Canadian Journal of Civil Engineering

OPEN ACCESS | Article

A numerical model study on Grasse River ice-control structures

Tomasz Kolerski[a] and **Hung Tao Shen**[b]

[a]Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Narutowicza 11/12, Gdańsk 80-233, Poland;
[b]Department of Civil and Environmental Engineering, Clarkson University, Potsdam, NY 13699-5710, USA

Corresponding author: **Tomasz Kolerski** (email: tomasz.kolerski@pg.edu.pl)

Abstract

Ice jams in the Grasse River have caused the erosion of capping material designed to prevent the resurfacing of the bed sediment in the polychlorinated biphenyl (PCB)-contaminated area. Two in-stream ice-control structures are proposed to avoid the jam-induced erosion of the capping material. These two ice-control options are a pier-type ice-control structure and a reconstruction of a small hydropower dam upstream of the capping site. A numerical model study using the DynaRICE model is conducted to evaluate the effectiveness of the proposed design. Flow and ice conditions corresponding to the 100-year return period of ice jam events obtained from analyzing historical breakup ice jam data are used in the evaluation. The results showed that these ice-control structures could reduce the ice discharge downstream and the size of the ice jam at the capping site to prevent the erosion and scour of the PCB-contaminated bed.

Key words: ice jam, breakup, numerical model, PCB contaminant, bed-sediment erosion

1. Introduction

The Grasse River flows to the northeast approximately 88 km from a dam located at Pyrites, NY, to its confluence with the St. Lawrence River, about 11.2 km east of the Village of Massena, NY (Fig. 1). The lower Grasse River flows through the Village of Massena before merging into the St. Lawrence River downstream of St. Lawrence/FDR Power Dam.

The release of polychlorinated biphenyls (PCBs) in the riverbed sediments has been a concern of the impacts on water quality (McShea et al. 2005). A comprehensive evaluation of site-specific data collected over the 10 years from 1993 to 2003 indicates that sediments are the primary source of the PCBs found in the water column and biota of the river (Quadrini et al. 2003). Therefore, engineering studies were carried out to evaluate capping as a remedy to reduce the exposition of the river biota to sediment-containing PCBs (Palermo 1998). In the summer of 2001, a pilot study was conducted that involved the construction of a subaqueous cap in an approximately 28 000 m^2 portion of the river (McShea 2003). A periodic bathymetric survey monitored the site, indicating that the capping material was eroded, exposing the underlying native soft clay bed sediment. The process was caused by the ice jam formed against the intact ice cover after breakup ice runs from upstream in 2003 and again in 2022 around the pilot capping reach. The erosion of capping material and native sediments was caused by high water velocity underneath the toe of a spring breakup ice jam formed at the capping site. Based on the numerical modelling results of the 2003 ice jam, a 25 in. thick armoured cap with cobble with a median size of 6 in. was designed to withstand the forces of the 2003 ice jam. This paper reviews the ice jam conditions in the lower Grasse River and evaluates the effectiveness of two proposed in-stream ice-control structures for reducing the ice jam potential with the two-dimensional ice dynamic model DynaRICE (Shen et al. 2000).

2. Ice jam in the lower Grasse River

The 2003 breakup jam in the river is used to illustrate the ice jam condition in the river. A similar situation occurred in 2022. In late March 2003, the discharge in the lower Grasse River increased from about 15 to about 180 m^3/s due to spring runoff on 28 and 29 March caused by rainfall and warm air temperature. As a result, the cover upstream of Massena started to break and run on 28 March. The ice run passed through the rapids in Massena and accumulated against the intact ice cover on the river. However, despite the high air temperature and rain, the cover strength was sufficient to hold the incoming ice into an ice jam. The location of the jam toe was not certain, but the downstream extension of the ice accumulation was observed to be at the area where the subaqueous capping pilot study had been undertaken. Consequently, the water stage downstream of the Power Canal, at Outfall 001, increased by about 3 m from the normal water level. From photographs of the fully developed ice jam, taken on 28 March, it could be estimated that the ice accumulation above the water surface was about 1.2 m thick. This ice jam constricted the flow area under the ice, particularly under the

Fig. 1. (*a*) The lower Grasse River proposed ICS sites and (*b*) Massena, NY (https://gis.ny.gov/civil-boundaries).

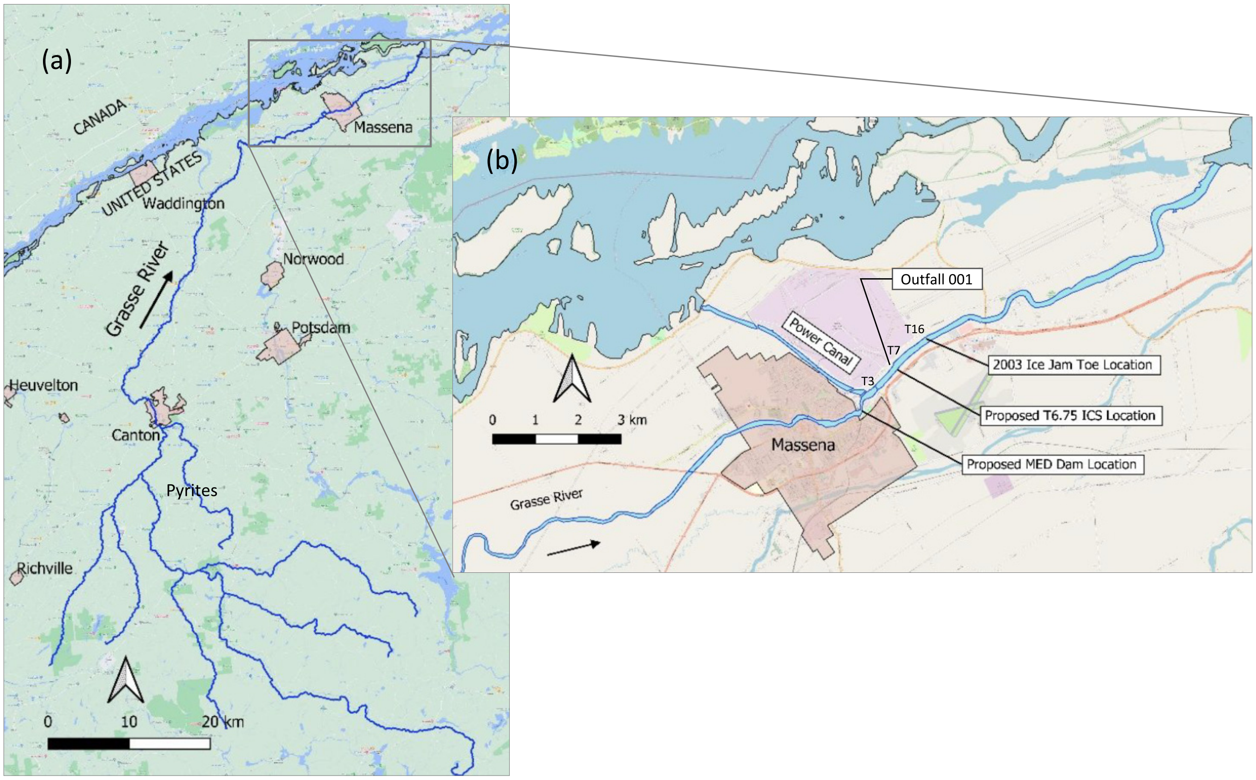
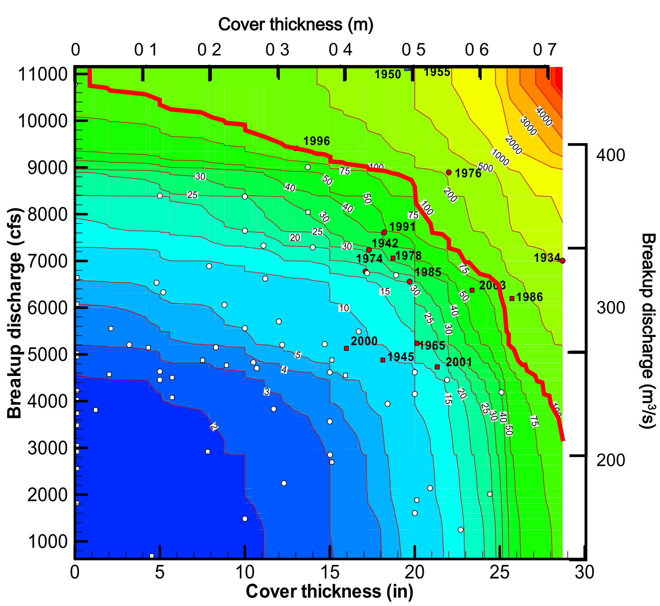


Fig. 2. Return period for combined breakup discharge and ice thickness, with past ice jam events marked. The thick line represents the 100-year return period.



toe, causing the armouring cap and bed material to scour. The jam was entirely cleared from the lower Grasse River the next day on 29 March. The jam release was caused by further deterioration of the supporting cover, which could not sustain the force from the jam. Although the jam has significantly impacted the armouring by eroding it, the post-jam monitoring did not show increased PCB concentration in sediment, water, and biota.

3. Modelling analysis of ice-control structures

Following the 2003 ice scouring event, several potential ice mitigation options have been proposed, including in-stream ice-retention structures to prevent ice from entering the jam-prone area from upstream. These include the restoration of a small hydropower dam for the Massena Electric Department, MED, and a pier-type ice-control structure. The DynaRICE model (Shen et al. 2000) is used to evaluate the effectiveness of these structures, emphasizing the ice retention capability, ice accumulation at the capping site, and resulting backwater profiles formed due to the jam mitigation structures.

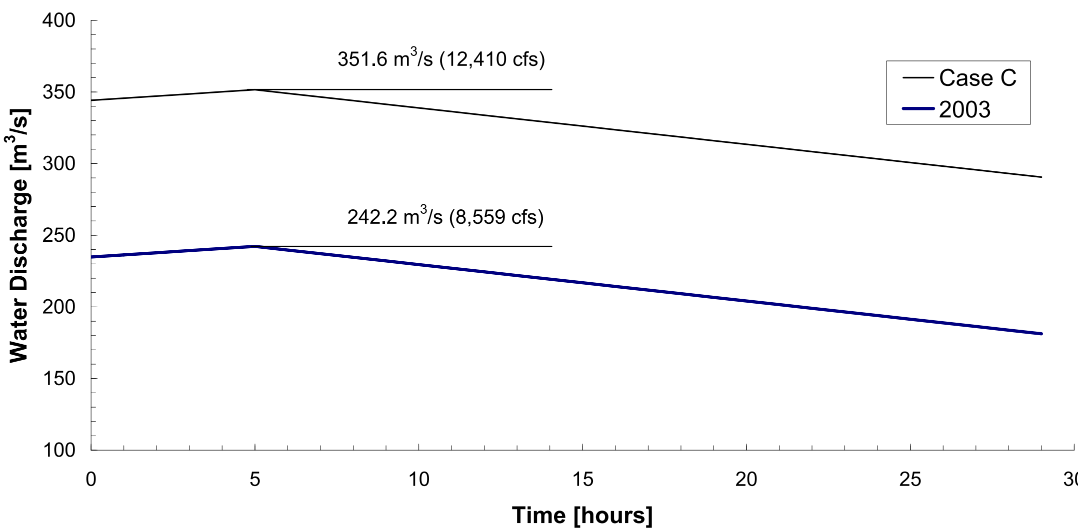
3.1. Ice and flow conditions

Shen et al. (2005) analyzed the frequency and severity of past ice jams on the lower Grasse River from 81 years of historical information, including the results of an extensive survey of tree scars along the banks and a hindcasting analysis based on water discharge and estimated ice thickness at the time of the breakup. From the analysis of the historical data, site-specific criteria were derived for the mechanical breakup and jamming potential based on ice thickness and stage increase during the breakup period. Considering that the surge wave and cover thickness govern the cover breakup and ice jam formation is governed by the mass of the ice run and

Table 1. 2003 event and sensitivity analysis conditions used in pier-type ICS and MED hydropower dam evaluations.

Case	Breakup discharge (m^3/s)	Peak discharge (m^3/s)	Cover thickness (m)	Ice volume (10^6 m^3)
2003	178	242	0.59	2.37
Case A	300	408	0.10	0.40
Case B	281	382	0.25	1.02
Case C	259	351	0.41	1.64
Case D	209	283	0.56	2.24
Case E	190	259	0.61	2.46
Case F	93	126	0.73	2.94

Fig. 3. Example of flow hydrograph made based on 2003 event hydrograph.



the ability of the flow to transport the ice, a combined probability analysis of river flow and ice cover thickness was performed to determine the recurrence intervals for various combinations of river discharge and ice cover thickness, as shown in Fig. 2. Conditions corresponding to the 100-year return period summarized in Table 1 are subsequently used in the evaluation of the ice-control structures (Quadrini et al. 2008).

Time-dependent water discharge is calculated for each 100-yr return period case based on the following equation:

$$(1)\qquad Q(t)^{100} = Q(t)^{03} \times \frac{Q_{\text{bk}}^{100}}{Q_{\text{bk}}^{03}}$$

where

$Q(t)^{100}$ = time-dependent discharge at the upstream model boundary for the 100-year event;
$Q(t)^{03}$ = time-dependent discharge at the upstream model boundary for the 2003 event based on instantaneous measurements of the stage at the Main Street Bridge during March–April 2003;
Q_{bk}^{100} = daily-averaged breakup discharge for a 100-year return period case;
Q_{bk}^{03} = daily-averaged breakup discharge for the 2003 event.

The example of flow hydrograph (Case C) made on the basis of 2003 event hydrograph is shown in Fig. 3. Similarly, ice supply for the various 100-year return period scenarios was proportioned to that of the 2003 event according to

$$(2)\qquad V_{\text{ice}}^{100} = V_{\text{ice}}^{03} \times \frac{h_i^{100}}{h_i^{03}}$$

where

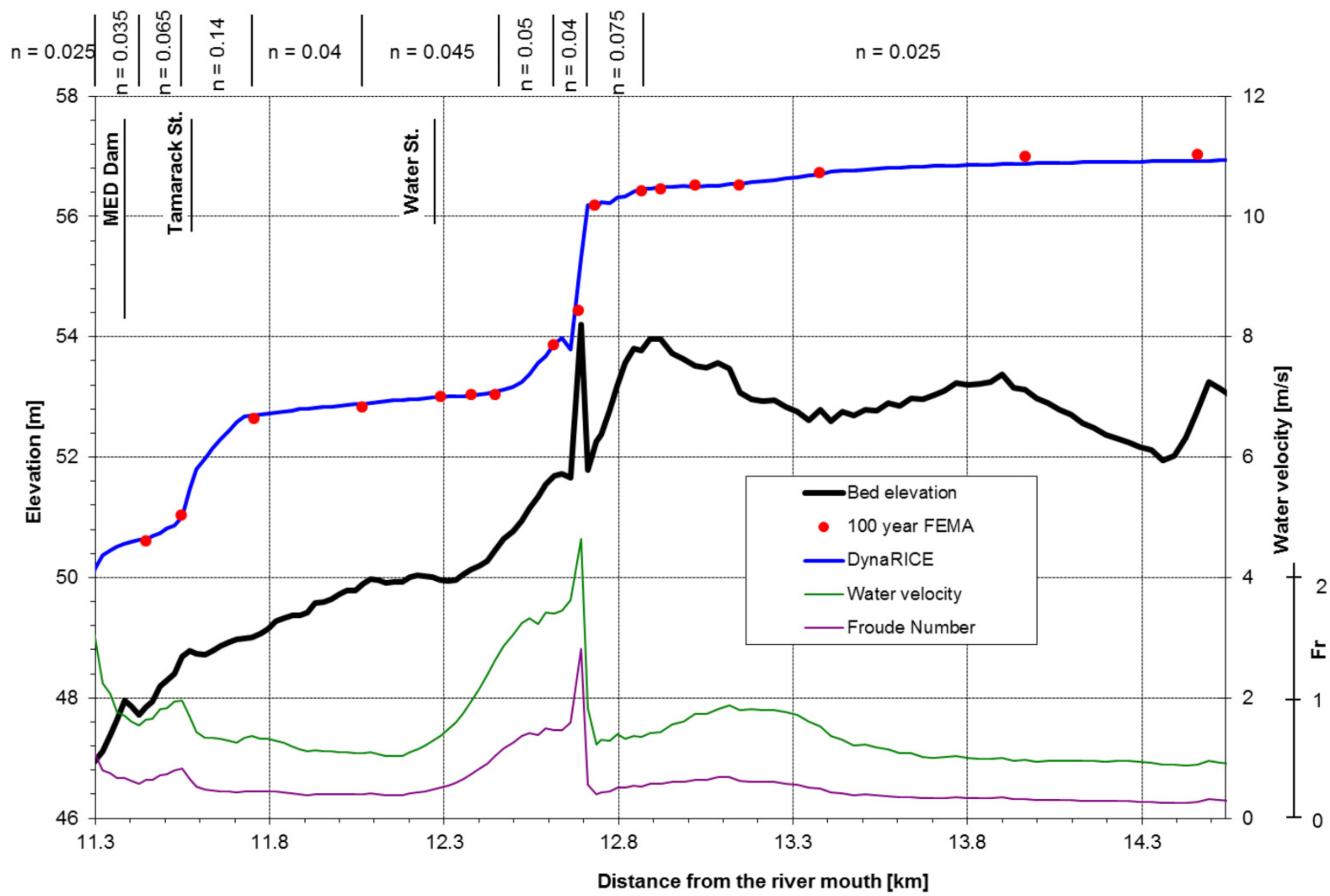
V_{ice}^{100} = ice supply for the 100-year event;
V_{ice}^{03} = ice supply for the 2003 event (304 000 m^3);
h_i^{100} = ice cover thickness at breakup for a 100-year return period case;
h_i^{03} = ice cover thickness at breakup for 2003 event (0.59 m).

3.2. Open-water calibration

The DynaRICE model was calibrated to match the FEMA 100-year open-water level based on the FEMA flood insurance study conducted before the breach of the weir in Massena in mid-1990 (FEMA 1980). In the FEMA study, the 100-year discharge for Grasse River was estimated at 427 m^3/s, and water levels were calculated for the 3.04 km long reach from the Railroad Bridge up to Town Line Road. For this calibration, the DynaRICE model domain contains a 15.3 km

 Can. J. Civ. Eng. **51:** 140–150 (2024) | dx.doi.org/10.1139/cjce-2023-0047

Fig. 4. Comparison between 100-year open water flow for 1980 FEMA condition and simulated by the DynaRICE model.



long reach of the lower Grasse River from its mouth to the Route 37 Bridge (Fig. 1*b*). This model domain is discretized into a finite-element mesh of 1914 elements, with an average longitudinal and transverse dimension of 35 × 20 m. The model was calibrated by adjusting the bed Manning's coefficients until the simulated water level matched the FEMA water surface profile. The bed Manning's coefficient and the water surface profile for this calibration are shown in Fig. 4. The old intact weir was located at mile 12.65 km with a top-of-weir elevation of 54.05 m (current condition is shown in Fig. 5).

3.3. Calibration for ice jam event

The data from the 2003 ice jam event were used to calibrate the ice jam model (Liu and Shen 2005). Boundary conditions for the hydrodynamics were specified as time-depended water discharge upstream and observed water level in the St. Lawrence River downstream. Ice was supplied from the upstream boundary. Field observation of the 2003 ice condition showed that the cover thickness in March was 20 cm, which was used for simulations. The ice concentration at the upstream boundary and the time-dependent variation of the jam development processes were not observed. The input ice concentration and the jam underside roughness were calibrated to match the final jam profile. The input ice concentration varied from 0.37 to 0.4, and Manning's coefficient of the jam varied linearly with the jam thickness from 0.03 to 0.13.

The model was calibrated by comparing the simulation results with the water level at transect T1, the extent of the ice jam, the ice jam toe location, and the tree scar data (Fig. 6). The chronology of the event is summarized in Table 2. In the model, the location of the jam toe was assumed based on field observation.

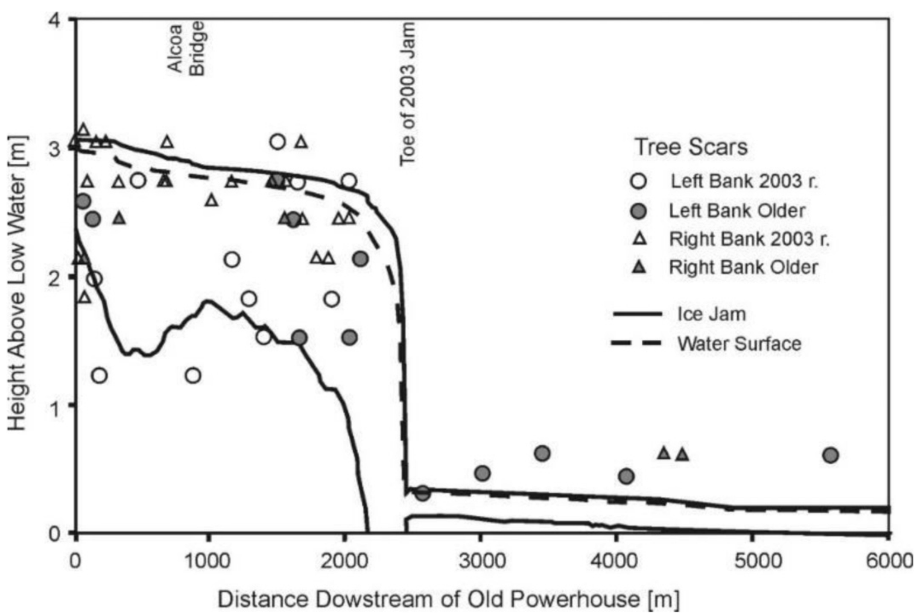
4. Modelling the MED Dam effect

The Massena Electric Department calls for a small one-turbine hydroelectric dam to be constructed in the Village of Massena. The proposed hydroelectric project seeks to provide several benefits to the local community, including the creation of long-term renewable energy, the restoration of recreational opportunities lost due to the breaching of the low-head dam in the Village of Massena, and opportunity for economic development. Evaluation has also been conducted to assess whether the project could provide an integrated solution to the long-term control of ice jams capable of causing the bed to scour in the lower Grasse River.

The modelling was based on normal pool elevation provided by MED, referenced to the North American Vertical Datum of 1988 (NAVD88). The DynaRICE model simulates the ice control with default threshold values of critical Froude

Fig. 5. The old Massena weir was breached in the mid-1990s; the photograph shows its current condition (photo by T. Kolerski).

Fig. 6. Maximum tree scar data, Lower Grasse River (Liu and Shen 2005).



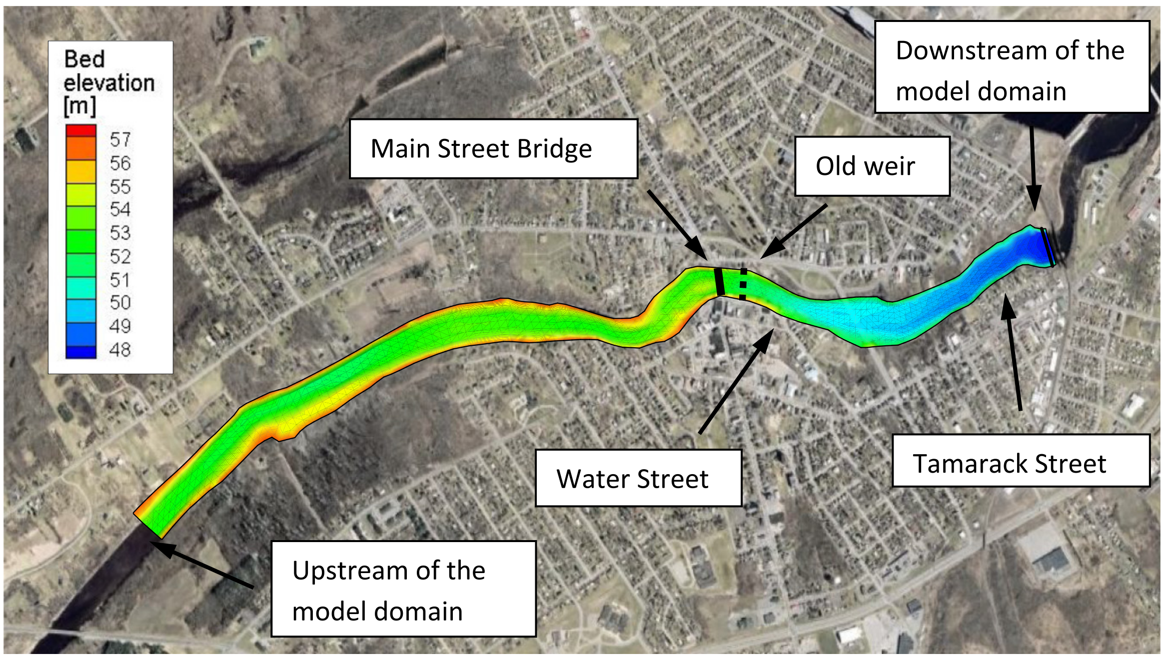
number Fr = 0.09 for jam progression and under-jam ice erosion velocity V_{eros} = 1.5 m/s (Tuthill and Gooch 1998). The critical line load in all cases was assumed to have a large value, i.e., a fixed barrier is assumed, and there will be no ice spill over the top of the dam. The height of the simulated dam was 3.35 m, which corresponds to the top of the gate opening level. For a 3.35 m barrier depth and a pool level of 54.35 m, the lower edge of the barrier, i.e., the top of the gate opening level, is at a level of 50.9 m.

The simulations conducted on the ice retention capability of the proposed MED Dam were based on the discharge and ice supply parameters presented in Table 1. Simulations for Cases A–F and the 2003 Case for a pool level of 54.25 m were conducted for 26 h until the ice jam was fully developed. Ice jam and water surface profiles are obtained for each case when maximum water levels are reached. Also included in these results are water surface levels at three key comparison points referred to herein as the west side of Tamarack

Table 2. Chronology of the 2003 ice jam.

Model time	Real-time		
Hour	Day	Hour	Description
0		6:30 a.m.	Ice run observed
5	27 March	11:30 a.m.	A small jam was observed near T3
10		4:30 p.m.	Jam observed downstream of outfall 001, T6.5
26	28 March	8:30 a.m.	Jam observed to have progressed to T16
42	29 March	12:30 a.m.	Assumed ice jam release time
50		8:30 a.m.	Observed no ice in the river
70	30 March	4:30 a.m.	End of simulation

Fig. 7. Simulation model domain. The bed elevation is based on the International Great Lakes Datum 1985 (IGLD85), and the image is from Google Maps.



Street, the west side of Water Street, and the upstream model boundary shown in Fig. 7.

In all simulated cases, the dam retained the entire ice volume, and the water velocity underneath the jam toe did not exceed the erosion velocity limit of 1.5 m/s. Table 3 summarizes the maximum water levels reached during the model runs at the three key locations. Figure 8 presented maximum water surface elevation profiles for all simulation cases.

In all cases, a thick ice jam toe is located at the MED Dam, except for Case F, where thicker ice accumulation occurred in the Water Street area. This situation is due to the lower flow velocity caused by the smaller water discharge and the larger channel depth near the Parker Avenue Bridge (about 0.8 km upstream of the MED Dam). Figure 9 shows the effect of different water discharge and ice supply combinations on ice jam and water level profiles. These plots show the simulated ice jam thickness and water surface elevations for fully developed ice jams.

Case C represents the condition of ice cover thickness of 0.41 m and breakup discharge of 259 m^3/s. For this case, the supplying ice volume is 1.64 million m^3, about 2/3 of the ice volume for the 2003 case. For such conditions, ice was pushed down by higher water discharge to the dam, forming a jam toe of about 6 m thick. Simulated water velocity under the ice jam toe approaches 1.5 m/s but is still below the threshold for ice erosion, and ice retention is expected. The calculated backwater profile for Case C reached the largest elevation among all the simulated cases and was 57.94 m at the upstream boundary of the model domain.

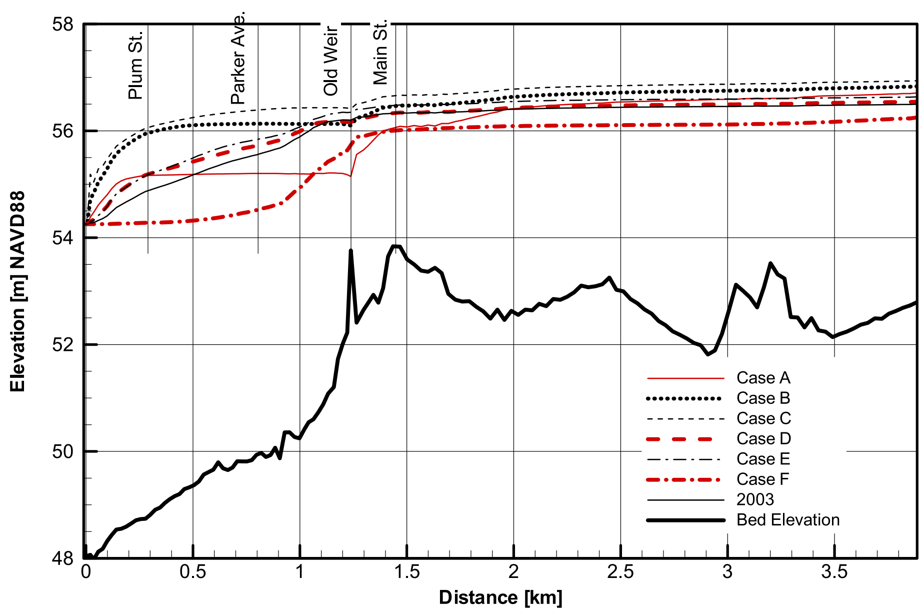
Case E is the closest to the reference 2003 jam case. The ice thickness of 0.61 m (in 2003 was 0.59 m) and breakup discharge of 190 m^3/s (in 2003 was 178 m^3/s) were used. Compared to Case C, the ice jam toe is thinner (around 3.5∼4 m), and ice is more uniformly distributed along the downstream section of the pool. The extent of the jam accumulation reached the old weir. Water velocity under the ice was significantly lower than that in Case C and never exceeded the value of 1.0 m/s.

The last case, Case F, shown in Fig. 9, is the condition for the largest ice volume (nearly 3 million m^3) with the lowest

Table 3. Comparison of simulated maximum water levels along the Grasse River in Massena.

Cases (peak flow & ice thickness)	Water level (m, NAVD 1988) and hour of occurrence					
	West side of Tamarack Street (0.39 km upstream of the dam)		West side of Water Street (1.37 km upstream of the dam)		Upstream boundary (3.89 km upstream of the dam)	
	m	Hour	m	Hour	m	Hour
2003	55.01	22	56.30	21	56.50	21
Case A	55.17	19	55.92	19	56.71	5
Case B	56.05	21	56.39	21	56.83	21
Case C	56.16	18	56.61	18	56.94	17
Case D	55.30	20	56.30	26	56.55	26
Case E	55.33	23	56.45	21	56.63	21
Case F	54.29	17	55.97	20	56.25	21

Fig. 8. Maximum water levels predicted during the simulation period for all cases with MED Dam.



breakup discharge (93 m^3/s), almost half of the breakup discharge observed during the 2003 event. For such conditions, ice was slowly moving down the pool, but due to increased depth downstream, the water drag was sufficient to push the ice to the dam. As a result, the ice filled the entire model domain, and the thickest ice accumulation formed downstream of the old weir. No significantly high water velocity was observed during the simulation, and the backwater elevation was the lowest of all the simulated cases.

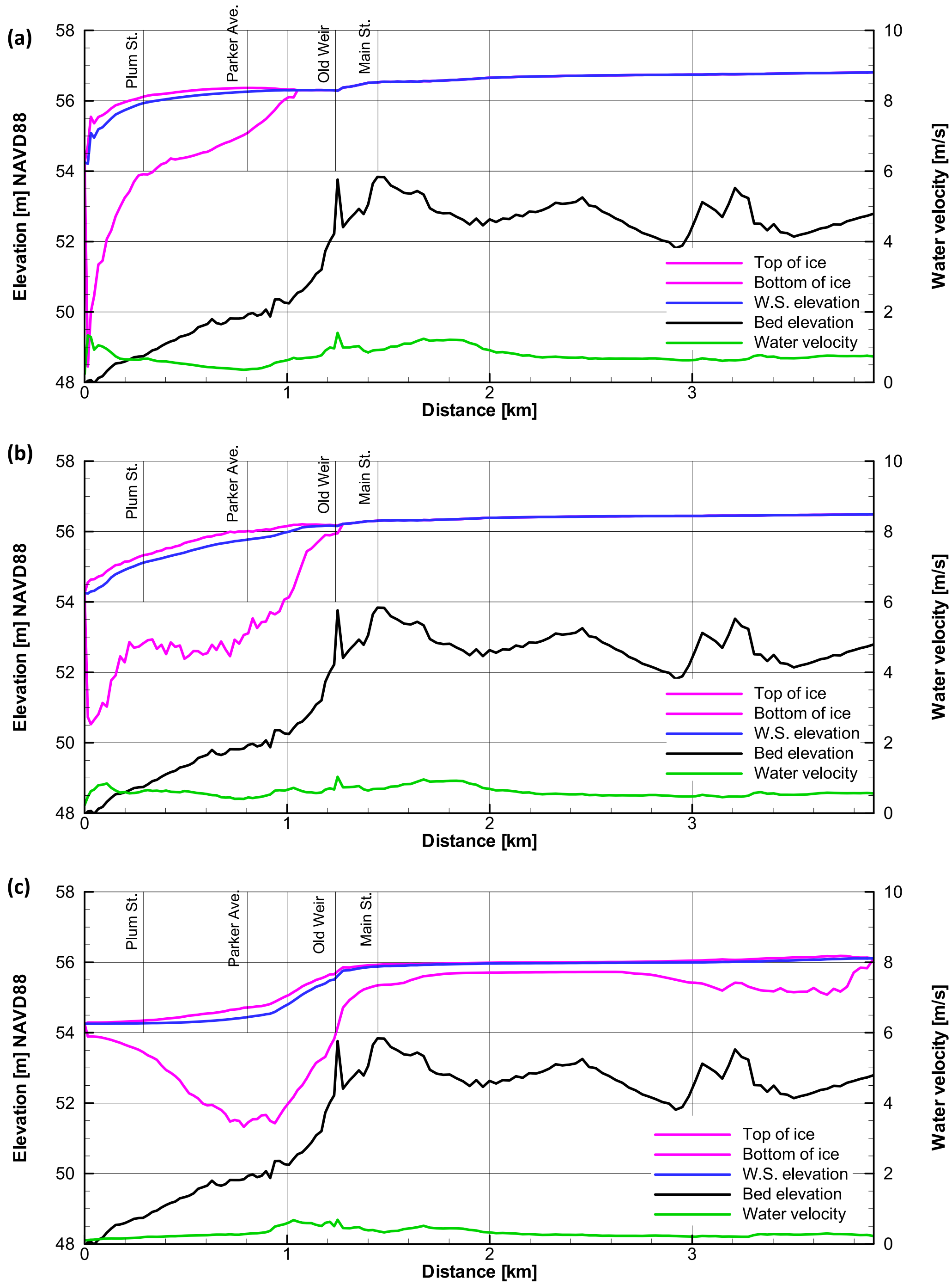
Based on the simulated results of the wide range of the ice volume and accompanying water discharge, it can be said that the most problematic conditions are produced by the ice jam formed at high water discharges. Water currents drag ice downstream and may lead to a partially grounded jam at the dam. Consequently, water surface elevation along the pool is rising and bringing the hazard of flooding upstream. On the other hand, for the condition of the lower water discharge, ice is more uniformly distributed over the entire pool without a significant increase in thickness.

5. Modelling the pier-type ICS effect

The proposed site of the pier-type ice-control structure is located at T6.75, 1 km downstream of the Massena Rapids (Fig. 1). The ICS was designed as an L-shaped barrier with a relief channel at the west bank of the river, as shown in Fig. 10 (Tuthill et al. 2008). Initial DynaRICE test runs indicated that ice retention without a relief channel could have relatively high under-ice currents with a velocity of about 2 m/s. However, further analyses with 60-, 100-, or 200 m long relief channels showed the under-ice flow velocity was significantly reduced when the relief channel length was 100 m or more. Based on these results, a relief channel length of 100 m was selected.

In all simulation cases, the ICS assumed a fixed barrier, i.e., 100% retention of the ice entering the site from upstream. Thus, it provides conservative estimates of water level increase upstream of the ICS. In these cases, flow is passed under, around, and to a lesser extent through the ice

Fig. 9. Simulated ice jam profiles with MED Dam at hour 26 for Case C (*a*), Case E (*b*), and Case F (*c*).



accumulated near the piers. Bathymetry incorporates the dredged area near the ice-control structure and bed armouring. The bathymetry of the relief channel and the design of the piers are shown in Fig. 10.

Figure 11 shows the predicted water level results from water discharge and ice supply. Cases B and C, with relatively high water discharge and ice supply, produced the highest water levels. Figures 12 and 13 show the jam profile, water depth, and velocity underneath the jam for Cases A and F. These figures demonstrate the interaction among the water discharge, ice supply, and channel bathymetry. In Case A, the high water discharge and low ice supply resulted in a short jam with a thick jam toe. In Case F, the low water discharge and high ice supply resulted in a long ice jam with a much smaller jam toe thickness.

6. Conclusions

This study assessed the ice retention capability and effectiveness of the potential structural ice-control solutions as

Fig. 10. Designed pier-type ICS location at transect T6.75 (*a*) and bathymetry of the ICS used in the DynaRICE model (*b*).

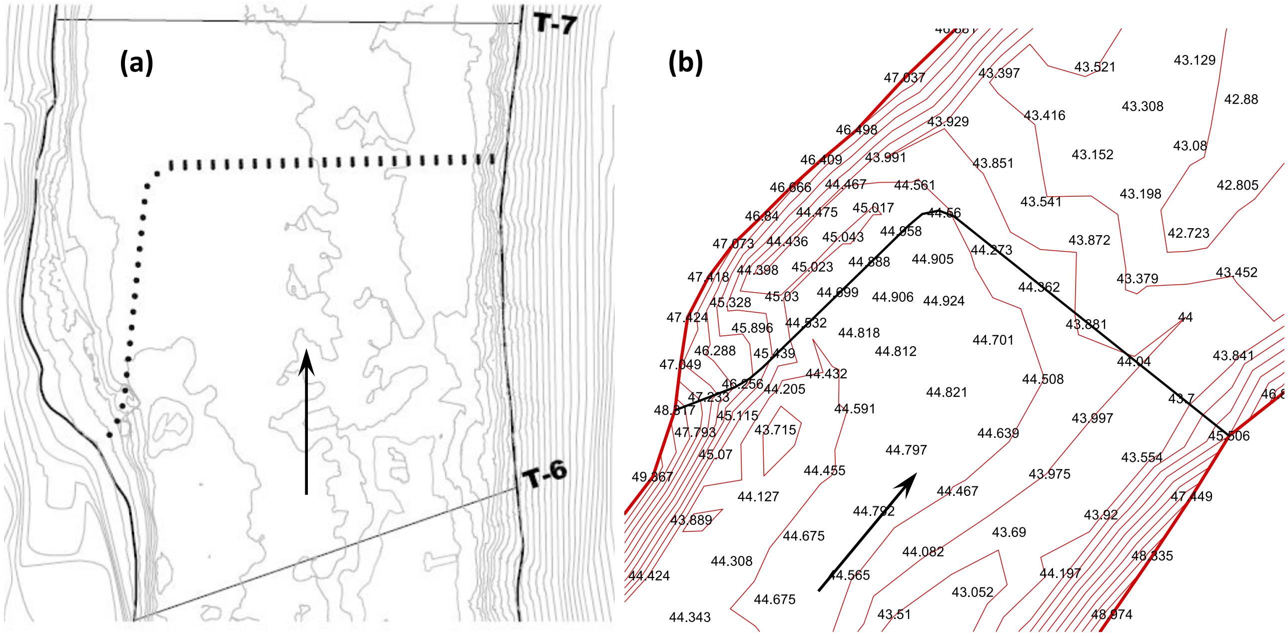
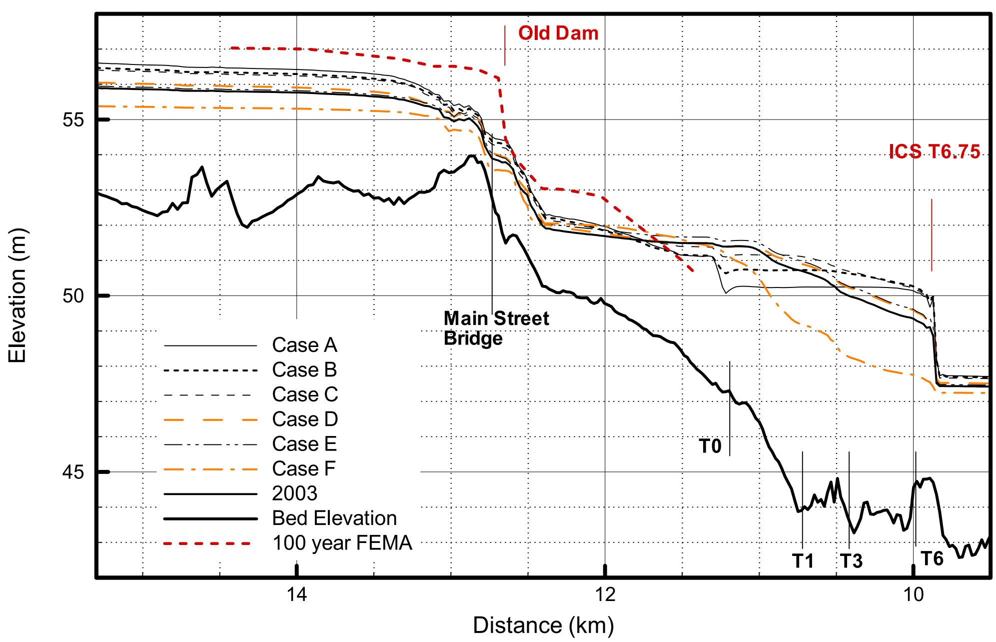


Fig. 11. Maximum water levels predicted during the simulation period for all cases with ICS.



part of the long-term remedial option to address potential exposures of PCBs in the bed sediment of the lower Grasse River. Two proposed structures were examined using the DynaRICE model: the MED Dam in Massena and the pier-type ice control structure. Sensitivity analysis was carried out for several combinations of breakup flow and ice supply conditions with a 100-year return period.

For the MED Dam, the model results showed that the proposed structure could be an effective barrier to the breakup ice run and a possible means of mitigating ice jams and ice jam scour on the PCB-contaminated site. The simulation results showed that the ICS would produce a stable ice accumulation upstream of the structure under the conditions tested. The simulation results also showed that ice jam would be partially grounded upstream of the ICS for all cases. Additionally, the ice accumulation upstream of the ICS had a characteristic shape of a thickened triangular region with the apex at the corner of the ICS and a resultant channelling of the flow towards the upstream end of the relief channel piers and the south side of the river.

Fig. 12. Case A—simulated jam profile, water depth, and velocity under the ice jam at hour 26.

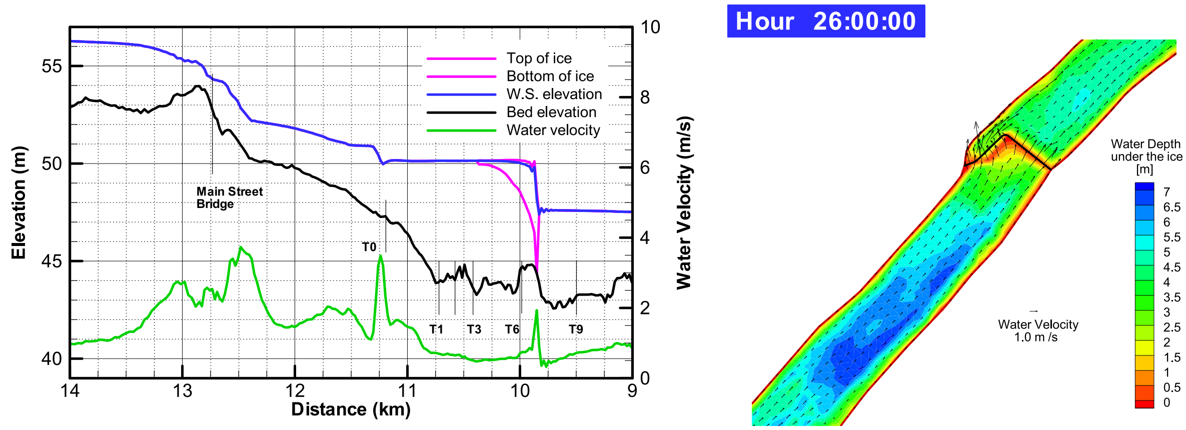
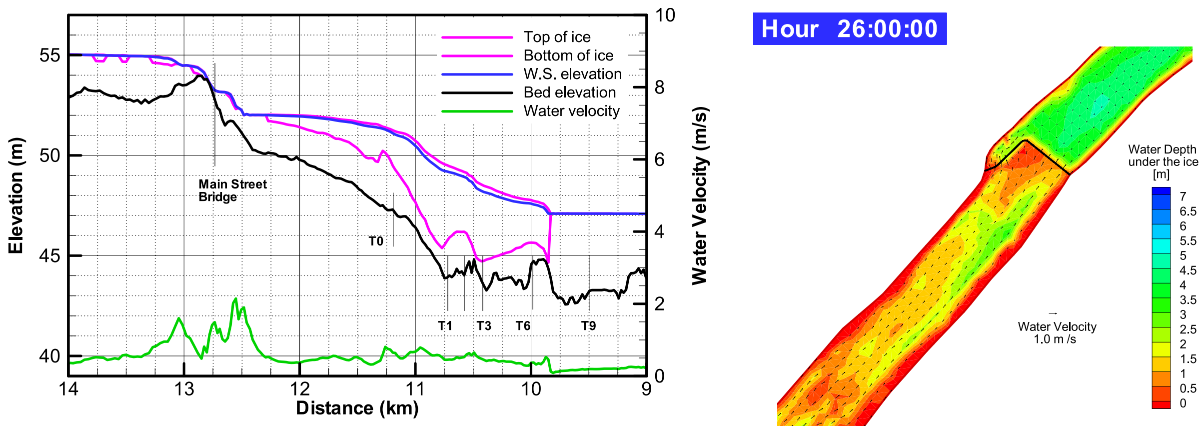


Fig. 13. Case F—simulated jam profile, water depth, and velocity under the ice jam at hour 26.



Comparisons to the FEMA 100-year open-water flood levels showed that the maximum predicted backwater levels produced by the ice accumulations exceed the 100-year open-water flood level in the approximately 1.9 km stretch of the river upstream of the ICS. However, further upstream, the maximum predicted backwater levels are lower than the 100-year open-water flood level.

Article information

History dates

Received: 30 January 2023
Accepted: 14 June 2023
Accepted manuscript online: 28 June 2023
Version of record online: 8 August 2023

Notes

This paper is part of the River Ice and Infrastructure Special Issue.

Copyright

Data availability

This manuscript does not report data.

Author information

Author ORCIDs

Tomasz Kolerski https://orcid.org/0000-0002-6235-6817
Hung Tao Shen https://orcid.org/0000-0001-9503-2088

Author contributions

Conceptualization, HT
Data curation, TK
Formal analysis, TK, HT
Investigation, TK, HT
Methodology, TK, HT
Software, TK
Validation, TK, HT
Visualization, TK
Writing – original draft, TK
Writing – review & editing, HT

Competing interests

The authors declare there are no competing interests.

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