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Modeling of River Ice Jams for Flood Forecasting in New Brunswick

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ABSTRACT

Ice jams cause major flooding and severe damages to communities and infrastructure along the Saint John River. As the climate changes within the Saint John River Basin, ice movement and the potential for ice jam damages may increase. There is a growing need to develop capability in forecasting and analyzing ice-jam-related flood events. The HEC-RAS model has been applied to recent events along the international Saint John River from Dickey, Maine, USA, to Grand Falls, New Brunswick, Canada where calibration data and local observers' reports on ice conditions are available. The model has been applied to various situations including ice jams formed during freeze-up, mid-winter thaw and during spring breakups. Difficulties encountered during model runs and methods to overcome these are discussed. In general, it is possible to obtain good agreement between computed and measured water levels by adjustment of various model coefficients such as the friction angle and the critical ice transport velocity. Model performance was improved considerably when a set of additional transects were generated by interpolation to reduce the transect spacing. Future work will include linking the model with remote-sensing imagery and developing operational procedures to forecast flooding associated with predictable ice jams.

Keywords: breakup; calibration; flooding; HEC-RAS; model input; prediction

INTRODUCTION

The province of New Brunswick is home to many scenic ecologically rich streams and most New Brunswickers live along their banks. Along with the benefits of riverside residence, however, come flood risks. Flooding may be caused by high water volumes under open water conditions or by a combination of moderate flows and ice jams. The Saint John River is the largest in the province, and prone to flooding, especially in middle and upper reaches, respectively defined as Mactaquac to Grand Falls and above Grand Falls. Ice-jam flooding in the Saint John River basin is responsible for 70% of total flood damage (Humes and Dublin, 1988), and there is evidence of increasing, climate-related, severity (Hare *et al*., 2007a, 2007b; Beltaos, 2002). To ensure the safety of the many communities and help mitigate flood impacts, the NB Hydrology Centre (HC), which is a part of the NB Dept. of Environment (NBENV), generates timely forecasts during high runoff periods. The forecasts are based on the numerical SSARR (Streamflow Synthesis And Reservoir Regulation) model which is an open-water hydrologic model. During periods of ice effects on stage, the model cannot provide accurate water levels, but the forecasts are

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supplemented by frequent local observers' reports on ice conditions. Such reports help the forecasters make qualitative judgments as to immediate risks.

Ice jam prediction is a problem of major practical significance, but so far only partially solved by river ice researchers and engineers. It is not yet possible to predict whether and when an ice jam will form at a particular location and when it might release. However, "proven" modelling capability has become available in recent years for predicting the water levels caused by an ice jam, given its location and extent as well as channel bathymetry and flow discharge (Beltaos, 2008). Though limited in scope, this type of modelling can be very useful in flood forecasting, especially where it can be coupled with insitu reports from local observers. To realize this potential, a modelling program was initiated, aiming at implementation, calibration, and eventual operational application of a river ice model on the upper Saint John River. This task is greatly facilitated by data collected under the Saint John River Ice and Sedimentation (SJRIS) study, which was jointly carried out in the 1990s by then NB Dept. of the Environment and Local Government (NBELG), NB Power and the National Water Research Institute (NWRI) of Environment Canada.

The objective of this paper is to provide a progress repot on this work. Following brief descriptions of the study reach and the ice regime of the upper Saint John, the choice and calibration of the model are discussed. Problems that were encountered in early model runs and adopted remedies are identified. Examples of model runs with and without ice jams are presented next and future steps discussed,

STUDY AREA

The Saint John River basin (55 100 km^2) forms a broad arc across southeastern Quebec, northern Maine (USA), and western New Brunswick. The upper Saint John River basin has a modified continental climate generally characterized by cold winters, cool summers, and no dry season. Mean annual precipitation is about 1100 mm, of which about 340 mm is snowfall. The Saint John River flows for approximately 700 km from Little Saint John Lake in the State of Maine, U.S.A. to the Bay of Fundy at Saint John, New Brunswick, Canada. The total fall of the river is about 480 m. Fig. 1 is a plan view of the St. John River from Dickey (Maine) to Beechwood (NB).

There are two hydropower generating stations (GSs) within the study area, one at Grand Falls and a second at Beechwood. The river upstream of Edmundston can be considered unregulated. From Dickey to Grand Falls, the river length is approximately 145 km. Between Dickey and Edmundston the river is steep and has a series of rapids that can delay, or even prevent, the formation of a stable local ice cover. These rapids can contribute to the generation of large volumes of frazil that eventually accumulate to form a solid ice cover or a hanging dam depending upon local hydraulic conditions and channel geometry (Beltaos *et al*., 2003). Generally, the river from Dickey to Edmundston is wide and shallow, with occasional islands that are far more prevalent above Fort Kent. The Saint John River from Edmundston to Grand Falls deepens in the backwater reach, where several large islands are also present. Backwater created by the Grand Falls Control Structure (GFCS) creates an almost flat water surface that extends up to 50 km upstream depending on the water level at the control structure and prevailing river flows (Beltaos *et al*., 2003). Between Dickey and Edmundston the river slope varies but is generally in the ballpark of 0.5 m/km. Above the Dickey bridge, the river steepens considerably (2 m/km). The stretch between Grand Falls and Beechwood is 64 km long. Under extreme low flows and maximum headpond level conditions, the backwater effect of the Beechwood dam extends 32 km upstream of the dam (to the mouth of the Aroostook River).

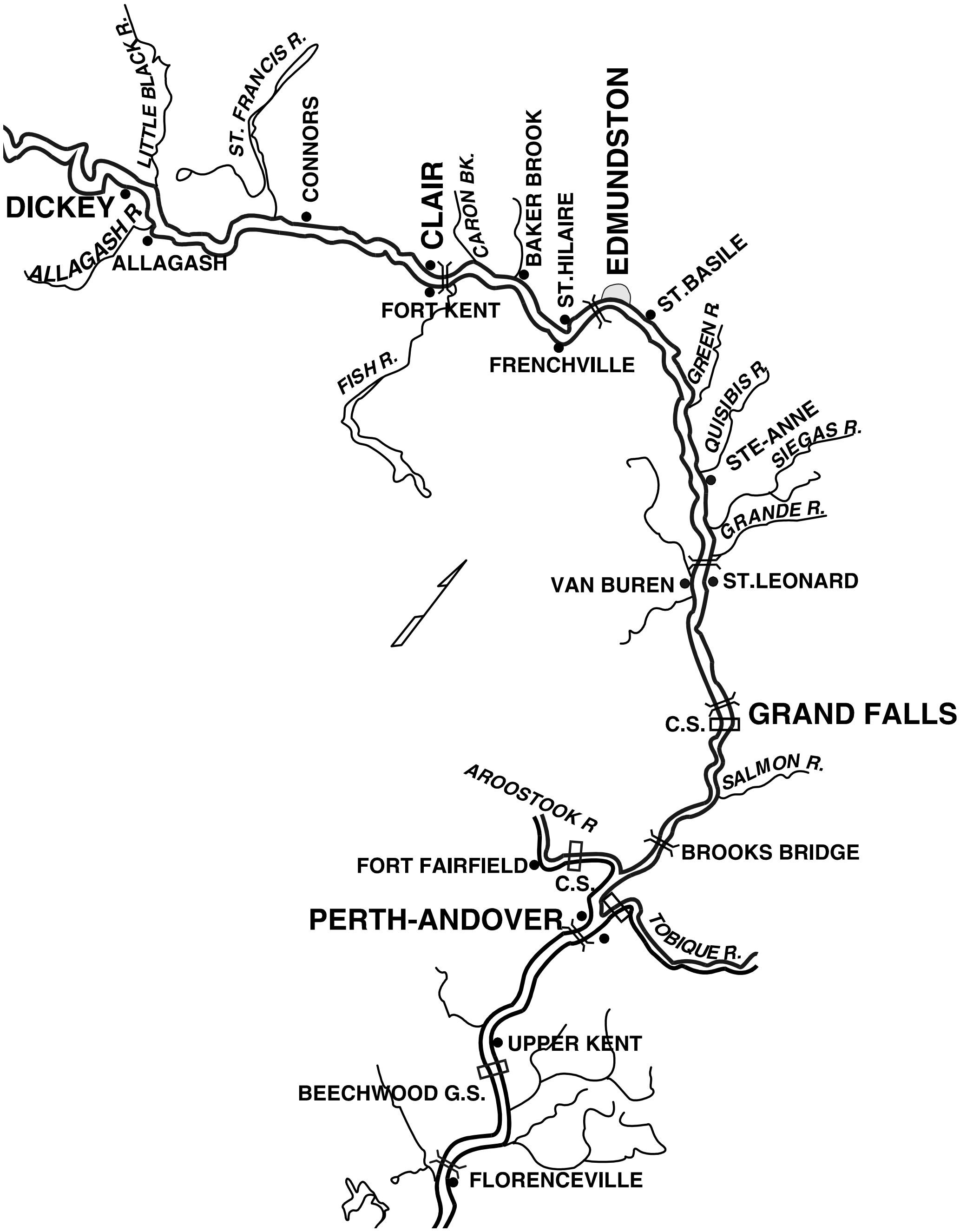

Figure 1. Study reach of the Saint John River. Channel width is exaggerated for convenience. From Beltaos *et al.* (2003).

ICE REGIME OF THE UPPER ST JOHN RIVER

The brief description of the ice regime presented in this section is based on more detailed information contained in Beltaos *et al*. (2003). The ice cover forms normally between late November and late January, and most frequently in December. The first ice cover appears in the Grand Falls headpond near the control structure, and quickly propagates upstream within the tranquil-flow reach towards Edmundston, where warm effluents from local paper mills suppress ice formation locally throughout the winter. At the same time, increasing amounts of slush are generated in the more rapid, upper reaches and the resulting ice pans eventually lodge at a few key locations. Ice covers then propagate upstream from these sites. It is thus common to encounter alternating open-water and ice-covered sections in the study reach during the freeze-up period. The spatial variation of ice thickness reflects differences in freeze-up timing and rate of freezing. Generally, the thickest ice is encountered near Dickey and Grand Falls. The Clair-Fort Kent reach freezes last and has the thinnest cover, typically attaining 0.5 m by the end of the winter.

Generally, spring breakup events occur in April and follow a common pattern. As temperatures rise and approach 0 °C, the ice cover downstream of Edmundston begins to recede in the downstream direction, owing to enhanced heat transfer at the open-water surface. When significant runoff is under way, the ice cover on several river sections between Clair and Dickey begins to break up, and small jams may form. With increasing flows, these jams eventually dislodge to form one or two major jams upstream of Clair. By this time, the relatively thin ice cover at and below Clair has already moved out and formed a jam near baker Brook (Fig. 1). When the above-Clair jams release, major ice runs occur that may be arrested and cause flooding at Baker Brook. More commonly, however, the ice runs easily dislodge the remaining sheet ice cover as far as Edmundston, and advance unhindered until they encounter the receding edge of the ice cover downstream of Edmundston. In this area, the relative thickness and strength of the local sheet ice cover and the significantly milder slope of the water surface can produce major ice jam floods (e.g. Ste-Anne de Madawaska, indicated simply as “Ste-Anne” on map, 1991, 1993).

On occasion, breakup may also occur in winter as a result of brief thaws and rainfall. Such events do not follow the above pattern and are often incomplete by the time the cold weather resumes.

MODEL SELECTION AND CALIBRATION

Several well-tested public domain models of ice jams are available (e.g. ICEJAM, RIVJAM, HEC-RAS). They are all based on similar equations and assumptions (steady state, one dimensional) but the HEC-RAS model is the most convenient for practical application: once implemented, it can be used for any type of condition such as open-water flow, sheet ice cover, ice jam, and any combination of these within the model reach. Channel bathymetry was specified by two sets of cross sections, respectively surveyed by NB Power in the 1920s and by NWRI in the 1990s.

The ice option of the HEC-RAS model requires the following input parameters:

-Locations of toe (downstream end) and head (upstream end) of an ice jam

-Locations of open-water and sheet-ice cover reaches

-Manning coefficients of river bed and sheet ice cover

-Thickness of sheet ice cover

-Manning coefficients of the undersides of ice jams (with default options of model-generated coefficients, which depend on jam thickness)

-Internal friction angle of the rubble comprising the ice jam (φ)

-Maximum allowable flow velocity underneath the jam (V_{max}). It is assumed that if this limiting value is exceeded, ice blocks within the jam will be mobilized and transported away by the flow. Consequently, a stable jam cannot exist if the under-ice velocity exceeds V_{max}.

Initial calibration was carried out with open-water and sheet-ice cover data in order to determine the respective Manning coefficients (bed, ice) over different sub-reaches of the study reach. The main data sources are three gauges, located near Edmundston (Water Survey of Canada), Fort Kent (USGS), and Dickey (USGS).

Several ice-jam data sets, obtained during the SJRIS study (Beltaos *et al.*, 1994; Beltaos and Burrell, unpublished data), were used to calibrate the model. An example of pre- and post-calibration results is illustrated in Figs. 2a and 2b. In this case, the default set of input parameters ($\varphi = 45°$; $V_{max} = 1.52$ m/s; Manning coefficient of ice jam = n_J = a function of the jam thickness) results in a thick jam with too high water levels. To adjust the input parameters, the following procedure was adopted: (1) adjust the internal friction angle, keeping V_{max} and n_J at default values, until good agreement with the measurements is obtained. (2) If this procedure does not result in satisfactory prediction, also adjust the value of V_{max} . (3) If step 2 does not work, either, also adjust the value of n_J . In the case depicted in Fig. 2a, step 1 was sufficient, with $\varphi = 51°$. This selection gave very good results, as shown in Fig. 2b.

A noteworthy feature in Figs. 2a and 2b, which also occurs in some other calibration runs, is the "bulge" in the predicted jam thickness near the head of the jam. It is difficult to account for this feature with what is known about the physics of ice jams (Beltaos, 1995). The RIVJAM model, for instance, does not exhibit such a "bulge" when applied to the same jam (Beltaos *et al.,* 1996) or to many other case studies (Beltaos, 1993). The most likely explanation is that the trial-and-error solution algorithm used in HEC-RAS for the ice-jam equations allows the user to specify the jam length, regardless of what the input parameters are. On the other hand, the more rigorous algorithm used in RIVJAM indicates that the jam length is a model output, that is, it depends on the input parameters. The input set must thus be adjusted until the known length is matched by the model output. Consequently, the bulge in Figs. 2a and 2b is an indication that the input set chosen in the HEC-RAS runs is very likely associated with a shorter jam, probably ending at km 43. However, because the location of the head has been fixed at 45 km, the model generates a fictitious profile to bridge the gap between 43 and 45 km.

The results of calibrations for all data sets are summarized in Table 1, where it maybe noted that the use of the default relationship (variable n_J) between jam roughness and thickness was the preferred option in all but one calibration set. This is consistent with indirect findings on freezeup jams by Nezhikhovskiy (1964) and with direct measurements on breakup jams (Beltaos, 2001). The limiting velocity, V_{max}, takes on calibration values between 1.0 and 1.5 m/s, representing a plausible range relative to what is known about the under-ice transport of ice floes (Beltaos, 1995). The angle of internal friction seems to vary from one jam to another, spanning the range 45° to 56°. As far as angles are concerned, this variation does not seem to be excessive. However, it is the passive resistance coefficient, K_p [$= \tan^2(45+\varphi/2)$] that largely determines the internal strength of the rubble in the jam. This coefficient is highly sensitive to the value of the internal friction angle. For φ = 45 to 56 degrees, K_p varies from to 5.8 to 10.7.

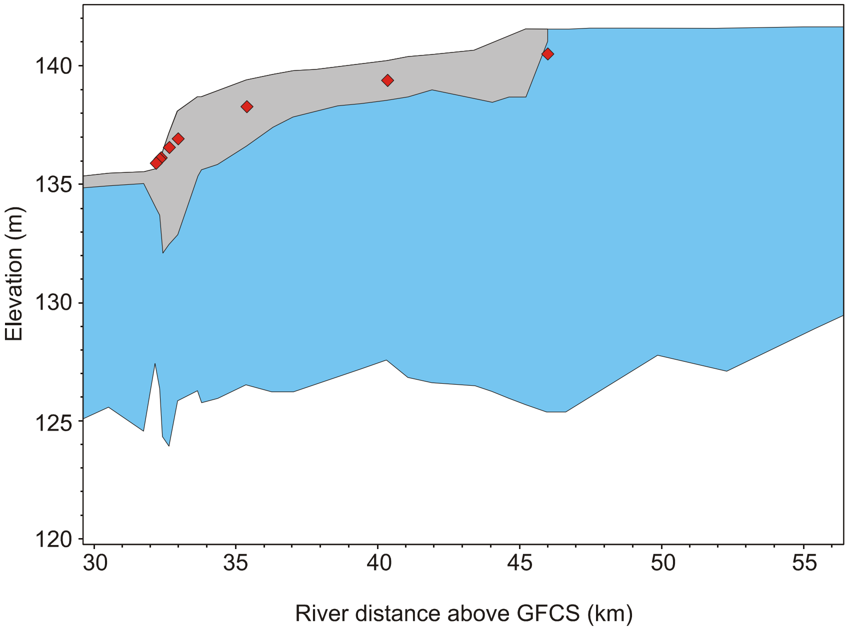

Figure 2a. Ice jam prediction using default values of input parameters, Saint John River near Ste-Anne de Madawaska. Data points represent measured water levels, April 12, 1991 (Beltaos *et al*., 1996). Shaded area represents extent of rubble beneath the water surface. The river bed boundary is a line connecting the deepest points at available cross-sections ("thalweg").

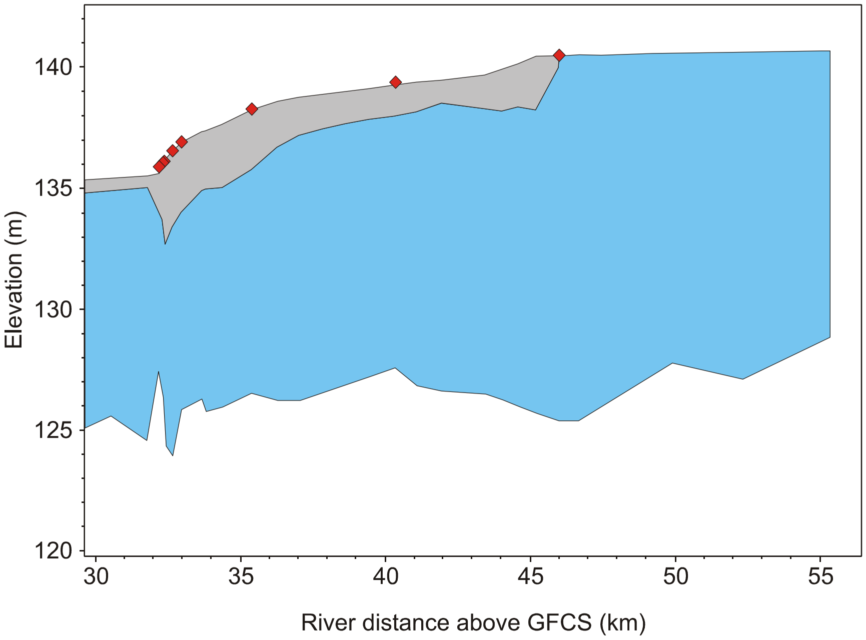

Figure 2b. Ice jam prediction following model calibration, Saint John River near Ste-Anne de Madawaska. Data points represent measured water levels, April 12, 1991 (Beltaos *et al*., 1996).

Table 1. Model parameters selected in calibration runs to match field data sets on breakup ice jams in upper Saint John River.

Ice jam location, Date	Jam length (km)	Model parameter			Agreement of model output with measured water levels along the jam
		Internal friction angle	V_{max} (m/s)	Manning Coefficient n_J ($s/m^{1/3}$)	
Near Ste-Anne de Madawaska, Apr. 12, 1991	13.8	51°	1.5 (default)	Variable (default)	Very good
Near St-Basil, Feb. 29 1996	4.2	54°	1.5 (default)	0.05	Optimum set, but results only "fair"
Near Siegas, Apr. 13 1993	9.6	51°	1.5 (default)	Variable (default)	Very good
Near Foley Brook, April 16, 1994	2.9	56°	1.1	Variable (default)	Very good
Near Dickey, April 16, 1994	5.9	54°	1.0	Variable (default)	Very good
Near Ledges, April 11, 1993	0.6	45° (default)	1.1	Variable (default)	Good
Near Caron Brook, Feb. 27, 1996	1.1	51°	1.5 (default)	0.05	Equally good results with either set of parameters
		56°	1.0	Variable (default)	
Near Petite Brook, April 21, 1996	6.3	45° (default)	1.4	Variable (default)	Good

MODEL APPLICATIONS

On any given year, model application begins when a good portion of the USJR forms an ice cover. The locations and extent of ice-covered reaches are identified by long term resident and highly experienced river ice observer, Mr. Roy Gardner. In recent years, the USJR has experienced rainfall events in December, which generate sufficient runoff to dislodge and break up any ice cover that may have already formed. These early-winter breakups result in ice jams that eventually freeze in place after the cold weather resumes. The jam water levels have been successfully modeled with the wide-jam option of HEC-RAS (Fig. 3). Here, "successful" modeling means that the water level recorded at the nearest gauge is reproduced to within 10 cm or so. It was found that after the river has re-frozen, the jammed portion is successfully modeled by using the ice cover option with the thickness specified according to what was calculated during the early winter breakup event. A gradual reduction in the jam roughness coefficient is also applied. This approach takes into account the fact that the jam forms under conditions of much higher flow than prevails during the winter but its underside may be smoothed over by thermal processes (Zufelt and Ashton, 1991). As the winter ends and the pre-breakup period begin, the ice thickness in the jammed reach may also have to be reduced in order to match the measured water levels.

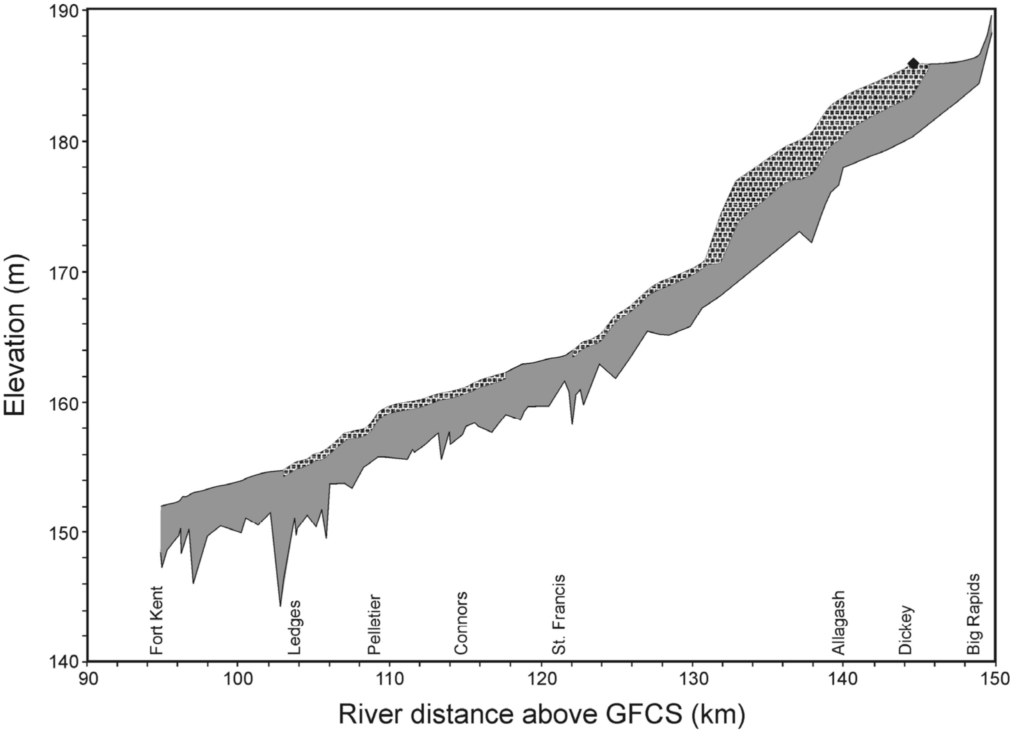

Figure 3. Calculated profile of December 2003 ice jam near Dickey, Maine, using default input. The model correctly reproduces the water surface elevation at the Dickey hydrometric station.

Spring breakup jams have also been successfully simulated in hind-casting mode. The toe and head locations are specified according to the observer's reports. An example is shown in Fig. 4. Here, a 2005 occurrence caused significant flooding in the community of Baker Brook, which is located along the left river bank (New Brunswick) between Clair and Edmundston.

No attempt has been made as yet to apply the model in forecasting mode, owing to a number of practical issues that remain to be resolved. These are discussed in the following section.

PRACTICAL ISSUES AND CHALLENGES

As work and familiarity with the model progressed, a number of difficulties were encountered, especially with earlier versions of the software. Initially, the river bathymetry was defined by inputting all of the cross sections that had, at one time or another, been surveyed within the study reach. These sections are spaced at variable intervals, sometimes amounting to several kilometers. With this spacing, it was often found that the model was generating highly implausible results. By trial and error, the problem was identified to be in the spacing of the sections. An interpolation routine was used to generate new sections between surveyed ones, and these were also introduced into the model. This intervention eliminated this difficulty. Current spacing of cross-sections is still variable but it is generally less than 1 km.

In many runs with previous versions of HEC-RAS, it was impossible to get the model to start or to compute a believable jam profile with physically plausible values of V_{max} (up to 2 m/s). The problem was completely rectified when V_{max} was increased to over 3 m/s. It is very unlikely that a

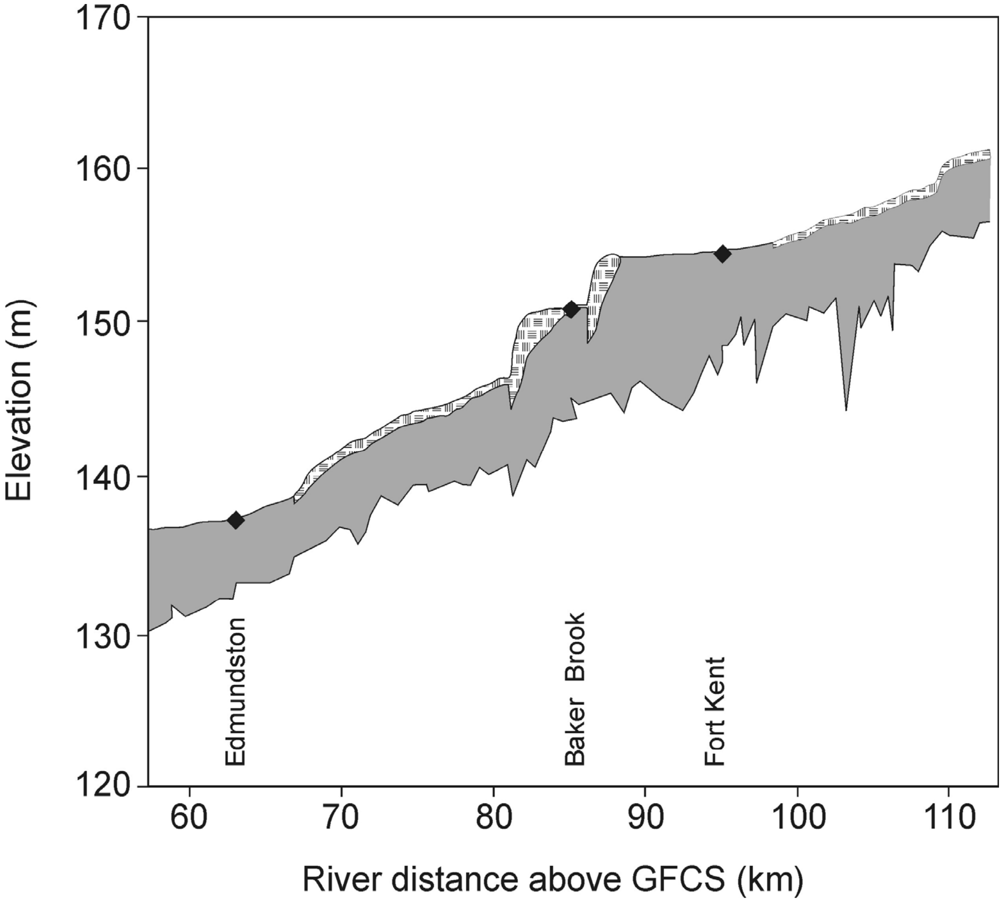

Figure 4. Calculated profile of April 8, 2005 ice jam near Baker Brook, New Brunswick, using default input. The model correctly reproduces the local (~83 km) value of the water surface elevation, and those measured at the Edmundston (~62 km) and Fort Kent (~95 km) hydrometric stations.

jam can form or remain stable under such extreme velocities. However, this situation has not so far been encountered with the current version of the model (Table 1). It is possible that the newly introduced thickness-dependent roughness coefficient (as opposed to a single value along the entire jam) has helped rectify this problem.

During early freezeup and early breakup periods, extensive reaches with partial ice cover may be present. HEC-RAS does not account for partial cover, but a method has been developed for adjusting the Manning coefficient of the ice cover in order to account for a given areal coverage, e.g. 50% ice cover over a specified segment of the river.

The experience gained to date points to reasonably robust input for the ice jam roughness and for the allowable under-ice velocity. The internal friction angle is more variable, and use of the default value may or may not always give good results. Before the model can be applied in forecasting mode, a sensitivity analysis needs to be carried out for sub-reaches where major jamming can cause damages to homes and infrastructure.

POTENTIAL FOR USE OF SATELLITE IMAGERY

C-CORE, through the Polar View Program, has provided radar satellite images for monitoring ice breakup and ice jams in the middle and upper Saint John River for the spring of 2007. The surface condition of the river was classified into five categories: open water, light ice, intact ice, lightly consolidated ice and heavily consolidated ice. The image for the Upper Saint John River received on March 6th 2007, indicated lightly and heavily consolidated ice along the reach from

Big Rapids to the mouth of St. Francis, as shown in Fig. 5. These were in agreement with the ice jams formed during and after the winter thaw, which occurred during January 9th and January 16th, 2007

There is potential for using satellite imagery to indicate the location and extent of ice jams. However, the current procedure for ordering images is rigid and requires two weeks' lead time to schedule image coverage. This would pose a challenge when trying to cover spring ice breakup events.

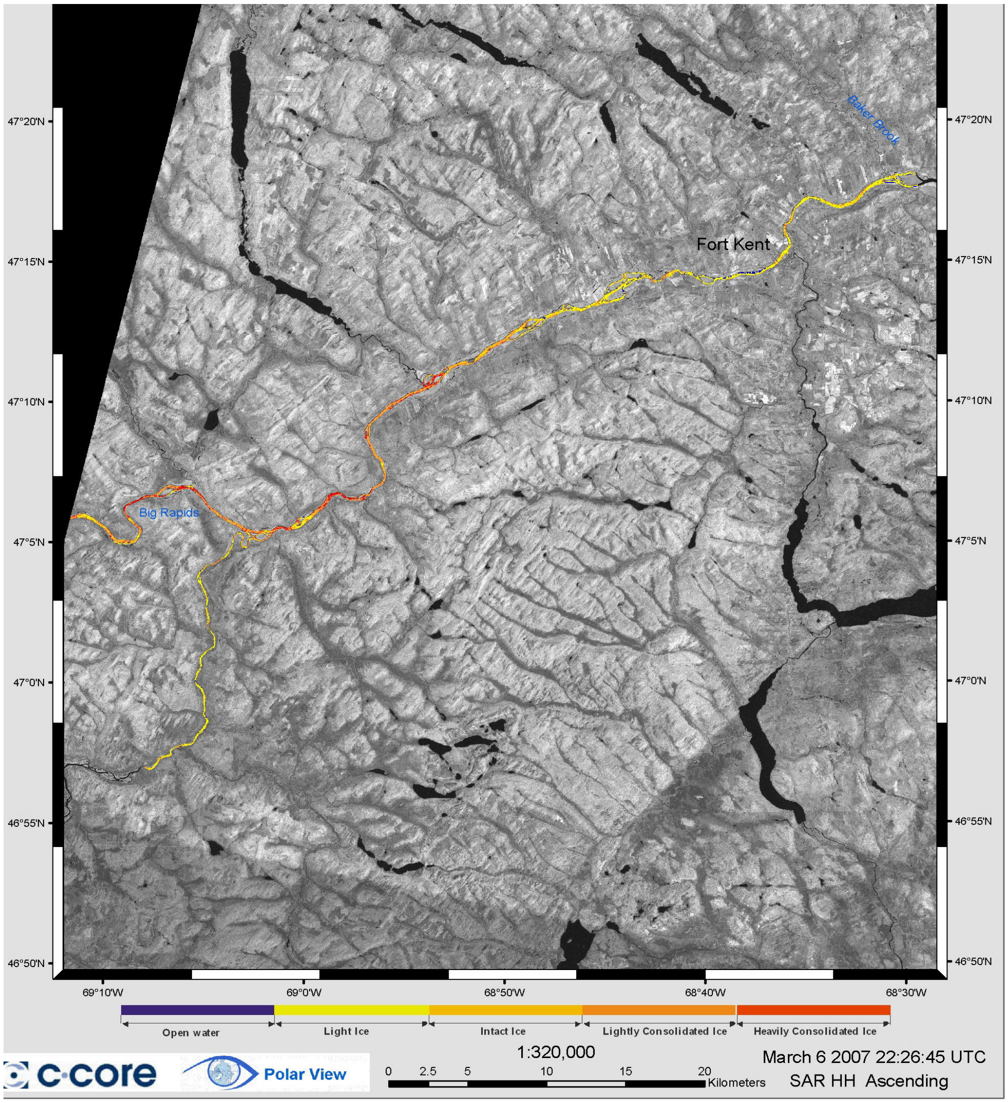

Figure 5. Radar Satellite image received on 6th March 2007 indicating heavily consolidated ice cover.

FUTURE WORK

The ultimate goal of this study is to apply river ice modelling in operational, real-time mode. The existing models cannot predict where and when a jam will form, but can still provide useful information when they are coupled with local observers' reports and with past experience. For example, on a given day a local observer may report that an ice jam is in place between two specific sites along the river. If the jam is not too far from an existing hydrometric gauge, the model can be calibrated with the prevailing flow to match the gauge-indicated water level, and then applied to predict likely water levels along the jam during the following few days, based on the forecasted flow values. Alternatively, hypothetical jams may be modeled at known jamming sites near vulnerable communities (such as Baker Brook and Ate-Anne de Madawaska in New Brunswick) in advance, to see whether there is flooding potential during the next 2-3 days, again using forecasted flows. This type of activity could also be coupled with GIS capability and Digital Elevation models to delineate potential inundation areas.

Building on the modelling experience that has been gained to date, the next step towards the above goal is to evaluate model sensitivity at selected sub-reaches of the upper Saint John River. This would help quantify the uncertainty associated with model runs and establish margins of error.

In addition to the upper Saint John River, damaging ice jams are also known to occur in the middle section of the river (Grand Falls to Mactaquac), notably near Perth-Andover and in the Simons-Hartland area. Plans are under way to extend the modelling work to the middle Saint John, where an adequate number of transects are already available via past surveys conducted by NB Power and Environment Canada (National Water Research Institute).

SUMMARY AND CONCLUSIONS

Ice jam flooding and damages occur frequently along the Saint John River. As a result of expanding urbanization, and climate-related concerns, there is an increasing need to develop capability in forecasting and analyzing ice-jam-related flood events. As a first step in this direction, the public-domain, user-friendly, HEC-RAS model has been implemented and tested in the upper portion of the Saint John River. Practical difficulties that were encountered in early applications of the model have been resolved, either via model upgrades or by input enhancements carried out by the writers, such as transect spacing. In general, it has been possible to obtain good agreement between computed and measured water levels with suitable adjustment of model coefficients such as the friction angle (45° to 56°) and the critical ice transport velocity (1.0 to 1.5 m/s). Initial assessment of radar-satellite imagery indicates potential for valuable, near real-time, information, though image scheduling is not yet sufficiently flexible. Future work will aim at developing operational procedures to forecast flooding associated with predictable ice jams. Model sensitivity assessment is a key step toward this goal.

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