Maximum Waterlevels Upstream of an Ice-Control Structure

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An ice-control structure (ICS) for Cazenovia Creek in West Seneca, NY will arrest breakup ice runs and hold the resulting ice jams essentially throughout typical breakup events. While this will reduce flood damages downstream, waterlevels upstream of the ICS will be higher than currently experienced, and upstream property owners must be compensated. We used HEC-RAS to model ice-jam hydraulics upstream of the ICS as a function of water discharge and ice volume. The initial ice-jam volume was the 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 1°C and minor washouts through the ICS at a rate of 1% of discharge. Although these appear to be conservative choices, ice losses become increasingly significant as discharge rises. They thus play an important role in reducing the stream-wise extent of high water caused by the ICS. By modeling these ice-loss processes, we may be able to design ice-control structures that maximize downstream flood protection yet minimize upstream impacts.

1. Introduction

Breakup ice jams can cause serious flooding in communities located along small, steep rivers. One mitigation approach is to arrest the breakup ice run and retain the resulting ice jam at a safe location upstream. Structures designed for this purpose include weirs with ice-retaining piers (Gooch and Deck 1990), closely spaced piers (Cumming-Cockburn 1986), widely spaced sloped blocks (Lever et al. 1997) and widely spaced cylindrical piers (Lever and Gooch, in press). However, by virtue of their ice-retaining function, these structures will cause higher waterlevels upstream than under existing (i.e., pre-project) conditions.

CRREL has recommended an ice-control structure (ICS) for Cazenovia Creek in West Seneca, NY that consists of nine 1.5-m-dia. × 3-m-tall cylindrical piers, with 3.7-m gaps between the piers (Figure 1). It will be located at a cross-section with a broad, treed floodplain. Physical model tests indicate that the ICS will arrest a breakup ice run and hold the resulting ice jam throughout most breakup events (Lever and Gooch, in press). By retaining ice arriving from many miles upstream, the ICS should significantly reduce ice-jam flood damages downstream.

The ICS, by design, will hold an ice jam at discharges much higher than that needed to clear a natural jam from the immediate upstream reach. Fortunately, Cazenovia Creek flows through a steep-walled valley along this reach, and most properties that abut the creek do not have structures within the valley. Nevertheless, upstream property owners that could experience higher waterlevels caused by the ICS must be identified and compensated.

We conducted a detailed study to determine the maximum upstream waterlevels caused by the Cazenovia Creek ICS (Lever et al. 2000; Lever and Daly, in review). The established 100-year open-water profile provided the only reference for high water under existing conditions because natural ice jams cause flooding downstream of the ICS. We used HEC-RAS, a numerical model developed by the Corps of Engineers, to model the ice-hydraulics of the ICS jam (USACE 1998a). As expected, the model predicts that maximum upstream waterlevels occur along the ICS jam rather than for open-water conditions. However, the upstream extent of the jam will decrease during breakup events as melting and washouts reduce the retained ice volume. Quantifying these ice losses thus becomes important for realistic modeling. Here, we describe the methods used with emphasis on the losses affecting ice-jam volume. We also discuss general implications for modeling upstream effects of breakup ice-control structures.

2. Ice-Hydraulic Conditions

The drainage area of Cazenovia Creek is 373 km^2. The main stem is about 27 km long from the confluence of the creek's east and west branches in East Aurora to the Buffalo River, and it contributes most of the ice volume to jams in the lower basin. Through this reach, the river is 30–40 m wide and its average slope is 0.0026.

Shear walls have been observed after breakup upstream of the ICS site, indicating at least temporary formation of ice jams. Under existing conditions, however, the damage-causing ice jams form when the ice run encounters the strong, thick ice sheet along the flatter reach below the ICS site. These jams may release after several hours and reform downstream until discharge is sufficient to clear ice into the Buffalo River and eventually into Lake Erie.

Hydrographs from the USGS gage on Cazenovia Creek show characteristics typical of ice-jam events. The ice-affected stage increases slowly as the event begins. When breakup occurs and an ice run passes the gage, the measured stage rises sharply and falls abruptly. The gage drops back to its open-water rating curve after the ice moves far downstream. The remainder of the hydrograph, including the broad peak, is unaffected by ice and can provide accurate discharge measurements. The maximum discharge of record (since 1941) was 380 m^3/s on 1 March 1955. It is not known whether this took place during or after spring breakup. The maximum discharge occurring during a known ice-jam event was 360 m^3/s on 22 January 1959, and the expected 100-year open-water discharge is 440 m^3/s.

3. Ice Breakup with Ice-Control Structure

Physical model tests (1:15 scale) were conducted at CRREL to determine the ice-holding capacity of a cylindrical-pier ICS (Lever and Gooch, in press). The piers were 1.5-m-dia. × 3-m-tall and were spaced with 3.0- to 4.3-m gaps (all dimensions here are equivalent full-scale values). Ice thickness ranged from 23–55 cm. The tests indicated that the ICS will arrest a breakup ice run and retain the resulting ice jam to discharges exceeding the design discharge

(170 m^3/s) without catastrophic releases. Piers spaced with 3.7-m gaps offered the best overall performance. We saw no improvement with 3.0-m gaps, and 4.3-m gaps tended to allow smaller floes or weaker ice to release more easily.

Based on the model tests, 30-cm-thick ice of moderate strength should start to wash out through the 3.7-m gaps at 200–230 m^3/s. The ICS should retain stronger or thicker ice to higher discharges. Smaller floes did wash out slowly, through the ICS gaps and onto the floodplain during all tests, reducing the ice volume upstream of the ICS. Nevertheless, for ice conditions that pose the greatest threat of downstream flooding (i.e., thick, strong ice), the ICS should hold ice well beyond 200 m^3/s.

The prototype ICS will retain breakup ice in the form of an ice jam. This jam will be grounded near the structure and free-floating beyond about 60 m upstream. In the same way as a natural ice jam, the ICS jam will cause much higher waterlevels along its length than would occur for the same discharge during open-water floods. However, washouts and melting of smaller floes will reduce the retained ice volume (and hence reduce jam length) throughout the event. Beyond about 230–280 m^3/s, the washout rate should accelerate, depending on the ice thickness and strength.

4. Numerical Ice-Hydraulic Model

We used HEC-RAS, a Corps numerical hydraulic model (USACE 1998a), to calculate water surface profiles through the ICS reach for both open-water and ice-jam cases. Briefly, HEC-RAS treats water flow as one-dimensional, steady, and gradually varied (spatially). At each cross-section, it can include an ice cover of known thickness or solve for the thickness of an ice jam according to ice-jam force-balance theory (USACE 1998b). The latter is a steady-state theory that treats the ice as a granular material with no cohesion. The program solves the one-dimensional force balance for the jam, where the under-ice water shear and jam self-weight are resisted by the shear strength of ice at the banks. The ice jam floats on the water and adds a rough top surface, resulting in waterlevels that are generally much higher than for open water at the same discharge. The user can constrain the jam to the main channel (appropriate for treed floodplains) and can set hydraulic roughness (Manning's n) of the ice to a fixed value or allow it to vary with jam thickness. The program calculates the volume of ice in a jam, which allowed us to simulate a jam of known volume at each discharge. In each case, open-water conditions were modeled upstream of the jam head.

The HEC-RAS model consisted of 50 cross-sections along 5.8 km of Cazenovia Creek, from 180 m downstream of Mill Road to 30 m downstream of Transit Road. It included the two bridges in the reach, at Mill Road and Leydecker Road. We input the nine 1.5-m-dia. × 3-m-tall cylindrical piers of the ICS using the HEC-RAS feature called "multiple blocked obstructions."

All model runs assumed subcritical flow. The downstream rating curve derived from the output of an earlier HEC-2 model (USACE 1986). We calibrated the model for open-water existing conditions using surveyed water-surface elevations (WSE's), a computed HEC-2 profile, and the established 100-year flood profile (Lever and Daly, in review). We also used data from the physical model to calibrate the HEC-RAS model for water-level change across the ICS.

The physical model provided WSE data with the ICS for many different ice-jam conditions. We selected three data sets (57, 170 and 173 m^3/s) that offered fairly long, steady state ice jams upstream of the ICS. As with all the tests, however, the jams were grounded at the ICS, a feature that cannot be modeled directly with HEC-RAS. Instead, we matched the measured WSE's by setting 1.8-m-thick ice covers along the first 15 m upstream of the ICS (Figure 2). We selected a conservative value of 0.08 for Manning's *n* of the underside of the ice jam (USACE 1998b) and used this for all the final ice-jam runs. Runs conducted with variable Manning's *n* (i.e., *n* increasing with jam thickness, USACE 1998b) yielded similar results. Also, runs with the jam toe at Mill Road converged with these results about 300 m upstream of the ICS (Figure 3). This suggests that our inability to model the grounded jam-toe probably has little effect on the results sought here.

Note that HEC-RAS treats the presence of an ice cover or jam at a cross-section as a geometric factor affecting the flow boundaries. That is, a new geometry file is needed for each variation in ice-jam characteristics (toe location, head location, roughness, over-bank ice, etc.). To converge to a target ice-jam volume for a given discharge, for example, we varied the jam-head location through individual geometry files.

5. Ice Jam Volume

Snowmelt often drives the peak annual hydrological event in Cazenovia Creek. Consequently, the expected 100-year open-water discharge (440 m^3/s) is similar to the highest ice-jam discharge in the 60-year record (360 m^3/s). The ICS could conceivably retain ice at these discharges if it is sufficiently thick and strong ice. The maximum high water induced by the ICS could be found by treating the ice volume as unlimited and calculating the waterlevels caused by an ice jam along the entire upstream reach at the 100-year discharge. However, such an analysis would be excessively conservative and unrealistic.

The ice volume in the ICS jam will always be finite, with the pre-breakup ice volume along the contributing reach as an upper bound. However, the initial ice run from upstream will leave ice floes along the banks, in the form of shear walls, and on the small floodplains that line the valley floor. Once the jam is formed at the ICS, melting and slow washouts will reduce its volume throughout the event. Lastly, at high discharge, ice washouts will accelerate as floes break and release through the ICS gaps. We estimated each term in this process to estimate the ice volume retained as a function of discharge, $V_j(Q)$. We then used $V_j(Q)$ to limit ice volume modeled in HEC-RAS at each discharge.

5.1 River Ice Suppl*y*

Buffalo District personnel conducted ice-thickness measurements in 1983 and aerial surveys in 1983 and 1985 to observe the ice-formation process and determine the ice supply in Cazenovia Creek (USACE 1986). They estimated that the pre-breakup ice supply "from the headwaters to Cazenovia Street" was 2.2×10^5 m^3 in 1983 and 2.6×10^5 m^3 in 1985. Although the ice-thickness data themselves are not available, maps used for the surveys during 1983 record solid ice about 21 cm thick. Consequently, the thickness of solid ice in 1985 was probably about 27 cm. These volume estimates are consistent with ice covering 100% of the 26 km of river from Cazenovia Street to East Aurora, assuming an average cover width of 37 m.

The river length from the ICS site to East Aurora is about 18 km. Along this reach, the average cover width is about 30 m. A reasonable estimate of the maximum average ice thickness immediately prior to breakup is 46 cm. This yields an ice volume of 2.5×10^5 m^3, which we may increase to 2.8×10^5 m^3 to allow for minor ice supply from the east and west branches (USACE 1986). This becomes our best estimate for the pre-breakup ice supply.

5.2 Transport Losses

Field measurements have shown that the ice volume in a breakup jam can be substantially less than the volume of the pre-breakup ice cover on the contributing river reach. The formation of shear walls and the stranding of ice floes on small floodplains are the main transport losses occurring during an ice run. The transport loss coefficient, C_t, is defined as the ratio of ice volume lost during a breakup run to the volume of the pre-breakup ice cover. It is thought to increase with the length of contributing reach (USACE 1982).

Table 1 lists values of the C_t available in the literature and those calculated here for the 1972 and 1985 ice jams on Cazenovia Creek. We derived the latter values using reported jam locations and lengths (USACE 1972, Predmore 1985). The transport loss coefficient is related to the ice-supply and ice-jam parameters as follows:

$$C_t = 1 - \frac{L_j}{L_r} \bullet \frac{B_j}{B_r} \bullet \frac{h_j}{t_i}(1 - p) \qquad (1)$$

where:

L_j, B_j and h_j are the length, width, and thickness of the jam, respectively
p is the porosity of the jam, assumed to be 0.4 (Prowse 1990)
L_r and B_r are the length and width of the contributing ice cover, and
t_i is the average ice thickness of the contributing ice cover.

Note that for ice jams on smaller rivers, typical values of $L_j/L_r \sim 0.1$, $B_j/B_r \sim 2$, $h_j/t_i \sim 4$ result in $C_t \sim 0.5$.

Nearly all of the available estimates of C_t, including ones based on jams in Cazenovia Creek, equal or exceed 0.3. The exception is for an ice jam on the Winooski River (which flooded Montpelier, Vermont, in March 1992), whose contributing reach was very short and had few overbank areas to strand ice. Therefore, although an average value of 0.5 could be justified, we will use $C_t = 0.3$ as a conservative estimate for transport losses.

5.3 Ice Melting

Ice breakup normally results from rapid snowmelt or heavy rainfall during periods of above freezing air temperatures. Upstream of an ice jam, air-water convection, solar radiation, groundwater inflow, fluid friction, and geothermal flux will all add heat to the river. With the assumption that little ice remains upstream or that it has been stranded above the waterlevel during the breakup surge, this heat flux will raise the water temperature entering a jam measurably higher than 0°C. The resulting melting and weakening of ice floes within a jam should be significant during long-duration, high-discharge events. These effects probably couple with rising hydrodynamic forces to release natural ice jams, although the loss of ice volume may not be visibly obvious.

Groundwater may contribute the largest heat flux into a river at breakup. Isotope studies have shown that pre-event water (i.e., groundwater) usually accounts for more than 50% of streamflow at peak discharge, even for snowmelt events (Buttle 1994). Depending on the actual flow paths, the temperature of this inflow could be close to the mean annual ground temperature (say, 10°C), and it consequently has significant potential to raise the river's water temperature or promote ice melting during breakup events.

Table 2 presents measurements of water temperature entering breakup ice jams. Because of high flow velocities and ice-jam roughness, nearly all the available heat is transferred to ice melting within ~ 1 km. If the jam is longer than this, ice melting at the upstream end will predominate. As the jam shortens, some warm water will persist to the toe and melt or weaken ice preferentially along the main flow paths. In the case of a jam at an ICS, this process will contribute to its ultimate release or washout.

Most of the properties of interest along Cazenovia Creek are more than 1 km upstream of the ICS. Also, porous flow through the grounded toe at the ICS should transfer sensible heat to ice melting very efficiently, even for short jams. Thus, we may assume that, regardless of jam length, 100% of the sensible heat of the water entering the jam will be lost to ice melting. Equating the sensible- and latent-heat fluxes then yields

$$Q \bullet \rho_w \bullet C_p \bullet \Delta T = h_f \bullet \rho_i \bullet \dot{V}_m \qquad (2)$$

where: Q is water discharge (m^3/s)

ρ_w and ρ_i are the densities of water and ice (1,000 kg/m^3 and 920 kg/m^3, respectively)

C_p is the specific heat of water (4.2 kJ/kg °C)

ΔT is water temperature above 0°C

h_f is the latent heat of fusion for ice (333 kJ/kg)

V_m is the volumetric melt rate of ice in the jam.

Inserting these parameters and re-arranging yields an expression for the ice-loss rate as a function of discharge and entering water temperature:

$$\dot{V}_m \sim 0.014 \bullet Q(\mathrm{m^3/s}) \bullet \Delta T(°\mathrm{C}) \qquad (3)$$

Thus, water entering a jam at 0.7°C will cause a volumetric melt rate of about 1% of river discharge. The data in Table 2 and the expected high proportion of groundwater inflow support a temperature difference at least this high. Therefore, we will use $\dot{V}_m(\mathrm{m^3/s}) = 0.01 \bullet Q(\mathrm{m^3/s})$ as our best estimate for the volumetric melt rate of the ICS ice jam.

5.4 Ice Washouts

During the model tests, we did not quantify the rate of ice loss attributable to major washouts or ultimate releases through the ICS. However, observations during washouts or releases at high discharge suggest that ice concentrations were on the order of 1% of discharge. Washouts of smaller ice floes through the ICS and onto the adjoining floodplain also occurred throughout the tests without release of the larger floes arched at a gap. For simplicity, however, we will assume that the washout rate, $\dot{V}_w$, is zero below 230 m^3/s, and increases to $\dot{V}_m(\mathrm{m}^3/\mathrm{s}) = 0.01 \bullet Q(\mathrm{m}^3/\mathrm{s})$ for discharge above 230 m^3/s. By neglecting washouts at low discharge, this approach should be conservative.

5.5 Hydrograph Rise Tim*e*

To determine ice-jam volume lost up to a given discharge, we must integrate the loss rates (expressed in terms of river discharge) with respect to time. This requires an expression for the rise time of a characteristic hydrograph: the slower the rate of rise is, the more ice volume is lost to melting and washouts up to a particular discharge.

We examined hydrographs from the 1972 and 1985 ice-jam events on Cazenovia Creek. The rise times between ice jam formation and peak discharge were 11 and 14 m^3/s per hour, respectively (Lever and Daly, in review). We therefore used a straight-line hydrograph that rises at 14 m^3/s per hour from a jam-formation discharge of 57 m^3/s. Although a hydrograph rises more slowly during the early portion of an event, use of the faster, near-peak rate produces a conservative estimate of ice volume lost to melting and washouts.

5.6 Ice-Jam Volume Versus Discharge

We combined the preceding terms to estimate the volume of ice in the ICS jam as a function of discharge, $V_j(Q)$. Transport losses of 30% reduce the estimated 2.8×10^5 m^3 pre-breakup ice supply to an initial jam volume of V_j (57 m^3/s) = 2.0×10^5 m^3. Following a straight-line hydrograph that rises at 14 m^3/s per hour, melting losses occur at a rate of 1% of discharge throughout the event. Above 230 m^3/s, additional losses due to washouts at the ICS occur at a rate of 1% of discharge. Figure 4 shows the resulting ice volume as a function of river discharge. Notice that the ice losses become particularly significant above 230 m^3/s, under the combined effects of melting and washouts, and that by 320 m^3/s essentially all the ice is gone. This is consistent with results from the physical model. Our estimate of $V_j(Q)$ should be conservative, and we used it to constrain the ice-jam length to predict upstream waterlevels.

6. Results

The open-water effect of the ICS is small and disappears beyond about 800 m upstream (Lever and Daly, in review). As expected, ice-jam conditions govern maximum waterlevels upstream of the structure.

Figure 5 shows ice-jam profiles at 110, 200, and 280 m^3/s, with ice volume limited according to discharge (Figure 4). HEC-RAS requires a fixed ice-jam thickness at the head of a jam, and we used 46 cm (i.e., the parent ice cover thickness) for all calculations. Open-water conditions prevail upstream of a jam. Notice that the jam length decreases dramatically with increasing discharge, primarily because of decreasing ice volume. The extent of high water caused by the ICS jam thus progressively diminishes as discharge increases. Note that jam length also decreases with increasing discharge for constant ice volume (owing to increasing jam thickness). However, the effect is small here relative to the effect of decreasing ice volume.

Figure 6 highlights the need to model upstream effects of an ICS using limited ice volume. At a discharge of 250 m^3/s, we estimate that the available ice-jam volume has dropped in half, to 1.0

$\times 10^5$ m^3 (Figure 4). As modeled by HEC-RAS, the ICS jam would extend less than 1,800 m upstream and cause no flooding beyond this point. By comparison, an ice jam at this discharge that extends throughout the upstream reach (~ 4,800 m) would require at least 5×10^5 m^3 and would flood all upstream properties.

We determine the maximum waterlevels expected upstream of the ICS by assembling the open-water and ice-jam profiles for all discharges into a single data file. Figure 7 shows the results graphically. All ice-jam profiles drop below the 100-year open-water profile beyond about 2,900-m upstream. From there to about 1,400 m upstream of the ICS, the 200-m^3/s ice-jam profile dictates maximum waterlevels. This results from a combination of moderate ice-jam length and moderate discharge. The discharge governing maximum waterlevels then increases with proximity to the ICS, such that 280 m^3/s dictates the maximum waterlevel expected at 600 m (a short jam combined with a high discharge). These results suggest that minor flooding may occur at two upstream structures during major breakup events (i.e., large ice supply and high peak discharge). Note also that the model predicts that ice jams at the ICS will not contact the bridge at Leydecker Road.

7. Discussion

The function of the Cazenovia Creek ICS is to arrest a breakup ice run, retain most of the ice throughout the event, and thereby reduce the ice-jam flood damages downstream. A direct consequence is that the ICS will induce higher waterlevels upstream than experienced under existing conditions. In this regard, it is similar to other flood control measures, such as dams, weirs, and levees. The real estate requirements for the project (e.g., flow easements, buy-outs, flood protection) depend primarily on the extent of this high water.

Clearly, the site selected for the ICS itself must be tolerant of high waterlevels. The Cazenovia Creek ICS will be located adjacent to a treed floodplain that routinely experiences open-water flooding. During major breakup events, this floodplain will help bypass peak discharges while retaining ice in the main channel.

We used a calibrated HEC-RAS model to determine the extent of high water induced beyond the ICS site. It should provide reasonable estimates of the water-surface profiles expected for both open-water and ice-jam events, with and without the ICS. Although dynamic shoving and thickening takes place during ice jams, the use of steady state hydraulics and ice-jam theory is reasonable over the duration of the event. A larger source of uncertainty is the ice volume retained as a function of discharge, $V_j(Q)$. Because ice-jam waterlevels are so much higher than even 100-year open-water ones, the length of the jam retained, or equivalently the ice jam volume, plays a significant role in determining the upstream influence of the ICS. Insofar as possible, we have based the terms that affect $V_j(Q)$ on data from our physical model, the literature, or ice-jam events in Cazenovia Creek itself, and have selected values at the conservative end of the ranges for each term. Consequently, the predicted maximum waterlevels caused by the ICS should be conservative.

Because we conducted this study to support a specific ICS project, some of the data used are site specific. Nevertheless, the analysis method should pertain to any ICS whose function is to retain ice throughout a breakup event. These structures intercept and retain flood-threatening ice runs, so that ice jams will exist upstream of them at discharges much greater than under existing conditions. Their upstream effects must therefore be assessed, particularly if these reaches do not currently experience any ice-jam flooding.

This work clearly highlights the need to quantify ice volume retained by an ICS during breakup events. The function $V_j(Q)$ strongly influences predicted upstream waterlevels. Because a cylindrical-pier ICS can retain an ice jam at very high discharge, assuming that ice volume is unlimited causes unrealistically high predictions of peak waterlevels. Unfortunately, the terms that influence $V_j(Q)$ are highly variable and hard to quantify for a given site: pre-breakup ice supply, transport losses, volumetric melt rate, and ICS washout rate.

As mentioned, we chose slightly conservative values for the ice-loss terms. In principle, statistical procedures could be used, but this would require statistical descriptions of each term, an even more difficult task. In addition, the computational effort could be prohibitive. Several HEC-RAS runs are required at each discharge, varying the head of the jam via the geometry file, to converge to the required ice jam volume for that discharge. Repeating the runs to generate complete statistical descriptions (e.g., stage-frequency curves) could be prohibitively expensive. Consequently, deterministic analyses of the type described here, guided by engineering judgment, may be the only practical way in the near term to assess the upstream effects of a breakup ICS.

8. Conclusions

A cylindrical-pier ice-control structure should reduce ice-jam flood damages along Cazenovia Creek by arresting breakup ice runs and retaining the resulting ice jams throughout typical breakup events. We used HEC-RAS to model the upstream effects of the ICS to assess real estate requirements for the project. 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 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. We used the envelope of maximum ice-jam waterlevels at each discharge to define the effect of the ICS relative to existing conditions, the latter taken as the 100-year open-water WSE profile. Our analyses suggest that the Cazenovia Creek ICS may cause minor flooding at two upstream structures.

The volume of ice retained by an ICS as a function of discharge plays a key role in assessing its upstream effects. Use of site-specific field data would be the best method to quantify $V_j(Q)$, but long records of pre-breakup ice supply, transport losses, and volumetric melt rates are difficult to obtain for each site of interest. Rather, additional measurements of opportunity of ice-run transport losses and water temperatures entering and exiting breakup ice jams would help constrain these parameters. Also, researchers should try to quantify ice washout losses through an ICS during model tests, as these strongly influence $V_j(Q)$ at high discharge. Nevertheless, even fairly conservative choices for each parameter should yield more realistic model predictions than assuming unlimited ice volume.

Interestingly, the ice-retaining capacity of an ICS must balance two needs: the need to protect downstream areas from natural ice-jam flooding and the need to minimize upstream flooding induced by the retained jams. Within our present modeling capabilities, the 3.7-m-gap, cylindrical-pier ICS designed for Cazenovia Creek appears to strike a good balance of these needs.

Acknowledgements

This work was funded by the U.S. Army Engineer District, Buffalo, in partnership with the Town of West Seneca and the State of New York. The authors gratefully acknowledge the assistance provided throughout the study by Ed Gustek, Larry Sherman, Phil Berkeley, and Mike Kerl. We also acknowledge the long-term support by the Corps of Engineers' Cold Regions Research Program, which supported the development of low-cost ice-control structures and the ice-jam modeling capabilities in HEC-RAS.

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Table 1. Transport loss coefficients for breakup ice jams.

Reference	River	Contributing Reach, L_r (km)	Transport Loss Coefficient, C_t	Comments
Calkins (1978)	Ottaquechee R.	42	0.9	Assumed jam porosity of 0.4
	White R.	23	0.9	Prowse (1986)
Prowse (1986)	Liard R.	480	0.8	Entire event
		150	0.4	Last 24 hrs of movement
Cumming-Cockburn (1986)	Credit R.	14	0.5	3 years of field surveys
Tuthill et al. (1996)	Winooski R.	5	0	Short reach, few overbank areas
This work	Cazenovia Cr.	19	0.3–0.5	1972 ice jam
		26	0.3–0.5	1985 ice jam

Table 2. Measurements of water temperature entering breakup ice jams. The heat-transfer length is the distance from the head of a jam to the point where the water has lost > 90% of its sensible heat.

Reference	River	Entering Water Temperature, ΔT (°C)	Heat-Transfer Length (km)	Comments
Calkins (1984)	Ottaquechee R.	0.7	1.3	Upstream of refrozen jam, time between breakup and measurement unknown
Prowse & Marsh (1989)	Liard R.	1.7	3.2	Measured during breakup event
Beltaos et al. (1998)	Matapedia R.	2.5	0.3	Time between breakup and measurement unknown
This work	Cazenovia Cr.	1.0	Unknown	Measured by USGS ~ 12 hrs after peak of 1985 ice-jam hydrograph

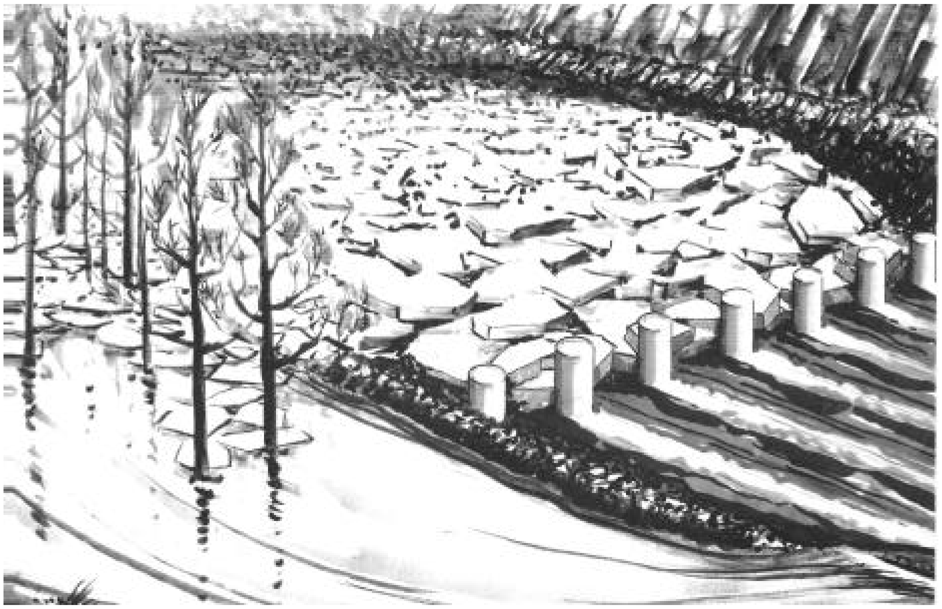

Figure 1. Concept drawing of Cazenovia Creek ice-control structure.

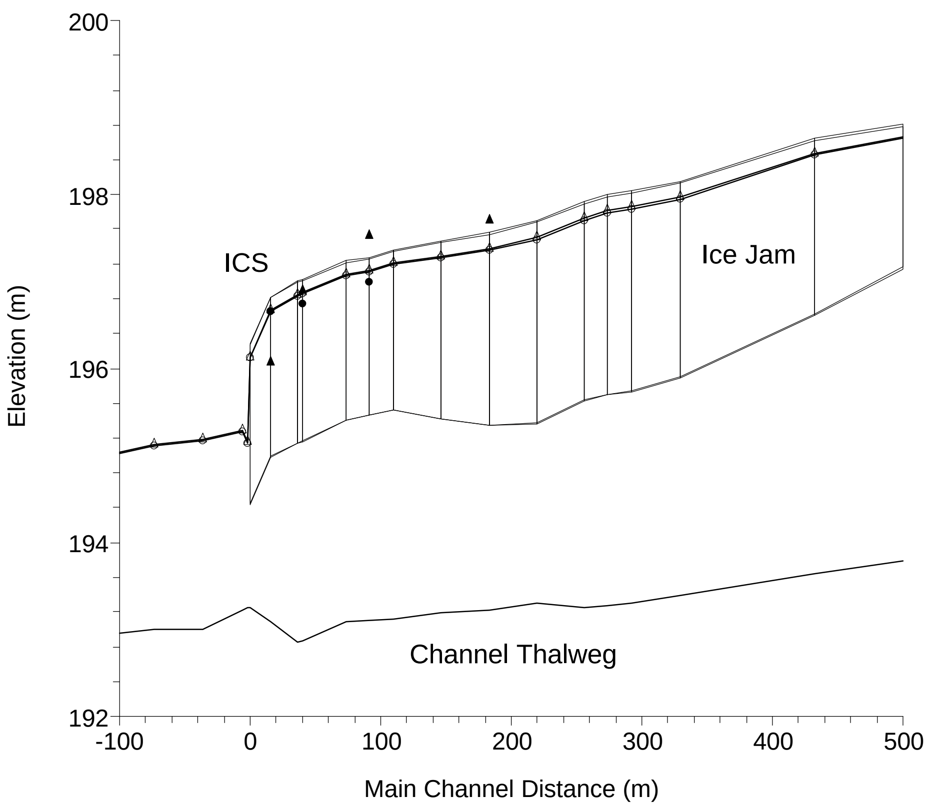

Figure 2. Comparison of ice-jam WSE's measured in the physical model (solid symbols) with HEC-RAS results near the ICS, for 170 and 173 m^3/s.

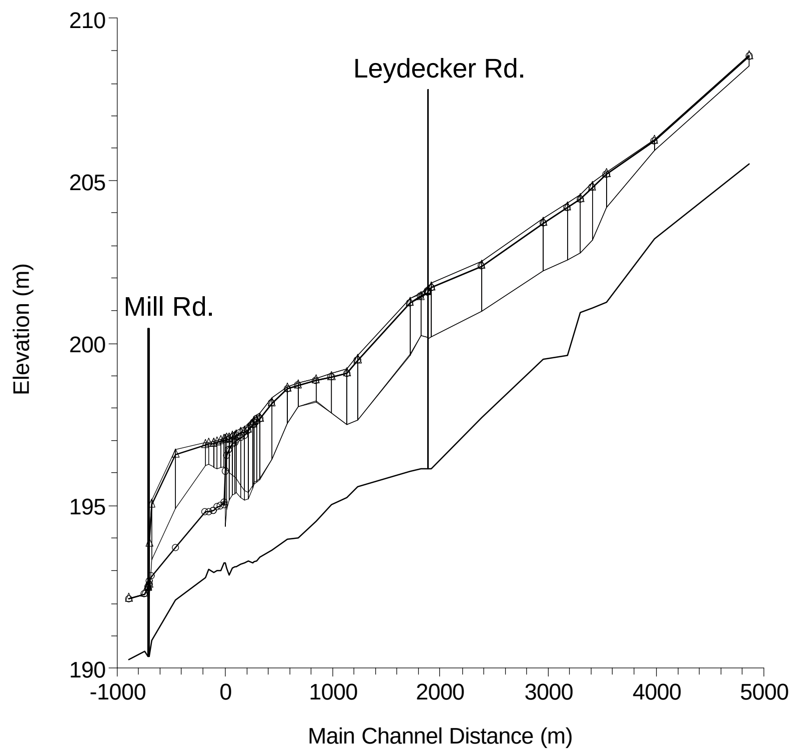

Figure 3. Comparison of WSE's from HEC-RAS models with ice jams initiated at the ICS (Distance = 0) and about 670 m downstream at Mill Road.

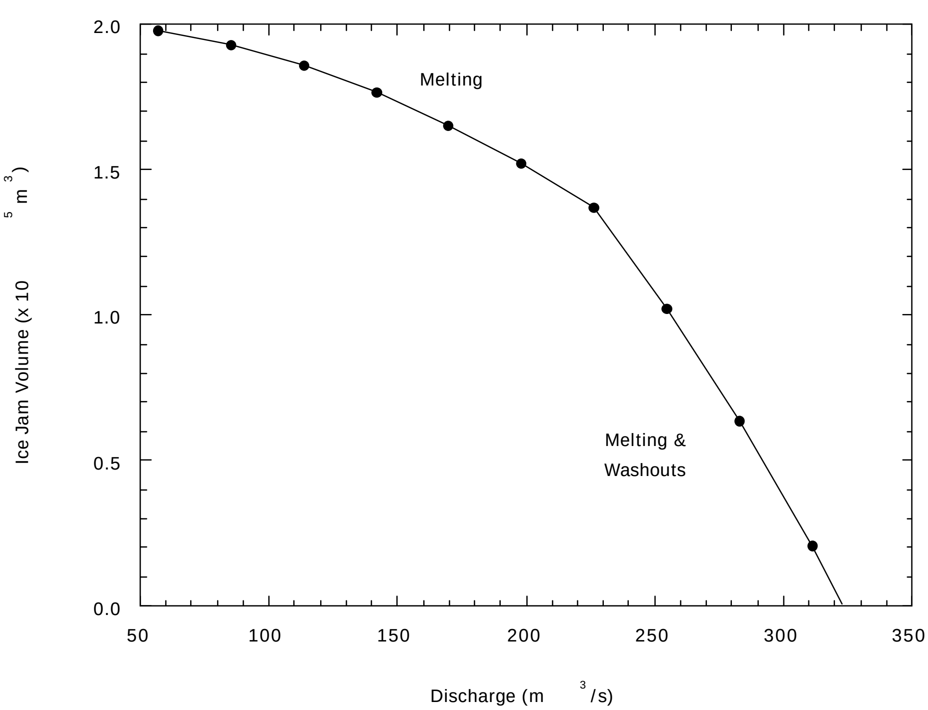

Figure 4. Volume of ice retained by the cylindrical-pier ICS as a function of river discharge.

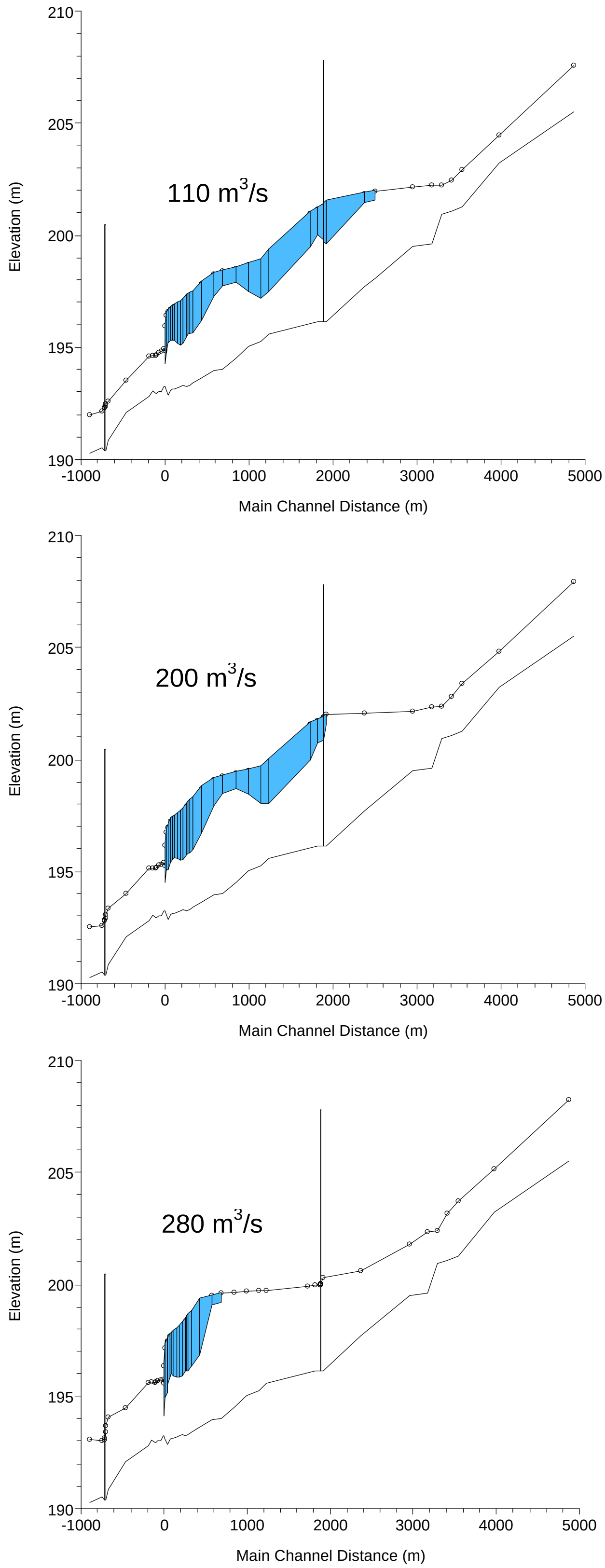

Figure 5. Ice jam profiles induced by the ICS at three discharges, with ice volume limited according to Figure 4.

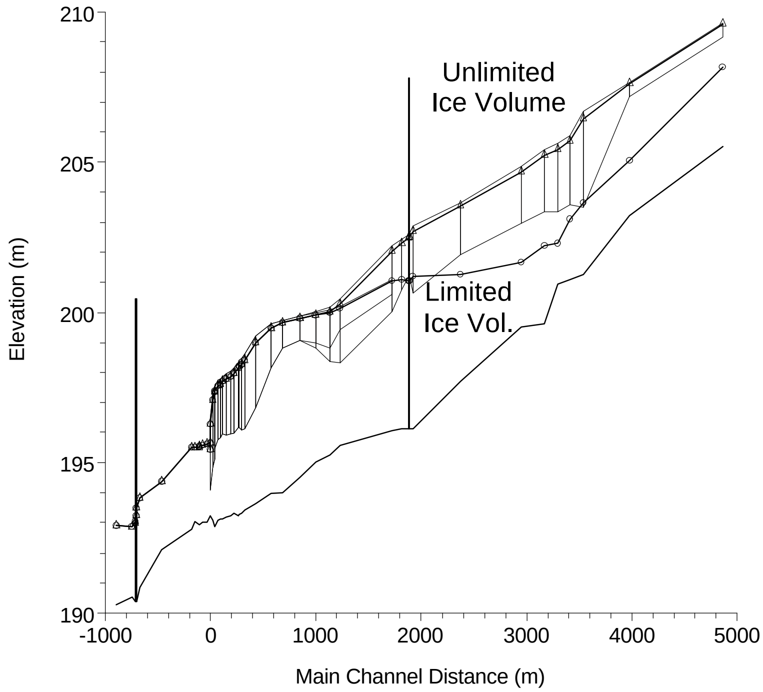

Figure 6. Comparison of ICS ice-jam profiles at 250 m^3/s for unlimited ice volume and ice volume limited according to Figure 4.

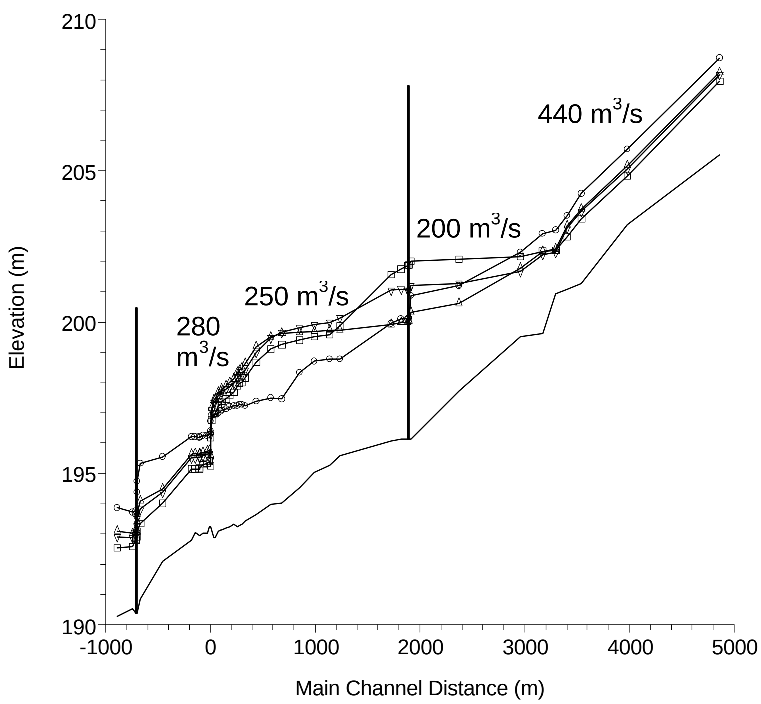

Figure 7. Maximum waterlevels expected upstream of the ICS, showing the governing discharge for various sections of the river. All profiles are for ice jams except the 440 m^3/s profile (100-year open water).