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Freeze-up ice-jam flood hazard assessment and mapping

Karl-Erich Lindenschmidt¹, Mohammad Ghoreishi¹ and Ali Khan²

¹*Global Institute for Water Security, University of Saskatchewan,
11 Innovation Boulevard, Saskatoon, Saskatchewan, Canada, S7N 3H5
karl-erich.lindenschmidt@usask.ca; mohammad.ghoreishi@usask.ca*

²*Ocean, Coastal and River Engineering Centre, National Research Council Canada
1 Arctic Avenue, St. John's, NL, A1B 3T5, Canada
amir.khan@nrc-cnrc.gc.ca*

Although ice-jam flooding in northern rivers is generally more severe during ice-cover breakup in spring, ice jams during river freeze-up and mid-winter breakup can also impose high flood hazard in some rivers, particularly those in regions with a maritime climate (e.g. Atlantic Canada). In this paper, we numerically simulate ice-jam flood hazard and carried out the flood mapping of a high ice-jam flood risk community along the Exploits River in Newfoundland where the most severe floods occur from ice jams formed during river freezing. A stochastic modelling approach was used to simulate the processes of ice-jam formation and flooding along the river during freeze-up. This approach uses a deterministic river ice hydraulics model that is run repeatedly within a Monte-Carlo framework. Input values for the parameters and boundary conditions were chosen randomly from frequency distributions. An ensemble of backwater levels was produced from which profiles of exceedance probabilities were calculated. The water level elevations are extrapolated into the floodplain to determine flood depths. This approach is a new method to estimate ice-jam flood hazard and risk stemming from river freezing.

Keywords: frazil ice; ice-jam flood hazard and risk; flood hazard assessment and risk mapping; stochastic modelling framework

1. Introduction

Frazil ice forms in turbulent water columns in shallow river segments often during cold winter nights. Large volumes of frazil ice and ice pans are typically produced during these events, which drift downstream to lodge at constrictions, meanders and at already existing ice covers (Ashton, 1986; Vergeynst et al., 2017). Once the ice lodges, frazil ice and ice pans accumulate to form ice covers through juxtapositioning (extension of ice covers in the upstream direction) or shoving and thickening, depending on the river discharge (flow rate), geomorphology of the river (e.g. slope of the river bed or thalweg) and meteorological conditions (e.g. freezing rate). The shoving and thickening stage is the more dangerous process since the ice can form hanging dams which cause channel constrictions and increased resistance to flow in the river. This damming effect, in turn, can cause water upstream of the ice jamming to back up and rise in elevation, leading to flooding of the riverbanks. These ice-jam floods are particularly dangerous for shoreline facilities and communities since the jamming and flooding can occur quite suddenly and rapidly, leaving little time for emergency response. Such events are typical of the fall, during freezing of a river. They have also been observed following ice cover break-up in mid-winter warm spells (De Coste et al., 2022).

Ice-jam flood hazard assessments and mappings have been carried out for several river reaches for the ice-cover breakup period during spring, for example along the Athabasca River at Fort McMurray (Lindenschmidt, 2023), lower Red River near Selkirk in Manitoba (Lindenschmidt et al., 2021) and the Peace River at the town of Peace River (Lindenschmidt et al., 2016). However, very few assessments and mappings have been carried out for rivers that undergo more severe ice-jam flooding during river freezing. Some rivers, especially those near Atlantic Canada, are susceptible to flooding from ice jams during the beginning of winter when the river freezes, such as the Exploits River in Newfoundland, which is the case study used here. In this paper, we use a computer model to study how ice jams affect flooding. We also map the flood risk for the community of Badger on the Exploits River.

2. Study site¹

The Exploits River is situated in central Newfoundland and drains an area of 7887 km² (outlet gauge at Charlie Edwards Point) with an average annual outflow of 238 m³/s (averaged between 2010 and 2019). The average temperature in February, the coldest month, is -8.2 °C (data averaged between 2000 – 2022). At freeze-up, “the volume of frazil slush produced along the Exploits River is massive. The 50 km reach above Badger contains all the elements of an ice factory [with portions of the reach remaining] as an open generator of frazil slush throughout the winter” (Fenco, 1985, p. 7-5). During freeze-up, frazil slush blocks the flow in the area about 2.5 km below Badger at Badger Rough Waters (see Figure 4) (Fenco, 1985, p. 7-4), causing high flood levels at Badger. This area has many riffles along the stretch.

3. Methodology²

River ice hydraulic model RIVICE

The river-ice model RIVICE was implemented to simulate the formation of ice covers along the Exploits River at Badger. RIVICE is a hydraulic model that produces a single output for a given set of inputs. It can simulate various river-ice phenomena, such as: a) border ice formation, b) generation of frazil ice and ice pans, c) juxtapositioning of incoming ice pans or floes upstream of the ice-cover front, d) shoving of the ice-cover front downstream into the ice-jam cover to increase its thickness (wide jam), e) submergence of ice pans at the ice-cover front

¹ adaptations from Lindenschmidt et al. (2023b)

² adaptations from Lindenschmidt et al. (2022, 2023a) and Lindenschmidt (2024); see also Gomez et al. (2024) from this proceedings volume.

and their movement downstream under the ice as ice-in-transit (narrow jam), f) deposition of the transient ice under the ice cover when the mean flow velocity drops below a certain threshold, and g) erosion (removal of ice pieces) of ice from the ice cover's undersurface when the mean flow velocity surpasses a certain threshold. RIVICE is a hydrodynamic model that conserves both mass and momentum of sub-critical fluid motion. The river-ice processes are loosely coupled to the fully dynamic wave simulation in which information about the two sets of processes, hydrodynamics and river ice, are exchanged after each time step before proceeding with the next time step. See Lindenschmidt (2017, 2024) for more detailed model descriptions.

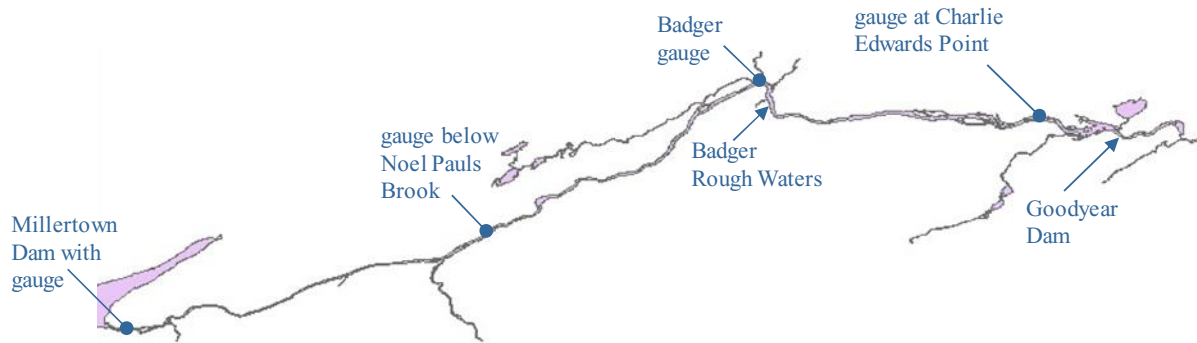


Figure 1. Subbasins of the Exploits River with outlets at Millertown Dam and Charlie Edwards Point (from Lindenschmidt et al., 2023).

Referring to Figure 2, RIVICE requires water discharge Q and ice pans V_{ice} to serve as inputs at the upstream boundary. The ice pans have a porosity PS and a thickness ST . The ice that flows in and piles up at the ice-cover front has a porosity PC and a thickness FT . The flow resistance depends on the bed roughness n_b and the ice underside roughness n_g . The n_b value is constant, but n_g increases with the ice-cover thickness. Other parameters related to ice processes are $K1$, which represents the ratio of longitudinal forces that are transferred to the banks and create friction between the ice cover and the riverbanks, and $K2$, which shows the degree of thickening required for the ice cover to resist shoving and thickening. The cross-section number x marks the location of the lodgement point, where the ice accumulates and forms the ice-jam toe. The parameter h describes the thickness of the initial, intact ice cover downstream of the lodgement, which extends to the downstream boundary. The water level W at this boundary is the downstream boundary condition for the model. Ice pieces along the undersurface may be removed if the mean flow velocity at a cross-section is higher than a threshold velocity v_e . This ice moves downstream until it reaches a place where the mean flow velocity is lower than another threshold velocity v_d and settles under the ice cover.

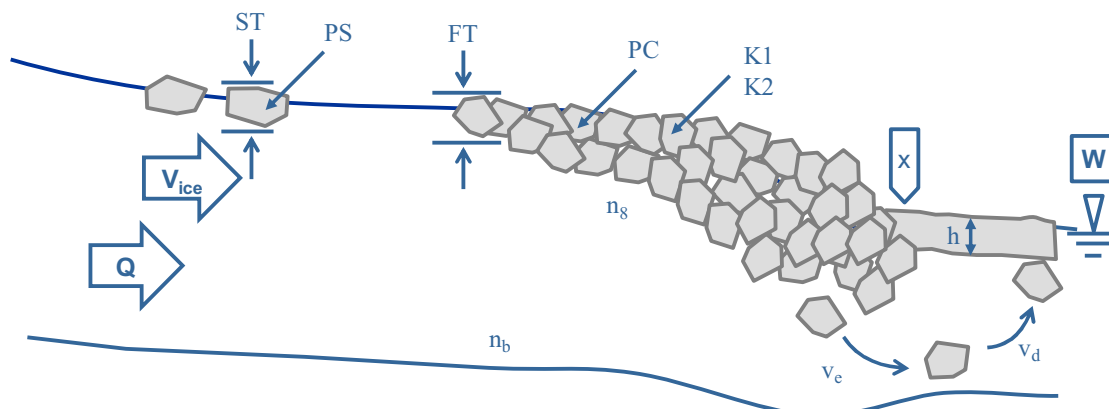


Figure 2. Parameters and boundary conditions in RIVICE.

Referring to Figure 3, there are different forces acting on and within the ice jam, such as thrust F_T created by the inflowing water pushing the ice-cover front, drag F_D due to the resistance of the water flowing under the ice cover, the component of the ice cover's weight F_W that is parallel to the bed slope, friction F_F between the ice cover and the riverbanks, and internal resistance F_I of the ice cover to more shoving and thickening. If $F_T + F_D + F_W < F_F + F_I$, the ice gets juxtapositioned at the ice front, and the ice cover extends upstream. If $F_T + F_D + F_W > F_F + F_I$, the ice cover shoves downstream (telescoping) and thickens until the forces balance out again.

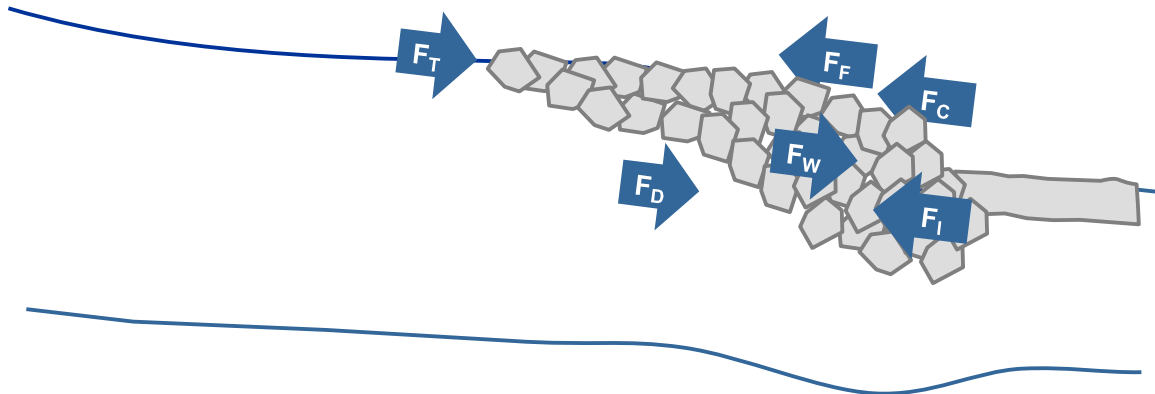


Figure 3. Forces acting on an ice jam in RIVICE.

Stochastic modelling framework

Since flood hazard is a probabilistic description of the water level elevation possible from flooding (exceedance probabilities of certain floodwater levels), a stochastic modelling approach was implemented to calculate flood hazard due to the processes of ice-jam formation and flooding at Badger during freeze-up. This approach embeds the deterministic river ice hydraulics model RIVICE into a Monte-Carlo framework in which the model is run repeatedly with different input values for the parameters and boundary conditions chosen randomly from frequency distributions. This produces a set of possible ice-jamming scenarios along a river segment of interest. Applying this method to estimate ice-jam flood hazards stemming from river freezing (Lindenschmidt 2023, 2024) is a novelty. Figure 4 illustrates the approach, which needs frequency distributions of the boundary conditions (shown at the top of Figure 4) and parameter values (not shown) to be input to the deterministic river ice hydraulic model RIVICE to yield ensembles of backwater level profiles.

The boundary conditions are:

- upstream water flow Q (Figure 4[a]) represented by an extreme-value distribution of the flows at the highest water levels during ice-jam events,
- volume of inflowing ice that forms the ice jam V_{ice} (Figure 4[b]),
- downstream water-level elevation W (Figure 4[c]) at a reservoir at Charlie Edwards Point. [*m a.s.l.*: meters above sea level]
- location of the ice-jam lodgment x (Figure 4[d]), distance in meters (or ‘chainage’) from a reference point.

Parameters are usually uniform distributions between minimum and maximum values calibrated through trial and error.

The framework uses the Monte Carlo approach (Figure 4[e]) to run the model hundreds of times, with each run having a different set of boundary conditions and parameter values randomly chosen from the distributions. One output is a set of backwater profiles (Figure 4[f]), which can be analyzed in a probabilistic way using percentile profiles of exceedance probabilities (Figure 4[g]). The water level heights at a gauge can then be matched to the annual exceedance probabilities of the heights recorded at the gauge (Figure 4[h]).

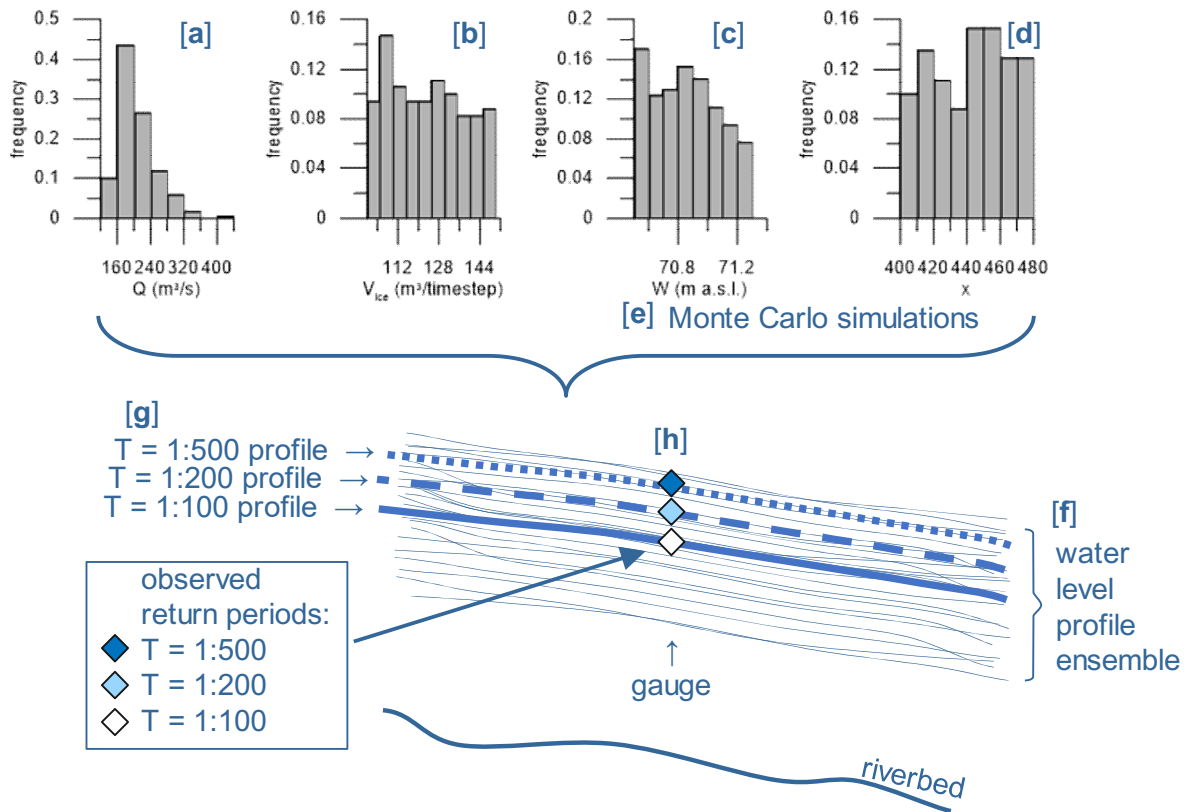


Figure 4. Conceptualisation of the stochastic modelling framework.

Ice-jam flood hazard and risk mapping

An ice-jam flood hazard assessment with its corresponding mapping were carried out for Badger. The 1:100, 1:200 and 1:500 AEP (annual exceedance probability) water level profiles derived from the Monte-Carlo simulations were extrapolated into the Exploits River floodplain to determine flood depths and extents throughout Badger. A step-by-step guide to the procedure is provided in Chapter 10 of Lindenschmidt (2024).

Following the assessment and mapping of the ice-jam flood hazard, which includes flood depths and extents, further steps were carried out in ArcGIS to compute the flood risk associated with the ice-jam floods. This involved correlating the flood depths, which are linked to flood return periods, with the cost of damages resulting from such floods. The procedure with an example tutorial is laid out in Chapter 11 of Lindenschmidt (2024).

4. Results and Discussion

Flood hazard assessment

An ensemble of 1120 backwater level profiles was produced within the Monte-Carlo framework from which 1%, 0.5% and 0.2% percentile profiles were plotted (see Figure 5) yielding profiles of the 1:100, 1:200 and 1:500 AEP. The water-level elevations for these three

return periods at the Badger gauge are, respectively, 100.3, 100.36 and 100.5 m a.s.l. These values seem reasonable, particularly for the 1:100 value which is only 0.1 m lower than the 100.4 m a.s.l. currently used by the town.

The profiles all pass through the ranges of the 1:100, 1:200 and 1:500 AEP derived from the stage frequency distribution of the instantaneous maxima of the water level elevations recorded annually during freeze-up events between 1991 and 2022. The range stems from values calculated using the generalise extreme value distributions fitted with three different methods: (i) method of moments, (ii) maximum likelihood and (iii) method of probability weighted moments.

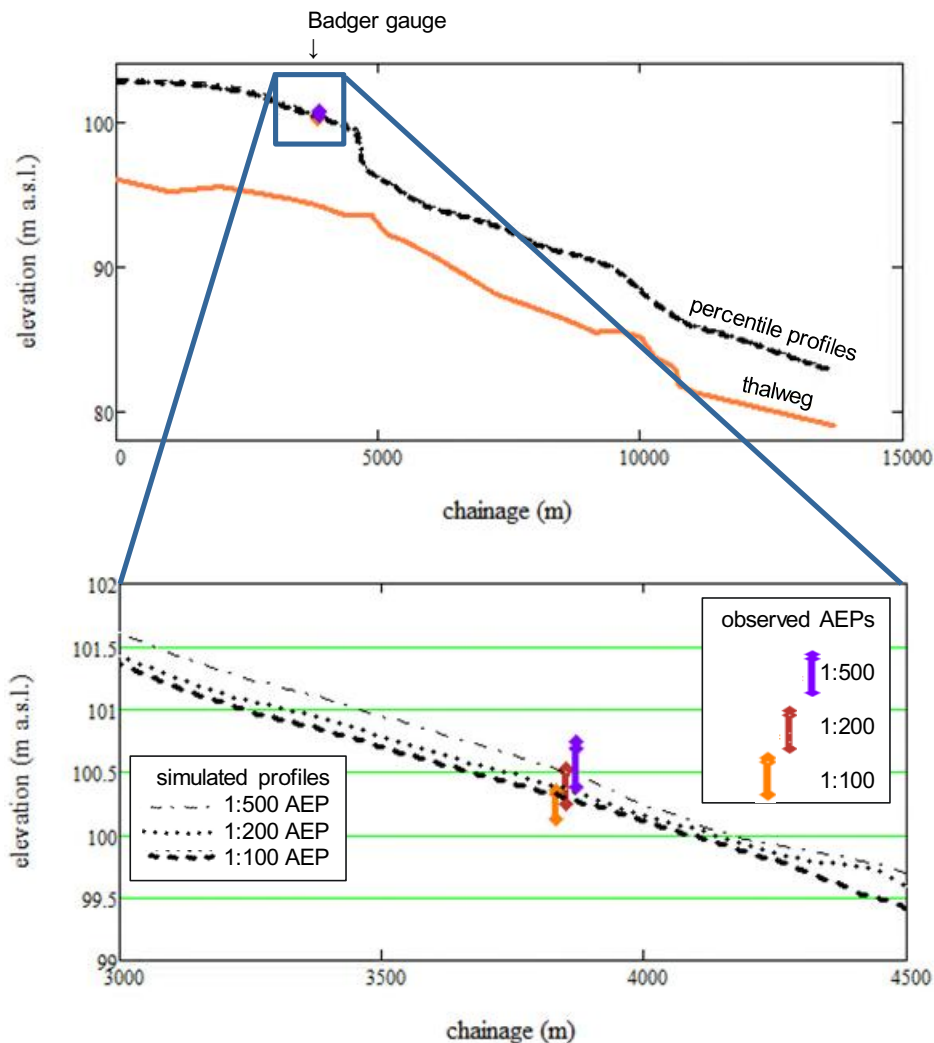


Figure 5. Percentile profiles along the Exploits River indicating the simulated 1:100, 1:200 and 1:500 AEP passing through ranges derived from the observed water-level elevations for the same AEP values.

Ice-jam flood hazard and risk mapping

The elevations of the percentile profiles extracted from the Monte-Carlo simulations were extrapolated horizontally into the floodplain on which Badger is situated. The floodwater depths are mapped in Figure 6 for the 1:100 AEP (top panel), 1:200 AEP (middle panel) and 1:500 AEP (bottom panel).

The ice-jam flood risk for each building point is mapped in Figure 7. Annual expected damages were calculated for each AEP to derive a total ice-jam flood risk of \$235,000/year. A comparison is made with risk calculated for Fort McMurray along the Athabasca River (Lindenschmidt, 2024, Chapter 11) in Table 1, with the flood risk for Fort McMurray being approximately 47 times that at Badger. This is reasonable since flooding in Fort McMurray encompasses approximately 23 times more building points (about 7000, as opposed to 300 for Badger) and the maximum 1:100 AEP flood depth at a building is 28% deeper in Fort McMurray than in Badger, i.e., ranging from 6.10 to 4.75 m, versus 6.10 m.

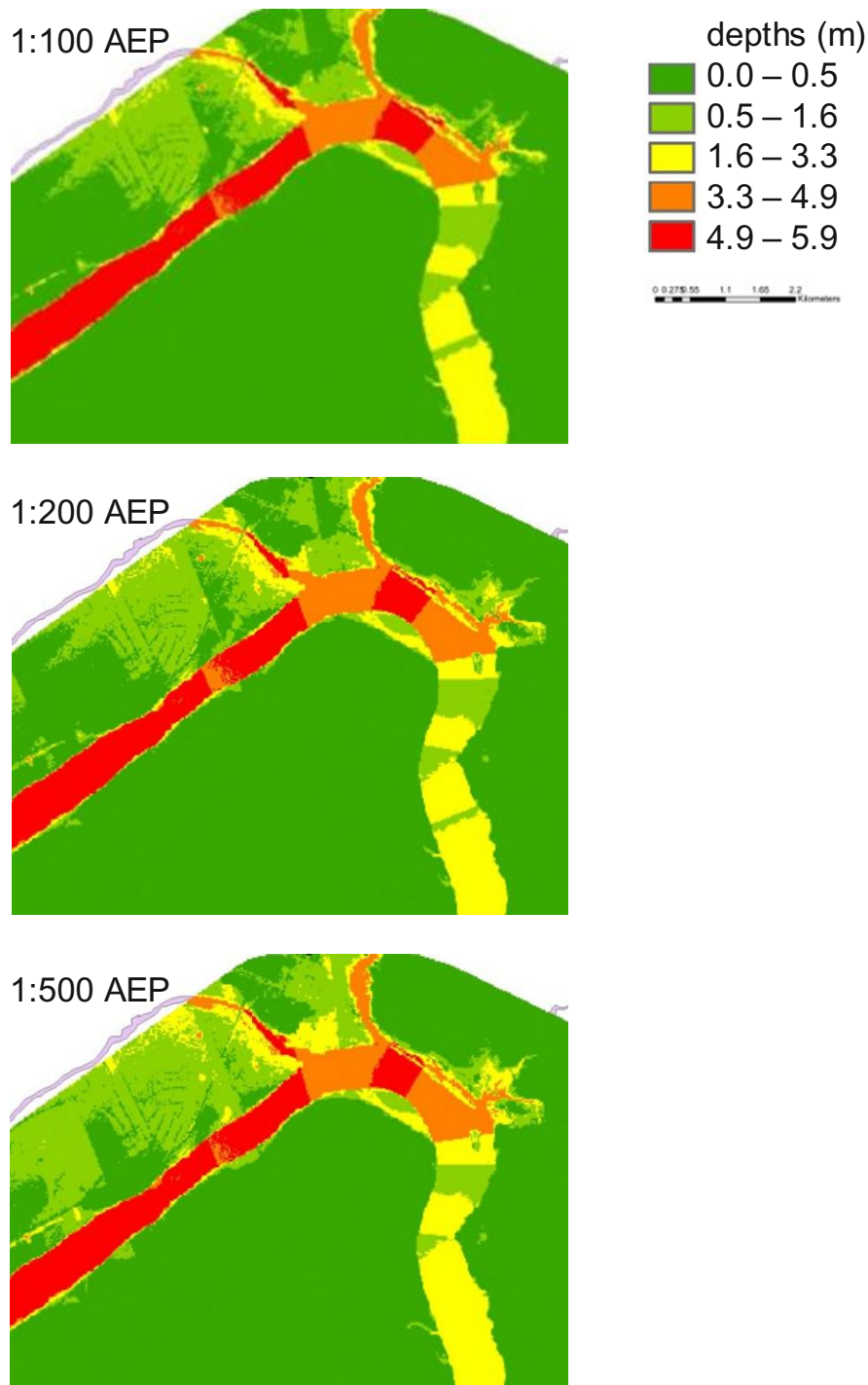


Figure 6. Flood depths for 1:100 AEP (top panel), 1:200 AEP (middle panel) and 1:500 AEP (bottom panel).

5. Conclusions

A river-ice model embedded in a Monte-Carlo Analysis framework was successfully implemented to determine freeze-up ice-jam flood hazard and risk. The town of Badger along the Exploits River in Newfoundland was used as a test case. The 1:100, 1:200 and 1:500 AEP formed the basis for the flood risk assessment. Damage curves (cost vs. flood depth) were associated with the flood depths for each building to determine the cost of flood damage repair and replacement for each return period. A total flood risk of \$235,000/year was calculated. A cost-benefit analysis may show that the risk may be low enough not to warrant the installation of flood defenses.

Table 1. Comparison of risk calculations for Bader and Fort McMurray.

location	risk (\$/year)	no. of building points	max. 1:100 AEP depth at buildings (m)
Badger	235,000	300	4.75
Fort McMurray	11,100,000	7000	6.10

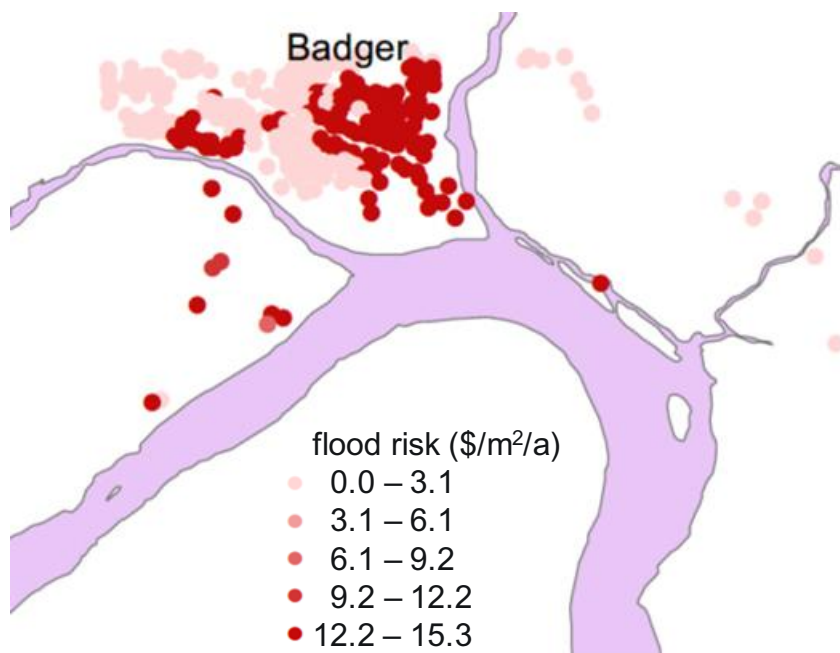


Figure 7. Ice-jam flood risk map.

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