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Tests of Numerical Models of Ice Jams – Phase 3

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This paper summarizes the results of the third in a series of tests that have been devised and coordinated by a sub-committee of the Committee on River Ice Processes and the Environment. This third phase is what has been called a “blind test”. It has been based on actual field data including bathymetry, river flow, and location of ice jam, but no data was provided to the modelers on ice thicknesses or water surface profiles. The modelers had to select appropriate parameters based on judgment, and run their models so as to provide the best possible reproduction of the actual ice jam profiles without foreknowledge of the field data. The field data on the ice jam profile was only revealed after the tests were completed and to permit comparison of the results with the prototype experience. The intent of this test was to provide a perspective on the performances of the models without the benefit of actual ice jam data upon which to calibrate the models.

During the Phase 3 testing period, the authors also became aware of a new numerical model that is currently being developed by LaSalle Hydraulic Laboratory and Quebec Hydro and is being incorporated into the Danish Hydraulic Institute’s MIKE-11 software. LaSalle Hydraulic Laboratory offered to test this model, and at this time, the results of the Phase 1 test are available, and are briefly reported.

1. Introduction

This paper summarizes the results of the third in a series of tests that have been devised and coordinated by a sub-committee of the Committee on River Ice Processes and the Environment (CRIPE). The previous tests reported in previous CRIPE River Ice Workshops focused on simulations with:

1. specified parameters to enable direct comparison of results for each model for a hypothetical river channel (Phase 1)
2. known ice jam thicknesses and water levels for an actual ice jam to enable the modeler to choose the best combination of parameters that would allow his/her model to fit the data (Phase 2).

This third phase is what has been called a "blind test". It has been based on actual field data including bathymetry, river flow, and location of ice jam, but no data was provided to the modelers on ice thicknesses or water surface profiles. The modelers had to select appropriate parameters based on judgment, and run their models so as to provide the best possible reproduction of the actual ice jam profiles without foreknowledge of the actual ice jam profile that occurred. The field data for the ice jam profile was only revealed after the tests were completed and to permit comparison of the results with the prototype experience. The intent of this test was to provide a perspective on the performances of the models without the benefit of actual field data upon which to calibrate the models.

The models that have been tested, and the modelers are:

1. RIVER1D – University of Alberta
2. ICESIM – Hatch Energy
3. CRISSP 2D – Manitoba Hydro
4. MIKE 11 – LaSalle Hydraulic Laboratory
5. ICEPRO – KGS Group
6. CRISSP 2D – Clarkson University
7. HEC-RAS – AMEC Earth and Environmental

The models are briefly described in this paper, and results are presented in a series of graphical displays.

2. Supplementary Phase 1 Test

The focus of this paper is primarily on reporting the results of the third phase of the CRIPE initiative to test ice jam numerical models. However, during the Phase 3 testing period the authors became aware of a new numerical model that is currently being developed by LaSalle Hydraulic Laboratory and Quebec Hydro and is being incorporated into the Danish Hydraulic Institute's MIKE-11 software. LaSalle Hydraulic Laboratory offered to test this model, and at this time, the results of the Phase 1 test are available, and are briefly reported below.

The Phase 1 Test adopted a simple hypothetical channel with a constant slope of 1 per 1000, and a constant width of 1000 m, with a steady flow of 3 000 m3/s. For further details and the information on the models tested, the reader is referred to the CRIPE Workshop paper that was written to document the Phase 1 results (Carson et al, 2003).

The figures that were prepared to show the results of the Phase 1 Test were amended to show the results of MIKE-11 simulations. They are shown in **Figures 2.1 and 2.2**. The results are closely comparable to the previous simulations by the other models.

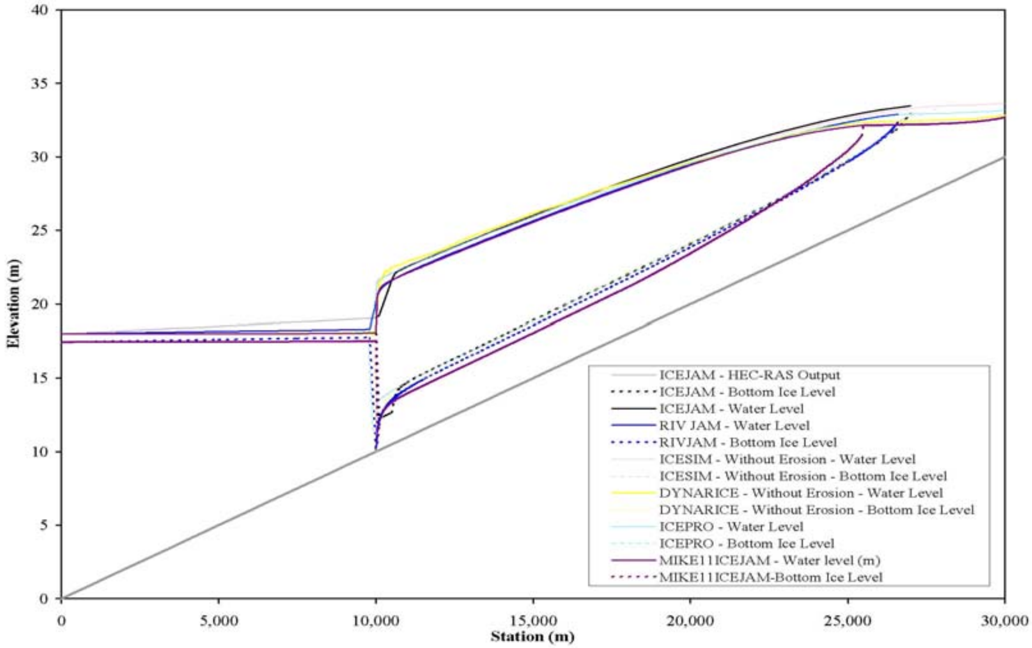

Figure 2.1 – Comparison of Mike-11 Results With Other Models Tested in Phase 1

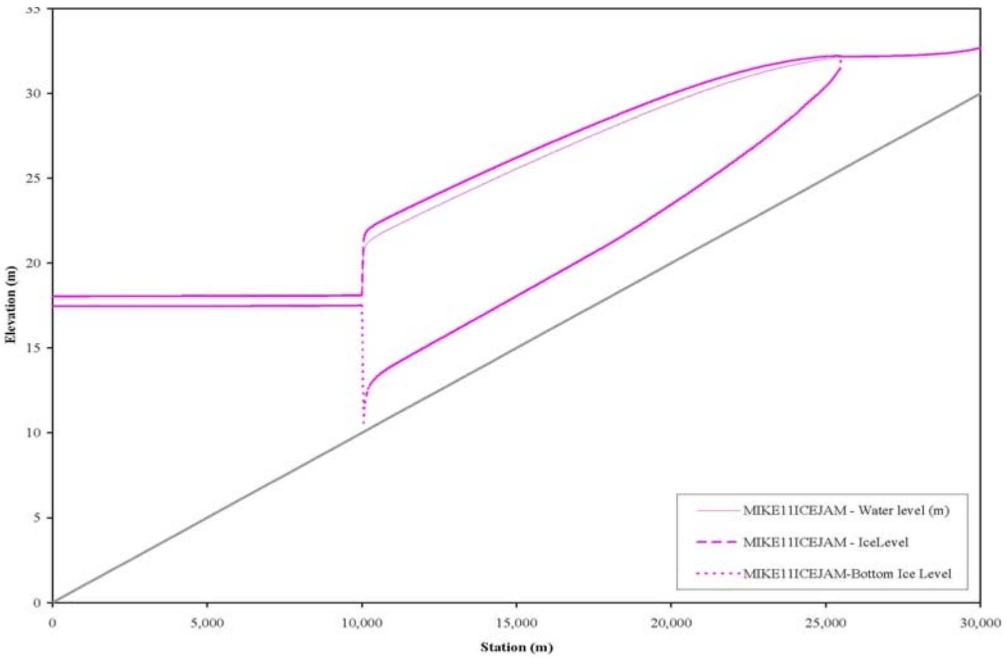

Figure 2.2 – Profiles Computed By MIKE-11 For Phase 1 Test

The paper that documented the Phase 1 Test Results also contained a description of the models in the form of response to key questions that were posed to the modelers. The answers from LaSalleHydraulic Laboratory to those questions as they pertain to MIKE-11 are summarized in the following list.

1. What is the name of the model?

Mike11-Ice; Ice jam Module
The Mike11-Ice model is made of two separate modules, the Ice Jam Module and the Frazil Ice Generation and Accumulation Module. Test Case 1 is modeled using the Ice Jam module.

2. In what computer language has it been formulated?

Fortran

3. Under what computer system is it capable of running?

PC under Windows XP

4. Minimum requirement of the system?

Any reasonably recent PC (Pentium)

5. When was the model developed, and by whom?

In 2005.
LaSalle Consulting Group for the theory and formulations
Danish Water and Environment, coding and integration to the Mike-11 platform

6. On what rivers has the model been known to have been run to analyze ice jams?

Saint-Timothée basin (Saint-Lawrence river, Montreal area)
The Ice-Jam module is seldom used, as we are more frequently involved in frazil ice generation and accumulation studies

7. Is the model proprietary?

Yes

8. If publicly available, from what source(s)?

Not available yet.

9. Is the model formulated to only address steady state conditions, or can it also simulate dynamic conditions?

Steady state only

10. On what basis are the stable ice thicknesses of the ice jam estimated?

The thickness profile is determined by the balance between weight of the ice along the slope, hydraulic shear stress, internal stress transmitted by adjacent part of the jam, and bank friction (Pariset & Hausser, Uzuner & Kenedy). The equation is solved by a relaxation method, the thickness of each and every cross-section being simultaneously adjusted at each iteration.

11. What criterion is used to determine if the leading edge of the ice is stable, or whether drawdown of the incoming ice would occur?

In the Ice Jam module, the ice is not "incoming", it is solely governed by local stability equation. The question of drowning or juxtaposition is addressed in the Frazil Ice model only, for the incoming, drifting ice pans.

12. What procedure is used to compute the water profile within the accumulation ice and in the open water?

Standard step backwater computation, using the Manning equation. Seepage through the ice jam may be included, according to a formulation proposed by S. Beltaos.

13. Is the model capable of simulating border ice, anchor ice?

Not the Ice Jam Module

14. Is the model capable of estimating the point where an ice jam may commence due to lodgment of the incoming ice?

No. The ice is not "incoming" (see item 11 above), but the model checks for the stability of the toe, arrested against a solid, unbroken static ice cover. The ice cover breaks if the longitudinal force exceeds the static cover strength, and the jam moves downstream

15. Does the model represent changing ice roughness with time?

Not in the Ice Jam module. There is no such thing as "time" in the steady computation. Ice jams characteristics are iteratively varied until a final, steady solution is achieved.

16. Does the model represent the reduction in the ice mass due to thermal effects during the simulation?

Not in the Ice Jam module.

17. Does the model represent entrainment of fragmented ice in the flow where velocities may cause that to occur? If so, how does it simulate this process? What limits to the erosion/deposition are assumed?

No explicit limitation of the velocity under the jam. Inclusion of seepage through the jam may be used to avoid excessive velocities in the toe region. Transport and deposition under the jam are not considered, because the final thickness is assumed to be reached by shoving of the ice mass.

3. Phase 3 Test

3.1. Description of Test

Third Phase of study involved application of the ice models in a "blind test". This offered a different prespective from the previous tests, in that the objective was not so much to compare individual models, but rather to investigate the performance of ice prediction models when used without the benefit of prior calibration.

To facilitate this test, data was initially solicited for an historical ice jam event for which no modeler had any prior knowledge or information. The data for this case was supplied by Dr. Spyros Beltaos of Environment Canada, who, at the time of the test, was the only one who knew of the river system, and/or the date associated with the event. Unfortunately, it also meant that Dr. Beltaos was not able to participate as a modeler as he did in the previous tests.

Data supplied to each modeler consisted of the following:

- Bathymetric data for 8 river cross sections which had been surveyed in the study reach. These sections were provided as a series of X-Y coordinates and chainages for each cross section.
- Observed water level and discharge measurements which were taken during an open water condition on the reach. This data could be used by each modeler, if deemed appropriate, to calibrate their models against these open water levels. This would help to establish the appropriate roughness value for each model for the river channel.
- The location of the head of the jam, as well as the toe of the jam.
- The discharge at the time of the jam, which was estimated to be 205 m^3/s.
- The typical thickness of the ice prior to development of the jam. The thickness of the ice in the reach was approximately 0.4 m.

Each modeler then took this data, and developed a model to simulate the winter jam event. Most modelers took advantage of the open water data to initially calibrate their models for the open water condition. After this, each modeler selected appropriate parameters for the ice jam based on judgment alone. Key parameters that needed to be selected by each modeler included strength parameters for the ice jam, the roughness of the jam, and the downstream water level for the jam (i.e. below the toe of the jam).

Once completed, modelers then submitted their results, along with assumptions, and parameters used to the Task Force. To ensure consistency, each modeller was asked to provide results in a consistent format to Dr. Beltaos. Once all results were received, Dr. Beltaos purged any information which could be used to identify the model used, and then forwarded the full set of results to the Task Force, along with observed water level and ice thickness data for the ice jam event. This strategy ensured that all results could be reported "anonymously", and that no simulation could be linked to the corresponding model.

3.2. Participating Models

In total, six different models participated in this third test. Each of the models are presented, and briefly described below.

RIVER1D – Yuntong She, University of Alberta
The River1D hydraulic flood routing model was originally developed by F. Hicks and P. Steffler of the University of Alberta. It solves the one-dimensional St. Venant equations using the characteristic-dissipative-Galerkin finite element scheme (Hicks and Steffler, 1992). The model can be applied for open water or ice covered flow situations and has been adapted to model thermal ice cover formation processes (Andrishak and Hicks, 2005). It has also undergone extensive development to incorporate ice effects in modeling ice jam release events, including consideration of ice in the receiving channel (She and Hicks, 2006a and 2006b). To facilitate the simulation of ice jam release events, a steady ice jam profile calculation component was incorporated to calculate ice jam, and associated water surface, profiles (She and Hicks, 2006). The jam profile calculation employs the steady flow ice jam stability equation, which follows the theory of Pariset et al. (1966) and Uzuner and Kennedy (1976), using a similar approach to that employed by Flato and Gerard in their ICEJAM model (1986). The ice jam stability equation is solved in a decoupled iterative sequence with the St. Venant equations, using the unsteady time stepping routine in the hydraulics component to achieve the iteration process. The version of the River1D model used for this study employs a non-prismatic trapezoidal approximation for the natural channel geometry, and Manning's equation for calculating the friction slope.

HEC-RAS - Dan Healy, AMEC Earth & Environmental

The U.S. Army Corps of Engineering Hydrologic Engineering Center's River Analysis System (HEC RAS) software provides open channel solutions for one-dimensional steady and unsteady flow hydraulics. The HEC RAS graphical user interface facilitates efficient model construction, model calibration, and fast interpretation of computed results. The basic steady flow computational procedure follows the solution of a one dimensional energy equation through an iterative procedure (standard step method). Energy losses attributed to channel roughness are estimated by Manning's equation and contraction/expansion losses are estimated as a function of the rate change in velocity head. HEC RAS computations account for energy losses associated with common channel obstructions (e.g. bridges, culverts, and weirs) and facilitates horizontal and vertical variation in channel roughness at each river cross section.

HEC RAS models ice covered channels as either a fixed intact ice cover of user specified thickness or as a wide channel ice jam. The ice jam formulations follow the jam stability equation for steady flow developed by Pariset et al. (1966) and Uzuner and Kennedy (1976). The computational approach is similar to that employed by Flato and Gerard's (1986) ICEJAM model. Steady flow computations (energy equation) proceed upstream based on previously calculated ice jam thickness, then, the computations progresses downstream to compute ice jam thickness by the jam stability equation. The solution continues in an iterative manner until converging to a desired (user specified) tolerance.

ICESIM - Joe Groeneveld, Hatch Acres

The ICESIM model was developed by Acres International Limited (now Hatch Energy) in the early 1970's to facilitate the design of hydroelectric plants on the Nelson River in Manitoba, Canada. Since then, the model has been improved in several stages, with careful attention paid to the principles of hydraulics and ice mechanics. The current version is a steady-state, one-dimensional program, able to simulate the formation process at freeze-up and parts of the breakup process, under a wide variety of conditions and types of rivers.

ICESIM considers, in discrete time steps, the various ice processes that affect the water surface profile along a river, namely

- rate of ice generation
- ice cover advance by frontal progression using a Froude number criterion
- ice deposition and transport
- ice erosion
- border ice growth
- ice retreat by shoving
- ice cover advance by staging
- anchor ice growth.

In general, after a change in the ice parameters during any one time step, the water surface profile is recomputed to update the hydraulic conditions in the river. Ice parameters and thicknesses are then recomputed based on this new profile, and the solution continues to iterate in this fashion until a final solution is derived for each time increment. ICESIM has been used in many hydrotechnical studies to analyze ice jam behaviour in the Saint Joint River (New Brunswick), to analyze ice processes at the Magpie River development (Ontario), Susitna River (Alaska), and Nelson River (Manitoba).

ICEPRO – Rick Carson, KGS Group

ICEPRO is similar to ICESIM, as Rick Carson was the principal author of both programs. Minor improvements in the details of the ice shoving have been introduced into the methodology of

ICEPRO, and the program uses a hydrodynamic subroutine that solves the St. Venant equations of motion, both in open water reaches as well as ice-covered reaches.

CRISSP 2D – Jarrod Malenchak and Mike Morris, Manitoba Hydro: **and Tomasz Kolerski and Hung Tao Shen, Clarkson University**

The CRISSP2D model is one component of the Comprehensive River Ice Simulation System Project (CRISSP) which was initiated in September of 2000 by a consortium of North American hydropower companies and is under the guidance of CEA Technologies Inc. CRISSP2D is a generalization of the DynaRICE model (Shen et al., 2000) to include thermal related processes.

The ice jam dynamics embodied within CRISSP2D (Liu et al. 2006) are the same as for the DynaRICE model (Shen et al. 2000, and Liu and Shen 2004). The model is a two-dimensional coupled hydrodynamic and ice dynamic model. The hydrodynamic component is based on a finite element architecture, includes seepage flow through the ice mass, and is capable of simulating trans-critical flow conditions with dry-wet bed conditions. The ice dynamic component includes internal ice resistance, bank friction, and bed resistance when the ice rubble is grounded. A more detailed description of the model formulation can be found in Shen et al. (2000).

3.3. Description of Ice Event

The ice jam event forming the focus of this test occurred along the Matapedia River near St Alexis, Quebec on April 22nd and 23rd, 1995. Dr. Beltaos and Mr. Brian Burrell were on site during the event, and were able to obtain a water level survey prior to release of the jam on April 23rd. The jam was approximately 700 m long, and exhibited thicknesses of up 3.5 m near the toe. Various photos were taken of the river at the time of the ice jam, and these are presented in **Figures 3.1 to 3.4**. It should be noted that none of the modeling participants saw these photos prior to applying their respective ice models.

Figure 3.1 – A view of the jam looking upstream

Figure 3.2 – A view of the jam looking downstream

Figure 3.3 – A view of the jam looking across the river

Figure 3.4 – A view of the head of the jam

3.4. Model Results

Once each modeler had completed his or her test, the results were forwarded to Dr. Beltaos who then assembled the results and passed them on the Task Force for analysis. As indicated above, the results were stripped of all text which could possibly be used to identify the modeler or model, thereby ensuring an anonymous presentation of results.

These results were then assembled into a series of graphs to show how each modeler interpreted the given data, and applied their respective models. As noted in Section 3.1, only cross sectional data and limited open water data were provided to each participant. Each modeler had to, based on judgment, select appropriate parameters for their respective ice model. Data that had to be estimated included limiting Froude numbers for ice cover advancement, ice strength parameters, ice volume, deposition and erosion velocities, porosity of the jam (where applicable), and as it turned out, most importantly, the downstream water level at the toe of the jam.

The results of the analysis are summarized in **Figures 3.5 to 3.7**. **Figure 3.5** provides a comparison of the observed and computed water surface profiles for each of the models. **Figure 3.6** compares calculated and observed ice thicknesses for the jam. **Figure 3.7** compares the range of manning n values assumed by the various modelers.

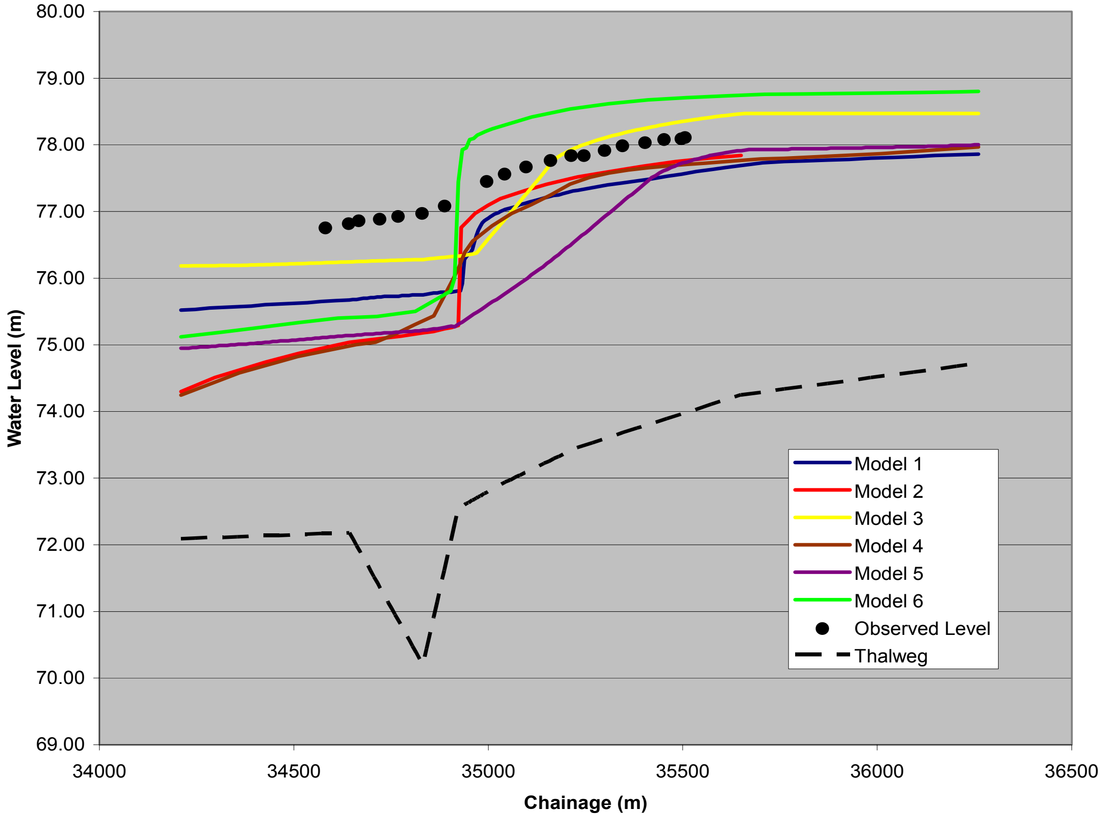

Figure 3.5 – Comparison of Computed Water Levels

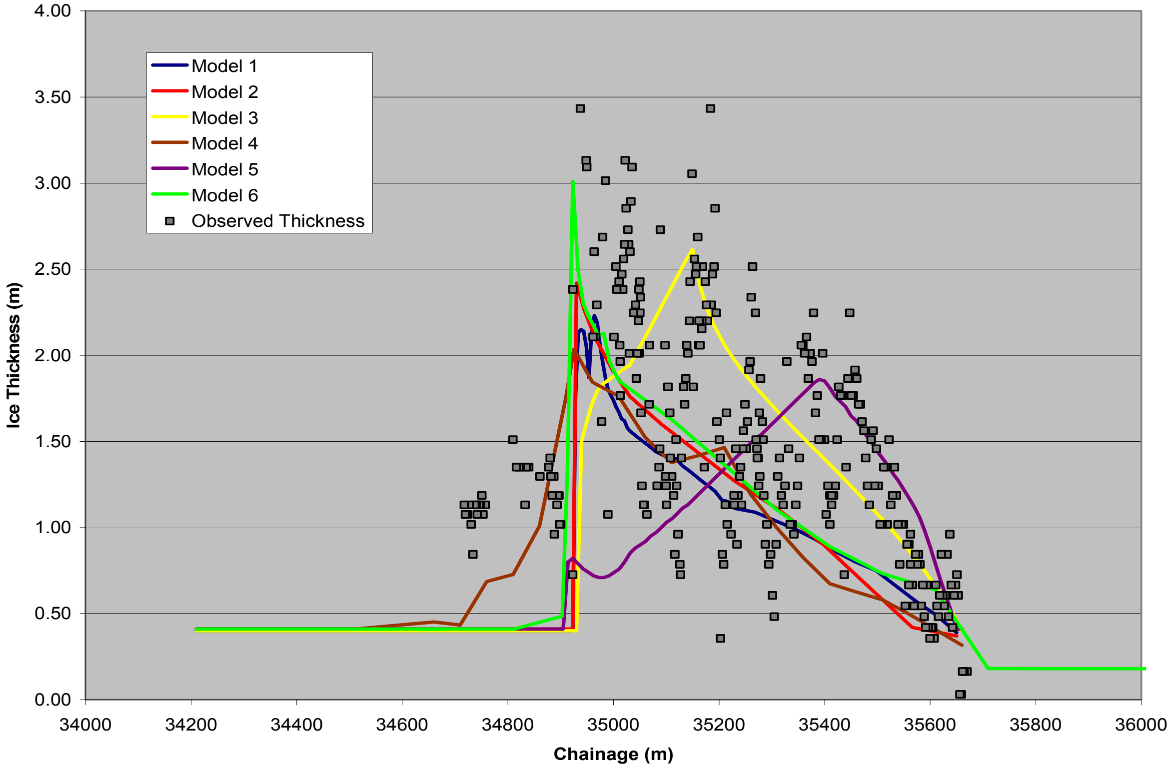

Figure 3.6 – Comparison of Computed Ice Thickness Within Jam

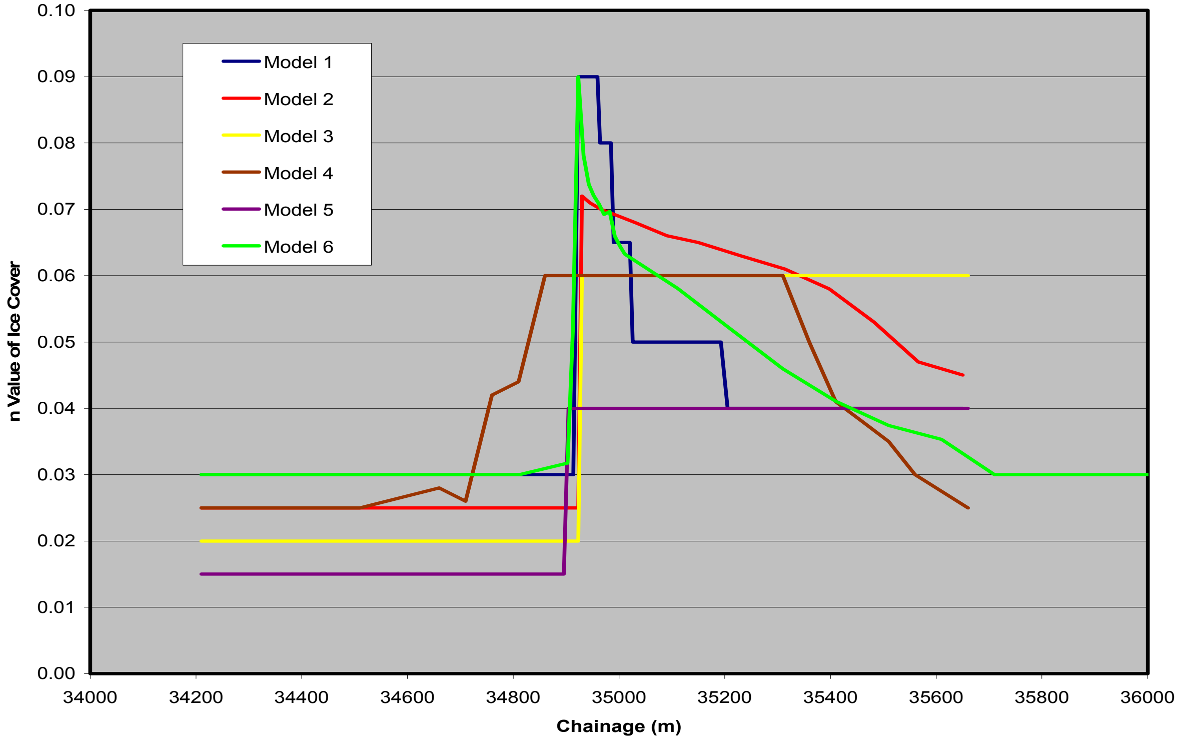

Figure 3.7 – Comparison of Estimated Ice Cover Manning's "n" Value

3.5. Discussion of Results

Upon reviewing the results of the various simulations, the following observations were drawn:

- As shown in **Figure 3.5**, the results showed some variability in the predicted water levels within and upstream of the jam. Predicted water levels at the head of the jam ranged from a low which was approximately 0.5 m below the observed level, to a high which was approximately 0.5 m above the observed level. All things considered, this represents a reasonable range considering the uncalibrated state of each of the models, and the small amount of information supplied to each modeler.
- As shown in **Figure 3.6**, the measured ice thickness data showed considerable variability. However, the overall average of the measurements was actually quite consistent with the majority of the model results. Most models produced similar ice thickness profiles, in spite of considerable differences in the downstream starting water level. The thickest portion of the jam was at the toe in most models (as it was in the observed data), although one model did show an increasing thickness with distance upstream.
- As shown in **Figure 3.7**, there was also relative consistency in the overall roughness values selected for the ice cover by the various modelers. Roughness values were, in general, largest in the area of the toe, and decreased with decreasing ice thickness. These values ranged from a Manning's coefficient of 0.04 to 0.09 at the toe of the jam.
- The biggest difference between the model solutions was likely related to the selection of a representative downstream water level for the jam event. This data was not supplied, and each modeler had to make an individual judgment on what would represent a suitable level given some broad qualitative guidance on the nature of the downstream channel. As indicated in **Figure 3.5**, there was considerable variation in the selected downstream water level. However, all modelers underestimated the downstream level, and this affected the simulated ice profile in all cases. Therefore the differences shown in predicted profiles and upstream water levels are a function not only of overall model capability, but also, of the ability of modelers to estimate this downstream level given minimal available data. It is interesting to note that since all modelers tended to underpredict downstream level, it is possible that the actual level may have been somewhat elevated from what would normally be expected.

4. Summary

This paper summarizes the results of the third in a series of tests that have been devised and coordinated by a sub-committee of the Committee on River Ice Processes and the Environment.

In this third phase, various ice models were applied in what has been called a "blind test". It has been based on actual field data including bathymetry, river flow, and location of ice jam, but no data was provided to the modelers on ice thicknesses or water surface profiles. The modelers had to select appropriate parameters based on judgment, and run their models so as to provide the best possible reproduction of the actual ice jam profiles without foreknowledge of the field data.

The field data was only revealed after the tests were completed and to permit comparison of the results with the prototype experience. The intent of this test was to provide a perspective on how well the models can perform without the benefit of actual field data upon which to calibrate the models. The results provide some measure of the variability in estimated water surface profiles that can result when these models are applied without the benefit of prior calibration. The results of this test resulted in estimated upstream water levels which varied by up to plus or minus 0.5 m.

5. Acknowledgements

The model authors gratefully acknowledge the generosity of Dr. Spyros Beltaos for supplying the data set used in this blind test, and for his assistance in gathering and forwarding all test results to the Task Force for analysis. We would also like to acknowledge the efforts of Mr. Brian Burrell who jointly with Dr. Beltaos collected the field data utilized in this blind test. Mr. Burrell was with the NB Department of the Environment and Local Government at the time of the jam event.

6. References

Andrishak, R. and Hicks, F. (2005) "Impact of Climate Change on the Peace River Thermal Ice Regime " Proc. 13th Wksp. on River Ice. 16-18 Sept. 2005, CGU - Hydrology Section, Comm. on River Ice Processes and the Env. (CGU-HS CRIPE), Hanover, NH, 21-40.

Hicks, F.E. and , Steffler, P.M., (1992) "A Characteristic-Dissipative-Galerkin Scheme for Open Channel Flow", ASCE Journal of Hydraulic Eng., 118(2): 337-352.

She, Y. and F. Hicks, (2006a) "Modeling Ice Jam Release Waves with Consideration for Ice Effects" Journal of Cold Regions Science and Technology, 45:137-147.

Liu, L. and Shen, H.T. (2004) "Dynamics of Ice Jam Release Surges," Proc., *17th International Symposium on Ice*, IAHR, St. Petersburg, 244-250.

Liu, L., Li, H., and Shen, H.T. (2006) "A Two-Dimensional Comprehensive River Ice Model," Proceedings, 18th IAHR Ice Symposium, Sapporo.

She, Y. and Hicks, F. (2006b), "Ice Jam Release Wave Modeling: Considering The Effects Of Ice in A Receiving Channel." Proc. 18th International Symposium on Ice. 28 Aug.-1 Sept. 2006, Sapporo, Japan, 8 pp.

Shen, H.T., Su, J., and Liu, L., (2000) "SPH Simulation of River Ice Dynamics," *Journal of Computational Physics,* 165(2), 752-770.