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Modelling freeze-up ice covers along the Exploits River, Newfoundland

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Although spring breakup ice jams have received more attention than freeze-up ice jams in the literature, perhaps due to their greater flood severity, freeze-up ice jams can still be a concern for flooding and pose highwater threats to riverside communities. This paper explores a methodology to model key processes of freeze-up ice jam flood hazard. These processes, modelled in the river ice hydraulic model RIVICE, are addressed using freeze-up along the Exploits River as a case study where the town of Badger is of most concern regarding ice-jam flood risk. Differences between simulated and observed extents of the ice cover and water level elevations served as objective functions for the calibration process, using the calibration of the heat transfer coefficient as an example. The calibration of the hydrological model HEC-HMS set up for the lower subbasin of the Exploits River drainage area is also introduced. The coupling of these two models will be used in future work for flood forecasting and climate change predictions.

1. Introduction

The objective of the project is to provide tools and information needed to increase infrastructure resilience to weather extremes and other phenomena induced by climate change. Flooding in Canada often results from riverine ice-related actions, such as ice jams, which are associated with blockages of ice and subsequent rapid rises in water levels. Severe ice jams and associated floods can have major socioeconomic consequences, not only with respect to people's safety and property but also to the security of infrastructure, transportation, inland navigation and energy generation.

The focus of this paper is determining the flood hazard induced by freeze-up ice jams along rivers. These hazards have received less attention than the ice-jam flood hazard caused by spring ice-cover breakup events. The Exploits River in Newfoundland is presented as a test case, where freeze-up jamming causes the severest and most frequent mode of flooding at the town of Badger. The river-ice model RIVICE was used to simulate the freeze-up events and HEC-HMS was incorporated for the hydrological modelling of the Exploits River's lower subbasin.

2. Study Site

The Exploits River basin is situated in central Newfoundland with a drainage area of 7887 km² (outlet at Charlie Edwards Point gauge). It can be subdivided into an upper subbasin (outlet at Millertown Dam) and lower subbasin (outlet at Charlie Edwards Point gauge), as indicated in Figure 1. The average annual flows between 2010 and 2019 at each of these outlets were 155 and 238 m³/s at the upper and lower subbasin outlets, respectively. The average temperature in February, the coldest month, for 2000 – 2022 was -8.2 °C with cumulative freezing degree days reaching between 522 and 1250 °C-day during those winters. Average annual total precipitation amounted to 1118 mm.

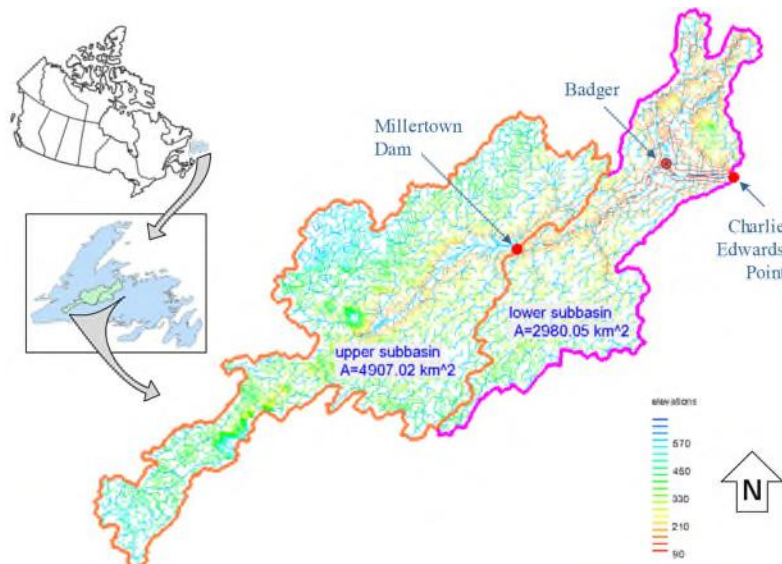


Figure 1. Basin delineation of the Exploits River.

The flow of the Exploits River in the lower subbasin, in which Badger is located, is regulated by the Millertown Dam. Flows for the two subbasin outlets, at Millertown Dam and Charlie Edwards Point, during the freezing season are shown in Figure 2. Flows are substantially increased during December, when freezing of the river begins (indicated in Figure 3 by the first b-flag of the freezing season recorded at Charlie Edwards Point; b-flags complement flow data to indicate flows are affected by backwater caused by an ice cover), and are an artifact of the flow regulation. The autumn flows of the nearby naturally-flowing Upper Humber River (drainage area at Reidville = 2,110 m²; distance between Reidville and Badger = 100 km) may represent a more typical maritime flow pattern of the area and are higher between September and November.

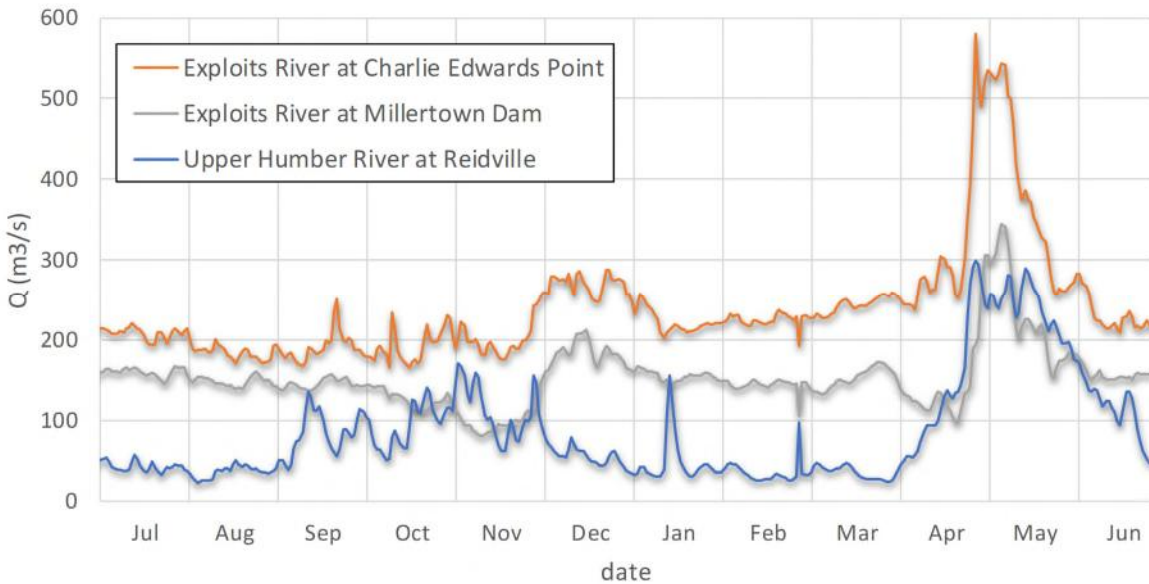


Figure 2. Daily flows averaged for the years between 2010 and 2019 at the subbasin outlets.

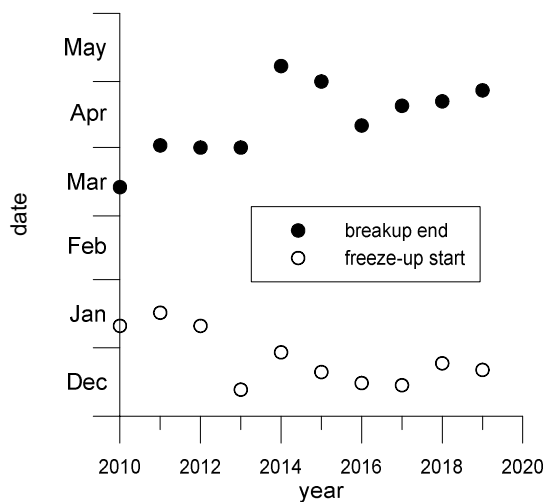


Figure 3: First (start of freeze-up) and last (end of breakup) b-flags recorded at Charlie Edwards Point gauge.

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). High flood levels at Badger during freeze-up occur due to a blockage of frazil slush in the area approximately 2.5 km downstream of Badger at Badger Rough Waters (see Figure 4) (Fenco, 1985, p. 7-4), a stretch dotted with many riffles. Once the ice cover has reached this point, the cover advances past the town with the water level rising in relation to the amount of frazil ice production, as shown in Figure 5.

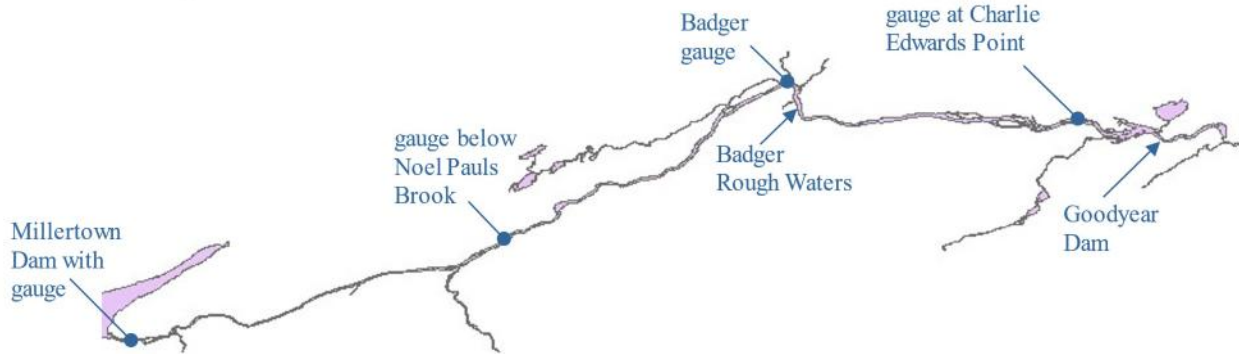


Figure 4: Exploits River.

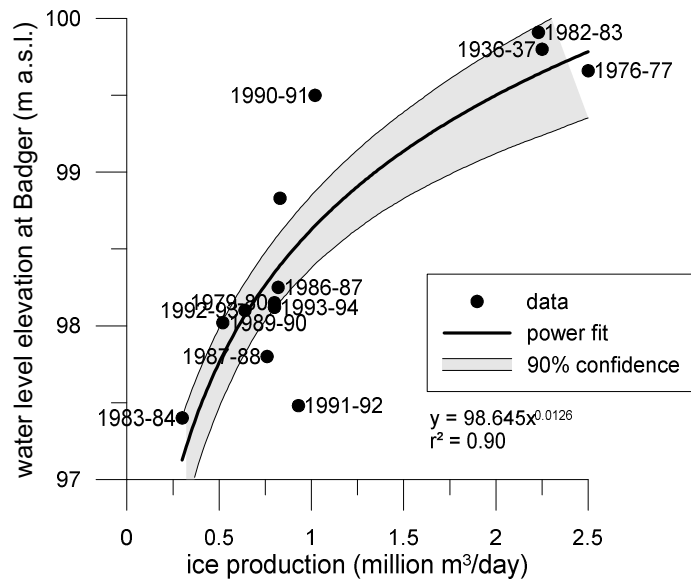


Figure 5: Production rate of frazil ice vs the water-level elevation at Badger as the ice-cover front moves upstream past Badger (data from Fenco, 1995, Table 4.1); the confidence band provides an estimated range of values calculated from the data that is likely to include an unknown population parameter 90% of the time.

“A key factor which determines if flooding will occur in one year as compared to another is the volume of frazil slush joining and thickening the advancing ice cover on those days in which the cover is passing through the Badger area” (Fenco, 1985, p. 7.4). Ice jam advisories and flood warnings are issued based on this relationship using an ice progression model operated by the Government of Newfoundland and Labrador. Flood alerts are issued to Fire and Emergency

Services and the Town of Badger based on water-level elevations and ice production rates summarised in Table 1.

Table 1: Threshold values for flood advisories and warnings;
AEP = annual exceedance probability

issuance	event	water-level elevation (m a.s.l.)	ice generation (million m ³ /day)
ice jam advisory	river bank full	98.5	0.9
flood warning	1:20 AEP	99.48	1.92
flood warning	1:100 AEP	100.36	2.66

3. River ice modelling

The river ice model RIVICE was used to simulate freeze-up along the Exploits River. Lindenschmidt (2020), Lindenschmidt et al. (2021) and Sheikholeslami et al. (2017) (excerpts of the latter two references were used for this section with permission) provide extensive descriptions of the river ice processes implemented in RIVICE. During freeze-up, frazil in the form of slush pans (A in Figure 6) is an important source of ice and is generated along the open water stretch upstream of the ice cover front (leading edge), when the water temperature T_w is at 0 °C and the overlying air temperature T_a is below freezing.

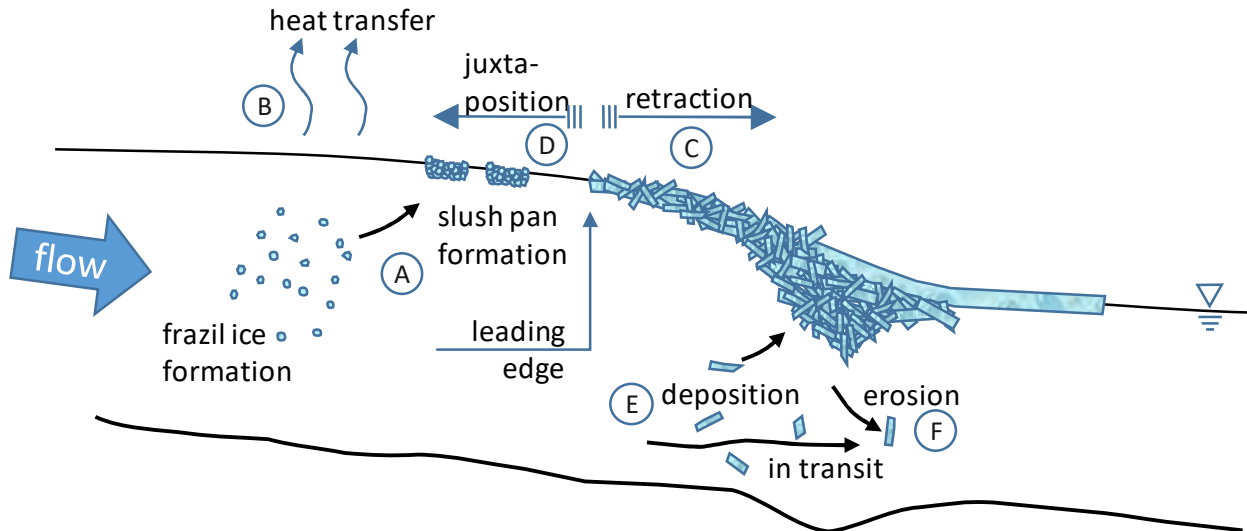


Figure 6: River ice processes simulated in the river ice model RIVICE; adapted from Sheikholeslami et al. (2017) (used with permission from ASCE).

The heat transfer q becomes (B in Figure 6):

$$q = H(T_w - T_a) \quad (1)$$

with H being the heat transfer coefficient typically ranging between 15 and 25 $\text{W/m}^2/\text{°C}$ depending on how conducive the site conditions are to heat transfer. Many factors can affect the water-to-air transfer of heat, including wind speed, the degree of wind sheltering along the river (high sloping banks with trees provide more sheltering) and the amount of longwave radiation (cloudy conditions), an important heat source that can slow down the production of frazil ice. Only the open-water areas contribute to the heat loss; heat loss through moving ice is considered negligible.

The frazil crystals conglomerate into flocs which then aggregate into slush pans that float to the top and flow along the water surface to the leading edge of the downstream ice cover. Once the ice reaches the leading edge, two processes are at hand for the progression of the ice cover. The first process is the shoving of the ice cover (C in Figure 6) in the downstream direction through “retraction” of the ice, which moves the already existing ice cover further downstream and thickens it. Retraction occurs when the summation of external forces on the cover (refer to Figure 7) – thrust of the flowing water against the leading edge F_T , the weight of the ice cover in the sloping direction F_W and the drag force on the ice cover’s underside by the flowing water F_D exceed the ice cover’s internal resistance F_I plus the frictional force of the ice cover along the river banks F_F , i.e. $F_T + F_W + F_D > F_I + F_F$. The second process is the progression of the ice cover upstream through juxtapositioning of the ice cover (D in Figure 6) when the internal resistance within the cover F_I plus the frictional force F_F remain larger than the summation of the external forces, F_T , F_W and F_D , i.e. $F_T + F_W + F_D < F_I + F_F$. The slush pans accumulate at the leading edge, stacking up against each other to extend the ice cover upstream. As more and more ice accumulates, external forcing anywhere along the juxtapositioned ice cover may be large enough to collapse and shove the ice cover in the downstream direction.

Ice under the cover may be eroded and transported downstream as ice in-transit. Should the mean flow velocity drop to below a velocity threshold value v_d , the ice will deposit on the ice cover underside (E in Figure 6). If the mean flow velocities underneath the ice cover increase and exceed a threshold value v_e the ice will erode from the underside (F in Figure 6).

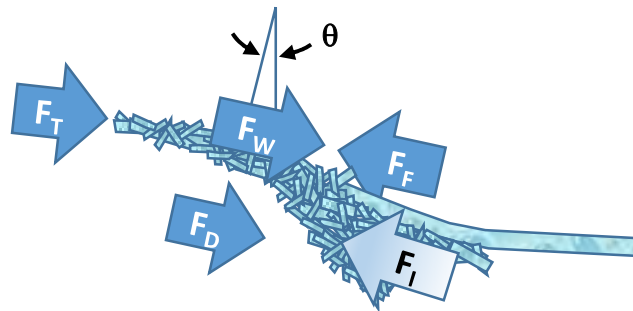


Figure 7: Forces applied to an ice-jam cover; adapted from Sheikholeslami et al. (2017) (used with permission from ASCE)

A RIVICE model has set up for the Exploits River between the Millertown and Goodyear dams (see Figure 4). The model was set up using cross-sections from a HEC-RAS model, available publicly at https://www.gov.nl.ca/ecc/files/Exploits_HECRAS_Steady-and-Unsteady.zip. The setup of the model required lining up and connecting the cross-sections to form a network along

the river. The spacing of these cross-sections are generally too coarse for ice modelling hence, additional cross sections are interpolated at 100 m intervals along the river. The HEC-RAS files also have a calibrated open-water profile which was used to calibrate the bed roughness coefficient of the RIVICE model (see Figure 8). Locations of the dams, gauges and flood vulnerable community, Badger, are also indicated in the figure.

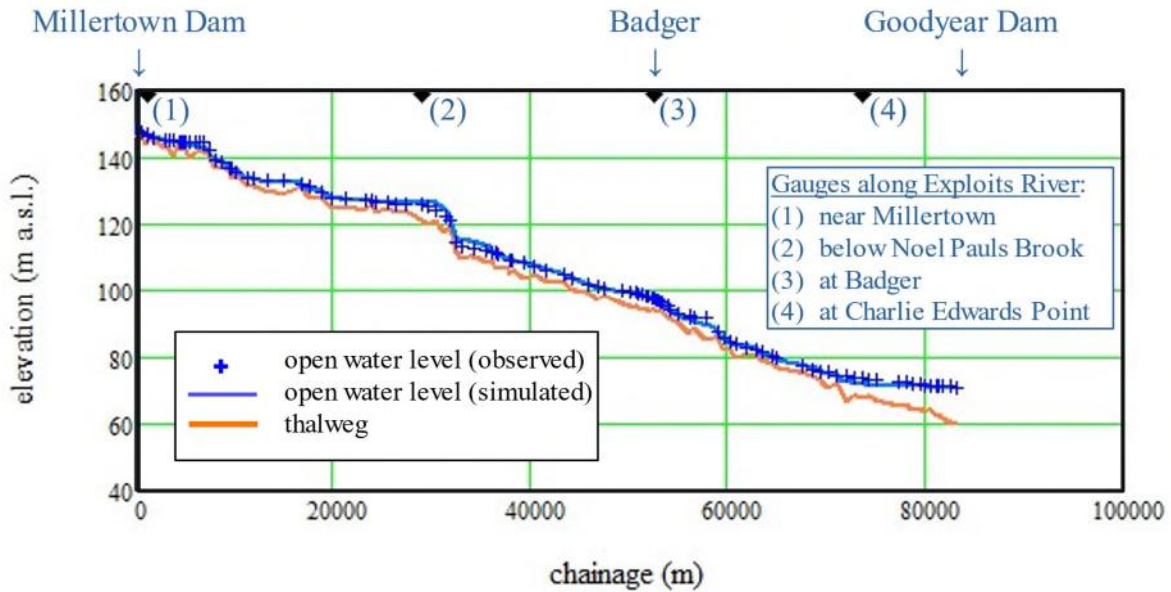


Figure 8: Longitudinal profile of RIVICE open-water calibration for the Exploits River.

Space-borne radar data (<https://www.exploitsriver.app/>) was used to track the ice cover progression at freeze-up along the Exploits River. For the freeze season of 2018 – 2019, the ice cover initiated at Charlie Edwards Point on 25 December 2018. The season was colder than average, as indicated in Figure 9 by the higher cumulative degree days of freezing compared to most other winters between 2000 and 2023, allowing the ice cover to reach Badger by the beginning of February 2019.

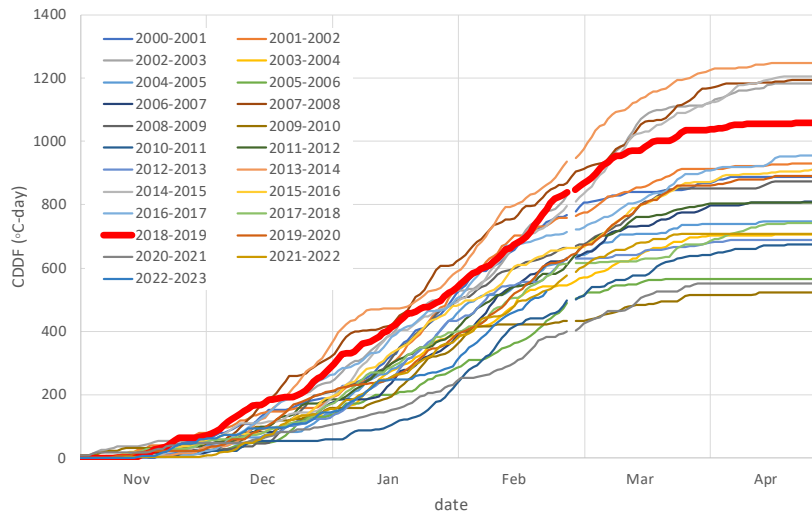


Figure 9: Cumulative degree-days of freezing (CDDF) at Badger for winters 2000 to 2022.

The ice-cover extents near Badger are shown for selected days in Figure 10. For example, the ice cover progressed upstream from 16 to 21 January 2019, when the CDDF averaged 9°C-day/day. However, from 21 to 28 January 2019, the mean CDDF was only 5.6°C-day/day generating less frazil ice. In fact, during this time the maximum daily air temperatures rose above 0°C for five of these eight days and the ice-cover front receded downstream with an open lead having formed in the cover. This shows that, even with daily mean freezing air temperatures, there is enough residual heat within the water and riverbed to reduce frazil ice formation and cause open leads to form in the ice cover. From 28 January to 2 February 2019, colder weather resumed during which time the average CDDF increased to 10.3°C-day/day and enough frazil ice was generated for the ice-cover front to progress further upstream past Badger.

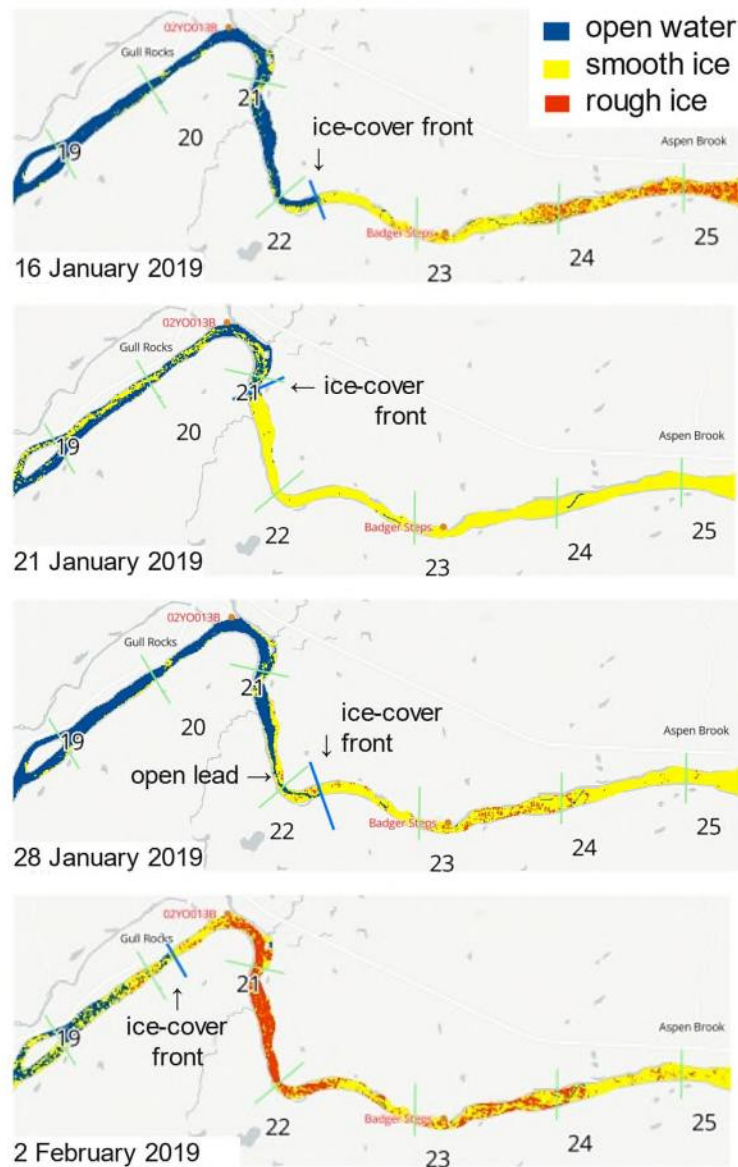


Figure 10: Ice classification along the Exploits River near Badger
(source: <https://www.exploitsriver.app/>)

Figure 11 shows the simulated ice cover progression during the freeze-up season of 2018 – 2019. Day numbers are indicated at the top of each graph which correspond to the date of freezing as indicated in Table 2.

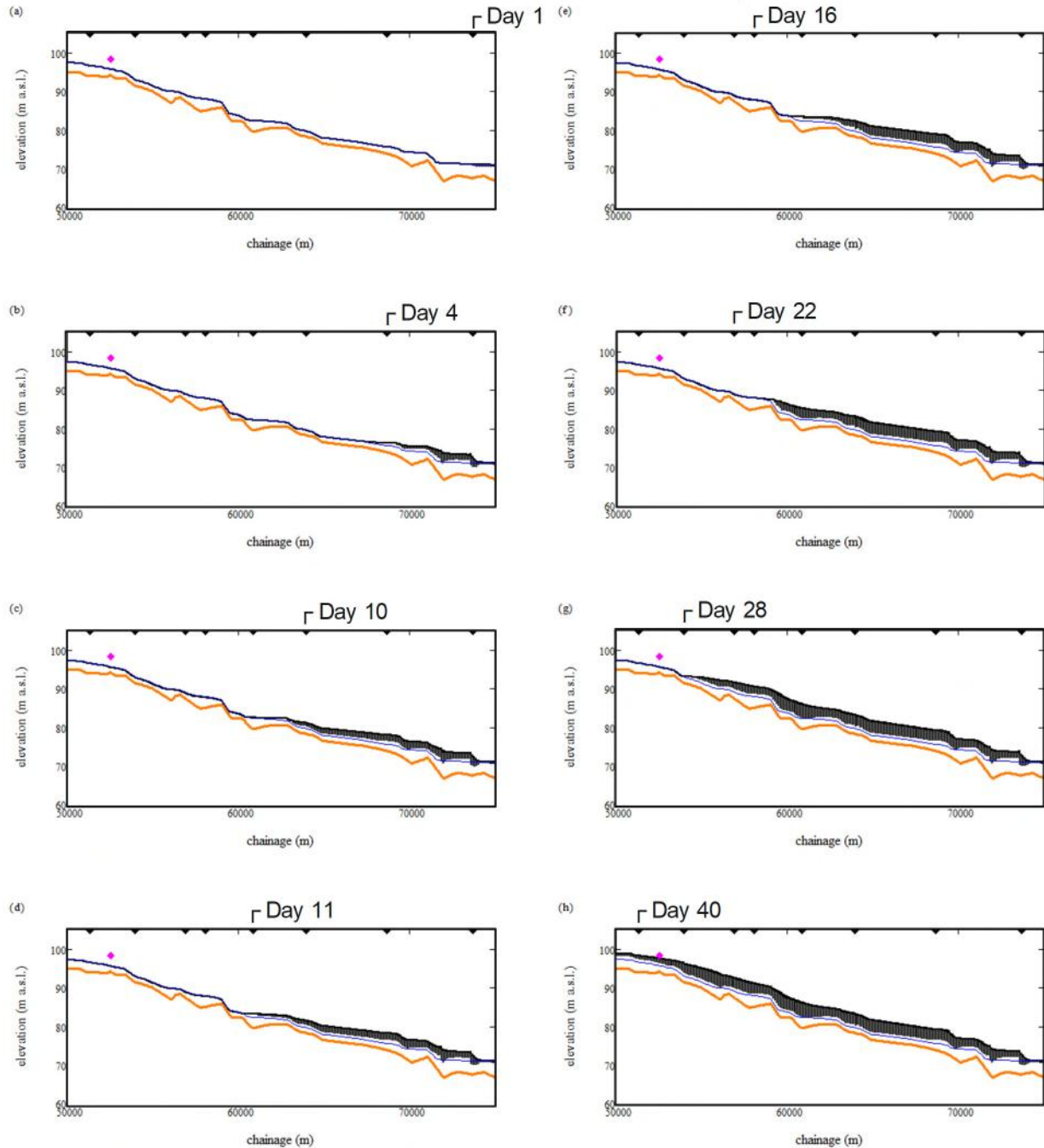


Figure 11: Profiles of water levels and frazil-generated ice covers with the selected number of days from 25 December 2018 pointing to the location of the observed ice-cover front. The sequence is from top to bottom along the left side and then top to bottom along the right side. The pink diamond is the maximum water level at Badger during freeze-up recorded on 2 February 2019.

Table 2: Satellite acquisition dates with corresponding time steps and simulation days.

date	simulation day	time step	ice-cover front chainage	comment
02-Feb-2019	40	115200	51295.5	
28-Jan-2019	35	100800	56800.0	front receded with open lead
21-Jan-2019	28	80640	53936.0	
16-Jan-2019	23	66240	56900.0	
12-Jan-2019	19	54720	58602.7	front receded with open lead
09-Jan-2019	16	46080	58077.5	
04-Jan-2019	11	31680	60847.4	
03-Jan-2019	10	28800	63947.9	
28-Dec-2018	4	11520	68644.9	
25-Dec-2018	1	2880	73664.6	

One drawback with the RIVICE simulations is that the ablation of the ice cover was not incorporated in the modelling. For example, for the timeframe 21 to 28 January 2019 (simulation days 28 to 35), the daily maximum air temperatures did rise above 0°C which lead to the formation of open leads at the ice-cover front and slight recession of the front in the downstream direction. This process was not captured by RIVICE, however two of the 8 days during this timeframe would not have generated frazil ice because the mean air temperatures on those days were above 0°C. Flows remained steady through January 2019 (mean = 240 m³/s; standard deviation = 18.8 m³/s) reinforcing the statement that the ice cover receded by ablation and not consolidation. Consolidation would perhaps have crushed the open lead.

The distance between the simulated and observed ice-cover front for any particular day has been coined the gap offset $gapOffset$ and, for a particular observation day d , has been formulated as:

$$gapOffset_d = ObsICFchainage_d - SimICFchainage_d \quad [1]$$

where $ObsICFchainage$ is the observed ice-cover front chainage and $SimICFchainage$ is the simulated ice-cover front chainage. If $gapOffset_d < 0$, then the simulated ice-cover front is downstream of the observed ice-cover front. Conversely, if $gapOffset > 0$, then the simulated ice-cover front is upstream of the observed ice-cover front. The total gap offsets $gapOffsetTotal$ for all observation days n becomes:

$$gapOffsetTotal = \sum_{d=1}^n gapOffset_d \quad [2]$$

which was used as an objective function to measure model performance. For $gapOffsetTotal < 0$, during ice-cover formation, the simulated cover front tends to lag behind the observed front. For $gapOffsetTotal > 0$, the simulated ice cover forms quicker than what was observed. The absolute value of all gap offsets $totalAbsGap$ was also considered as an objective function as:

$$totalAbsGap = \sum_{d=1}^n |gapOffset_d| \quad [3]$$

Figure 12 provides an example of optimizing the heat transfer coefficient H , for which $gapOffsetTotal$ needs to be minimised and $totalAbsGap$ needs to approach the value 0 as closely as possible. The value $H = 10 \text{ W/m}^2/\text{°C}$ appears to yield the best calibration result.

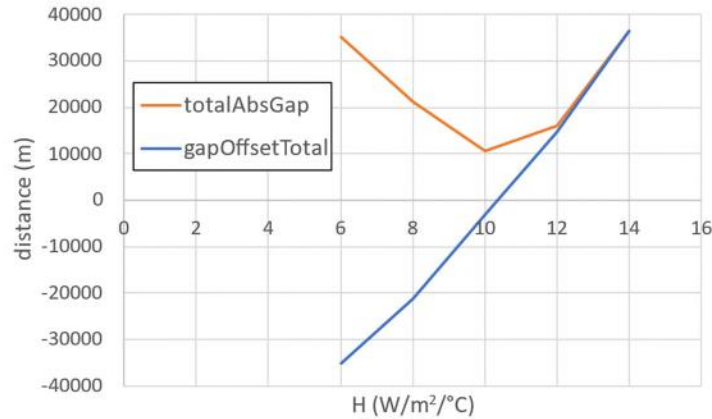


Figure 12: Values of objective functions

4. Hydrological modelling

A hydrological model coupled to the RIVICE is required to apply the models for:

- forecasting (determine the volume of ice generated that can lead to flooding for operational purposes, i.e. short term) or
- prediction (changes to the hydraulic and ice regimes due to future climate, i.e. long term).

The flows of the upper subbasin are regulated by the Millertown Dam which may bias the forecasting and prediction results. However, this bias can be reduced if dam operations are known in the near future (in the context of flood forecasting) or the assumption is made that seasonal variations in the dam operations will maintain the same pattern in the far future (in the context of climate change predictions).

The flows from the lower subbasin were simulated using the hydrological model HEC-HMS. A HEC-HMS model, available at https://www.gov.nl.ca/ecc/files/HECHMS_WebPosting.zip, was modified for the lower subbasin of the Exploits River between Millertown and Goodyear dams (Figure 13) to produce daily streamflows in the period spanning from 2009 to 2020. Precipitation and temperature data were obtained from Environment and Climate Change Canada records. Data on flow measurements in and around the Exploits River basin were collected from Water Survey of Canada data. Observed flows recorded at the Millertown Dam served as the upstream boundary condition of the model.

In this study, HEC-HMS was employed to simulate various hydrological processes, integrating different methods to represent canopy and surface dynamics, infiltration and surface runoff, direct runoff response, recession of baseflow, snowmelt, and channel flow routing. For the representation of canopy and surface processes, the simplified approaches of the simple canopy and simple surface methods were utilized to account for vegetation cover and surface characteristics. The

Green and Ampt method, known for estimating infiltration rates based on initial soil moisture and hydraulic conductivity, was used as the loss method, with carefully calibrated parameters to ensure accurate simulation of infiltration and surface runoff. The Clark Unit Hydrograph method was chosen to simulate the subbasin's direct runoff response, incorporating calibrated storage coefficient and time of concentration. Additionally, the linear reservoir baseflow method was employed to simulate baseflow recession, while the snowmelt method utilized a temperature index approach. For channel flow routing, the well-established Muskingum-Cunge model was selected, considering wave speed, storage, and friction in river channels.

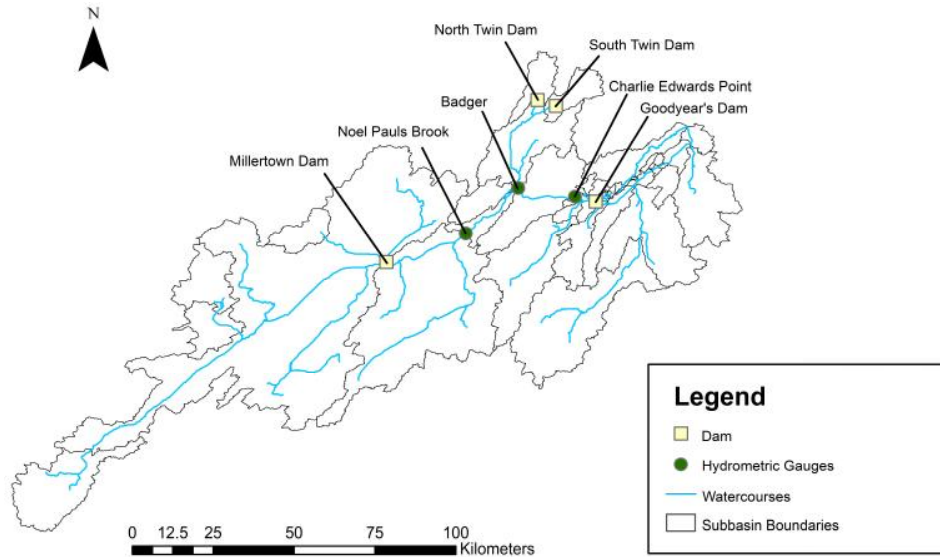


Figure 13: Subbasin delineation for Exploits River HEC-HMS basin model.

The three active hydrometric gauges below Noel Pauls Brook, at Badger and at Charlie Edwards Point were used to assess the model performance using the Nash-Sutcliffe Efficiency (NSE) between simulated and observed flows as the objective function. The simulated streamflow was calibrated based on the three hydrometric stations in Exploits River from 2009 to 2020 (Figure 14). Future work will concentrate on coupling the hydrological simulation results to the RIVICE simulations of freeze-up ice-cover formation.

5. Conclusions

Methodologies were presented to model the progression of freeze-up ice covers along the Exploits River and runoff from the river's lower subbasin. The models were successfully calibrated and can now be implemented for freeze-up ice-jam flood forecasting and predicting future freeze-up behaviour in the region's changing climate.

Acknowledgments

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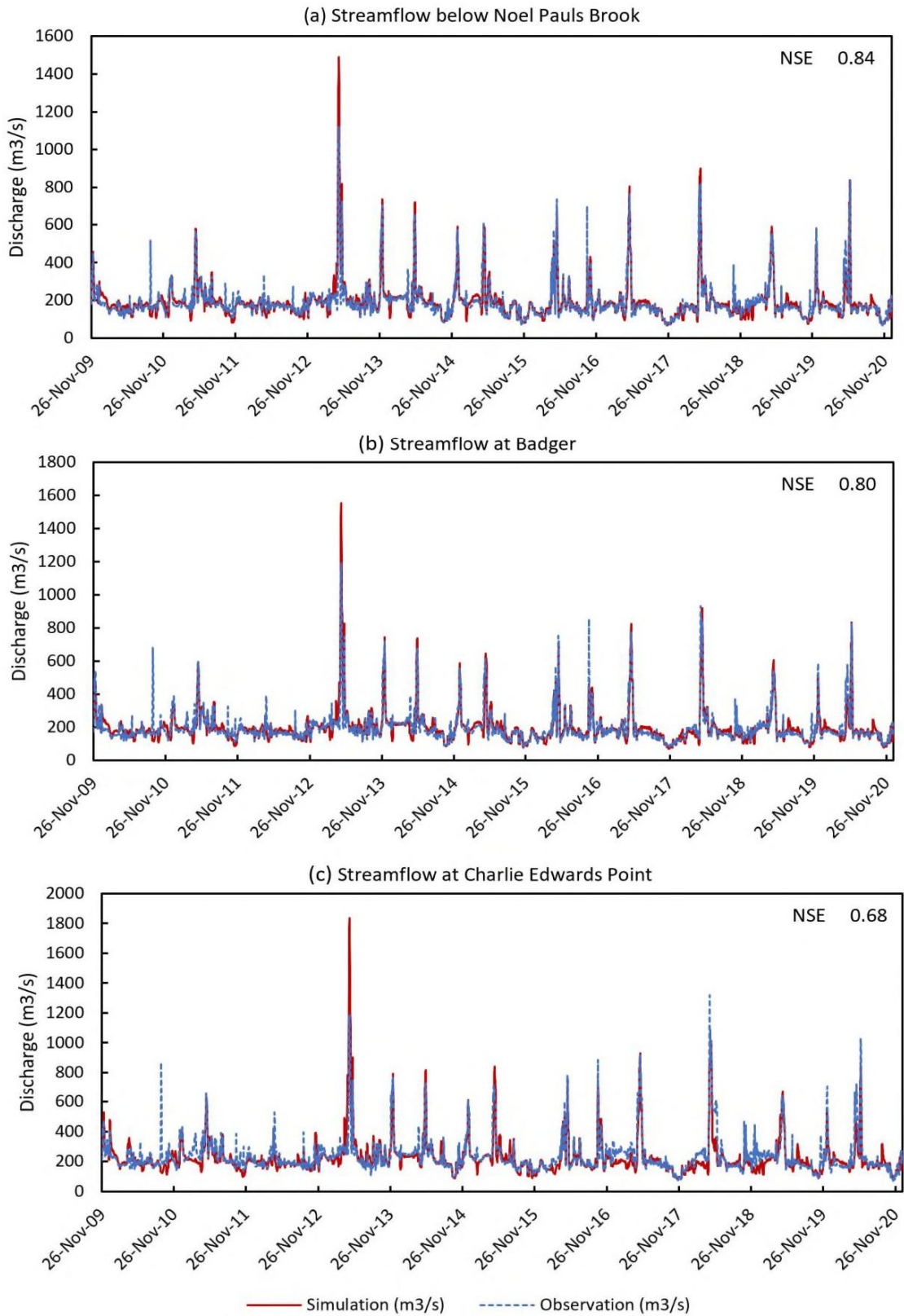


Figure 14: Observed and simulated flows along the Exploits River (a) below Noel Pauls Brook, (b) at Badger and (c) at Charlie Edwards Point.

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