CGU HS Committee on River Ice Processes and the Environment
13th Workshop on the Hydraulics of Ice Covered Rivers
Hanover, NH, September15-16, 2005

Incorporating Ice Effects in Ice Jam Release Surge Models

Y. She and F. Hicks
Dept. of Civil and Environmental Engineering
University of Alberta, Edmonton, AB, Canada, T6G 2W2
yshe@ualberta.ca and fhicks@ualberta.ca

The sudden release of river ice jams often produces high water velocity and rapid increases of stage, which can be destructive to life and property. The highly dynamic flow involving ice interaction makes this one of the most complex problems in river ice engineering. Here the extent of ice complexity necessary to successfully model such events is explored. To do this, ice effects were incorporated into a fully dynamic 1-D hydraulic model, using an uncoupled conservation of ice mass equation, and empirical approximations of ice resistance effects in the total flow momentum equation. The model's performance is compared to the published results of Liu and Shen for their highly sophisticated ice hydrodynamic model which incorporates ice effects more deterministically, applied to a hypothetical ice jam release. This model is then tested for the case of a major ice jam release measured on the Athabasca River in northern Alberta, Canada. This approximate formulation is found to provide good agreement for both the stage and discharge hydrographs, and also for the propagating ice profile after release.

1. Introduction

Because of the dynamic nature of river ice jam release events, and the significant flood risk they pose, it is highly desirable to be able to predict the speed and magnitude of the resulting release waves. This is a highly complex problem involving not only dynamic flow hydrodynamics but the interaction of the ice and water as well. A number of researchers have attempted to model the propagation of ice jam release waves, most using one-dimensional hydrodynamic models and neglecting ice effects on the propagating wave (e.g. Beltaos and Krishnappan 1982, Blackburn and Hicks 2003). Although reasonable approximations could be achieved, difficulties were encountered in matching the shapes of measured stage hydrographs, suggesting that ice effects could not reasonably be neglected. Jasek (2003) conducted field investigations documenting ice jam release events and found that the release wave celerity was affected by different ice conditions. Liu and Shen (2004) further explored this issue, by applying a two-dimensional coupled flow and ice dynamic model (DynaRICE) to investigate the ice resistance effects (both internal resistance and boundary friction resistance) on ice jam release wave propagation in an idealized channel. Comparisons between the simulation results obtained with and without inclusion of ice dynamics showed that the ice effects decrease the peak discharge and slows down the release processes.

Given the clear implication that ice effects likely need to be incorporated into flood forecasting models to obtain realistic predictions for these types of events, the question arises as to how sophisticated the resulting models need be to provide meaningful forecasts. In this investigation, a simplified one-dimensional flow and ice dynamic model is presented and tested to explore that question. In this approximate formulation, the ice released from the jam is assumed to move at the surface water velocity, and equations of total (ice + water) mass and momentum are solved with ice mass conservation in an uncoupled sequence. Ice momentum effects are considered empirically in terms of bank resistance to the ice, which is accounted for by introducing a resistance term into the total flow momentum equation. Longitudinal diffusion of the ice mass is approximated with an empirical diffusion term in the ice mass continuity equation. The resulting equations are solved using the *characteristic-dissipative-Galerkin* (CDG) finite element scheme (Hicks and Steffler 1992). The numerical results are first compared with Liu and Shen's (2004) two-dimensional model results for a hypothetical ice jam release event. The model is then evaluated with actual data for the 1993 release event on the Saint John River documented by Beltaos et al. (1994), and for the 2002 ice jam release event on the Athabasca River documented by Kowalczyk and Hicks (2003).

2. Model Description

The hydraulic model developed in this investigation was built on the public domain software *River1-D* which employs the CDG finite element scheme. By assuming the ice and water move together at the same velocity, the ice and water total equations of mass and momentum for rectangular channel can be written as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad [1]$$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(UQ\right)}{\partial x}+gA\frac{\partial H}{\partial x}=-gAS_f+gAS_0-2\,R_i gB\eta S_f \qquad [2]$$

where,

H is the elevation of water surface above a specific datum;
A is total area of the cross-section under the water surface, measured perpendicular to the flow;
Q is the total discharge, including both the moving ice and water;
U is the ice and water velocity; $\eta =$ ice thickness; and
S_f is the friction slope, which can be evaluated as

$$S_f=\frac{U|U|}{gRC_*^2} \qquad [3]$$

when using Chezy's equation(with C_* representing the non-dimensional Chezy coefficient and R is the hydraulic radius), or as

$$S_f=\frac{n^2U|U|}{R^{4/3}} \qquad [4]$$

when using Manning's equation (with n representing Manning's resistance coefficient).

The last term in equation [2], accounts empirically for the bank resistance to the ice. Here, R_i is a resistance coefficient, which is the product of the coefficient of lateral thrust and friction coefficient between bank and ice. Reasonable value of R_i should be less than one. Larger values can be employed to approximate additional resistance effects, such as internal resistance within the ice mass.

The ice mass continuity equation is:

$$\frac{\partial\eta}{\partial t}+\frac{\partial(U\eta)}{\partial x}=D\frac{\partial^2\eta}{\partial x^2} \qquad [5]$$

in which D is an artificial numerical diffusion coefficient which empirically accounts for the longitudinal diffusion of the releases ice mass.

The total mass and momentum equations and the ice mass continuity equation are all solved using the CDG finite element scheme in an uncoupled sequence. First the flow hydrodynamics at a give time step are determined (based on the ice solution at the previous time step), and then these flow properties are used in the subsequent solution of the ice mass continuity equation before moving on to the next time step.

To make it convenient to simulate ice jam release events, the *River1D* model was also modified to establish initial condition profiles, by incorporating the steady ice jam profile equation. This is solved in a decoupled iterative solution with the hydrodynamic equations, using a steady carrier flow. In this manner, the unsteady hydrodynamic solution provides the mechanism for an iterative solution of an initial ice jam profile.

2. Model Application

2.1 Comparison to Liu and Shen's (2004) ice jam release model simulations

Liu and Shen (2004) developed a hypothetical test case, adapted from the 1993 release event on the Saint John River documented by Beltaos et al. (1994). In their test case, Liu and Shen (2004) approximated the Saint John River as a rectangular channel 100km long and 600m wide, with a bed slope of 0.0004 for the first 30km, and 0.0001 for the remaining 70km downstream. A constant value of Manning's *n* of 0.03 was used for the river bed, a constant inflow discharge of 2000m^3/s was set at the upstream boundary, and an uncontrolled condition was used at the downstream boundary. The initial water surface and ice jam profiles for their test case are depicted in Figure 1.

An identical test case was set up for the model presented here, with the exception that the downstream boundary was eliminated from consideration by extending the modeled reach further downstream. Based on a series of test runs the optimal values of R_i and D were found to be 3.5 and 100, respectively. Comparison of the simulated stage and discharge hydrographs at different location downstream of the jam toe are depicted in Figure 2 and Figure 3, respectively. Similarly, the ice jam profiles at 4, 10, 20 and 60 minutes after the jam release are shown in Figure 4. Results published by Liu and Shen (2004) from their the two-dimensional coupled flow and ice dynamic model (DynaRICE) are shown for comparison purposes. As the figures illustrate, the approximate model presented here performs well when compared to the much more sophisticated DynaRICE model. This suggests that reasonable forecast might be achievable with the simplified model.

To explore and illustrate the ice effects in the present model, *River1-D* simulations for this same test case were conducted setting both R_i and D to zero. The simulated stage and discharge hydrographs at 50 and 75km were compared with the results presented earlier (considering ice effects). As shown in Figure 5, incorporating ice resistance significantly changes the shape of both the stage and discharge hydrographs. The ice effectively holds back the release wave, lowering the resulting peak discharge. In particular, backwater effects are evident on the stage hydrographs for the simulations incorporating ice resistance, which is significant since the inability to model this effect was a key limitation of earlier modeling efforts (e.g. Blackburn and Hicks 2003). Another interesting effect of including ice resistance is seen in the stage and discharge hydrographs at 75km, in which a second peak occurs at about 9 hours. Because the ice is moving at the water velocity, which is slower that the release wave velocity, this second peak occurs as the ice accumulation subsequently passes through station 75km.

2.2 Comparison to Beltaos et al.'s (1994) observations – St. John River

The *River1-D* model was next used to simulate the 1993 event on the Saint John River using varying width rectangular channel approximation based on the actual channel geometry (as developed and tested by Hicks *et al.*, 1997). This event involved a 20km long ice jam poised with its toe at station 69km. The initial water surface and ice jam profiles were estimated by performing an ice jam profile calculation using the *River1-D* model based on the flow condition right before the release occurred (at 9:00 on April 15, 1993). Figure 6 illustrates the resulting profile obtained with the model as well as the ice jam profile measured on April 14, 1993, for comparison. The computed ice jam profile is slightly lower than the measured one, which accounts for the lower discharge on the day of release, as compared to that on the day the jam profile was measured.

Unsteady flow simulations were conducted both with ice and without ice resistance effects. Based on a series of tests, it was found that the optimal values of R_i and D were 0.5 and 100, respectively. Figure 7a presents the results of the simulations in comparison with the available verification data at a station approximately 5km downstream of the released point, illustrating the backwater effect obtained in the recession portion of the stage hydrograph when including ice. As was expected from earlier investigations (Hicks *et al.* 1997, Blackburn and Hicks, 2003). The use of a rectangular channel approximation results in a stage hydrograph approximately 1m higher than observed. However, lowering the solution obtained with R_i =0.5 and D = 100, by 1.0 m and comparing that to the results obtained by Blackburn and Hicks (2003) obtained using natural channels geometry (but no ice effects), it appears that the inclusion of ice effects does improve agreement with the shape of the recession portion of the stage hydrograph. This suggests that consideration of both ice and natural channel geometry is important to providing realistic water level forecasts.

2.3 Comparison to Kowalczyk and Hicks' (2003) observations – Athabasca River

The River1D model was then evaluated using actual data obtained during a large ice jam release event on the Athabasca River, AB in 2002 (Kowalczyk and Hicks, 2003).

Since the Athabasca River can be characterized as a wide and shallow channel, a variable width rectangular cross section approximation is adequate. The resistance characteristics along the study reach are listed in Table 1. Kowalczyk and Hicks (2003) provide a description of the event which involved an ice jam approximately 10 km in length poised about 1km upstream of Crooked Rapids (about 35 km upstream of Fort McMurray, AB). The carrier discharge has been estimated at about 850m^3/s. The ice jam profile was not measured, sue the the reamote location of formation. Therefore, a profile was calculated using the River1D model, determined by trial and error to obtain a good match with the measured stage hydrograph at station G140 upon release(Figure 9). Open water in the receiving channel was assumed. The computational results with ice and without ice are shown in Figure 10 together with the measured stage hydrographs.

As the figures illustrate, for this case, inclusion of ice effects did not seem to improve the model's ability to simulate the water level hydrographs correctly. This actually makes sense when one considered the observations of Jasek (2003) that ice effects on the propagating wave are most significant only for the first jam length of propagation, approximately. All of the comparison stations in this case are located much further downstream.

Table 1. Bed roughness characteristics for the Athabasca River study reach.

From (km)	**To (km)**	**Manning's** n **(dimensionless)**	**Roughness height** k **(m)**
0 *	296.55	0.030	0.24
296.6	300.4	0.020	0.02
300.45	319.4	0.030	0.24
319.45	400	0.035	0.61

* Station 0 *km* is set at the mouth of Lake Athabasca

3. Summary and Conclusions

The River1D model was adapted to consider ice jam resistance effects on propagating ice jam release waves. In the model, the total (ice plus water) mass and momentum conservation equations are solved together with a conservation of ice mass equation, in an uncoupled sequence. Ice resistance effects were approximated through an empirical term in the total flow momentum equation and an empirical ice diffusion approximation in the ice continuity equation. The resulting model appears to perform well when compared to the two-dimensional ice dynamic model DynaRICE for a hypothetical ice jam release event (Liu and Shen 2004).

The model was further tested for two observed ice jam release events: one on the Saint John River in 1993 (documented by Beltaos *et al.* 1994)and one on the Athabasca River (documented by Kowalczyk and Hicks, 2003). The results for the former case suggests that inclusion of ice effects improve the shape of the recession portion of the stage hydrograph when compared to measured data at a station lees than one jam length downstream of the released toe. However, it seems clear that consideration of natural channel geometry is important in that case as well. For the Athabasca River event, inclusion of ice effects did not seem to improve results when compared to measured stage hydrographs more than 1 to 2 jam lengths downstream of the released toe. Clearly more comprehensive field data is still needed to provide further validation of models of this type.

Acknowledgments

This research was funded by the Natural Sciences and Engineering Research council of Canada through the MAGS (Mackenzie GEWEX Study) Research Network. This support is gratefully acknowledged.

References

Beltaos, S. and Krishnappan, B.G. (1982). “Surges from Ice Jam Release: A Case Study” Canadian Journal of Civil Engineering, Vol. 9: pp. 276-284.

Beltaos, S., Burrell, B. C., and Ismail, S. (1994). ‘‘Ice and sedimentation processes in the Saint John River, Canada.’’ Proc., 12th Int. Association for Hydraulic Research Symposium on Ice, Norwegian Institute of Technology, Trondheim, Norway, 11–21.

Hicks, F.E. and Steffler, P.M. (1992). “A Characteristic-Dissipative-Galerkin Scheme for Open Channel Flow” ASCE Journal of Hydraulic Engineering, Vol. 118, No.2, pp. 337-352.

Hicks, F.E., McKay, K. and Shabayek, S. (1997) “Modelling an Ice Jam Release Surge on the St. John River, New Brunswick”, Proc. of the 9th Workshop on the Hydraulics of Ice Covered Rivers, Fredericton, N.B, pp. 303-314.

Jasek, M. (2003). “Ice jam release surges, ice runs, and breaking fronts: field measurements, physical descriptions, and research needs” Canadian Journal of Civil Engineering, Vol. 30: pp. 113-127.

Blackburn, J. and Hicks, F. (2003). “Suitability of Dynamic Modeling for Flood Forecasting during Ice Jam Release Surge Events” Journal of Cold Regions Engineering, Vol. 17, No. 1, pp. 18-36.

Kowalczyk, T. and F. Hicks (2003) “Observations of Dynamic Ice Jam Release on the Athabasca River at Fort McMurray, AB, Proc. 12th Workshop on River Ice. 18-20 June 2003, CGU - Hydrology Section, Comm. on River Ice Processes and the Env., Edmonton, AB, pp. 369-392.

Liu, L.W. and Shen, H.T. (2004). “Dynamics of Ice Jam Release Surges” Proc. of the 17th International Symposium on Ice. St. Petersburg, Russia, 8 pp.

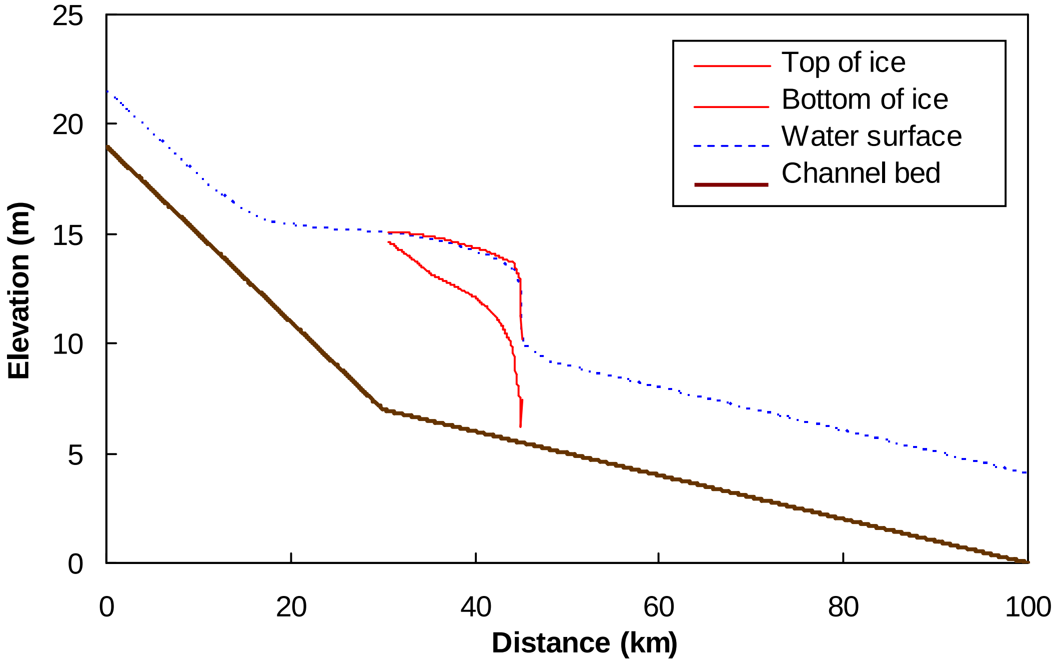

Figure 1. Liu and Shen's (2004) test case for ice jam release simulation.

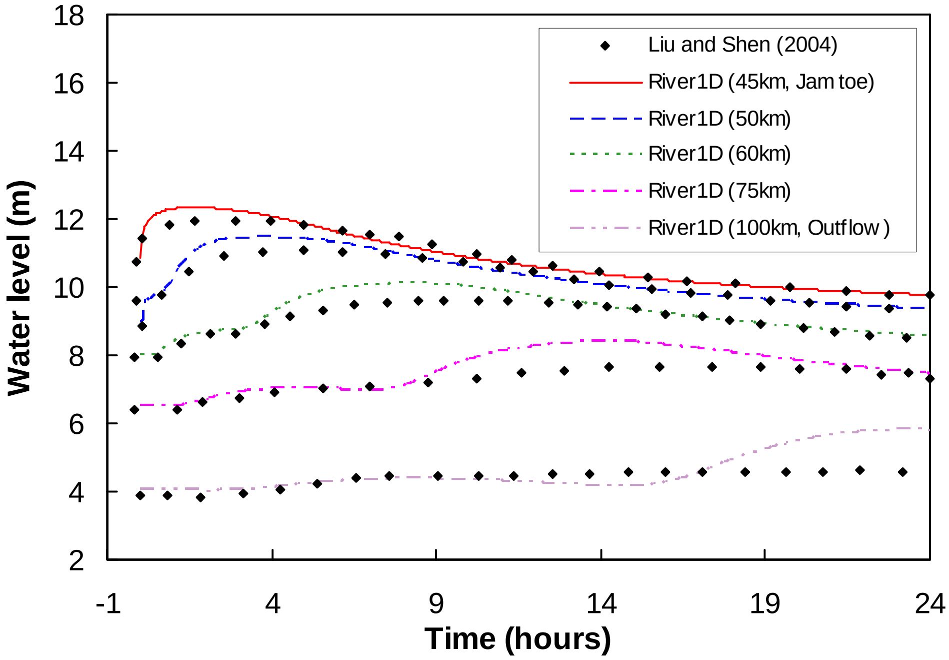

Figure 2. Comparison of *River1D* with Liu and Shen's (2004) results for water level.

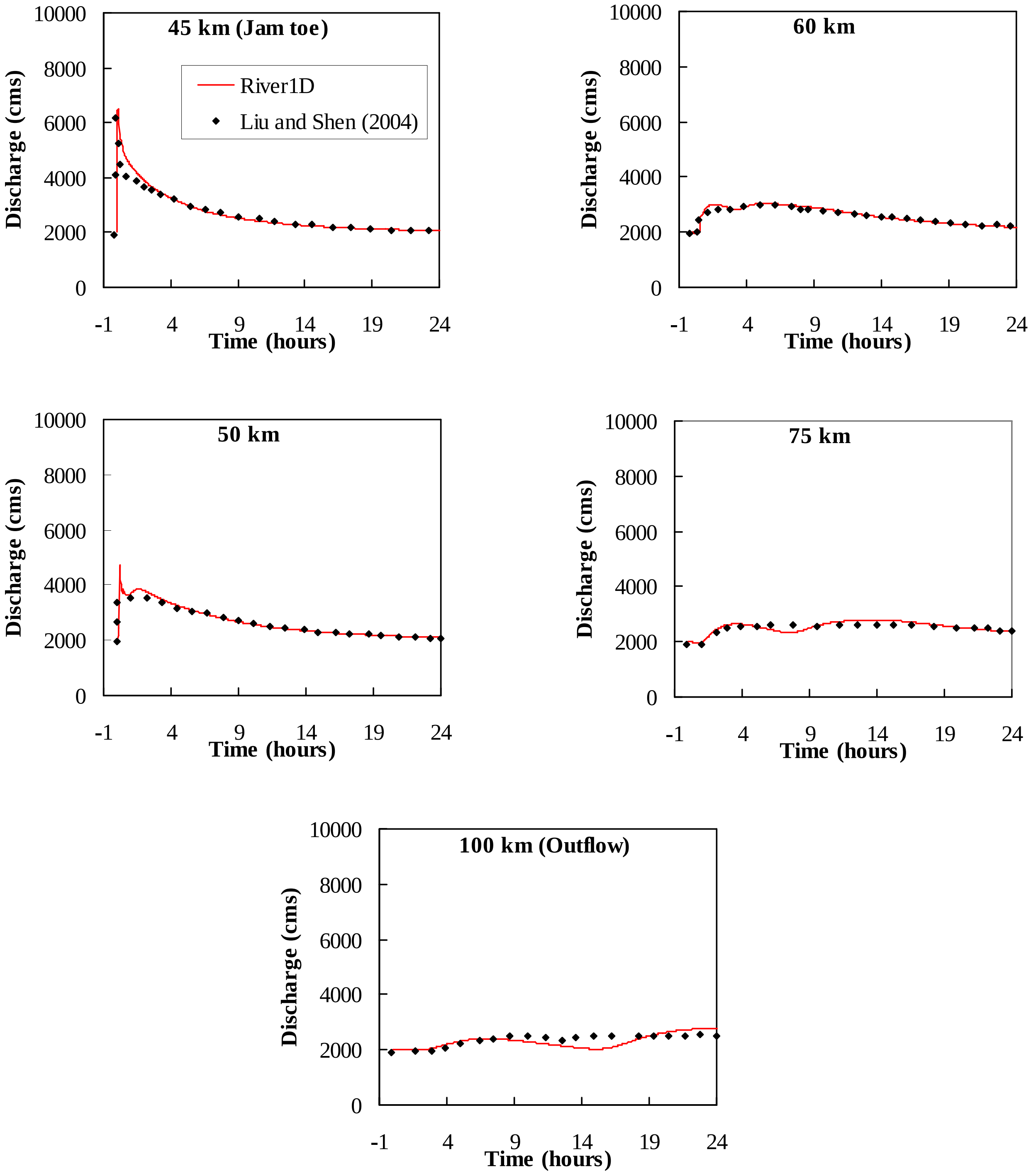

Figure 3. Comparison of *River1D* with Liu and Shen’s (2004) results for discharge.

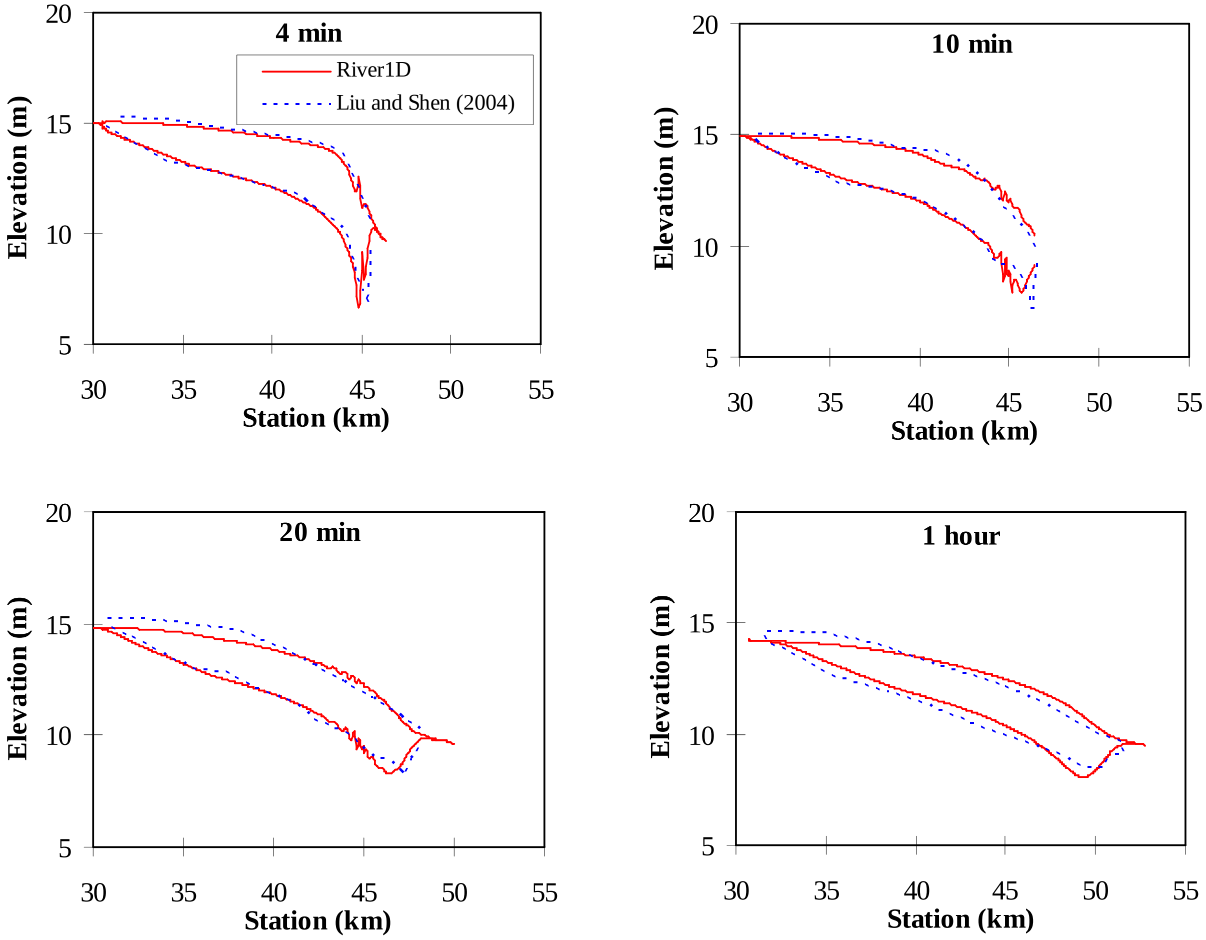

Figure 4. Comparison of *River1D* with Liu and Shen’s (2004) results for ice jam profiles at different time after the release.

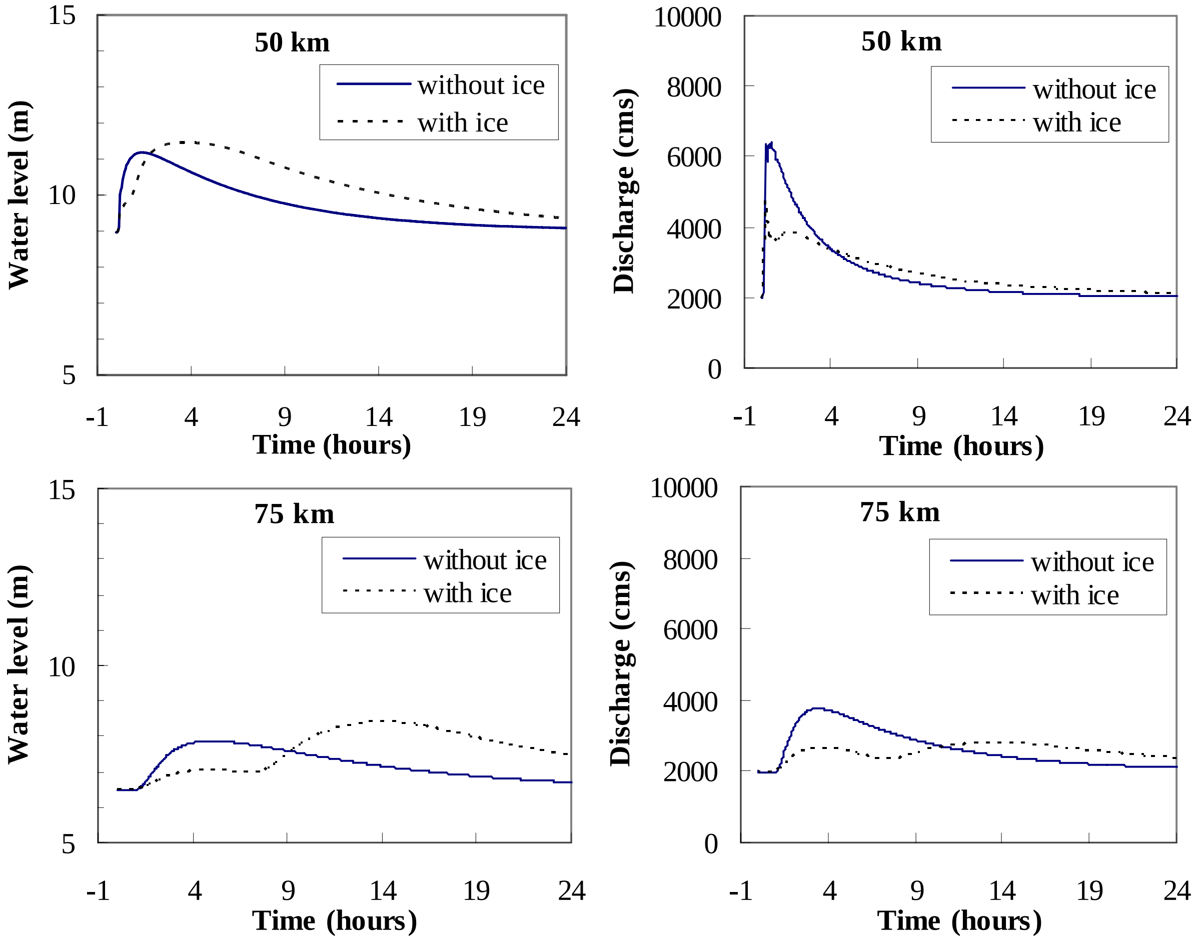

Figure 5. Ice effects on stage and discharge hydrographs.

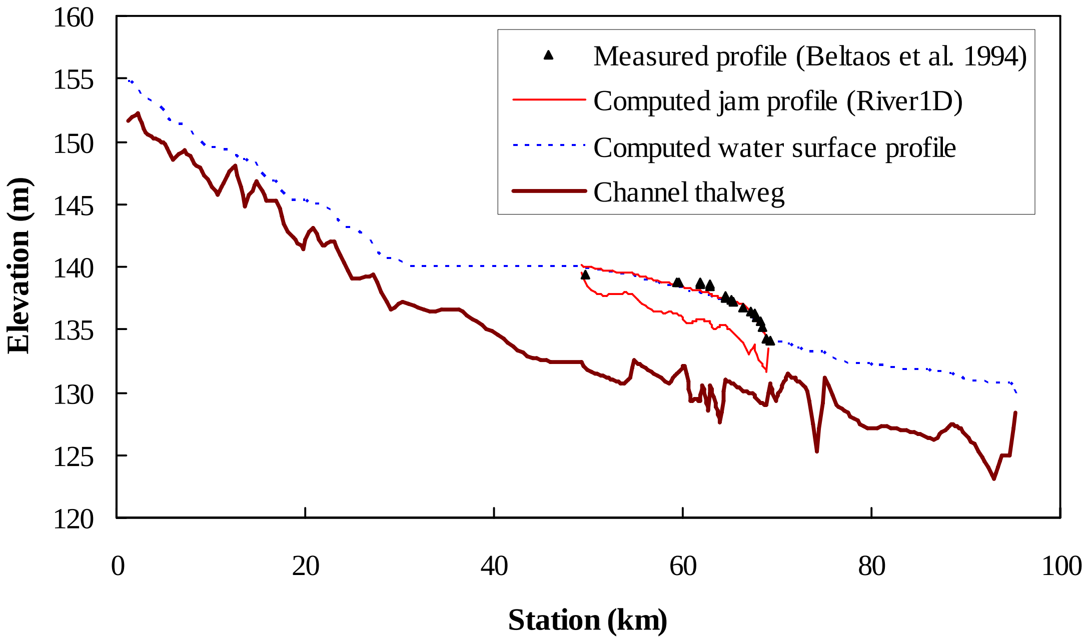

Figure 6. Water surface and ice jam profile computed for the Saint John River for 9:00 on Apr.15, 1993 and the measured profile on Apr.14, 1993.

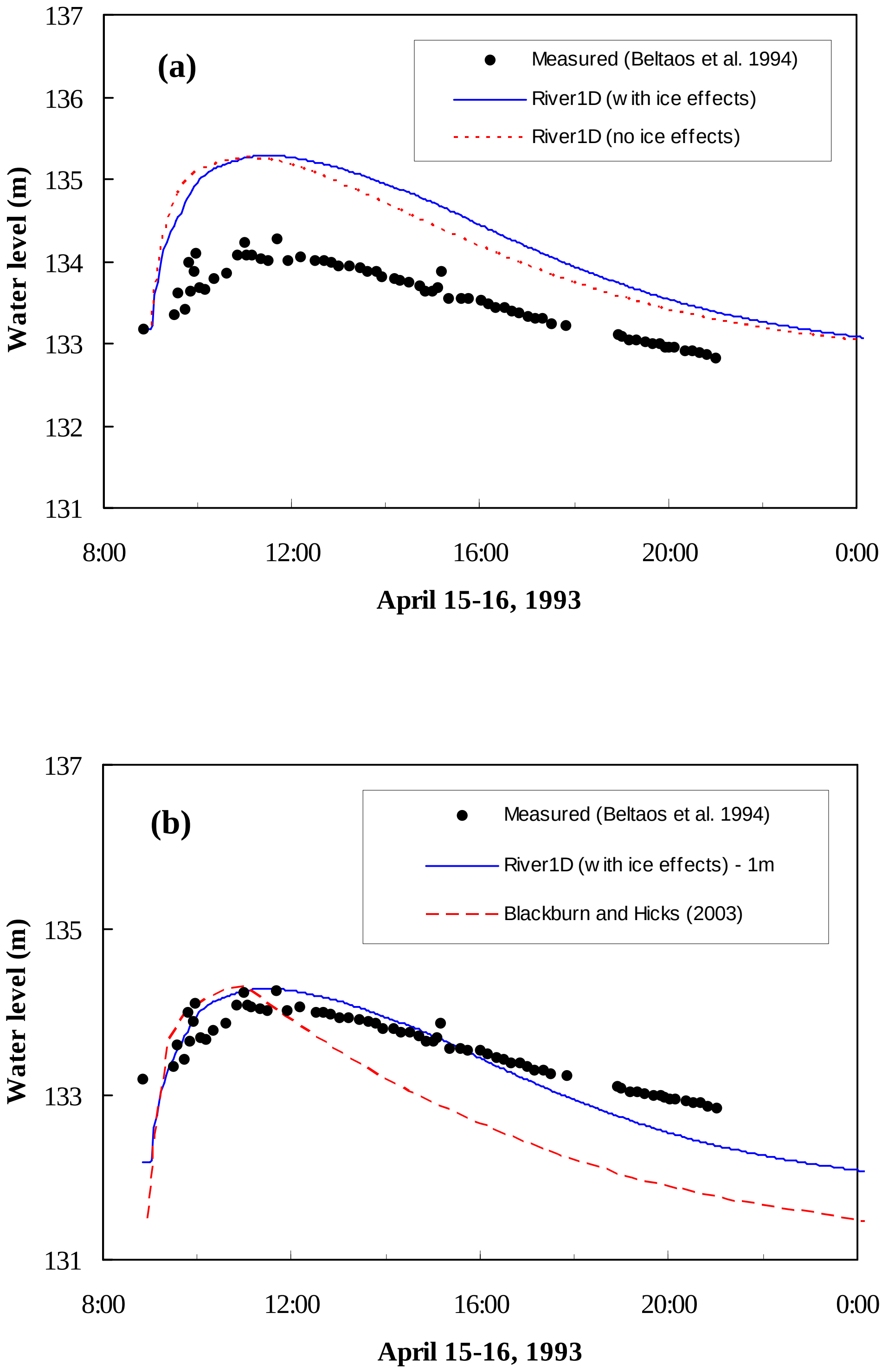

Figure 7. Comparison of measured and computed water levels at St Leonard (74.26km) for Saint John River ice jam release event.

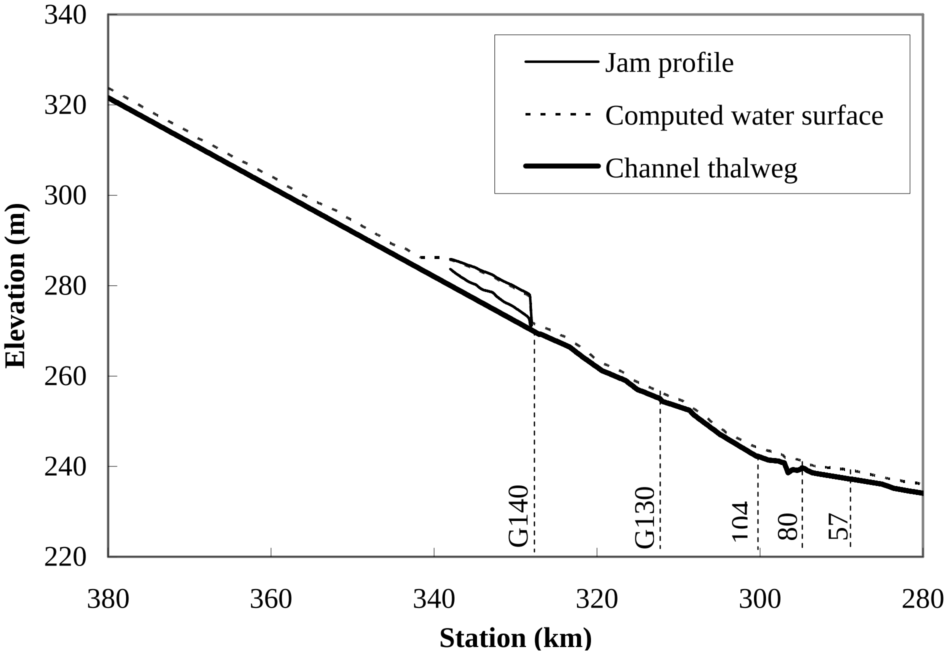

Figure 8. The initial water surface and ice jam profile on the Athabasca River, both computed using River1D.

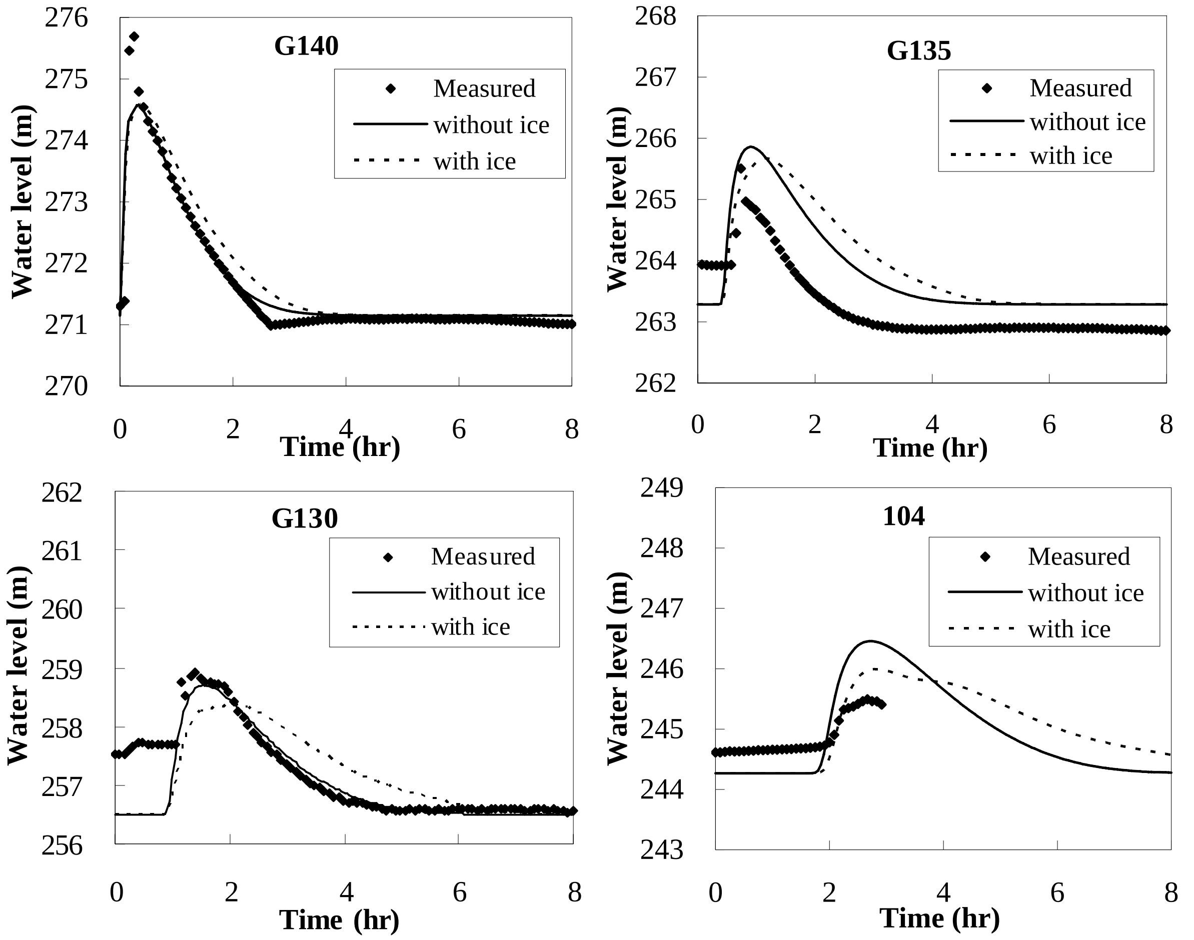

Figure 9. Comparison of measured and computed stage hydrographs at different stations on the Athabasca River for the 2002 event.