically based formulae which have been developed independently by various investigators to characterize different ice processes. The model has the capability of calculating the backwater surface profiles caused by ice in rivers.

The ICESIM model considers the following ice processes that affect the water profile along a river.

a) **Rate of Ice Generation**
Daily volumes of ice supply are normally stipulated in the case of breakup conditions where guidance is obtained from ice thickness measurements. In the case of freeze-up, the volume of ice generated is calculated using heat transfer theory. The heat transfer theory uses mean daily temperatures as proposed by Michel (1971).

The rate of advancement of the upstream edge of an unconsolidated ice cover depends on the rate of ice supply from upstream. In periods of freeze-up, the upstream edge (or 'tail') of a growing ice jam may pause for several days in one location while a mass of ice accumulates. During breakup the rate of ice supply is typically large, and results from dislodgment of an upstream ice cover. When the river is congested with broken ice, some other aspects of the progression of the stable ice front require special treatment as described in (g).

b) **Ice Cover Advancement by Juxtaposition**
In a tranquil slow-moving river, ice floes and slush simply drift downstream until stopped by an existing stationary ice cover, island, bridge piers or any other obstruction in the river. This queuing process is sometimes call 'juxtaposition'. The upstream accumulation against the flow requires a minimum thickness and, if necessary, the upstream edge of the ice cover may be thickened as it progresses.

c) **Ice Cover Advancement Controlled by Hydrodynamic Stability**
During ice cover formation at higher velocities, incoming slush pans underturn and are swept under the existing cover. This occurs such that the leading edge reaches a maximum thickness of approximately one-third of the water depth (Pariset, Hausser and Gagnon, 1966). The 'swept under' ice is carried downstream under the ice cover until it reaches a location of lower velocity where it can be deposited. Eventually the accumulating mass deposits under the downstream ice cover may cause the water level to rise to the point where the flow velocities are slow enough for the ice cover to progress upstream by juxtaposition. The point at which the ice cover begins to progress upstream can be calculated from the critical Froude number, which is an input variable to the model.

The theory which relates the water level at which the cover is able to advance and the Froude number is based on the Bernoulli equation considering nonsubmersion of the frontal edge, and the continuity equation (Pariset and Hausser, 1961). Numerous laboratory and field measurements have shown that this concept accurately describes the stability of loosely floating ice pieces at the upstream edge of an ice cover.

d) **Ice Transport and Thickening by Deposition**
Ice swept under the tail (upstream edge) of an ice jam is carried by the flow until hydraulic conditions permit it to deposit underneath the ice cover. ICESIM uses a simple limiting velocity criterion. Michel (1971) gives values ranging from 0.3 to 2 m/s. The data upon

which these estimates are based has been obtained from observation of the deposition of frazil slush during the ice formation period. Frazil is easily transported by flow due to its high porosity and low density. Solid ice floes, as would exist during breakup, have greater flotation and angularity, and require higher velocities to keep them in movement under the ice cover. Hence, the deposition velocity would be expected to be larger for spring breakup conditions.

When ice is available, it is transported downstream until it reaches a location where the velocity is less than the specified maximum. Deposition occurs at this location. If deposition of the entire volume of ice at a section were to result in a velocity in excess of the maximum for this location, then an appropriate portion is again transported further downstream to other low velocity areas.

e) Ice Erosion

A check for ice erosion is incorporated in the water surface profile calculations. The program uses a second limiting velocity criterion. Although field data are seldom available to determine this parameter, it is obviously greater than the deposition velocity. Once ice is deposited under a cover, it tends to "lock" in place. Consequently, the force and hence the flow velocity must be greater to remove ice once it has been deposited.

If the velocity at any section is less than or equal to a maximum noneroding velocity, then the ice cover will not erode. Otherwise, the volume of eroded ice is calculated and it is deposited downstream.

f) Mechanical Thickening by Shoving

As the length of the jam increases, large forces develop in the ice cover and the cover may thicken and consolidate in order to maintain force equilibrium. The principal forces acting on an ice jam and the resulting thicknesses are dependent on whether a river is classified as 'narrow' or 'wide'. In a 'narrow' river, forces generated by the water on the underside of the ice are readily transmitted by the ice cover to the banks, and the maximum force within the jam occurs at its leading edge. In this case, the ultimate ice thickness would be calculated to satisfy hydrodynamic stability criteria. In a 'wide' river, the ice cover must thicken by a series of shoves or internal collapses to be able to successfully withstand the applied forces and to transfer them to the river banks and to the downstream ice cover. In this case the ultimate thickness varies through the length of the jam as required by force equilibrium.

As the tail of the ice jam progresses upstream, stresses in the ice cover increase. The forces derive from the drag force of the flow under the cover, the shearing stress of wind on the cover (negligible in most cases), the component of ice weight along the slope of the ice/water interface and the hydrodynamic thrust on the leading edge of the cover. These forces must be opposed by the internal resistance of the cover. If the imposed driving forces exceed the internal resistance force, the cover will be unstable and a 'shove' will occur. Figure 1 shows the forces acting on the ice jam.

Pariset, Hausser and Gagnon (1966) showed that the two major driving forces acting on an ice jam in a wide river are the forces caused by friction on the underside of the cover (f_2) and by the component of weight of the cover in the direction of the slope of the ice-water interface (f_3).

In ICESIM, if the net downstream force exceeds the internal resistance of the ice cover, a shove occurs permitting the ice cover to thicken to its internal equilibrium thickness. When a shove occurs, the required stable thickness of the ice cover is computed for this reach and the process continues in a downstream direction. Next, the backwater profile is recomputed while ensuring that the erosion velocity is not exceeded at any section. The volume of ice required to thicken all of the unstable cross-sections is then calculated. The model can also make allowance, if deemed appropriate, for a reduction in downstream forces due to the grounding of an ice cover, or additional resisting forces due to the presence of islands.

g) Ice Cover Advancement in Congested Rivers

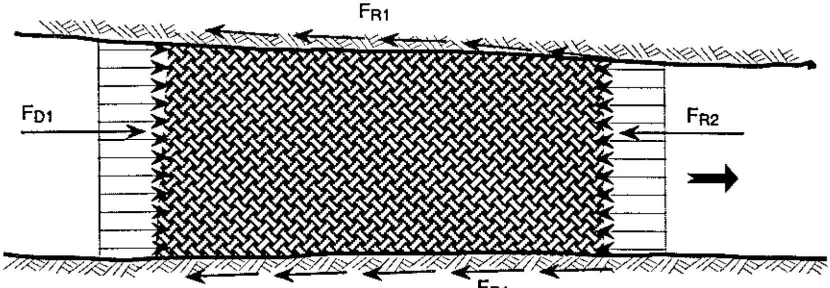
When ice arriving at the leading edge of a jam fills the river from bank to bank, the cover is observed to advance upstream at lower water levels and higher velocities than could occur with moderate rates of ice delivery. Such congested movement of ice most often occurs as an upstream jam releases and is transported downstream as a nearly coherent mass. The same process occurs in a jam undergoing consolidation by shoving. In both cases this movement of the ice cover stops when force equilibrium can be reestablished.

The advancement of the ice cover under congested river conditions is simulated by the normal force equilibrium features of ICESIM.

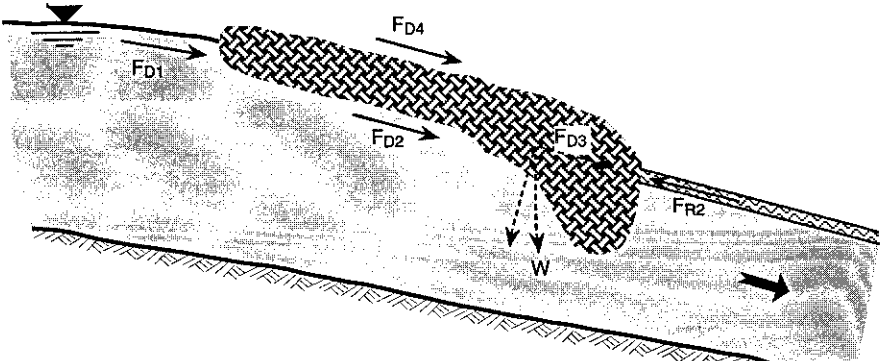
JAMSIM MODEL

The JAMSIM computer simulation model was developed in order to model the characteristics of alternative locations along a river with respect to variations in the stable equilibrium cross-sectional area of an ice jam for varying discharges and water levels. For any particular discharge and water level, the stable cross-sectional area of a stationary broken ice melee can be determined based upon the force balance analyses that have been incorporated into ICESIM and JAMSIM. The JAMSIM model calculates the stable cross-sectional area of ice accumulation for each river cross-section starting at the upstream end of a reach. The model assumes that a thermal ice cover (and associated backwater profile) exists downstream from the head of the broken melee. Therefore, the model is applicable only to the formation of breakup ice jams.

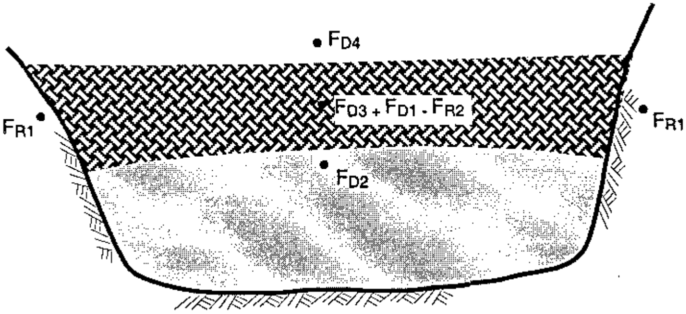
A moving melee of broken ice is influenced by the same forces as those that affect a stationary ice jam. However, some of these forces are slightly different as outlined below.



Plan



Longitudinal Section



Cross Section

Driving Forces
- Hydrodynamic $F_{D1} = f\ (V)$
- Drag $F_{D2} = f\ (Q, V,$ roughness, geometry$)$
- Weight $F_{D3} = f\ ($ice density, slope$)$
- Wind $F_{D4} = f\ ($speed & direction$)$

Resistance Forces
- Shear at Bank $F_{R1} = f\ ($cohesion, friction contact area$)$
- Downstream Resistance $F_{R2} = f\ ($downstream ice strength, islands, bidges, ice booms, etc.$)$

Figure 1
Forces Acting on an Ice Jam

- The under ice hydraulic drag force (a driving force) is less for a moving melee of ice because the force is determined by the relative velocity of water under the moving ice. If the ice melee is moving at the same velocity as the underlying water, then the under ice hydraulic drag force will be zero.

- A component of the bank resistance of the moving melee will be determined by the coefficient of kinetic friction as opposed to the larger coefficient of static friction for a stationary jam. Consequently, the resisting force will be less for a moving melee of ice than for a stationary ice jam.

Initially, attempts were made to evaluate the force balance for various assumed relative velocities of moving ice and water, but in the end it was concluded that there were too many unknown conditions to permit adequate analytic resolution of the problem. Consequently, it was decided that the most practical manner to evaluate the problem was to assume that the reduction in drag (driving) force was counter balanced by the reduction in bank resistance. Therefore, the stable equilibrium ice area for a stationary jam would be expected to be about the same as the ice area for a moving melee of broken ice.

Using the results of JAMSIM, it is possible to evaluate the propensity for ice jam lodgment in particular reaches of a river. If a moving melee of ice is traveling down a uniform prismatic channel of constant cross-sectional area under steady uniform flow conditions, a stationary ice jam would not be expected to occur because no channel geometry changes would 'trigger' a jam lodgment. Alternatively, if the channel contained a change in cross-section that resulted in a smaller stable equilibrium cross-sectional area of ice, relative to that of the immediate upstream sections, it would be expected that a lodgment might occur. This lodgment would be expected because of the effect of mass continuity and inertia of the moving ice.

In order to maintain mass continuity of the moving ice, it is necessary that a smaller cross-sectional area of ice move at a higher velocity. However, because of the inertia of the moving ice, the ice might not change velocity quickly enough to prevent congestion. Consequently, the accelerating ice might have a cross-sectional area greater than the stable equilibrium ice area and as a result a jam lodgment could occur. If the changes in the channel occurred gradually enough that the moving ice melee could accelerate without creating a situation where the continuity derived area[5] was greater than the force equilibrium derived area, lodgment would probably not occur.

It should be noted that the computations done by JAMSIM must always be considered in light of the assumptions that went into development of the model, i.e., that the reduction in driving forces for a moving melee of ice is counter-balanced by the reduction in bank resistance. The propensity for lodgment will also be determined by the momentum of the moving ice melee and how quickly the ice can accelerate and reconfigure itself so that lodgment does not occur even in a narrowing, constricting channel reach. Nevertheless, even with these limitations, the model can be used to

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[5] The continuity derived area is derived from the fact that the product of the moving ice velocity and the ice cross-sectional area is a constant, i.e., if the moving melee accelerated to say twice the velocity, then the ice cross-sectional area would be halved.

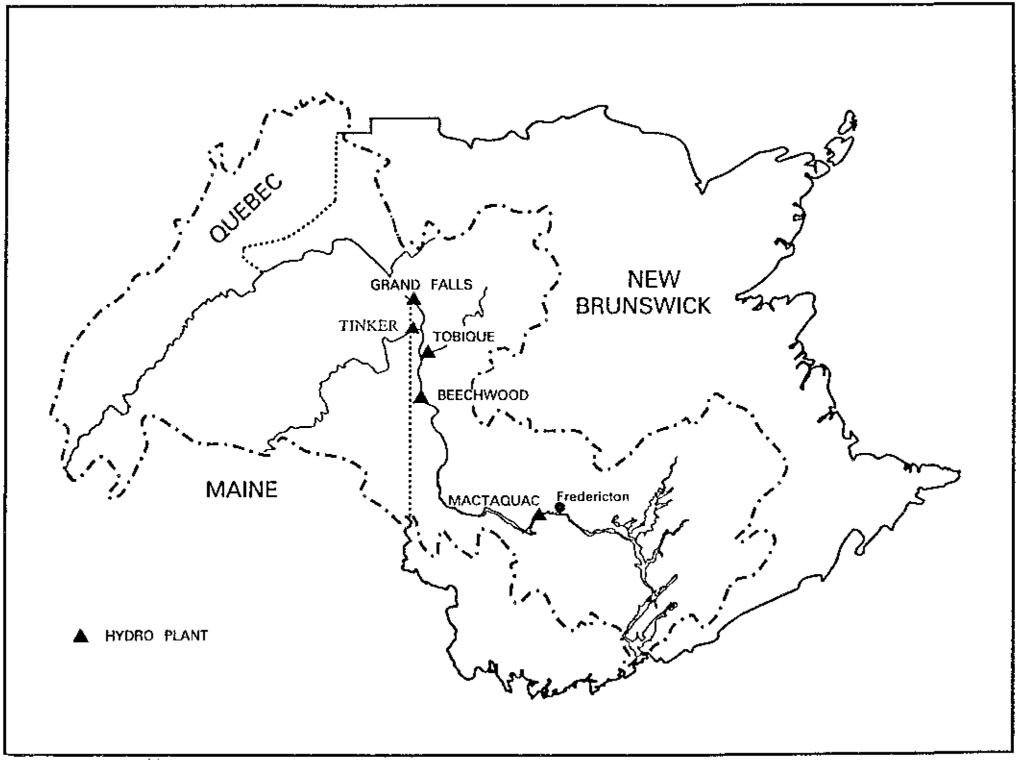

FIGURE 2
SAINT JOHN RIVER BASIN

evaluate the propensity for jam lodgment in particular river reaches for different discharge and downstream water level scenarios.

By using JAMSIM to determine the stable cross-sectional area of ice accumulation for particular river reaches, it is possible to evaluate the propensity for jam lodgment at certain locations within a reach. The results of these evaluations are useful in making decisions for selecting locations for pipe and bridge crossings, as well as to assist in the planning of other infrastructure projects along a river reach.

The JAMSIM model can also be used to examine the sensitivity of propensity for lodgment to variations in river discharge and downstream water levels. These downstream water levels can be routed or controlled. This sensitivity analysis permits examination of alternative operating strategies for managing hydropower dams during ice breakup periods.

The JAMSIM model was originally developed to assist in analyzing ice jam events in the Saint John River upstream from the Mactaquac and Beechwood hydro generating stations. The following sections present the application of the model to the Saint John River reach upstream from the Beechwood dam.

APPLICATION OF JAMSIM TO THE SAINT JOHN RIVER

The Saint John River is one of the larger rivers flowing into the Atlantic ocean. It is 720 km long and drains an area of 54,600 km^2 before it empties into the Bay of Fundy at the Reversing Falls near the city of Saint John. The main stem of the river has three hydro developments located at Grand Falls, Beechwood and Mactaquac. There are two other hydro developments located on the Tobique and Aroostook rivers near their confluences with the Saint John River (see Figure 2). Ice breakup and jamming is a common event at many locations along the Saint John River, causing water and ice damage.

The river reach upstream of the Beechwood dam has been subjected frequently to ice jam flooding and damages, particularly in the Perth-Andover area 25 km upstream of the dam. Figure 3 shows the common locations of ice jams in this river reach. Ice jam observations, over the years, indicate that there is a pattern for the ice movement in this reach. When an ice jam is released from one location, it is likely to re-lodge at a number of the other common ice jam locations downstream. Historically, most of the damages in the Perth-Andover area have occurred when an ice jam is lodged near the Upper Kent location.

The analyses reported herein were summarized from a study which was undertaken as a part of ongoing efforts to better understand the mechanism of ice jam progression in the Beechwood head pond, and consequently to devise a revised operating strategy for the Beechwood dam. The JAMSIM model was used as a tool to achieve this goal. The following is a presentation of the model applications, results, and interpretations.

The JAMSIM model has been used to calculate the area of stable ice accumulation (ice jam) at each available river cross-section in the thirty km reach upstream of the Beechwood dam. The

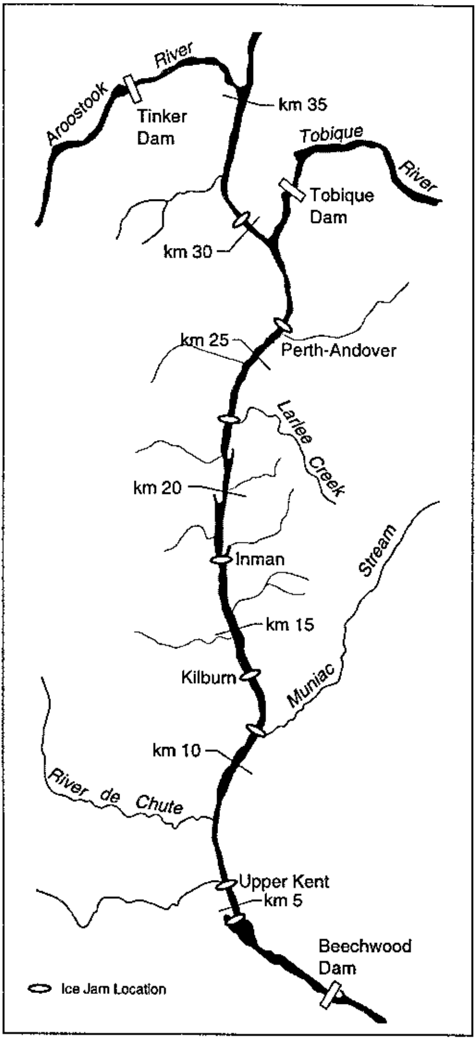

Figure 3
Common Ice Jam Locations
St. John River - Beechwood Reach

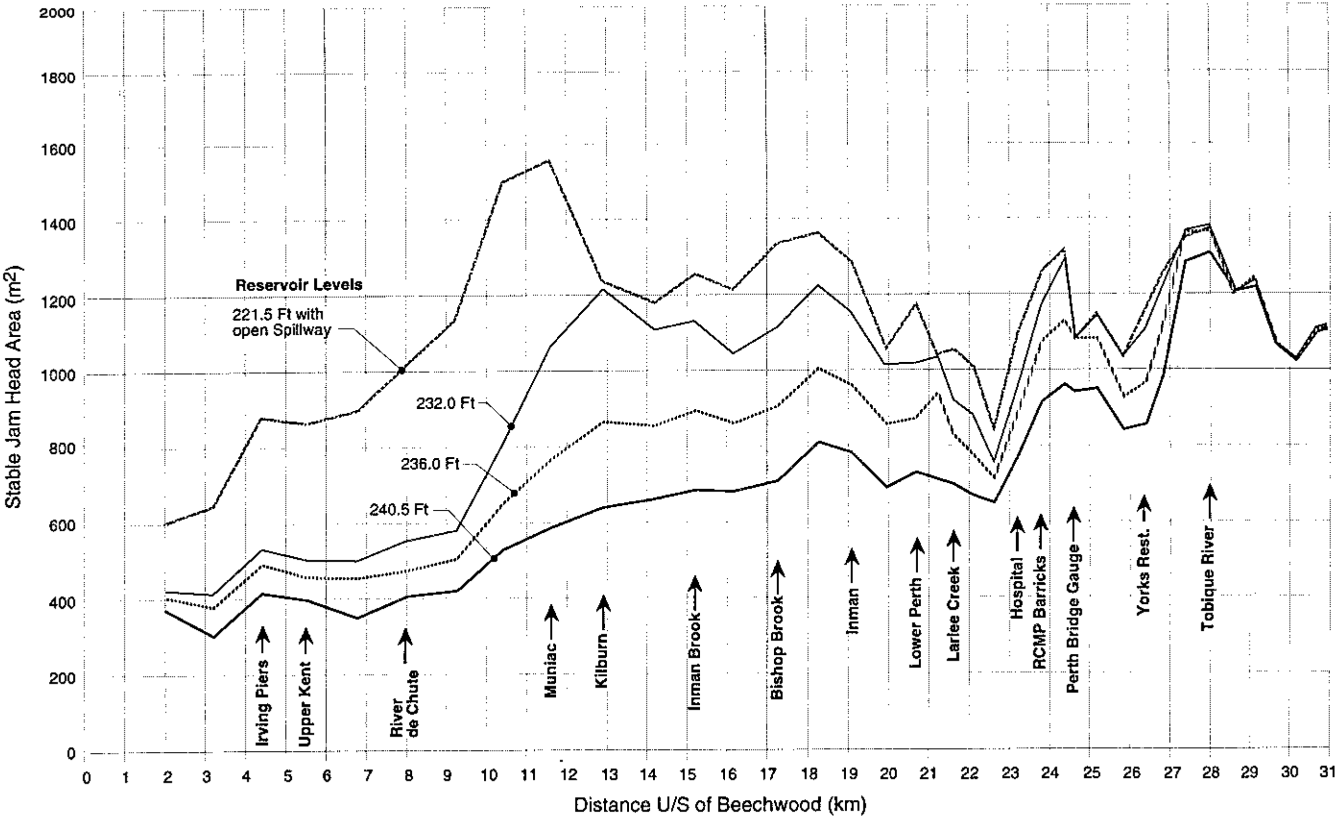

Figure 4
Propensity for Ice Jam Lodgement in the Beechwood Reach for 100,000 cfs

model simulations were undertaken for a wide range of river flows (50,000 to 200,000 cfs, at 50,000 cfs increments) and alternative water levels at the dam. Figure 4 presents the model simulation results for a river flow of 100,000 cfs. It is expected that the propensity for an ice melee to lodge increases as the area of stable jam decreases , relative to the area of stable jam at the immediate upstream jam locations. It is also expected that the propensity for jam lodgment increases as the rate of such change increases. However, it is not possible to determine the critical value of such a rate of change of stable jam area. Nevertheless, the figure can be used to assist in developing an operating strategy for the Beechwood dam as the ice melee travels downstream in the head pond.

Ice jams generally move through the Perth-Andover bridge (km 25) when the inflow into the head pond is in the range of 80,000 to 110,000 cfs, depending on the physical properties of the ice and the water levels downstream. Normally, ice jams upstream of Perth-Andover bridge do not cause any appreciable damages. Consequently , it is desirable to attempt to keep ice jams upstream of the bridge as long as possible. This objective can be achieved by maintaining the water level at the dam at the highest permissible level until the ice starts to move through the bridge. This strategy is denoted on Figure 5 by point "A". If the water level at the dam is kept constant when the ice moves through the Perth-Andover bridge, trajectory "c" on Figure 5 results. Under this scenario, the area of stable jam area is reduced by about one third as the ice melee reaches the next ice jam location, just upstream of Larlee Creek (km 22). This would result in an increasing propensity for re-lodgment at or near km 22. The propensity for lodgment at this location however, is reduced if the stable ice jam area can be kept nearly constant, or increasing. This would require lowering of the water level at the dam, as quickly as possible, to the lowest level possible as the ice starts to move through the bridge. This is shown on Figure 5 by trajectory "a". Considering the short distance between the bridge and Larlee Creek (about 3 km), as well as the response time between the dam and Larlee Creek, a realistic and achievable goal is likely somewhere between trajectories "a " and "c", which is shown on Figure 5 by trajectory "b". The corresponding head pond water level is indicated by point "B".

As the ice passes, or is released from, the Larlee Creek location, the propensity for jamming at the intermediate locations in the Larlee Creek to River de Chute reach (km 22 to km 8) will be reduced by lowering the water level at the dam, according to trajectory "d" on Figure 5. However, the area of stable ice jam decreases rapidly in the reach immediately downstream of km 10, thereby significantly increasing the propensity for ice lodgment in the River de Chute-Upper Kent reach (km 10 to km 5) should the ice move to this reach while the water level is low. Considering that most of the damages in the village of Perth-Andover occur when the ice is lodged in the Upper Kent area, a preferred approach is to allow the water level to climb up until the ice passes km 18 then gradually lower the head pond water level to point "C" according to trajectory "e" on Figure 5. Once the ice moves downstream of km 10 toward Upper Kent, the propensity for lodgment will be reduced if the head pond is drawn down further. Trajectory "f" on Figure 5 shows this strategy as the ice moves from point "C" to "D".

It should be noted that the above discussion is based on the river flows being constant at 100,000 cfs for the entire period during which the ice travels between Perth-Andover and Upper Kent. In reality however, river flows during the ice run period increase rapidly and could reach 200,000 cfs by the time the ice passes the Upper Kent location (km 5). Figure 6 shows the area

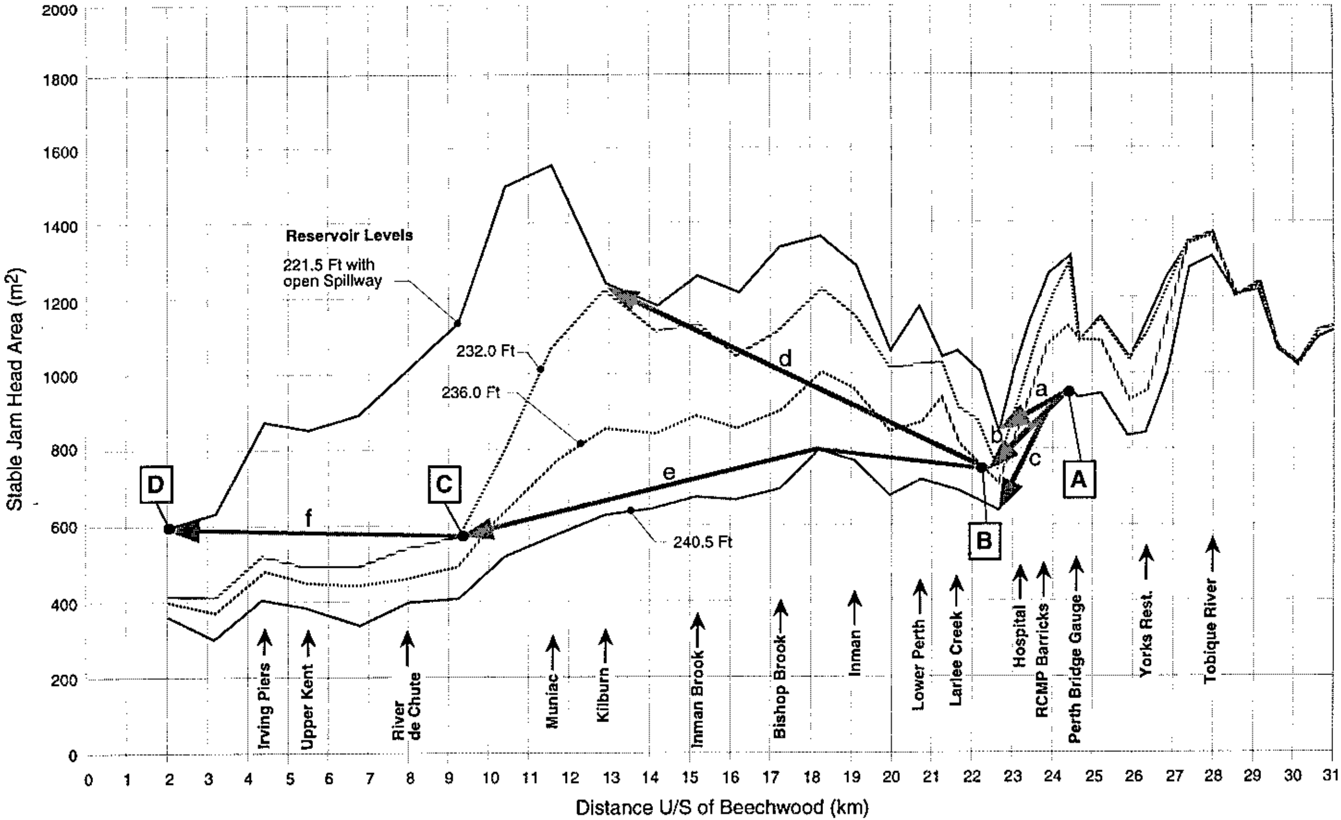

Figure 5
Possible Beechwood Operating Strategies to
Reduce the Propensity for Ice Jam Lodgement at 100,000 cfs

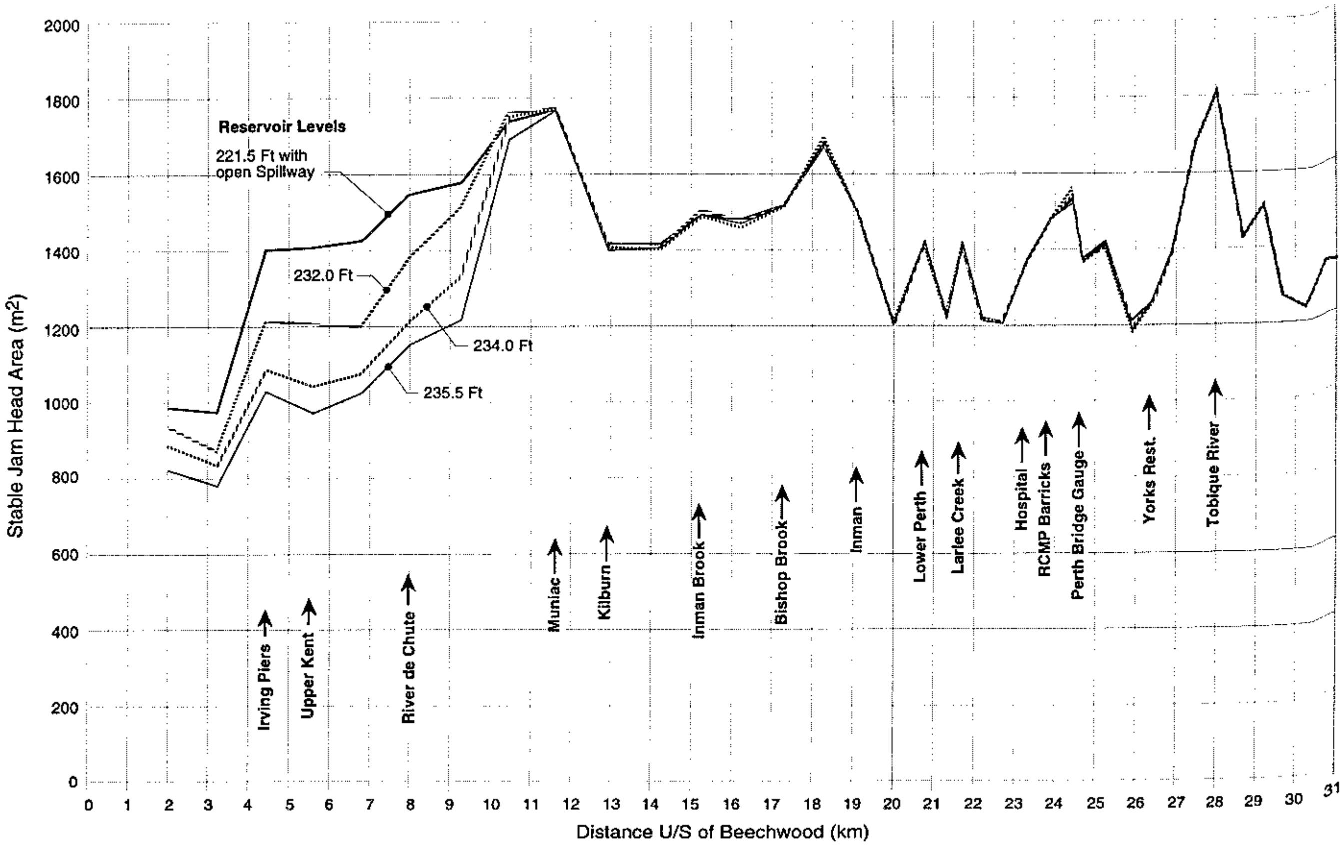

Figure 6
Propensity for Ice Jam Lodgement in the Beechwood Reach for 200,000 cfs

of stable ice jam along the 30 km reach upstream from Beechwood dam for river flows of 200,000 cfs. Comparative analyses of Figures 4 and 6 leads to the conclusion that the capability for manipulating the head pond water levels as a means of influencing ice movements in the head pond upstream from km 10, gradually diminish as the river flow increases.

The precise behavior of ice movement in the reach is difficult to predict due to the dynamic characteristics associated with it including, but not limited to, rate of change of river flows and the physical properties of the ice supply. It is possible however to use JAMSIM results to reasonably predict where ice melee may lodge, and to assess the behavior for alternative operating strategies.

CONCLUSIONS

The area of the head (downstream end) of a stable ice jam is dependent on the prevailing river flows and the river geometry, mainly the flow cross sectional area. In the case of a controlled river reach, the area of the head of a stable ice jam is influenced by the downstream water level and the influence of the downstream water levels on the area of stable jam progressively deminishes as the river flows increase. The results of the JAMSIM model demonstrate that the rate of change of the area of stable jam head along a river reach can be used to assess the relative propensity for ice jam lodgment along a river reach. The model results can also be used to evaluate alternative strategies for operating downstream river control structures so that the likelihood for ice jam lodgment in the upstream reach is reduced.

ACKNOWLEDGMENTS

Over a period of many years, New Brunswick Power have invested heavily in research and development to better understand the ice regime of the Saint John River. This effort has resulted in the development of a number of tools that are used to assist with head pond operations during ice breakup periods. The JAMSIM model is one of these tools. The authors would like to thank New Brunswick Power for the opportunity to share these developments with the scientific and engineering community.

REFERENCES

Michel, B. (1971). "Winter Regime of Rivers and Lakes."

Pariset, E. and R. Hausser (1961). "Formation and Evaluation of Ice Covers on Rivers", Transactions of the Engineering Institute of Canada, Volume 5, No.1, p 41.

Pariset, E., R. Hausser and A. Gagnon (1966). "Formation of Ice Covers and Ice Jams in Rivers", ASCE Journal of the Hydraulics Division, Volume 92, HY6, pp 1 - 24.