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Modeling river ice with HEC-RAS

Steven F. Daly and Carrie M. Vuyovich
ERDC/CRREL
72 Lyme Road
Hanover, NH 03755
Steven.F.Daly@erdc.usace.army.mil ; Carrie.M.Vuyovich@erdc.usace.army.mil

The Corps of Engineers Hydraulic Engineering Center's River Analysis System (HEC-RAS) is powerful tool for performing one-dimensional hydraulic calculations for a full network of natural and constructed channels and provides input and output information in tabular and graphical formats. HEC-RAS can simulate channels with ice covers of known thickness and roughness. It can also simulate wide river ice jams by adjusting the jam thickness and roughness until the ice jam force balance equation and the standard step backwater equation are satisfied. This paper reviews the use of RAS to simulate river ice. The input data requirements, solution procedure, the ice jam parameters, and problems that can arise in simulations are discussed. Several studies that used HEC-RAS simulations are reviewed.

1. Introduction and Background

The Hydrologic Engineering Centers River Analysis System (HEC-RAS) (U.S. Army Corps of Engineers 2002a, b, c) is an integrated system of software designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels and provide input and output information in tabular and graphical formats. The current version of this program will perform steady and unsteady flow analysis for subcritical, supercritical, and mixed flow regimes. Input and output data is provided in graphical as well as tabular formats. The HEC-RAS computer program uses a graphical user interface (GUI) for input and output data entry, and computational "engines" to perform the actual calculations. The program incorporates separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities.

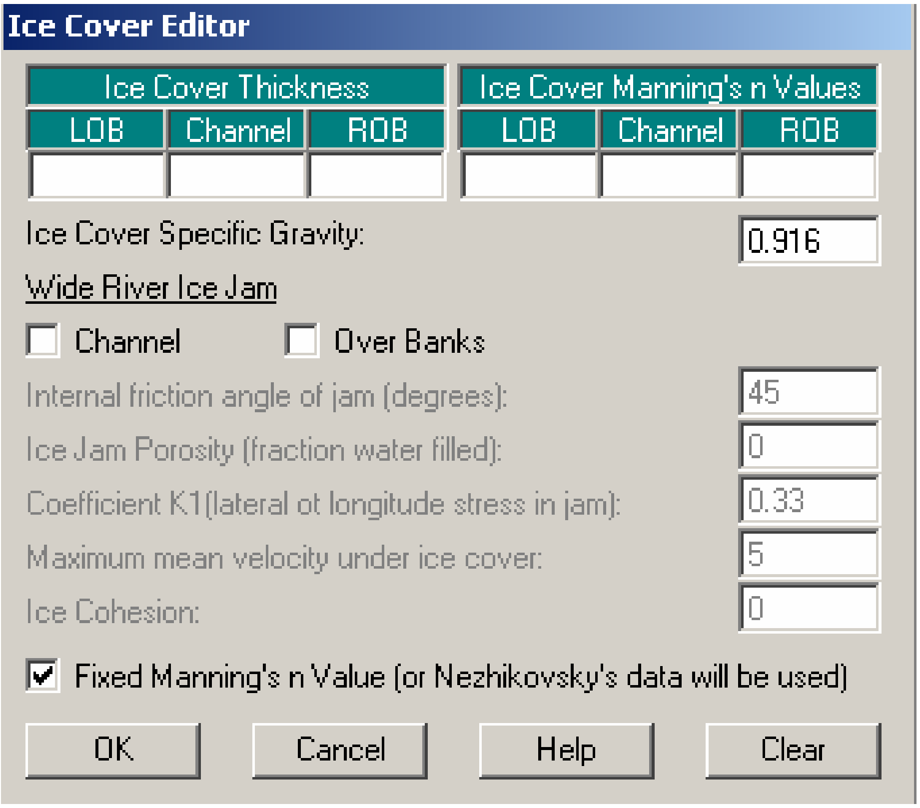
HEC-RAS allows the user to model ice-covered channels with known ice properties, or to simulate wide-river jams (Daly et al 1998). The first case, the user specifies the ice cover thickness and roughness at each cross section. Different ice cover thicknesses and roughnesses can be specified for the main channel and for each overbank, and both can vary along the channel. In the second case, the ice jam thickness is determined at each section by solving the ice jam force balance equation. The ice jam can be confined to the main channel or can include both the main channel and the overbanks. The material properties of the wide-river jam can be selected by the user and can vary from cross section to cross section. The user can specify the hydraulic roughness of the ice jam or HEC-RAS will estimate the hydraulic roughness on the basis of empirical data.

In this paper reviews the use of HEC-RAS to simulate ice. The input data requirements, solution procedure, the ice jam parameters, and problems that can arise in simulations are discussed. Several studies that used HEC-RAS simulations are reviewed. Future directions of HEC-RAS ice simulations are outlined.

2. Input Data Requirements

HEC-RAS has a graphical user interface for entering data from the keyboard. In addition, time-varying data can be automatically entered from the HEC-DSS database. Geospatial data in ArcView GIS (or ArcInfo) can also be entered using a graphical user interface. The interface allows the preparation of geometric data for import into HEC-RAS and processes simulation results exported from HEC-RAS.

River Ice Conditions. Information describing the ice conditions in the channel is entered as Geometric Data. The User's Manual (U.S. Army Corps of Engineers. 2002b) has a complete description of the data entry procedure for HEC-RAS. Geometric data describes the river channel geometry by abstracting a series of arbitrarily spaced cross sections along the length of the channel. The cross section spacing must be sufficient to adequately describe the hydraulics of the channel. Each cross section is divided into a channel portion, and a left and right overbank. The ice conditions must be described at each cross section along the channel where ice exists. The user is required to enter the thickness and the Manning's roughness coefficient of the ice cover for the channel and left and right overbanks at each river cross section where the ice is present. The user can use the entered values in the hydraulic simulation or can set these values as the initial and minimum estimates of the thickness of a wide river jam.



Ice Cover Editor

Ice Cover Thickness			Ice Cover Manning's n Values		
LOB	Channel	ROB	LOB	Channel	ROB

Ice Cover Specific Gravity: 0.916

Wide River Ice Jam

☐ Channel ☐ Over Banks

Internal friction angle of jam (degrees): 45

Ice Jam Porosity (fraction water filled): 0

Coefficient K1(lateral ot longitude stress in jam): 0.33

Maximum mean velocity under ice cover: 5

Ice Cohesion: 0

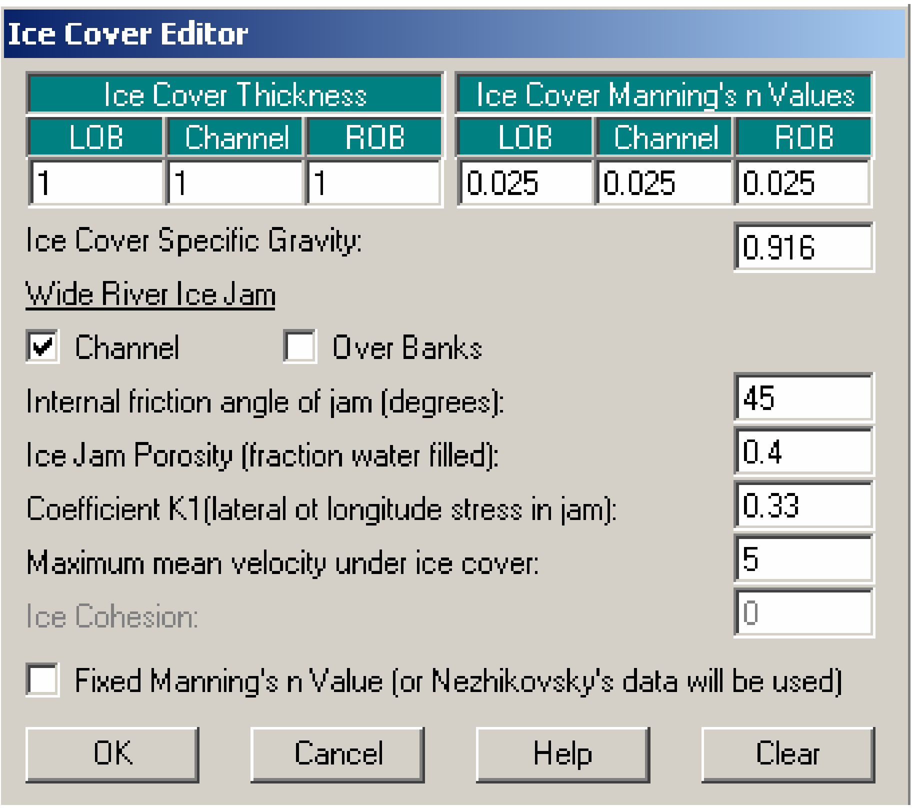
☑ Fixed Manning's n Value (or Nezhikovsky's data will be used)

Figure 1. Ice Cover Editor

The Ice Cover Editor is displayed in Figure 1. This editor is selected to enter the ice properties for each section from the Cross Section Data window under the Options menu. The ice cover thickness is entered in the three upper left entry boxes for the left overbank (LOB), the Channel and the right overbank (ROB). The ice cover Manning's n values are entered in the three right entry boxes in the same way. The ice cover properties will be considered fixed for the simulation unless one of the boxes under "Wide River Ice Jam" is checked.

If one of the boxes under the "Wide River Ice Jam" is checked, then a wide river ice jam is assumed to occur at this section. If the Channel box is checked, the ice cover will be confined to the channel only. If the "Over Banks" box is checked, the ice jam will be allowed in both the channel and the overbanks. If the jam is allowed to enter the overbanks; then the hydraulic properties of the channel and the overbanks will be combined in determining the hydraulic conditions that impacts the ice jam.

The user can modify the parameters of the wide river ice jam. Default values are provided as a guide. The first three values determine the material properties of the ice jam. They are the internal friction angle of the ice; the ice jam porosity; and the ratio of lateral to longitudinal stress. White (1999) provides an overview of the measured and estimated values of these parameters. The fourth value is the maximum allowed velocity under the ice jam. This parameter is necessary to prevent the ice jam from grounding on the bed. (Flato and Gerard 1986, Flato 1988). There will be short discussion of it in a later section of this paper. The fifth and final parameter sets the ice cohesion. However, in HEC-RAS wide river jam simulation, the ice cohesion is always set to zero and cannot be modified by the user.



Ice Cover Thickness			Ice Cover Manning's n Values		
LOB	Channel	ROB	LOB	Channel	ROB
1	1	1	0.025	0.025	0.025

Ice Cover Specific Gravity: 0.916

Wide River Ice Jam

☑ Channel ☐ Over Banks

Internal friction angle of jam (degrees): 45

Ice Jam Porosity (fraction water filled): 0.4

Coefficient K1(lateral ot longitude stress in jam): 0.33

Maximum mean velocity under ice cover: 5

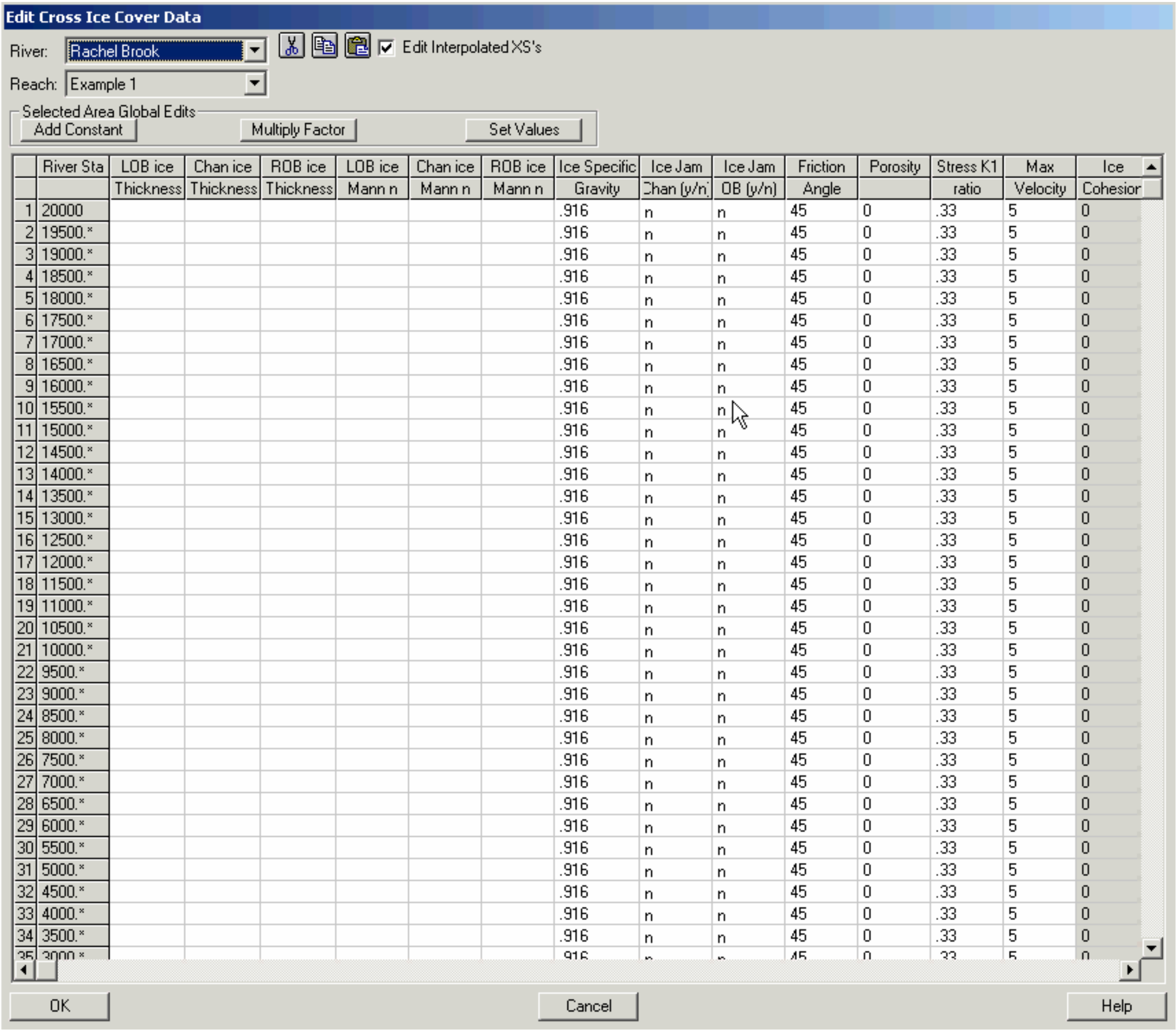
Ice Cohesion: 0

☐ Fixed Manning's n Value (or Nezhikovsky's data will be used)

Figure 2

The final data to be entered decides if the hydraulic roughness of the wide river jam will be allowed to vary based on the jam thickness and the channel depth. Measurements in the field suggest that this is appropriate (Nezhikovskii 1964; Beltaos 2001). The measurements of Nezhikovskií were used to develop an empirical estimate of the bottom roughness of an ice jam as a function of the jam thickness and channel depth. If the boxed is checked, the Manning's n value entered by the user will be used. The default is to have the box checked.

This method of entering the data cross section by cross section can become labor intensive if there are many cross sections in the HEC-RAS simulation that have ice. A short cut table labeled "Ice Cover", found under the "Table" menu of the Geometry Editor can be used to quickly enter the data for all the cross sections at once. The table is show in Figure 3. The table is probably the most common means by which the ice cover data is entered into HEC-RAS.



River: Rachel Brook

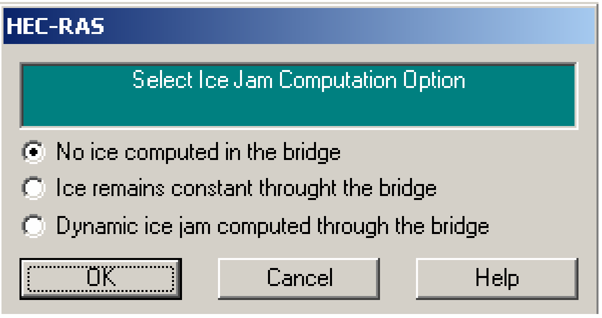
Reach: Example 1

☑ Edit Interpolated XS's

	River Sta	LOB ice Thickness	Chan ice Thickness	ROB ice Thickness	LOB ice Mann n	Chan ice Mann n	ROB ice Mann n	Ice Specific Gravity	Ice Jam Chan (y/n)	Ice Jam OB (y/n)	Friction Angle	Porosity	Stress K1 ratio	Max Velocity	Ice Cohesion
1	20000							.916	n	n	45	0	.33	5	0
2	19500.*							.916	n	n	45	0	.33	5	0
3	19000.*							.916	n	n	45	0	.33	5	0
4	18500.*							.916	n	n	45	0	.33	5	0
5	18000.*							.916	n	n	45	0	.33	5	0
6	17500.*							.916	n	n	45	0	.33	5	0
7	17000.*							.916	n	n	45	0	.33	5	0
8	16500.*							.916	n	n	45	0	.33	5	0
9	16000.*							.916	n	n	45	0	.33	5	0
10	15500.*							.916	n	n	45	0	.33	5	0
11	15000.*							.916	n	n	45	0	.33	5	0
12	14500.*							.916	n	n	45	0	.33	5	0
13	14000.*							.916	n	n	45	0	.33	5	0
14	13500.*							.916	n	n	45	0	.33	5	0
15	13000.*							.916	n	n	45	0	.33	5	0
16	12500.*							.916	n	n	45	0	.33	5	0
17	12000.*							.916	n	n	45	0	.33	5	0
18	11500.*							.916	n	n	45	0	.33	5	0
19	11000.*							.916	n	n	45	0	.33	5	0
20	10500.*							.916	n	n	45	0	.33	5	0
21	10000.*							.916	n	n	45	0	.33	5	0
22	9500.*							.916	n	n	45	0	.33	5	0
23	9000.*							.916	n	n	45	0	.33	5	0
24	8500.*							.916	n	n	45	0	.33	5	0
25	8000.*							.916	n	n	45	0	.33	5	0
26	7500.*							.916	n	n	45	0	.33	5	0
27	7000.*							.916	n	n	45	0	.33	5	0
28	6500.*							.916	n	n	45	0	.33	5	0
29	6000.*							.916	n	n	45	0	.33	5	0
30	5500.*							.916	n	n	45	0	.33	5	0
31	5000.*							.916	n	n	45	0	.33	5	0
32	4500.*							.916	n	n	45	0	.33	5	0
33	4000.*							.916	n	n	45	0	.33	5	0
34	3500.*							.916	n	n	45	0	.33	5	0
35	3000.*							.916	n	n	45	0	.33	5	0

Figure 3. Ice Cover Table

Estimating wide-river jams at bridges. There has been little or no research on the impacts of bridges on wide river jams. The current version of the ice jam force balance equation does not account for ice contacting the low steel of the bridge. In order to accommodate bridges in the simulation and to acknowledge the lack of understanding of the possible influence of bridges on the ice jam force balance equation, the user is given the option of controlling the wide river jam calculations at the bridges. This is done through the Ice Options under the Options menu of the Bridge/Culvert Window of the Geometry editor. The three options are listed in Figure 4. The second option is suitable for the hydraulic simulation with an ice cover of known thickness and roughness. The third option calculates the wide river jam through the bridge. However, the impact of the low steel and other structural elements of the bridge are not taken into account.



● No ice computed in the bridge
○ Ice remains constant throught the bridge
○ Dynamic ice jam computed through the bridge

Figure 4. Ice jam computation options at bridges

Discussion of maximum velocity parameter. In the development of the ice jam force balance equation, it was assumed that the ice cover floats at hydrostatic equilibrium. This assumption is not necessarily required but was used to simplify the estimation of the vertical stress distribution in the fragmented ice cover. If the ice is floating at hydrostatic equilibrium, then only the ice cover thickness is required to estimate the vertical stress distribution. If the ice cover is not floating at hydrostatic equilibrium, but rather the bed of the channel supports a portion of the cover's weight, then the estimation of the vertical stress profile depends on both the thickness of the ice cover and the depth of the flow relative to the ice cover thickness. In addition, if the ice cover contacts the bed, then flow through the interstitial passages of the ice cover becomes significant. In the current version HEC-RAS, only flow under the ice cover is accounted for. High Reynolds number flow through an ice jam can be simulated through modification of the hydraulic conveyance of a section to account for the friction losses (Daly and Hopkins 1998) but this has not yet been included in HEC-RAS. As a result, it is important that the ice cover does not contact the bed in order that the ice cover always floats at hydrostatic equilibrium, and that the hydraulic conveyance is accounted for appropriately. In order to assure this, a maximum velocity parameter is required (Flato and Gerard 1986, Flato 1988) during the solution of the ice jam force balance. This can be seen by rearranging the continuity equation, $V = Q/A$, where Q = the discharge, which is set by the user, A = the flow area and is, in practice, the area under the ice cover; and V = the flow velocity. As the flow area is reduced, and as Q is a constant at each section for each simulation, the velocity, V, must increase. If a maximum velocity limit is set for V, then an effective minimum cross sectional flow area is set for A. If A goes to zero, then the ice cover contacts the bed and the above assumptions are violated.

There may, in fact, be a flow velocity that is too high to allow a wide river jam to exist, but this is not the motivation for the maximum velocity parameter, as we have seen. Users must be aware of the implications of this parameter during simulations of wide river jams. In reaches where the maximum velocity parameter is met or exceeded, the ice cover will not thicken. In steep reaches, this may occur with the initial thicknesses that the user has entered - and the wide river jam thicknesses will not be calculated. If this is the case, and the user reasonably expects that the ice jam thickness should be greater, then it may be necessary to increase the value of the maximum velocity parameter. The program will provide the user a message for each cross section where the maximum velocity parameter has been met.

Selection of the ice covered areas. Prior to the start of the simulation, the user must determine the extent of the river ice cover and the extent of the ice jams, if present. HEC-RAS cannot determine the location of the river ice jams. HEC-RAS can estimate the ice volume of the jams but cannot limit the length of the jam based on volume. Simulations with an ice cover of known thickness and roughness can have the ice cover in the channel, in the overbanks, or any combination of the channel and overbanks. The ice cover does not have to be continuous, but can have open water reaches.

The widths of the channel and overbanks can be set by the user in the Cross Section Data window for each section. An example of a river ice simulation would be that of an ice covered river with a navigation track down the approximate center of the channel. The navigation track would be essentially ice-free or open. In this type of simulation, it may be appropriate to investigate several different widths of the navigation track. Changing the navigation opening would involve adjusting the left and right bank stations for each cross section. Modifying the channel width in this manner cross section by cross section can become labor intensive if there are many cross sections in the HEC-RAS simulation that have ice. A short cut table, labeled Bank Stations…", found under the "Table" menu of the Geometry Editor can be used to quickly enter the Bank Stations for all the cross sections at once. This is a short cut method for modifying the width of the open water track down the center of channel. The user must also note the hydraulic roughnesses of the overbank areas and the channel. As the relative widths of the overbanks are changed, the overall hydraulic roughness of the channel may change, if the overbanks and channel have differing hydraulic roughnesses.

Simulations of a wide river jam must have a section with known thickness and roughness at each end of jam. The thickness and roughness of these sections will not be changed during the ice jam simulation. If sections with fixed thickness and roughness are not selected at each end of the wide river jam, an error will occur. This requires the user to select the entire location where the wide river jam occurs prior to the simulation.

3. Previous Studies

Four studies that used the ice option of HEC-RAS will be reviewed in this section. These studies were selected because different aspects of ice analysis are highlighted in each study.

Project: Whitney Point Lake Study (Zufelt and Daly 2002, Daly, Zufelt, and Sodhi 2001)
Synopsis: The Baltimore District of the U.S. Army Corps of Engineers investigated eliminating the current winter drawdown of Whitney Point Lake, a project located on the Otselic River in Broome County, New York, about 20 miles north of Binghamton, NY. The primary purpose of the project is to provide flood control for the Tioughnioga River downstream of Whitney Point Village, the lower reach of the Chenango River, and the Susquehanna River downstream of Binghamton. The intended operational change entails eliminating a current winter drawdown for environmental enhancement. The study addressed the effects of eliminating the drawdown on water levels upstream of the project when ice was present. Of particular concern was the formation of ice jams.
HEC-RAS Data: The geometry for the HEC-RAS model was developed from a GIS (geographic information systems) database that included topographic data at 10-foot contours and hydrographic data at 2-foot contours. Cross sections were abstracted from this information

and entered into HEC-RAS using the GEO-RAS extension of ArcView (Corps of Engineers 2002d). All cross sections were extended to a contour elevation of at least minimum elevation, if possible. Bridge information was taken from the maintenance drawings developed by the county highway department. The channel roughness was estimated on the basis of accepted ranges for rivers with this plan form and appearance. The ice thickness was estimated based on recorded freezing degree-days.
HEC-RAS Results: Freeze-up water levels with and without planned changes; estimation of breakup ice jam locations based on empirical breakup criteria; ice jam flood levels with and without planned changes; and the hydraulic data estimation used to estimate forces on existing bridge.

Project: Upper Ohio and Monongahela Ice Passage Study (Tuthill and Daly 2002, Tuthill and Daly 2001)
Synopsis: River ice periodically impedes winter tow traffic on the major inland waterways in the U.S. During ice periods, moving vessels continually re-break the ice cover on the navigation channel creating an accumulation of broken ice pieces known as brash ice. In the pools above navigation dams where water velocity is typically low, brash ice congestion may become severe enough to bring tow traffic to a standstill. This nearly occurred in January of 2001 on the upper Ohio and Monongahela Rivers where the Pittsburgh District of the US Army Corps of Engineers operates a series of 15 locks and dams. In response, the towing industry asked the Corps about the possibility of releasing extra water at dams to clear brash ice downstream. At the district's request, the Cold Regions Research and Engineering Laboratory (CRREL) studied the problem in an effort to determine what flow levels and durations would be needed and to clear brash ice from the pools under a variety of scenarios. Based on observation and theory, CRREL developed relationships between discharge, time and brash ice volume cleared from the navigation channels above each gated dam in the Pittsburgh District.
HEC-RAS Data: The geometry for the HEC-RAS model was based on measured river geometry (provided by Pittsburgh District of the Corps Hydraulics and Hydrology Section) available in HEC-2 format. The model had been calibrated for open water conditions. We modeled an open channel case and a centrally aligned open channel bordered on the sides by 15-cm-thick sheet ice (n = 0.015). According to District personnel the 15-cm sheet ice thickness represents relatively severe winter conditions for the region and the Manning's roughness of 0.015 is reasonable for a sheet ice cover (US Army 1999).
HEC-RAS Results: We modeled an open channel case and a centrally aligned open channel bordered on the sides by 15-cm-thick sheet ice (n = 0.015). According to District personnel the 15-cm sheet ice thickness represents relatively severe winter conditions for the region and the Manning's roughness of 0.015 is reasonable for a sheet ice cover (US Army 1999). The width of the central open channel represented the area of the channel opened by navigation traffic in the river. Two different widths were investigated. Estimations were made of the minimum flow velocity required to move ice to the dams. Interviews with lock personnel were made to confirm required flow rates based on actual gate openings.

Project: Ice Forces on Pedestrian Bridges in Grand Forks, ND (Daly, Haehnel, et al 2002)
Synopsis: The St. Paul District of the Corps of Engineers is developing plans for two pedestrian bridges to be located at Grand Forks, North Dakota, over the Red River of the North. The elevation of the low steel of the proposed designs will be submerged by flow during an

approximately 10-year or greater return period flood. As a result it is likely that river ice will often hit the bridge superstructure. To estimate the loads that the ice may produce on the bridge piers and superstructure, the likely interaction of the river ice and the bridge must be determined and the different modes of ice action on the bridge described. The HEC-RAS model was used to describe the likely interaction between the flow, the river ice, and the proposed bridges. This information was used to evaluate the ice forces on the proposed pedestrian bridges over the range of flows that will contact the bridges and the range of ice conditions.

HEC-RAS Data: The St. Paul District, using measured river geometry, developed The HEC-RAS model. The model had been calibrated for open water. Ice thickness was estimated based on recorded freezing degree-days and verified against measurements.

HEC-RAS Results: The HEC-RAS model was run with an ice cover for the 1.01-, 1.05-, 1.11-, 1.25-, 2-, 5-, and 10-year events to determine the conditions that would lead to ice interaction with the bridge and where the on the bridge the ice would hit (for events greater than a 10-year event the bridge deck is fully submersed and it is assumed the ice would not interact with the bridge). For these same events HEC-RAS was used to determine the thickness of an ice jam that would form against the bridge from a 1- and a 2-foot thick ice cover. This information was used to determine if the ice forces on the bridges are augmented by jam formation. In each case the thickness of the ice jam accumulation was not significantly thicker than that of the ice cover due to the extremely mild gradient of the river. HEC-RAS was also used to develop hydraulic data used to determine forces on the proposed bridge.

Project: Cazenovia Creek Ice Control Structure (Lever and Daly 2003, Lever, Gooch and Daly 2000)

Synopsis: CRREL has recommended a cylindrical-pier ice control structure (ICS) for Cazenovia Creek in West Seneca, NY. The ICS will arrest a breakup ice run and hold the resulting ice jam throughout typical breakup events. Consequently, water levels upstream of the ICS will be higher than under existing conditions. We used HEC-RAS to determine the maximum ice-jam water elevations upstream of the ICS and compared the results with the 100-year open-water profile to assess the upstream effects of the ICS.

HEC-RAS Data: The model consisted of 50 cross-sections along 5.8 km of Cazenovia Creek. The cross-sections came from three sources: (1) an HEC-2 model that used surveyed cross-sections from 1984, (2) closely spaced surveyed cross-sections obtained in 1998, and (3) supplemental cross-sections determined from 1:2400-scale topographic maps. As far as possible, we checked these data for consistency in terms of vertical and horizontal alignment. The HEC-RAS model included the two bridges in the reach. We input the nine 1.5-m-dia. x 3-m-tall cylindrical piers of the ICS using the HEC-RAS feature "multiple blocked obstructions."

HEC-RAS Results: Essentially, the stream-wise extent of the ICS jam dictates the extent of high water. Therefore, estimated ice-jam volume as a function of discharge plays a key role in the modeling. The initial ice-jam volume was the pre-breakup ice supply estimated from field data, less 30% transport losses. At each discharge, we reduced the available ice volume to account for melting by water entering the jam at 0.7°C and minor washouts through the ICS at a rate of 1% of discharge. Although these appear to be conservative choices, they significantly reduce the ice-jam length, and thus the extent of high water, as discharge increases. The maximum ice-jam water levels at each discharge formed an “elevation envelop” to determine the effect of the ICS on upstream property owners.

4. Summary

This paper reviews the use of RAS to simulate river ice. The input data requirements were discussed. In particular, ice jams at bridges, the maximum velocity criteria and the location of the ice jam were discussed. Several studies that used HEC-RAS simulations were reviewed.

5. References

Beltaos, S. (2001) Hydraulic roughness of breakup ice jams Journal of Hydraulic. Engineering. American Society of Civil Engineers. 127(8), pp 650-656.

Daly, S.F., R. Haehnel, D. Sodhi, and C. Vuyovich (2002) Ice Forces on Proposed Pedestrian Bridges, Grand Forks, ND. Report Prepared for the St. Paul District, Corps of Engineers. U.S. Army Engineering and Research Center, Cold Regions Research and Engineering Laboratory, Hanover, N.H.

Daly, S.F., J. Zufelt, D. Sodhi (2001) Ice Impacts on the Upper Lisle Bridge resulting from the proposed change in operation of Whitney Point Lake Project. Report prepared for the Baltimore District, Corps of Engineers, Baltimore, MD

Daly, S.F., G. Brunner, S. Piper, M. Jensen, and A. Tuthill (1998) Modeling Ice Covered Rivers Using HEC-RAS. In Cold Regions Impact on Civil Works, D.E. Newcomb, ed., Proceedings of the American Society of Civil Engineers 9th International Conference on Cold Regions Engineering, Duluth, MN, Sep. 27-30, 1998, pp 373-380.

Daly, S.F., and M. Hopkins (1998) Simulation of River Ice Jam Formation. In Ice in Surface Waters, H.T. Shen, ed., Proceedings of the International Association of Hydraulic Research 14th Ice Symposium, Potsdam, NY, July 27-31, 1998, Vol. I, pp 101-108.

Flato G., and Gerard, R. (1986) Calculation of ice jam thickness profiles. Fourth workshop on Hydraulics of River Ice, Montreal, June 19-20.

Flato G. (1988) Calculation of Ice Jam Profiles. MSc. Thesis, Dept. Of Civil Engineering, University of Alberta, 177 pp.

Lever, J.H. and S.F. Daly (2003) Upstream effects of the Cazenovia Creek ice control structure, Journal of Cold Regions Engineering, ASCE, Vol 17. No. 1., March 2003, pp 3-17

Lever, J.L, G. Gooch and S.F. Daly (2000) Cazenovia Creek Ice-Control Structure. U.S Army Engineering Research and Development Center, Cold Regions Research and Engineering Laboratory, ERDC/CRREL TR-00-14.

Nezhikovskii, R.A. (1964) Coefficient of roughness of the bottom surfaces of slush ice covers. Soviet Hydrology, Selected Papers, no. 2, pp.127-150.

Tuthill, A.M. and S.F. Daly (2002) Ice Passage at Gated Navigation Projects in the Upper Ohio River Basin In Proceedings, 11th International Conference, Cold Regions Engineering, May 20-22, 2002, Anchorage, Alaska. Cold Regions Impacts on Transportation and Infrastructure. (Kelly S. Merrill, Ed.) Reston, VA: American Society of Civil Engineers, pp. 816-827.

Tuthill, A.M. and S.F. Daly (2001) Ice Passage at Gated Navigation Projects in the Upper Ohio River Basin. Report prepared for the Pittsburgh District, Corps of Engineers, Pittsburgh, PA

U.S. Army Corps of Engineers. (2002a) HEC-RAS River Analysis System. Hydraulic Reference Manual. Version 3.1. U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, CA, November 2002. http://www.hec.usace.army.mil/software/hec-ras/hecras-document.html

U.S. Army Corps of Engineers. (2002b) HEC-RAS River Analysis System. User's Manual. Version 3.1. U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, CA, November 2002. http://www.hec.usace.army.mil/software/hec-ras/hecras-document.html

U.S. Army Corps of Engineers. (2002c) HEC-RAS River Analysis System. Application Guide. Version 3.1. U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, CA, November 2002. http://www.hec.usace.army.mil/software/hec-ras/hecras-document.html

U.S. Army Corps of Engineers. (2002d) HEC-GeoRAS An extension for support of HEC-RAS using ArcView GIS. U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, CA, October 2002. http://www.hec.usace.army.mil/software/hec-ras/downloads/georas_3.1_users_manual.pdf

White, K (1999) Hydraulic and Physical Properties Affecting Ice Jams. U.S Army Engineering Research and Development Center, Cold Regions Research and Engineering Laboratory, CRREL Report 99-11,Hanover, NH

Zufelt, J, and S.F. Daly (2002) Reservoir Operations and their Effect on Ice Regime. In Proceedings, 11th International Conference, Cold Regions Engineering, May 20-22, 2002, Anchorage, Alaska. Cold Regions Impacts on Transportation and Infrastructure. (Kelly S. Merrill, Ed.) Reston, VA: American Society of Civil Engineers, 804-815.