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Development of an ice-jam flood forecasting modelling framework for freeze-up/winter breakup

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ABSTRACT

River ice-jams can create severe flooding along many rivers in cold regions. While ice-jams often form during the spring breakup, the mid-winter breakup can cause ice-jamming and flooding. Although many studies have already been focused on forecasting spring ice-jam flooding, studies related to forecasting mid-winter breakup jamming and flooding severity are sparse. The main purpose of this research is to develop a stochastic framework to forecast the severity of mid-winter ice-jam flooding along the transborder (New Brunswick/Maine) Saint John River of North America. A combination of hydrological (MESH) and hydraulic model (RIVICE) simulations was applied to develop the stochastic framework. A mid-winter breakup along the river that occurred in 2018 has been hindcasted as a case study. The result shows that the modelling framework can capture the real-time ice-jam severity. The results of this research will help to improve the capacity of ice-jam flood management in cold regions.

Key words: flood forecasting, freeze-up, hydrology, river hydraulics, stochastic approach, winter breakup

HIGHLIGHTS

- First attempt to forecast freeze-up/winter breakup flood severity.
- Stochastic modelling approach for winter breakup.
- Hydraulic modelling for winter ice-jam formation.
- Estimating real-time ice-jam flood severity.
- Estimating freeze-up ice volume using modelling results.

INTRODUCTION

Ice processes are crucial hydrological factors for many rivers in cold regions. The presence of ice in lotic waters alters the flow conditions, water quality, and geomorphological and ecological settings of rivers (Prowse 2001). One of the more extreme river ice processes, ice-jam formation, can create rapid water level fluctuations and severe flooding, which have caused millions of dollars of property and business losses to riverside communities. Moreover, the dynamic behaviour of ice processes can interrupt hydropower generation, disrupt hydrometric data recording, and affect navigation. Ice-jams are capable of significant erosion of river beds and banks. Furthermore, ice-jams can cause disturbances within the aquatic environment and adversely impact aquatic habitats (e.g., increased fish mortality and destroyed spawning grounds). River ice dynamics also control dissolved oxygen concentration and can change the mixing process within the water column by scouring transporting and depositing sediment.

Ice-jams often occur during spring breakup; however, winter ice-jams are also frequent in various rivers in cold regions (De Coste *et al.* 2022). Winter ice-jams can occur during freeze-up and stable ice cover periods and are often caused by brief thaws, rain-on-snow events, and high flow conditions along the river (Beltaos 2002). Winter ice-jams are often unanticipated and difficult to manage, as subsequent cold air temperatures freeze the flooded water in place for the entire winter period. Winter ice-jams can form relatively thick and competent ice covers and intensify the following spring breakup conditions and ice-jam formations. Many recent studies have reported an increasing trend in winter breakups throughout North America (Carr & Vuyovich 2014; Das *et al.* 2022a, 2022b; De Coste *et al.* 2022). Newton *et al.* (2017) reported a total of 52 mid-winter

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breakup events in Western Canada and Alaska since 1950. In recent years, winter breakup has become a common occurrence along the Saint John River in Maine, USA and New Brunswick, Canada, where 27 freeze-up/winter breakup events have been observed since 1981 (Das *et al.* 2022a, 2022b). A similar increasing trend has been observed along other rivers in the United States, such as Picataquis River in Maine (Huntington *et al.* 2003), the Fox River in Wisconsin, and the Grand River in Michigan (Carr & Vuyovich 2014). A mid-winter breakup has also been observed on the Klondike River, Yukon (Janowicz 2010).

Since hydroclimatic factors are the major drivers of the occurrences of winter breakup, current changing climatic trends can greatly influence the pattern and severity of this type of event in the future (Beltaos 2002; Turcotte *et al.* 2019; Burrell *et al.* 2022). Several studies suggest that a warmer climate will result in a higher frequency of winter breakup occurrences and increase the risk of winter flooding along many communities in cold regions (Das *et al.* 2022a, 2022b; Lamichhane *et al.* 2022). Therefore, it is very important to develop a forecasting framework to examine the severity of winter breakup to reduce flood impacts and better prepare for emergency measures. Although many studies have already focused on spring ice-jam flood forecasting, no study has focused on winter ice-jam flood forecasting.

Many tools have been introduced to forecast river ice-jam conditions, such as empirical approaches, logistic regression, discriminant function analysis (White 2003, 2008), and multiple linear regression (Mahabir *et al.* 2006, 2008). However, these tools are limited to establishing a relationship between hydrometeorological variables and providing the occurrences of ice-jamming and breakup dates rather than estimating the backwater level of the river during ice-jam formation. Moreover, these methods are site-specific and challenging to implement in different geomorphological settings. Some data-driven machine learning models have also been introduced to predict breakup conditions (dates and flows), such as the k-nearest neighbour algorithm (Sun & Trevor 2017), decision-tree models (Sun 2018), neural networks (Mahabir *et al.* 2008; Wang *et al.* 2008; Guo *et al.* 2018), and fuzzy-logic models (Sun & Trevor 2015; Zhao *et al.* 2015). The combination of one or two of these models has also proven to produce better prediction accuracy (Sun & Trevor 2017, 2018a, 2018b). Although these models produce useful results, the lack of interpreting physical processes between the inputs and outputs makes it challenging to decision-making during emergency situations. Moreover, the data-driven models highly depend on the data availability and quality. Some attempts have also been carried out by applying various deterministic models to forecast flood water levels for ice-jam, such as River2D (Brayall & Hicks 2012), HEC-RAS (Beltaos *et al.* 2012), and RIVICE (Lindenschmidt *et al.* 2019). However, properly parameterizing a deterministic model to forecast ice-jam flooding is often challenging, which requires many parameter and boundary conditions, such as streamflow forecast, ice-jam locations, and ice volume. In recent years, Lindenschmidt *et al.* (2019) developed a stochastic framework for real-time ice-jam flood forecasting, combining hydrological and hydraulic models to produce an ensemble of ice-jam flood water level profiles during the progression of spring breakup. This approach was then tested in various rivers in Canada, such as Lower Red River, Manitoba (Williams *et al.* 2021) and Saint John River, New Brunswick (Das *et al.* 2022a, 2022b). This prominent flood forecasting approach has been applied in this study for mid-winter ice-jam flood forecasting.

The main purpose of this study is to develop a framework for forecasting mid-winter ice-jam flooding. The specific objectives are (i) to analyze mid-winter breakup along the Saint John River from Dickey, Maine, USA to Grand Falls, New Brunswick, Canada; and (ii) to develop a stochastic framework for mid-winter ice-jam flood forecasting.

METHODOLOGY

Study site

The Saint John River Basin (SJRB) is a coastal basin in North America (Figure 1). The basin area is about 55,100 km^2 across northern Maine, USA and southeastern Quebec and western New Brunswick, Canada. The Saint John River is a 708 km long river that originates in northern Maine, flows through the western part of New Brunswick and finally drains into the Atlantic Ocean in the Bay of Fundy. The elevation drop along the river is about 480 m. Historically, the river is prone to spring ice-jam formation, as the river channels are conducive to this phenomenon. The river reach from Dickey to Fort Kent (see Figure 1) is relatively steep and has a series of rapids. These rapids are the main source of frazil ice generation throughout the freeze-up season. The reach from Fort Kent to Edmundston is relatively wide and shallow and the reach downstream from Edmundston is comparatively narrow and deep. The islands and sandbars along the river split streamflows into multiple channels. Recently, frequent freeze-up/winter breakup and associated ice-jam events have been observed along the river. Figure 1 illustrates the historical mid-winter/freeze-up breakup and ice-jamming locations along the river since 1981. These breakup events are distributed throughout the river from Dickey to Grand Falls.

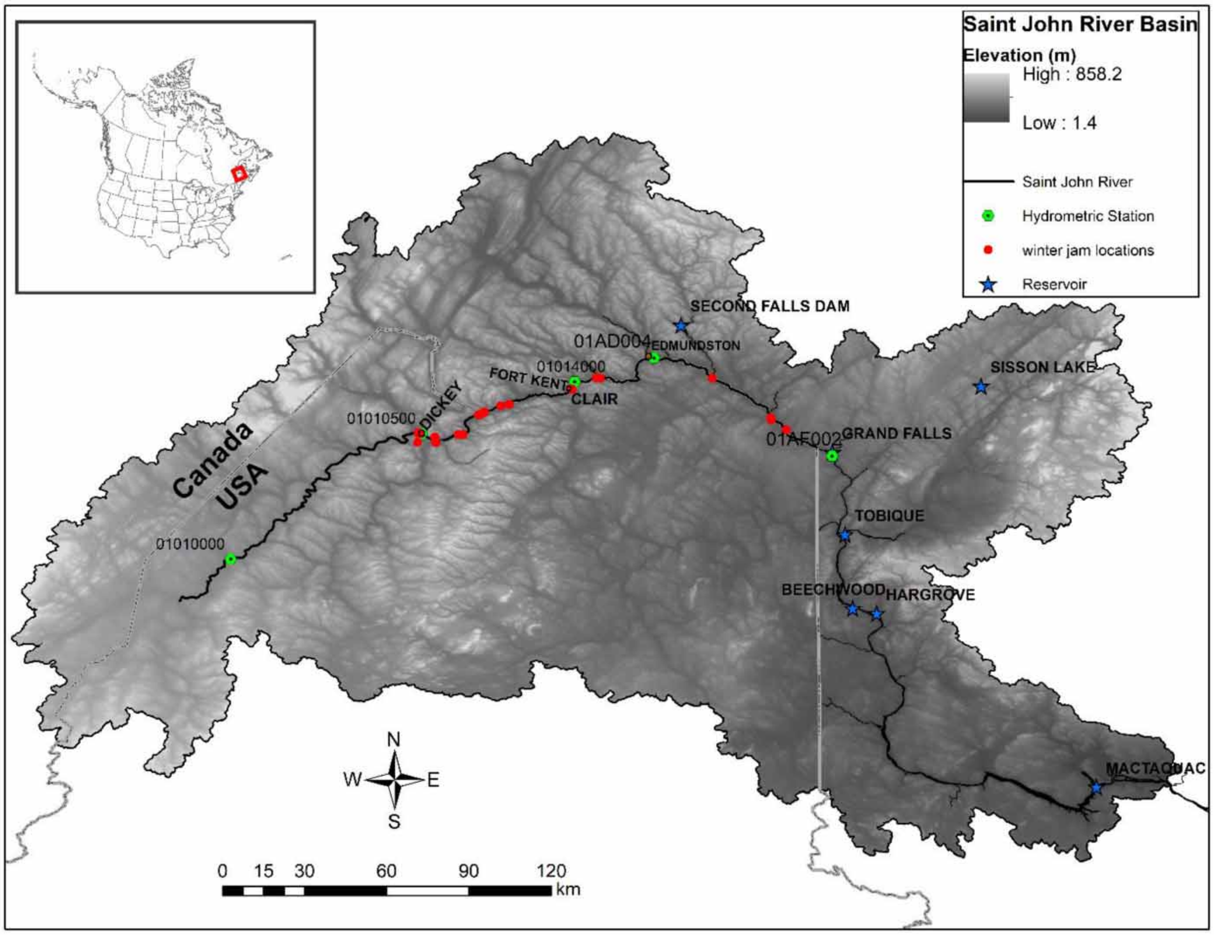

Figure 1 | The Saint John River with winter ice-jam locations and gauge stations.

Hydrometric data preparation

Hydroclimatic data (e.g. streamflow and temperature) were analyzed and used to examine the winter breakup along the river. Daily mean streamflow data were obtained from the hydraulic gauge stations at Fort Kent (#ID: USGS01014000), Edmundston (#ID: WSC01AD004), and Grand Falls (#ID: WSC01AF002). The gauge station at Fort Kent is operated by the U.S. Geological Survey (USGS) (https://waterdata.usgs.gov/nwis) and Edmundston and Grand Falls are operated by Water Survey Canada (WSC) (https://wateroffice.ec.gc.ca/) (Figure 1). It should be noted that ice-related data are occasionally unavailable because ice events often damage the gauge station and stop data recordings during the events. Observed mean daily air temperature data were obtained from meteorological stations (Climate ID # 8101303) at Edmundston, New Brunswick, Canada.

The meteorological forcing data (wind speed, air temperature, specific humidity, incoming longwave radiation, barometric pressure, and incoming shortwave radiation) required for MESH simulations were obtained from the Regional Deterministic Prediction System (RDPS, Caron *et al.* 2015), which has spatial and temporal resolutions of 10 km and 1 h, respectively. RDPS is a part of the Global Environmental Multiscale (GEM) numerical weather prediction model (Côté *et al.* 1998), developed and operationally run by ECCC, and provides short-term forecasts (3.5 days). For model calibration and validation purposes, meteorological forcing data were archived from the first day of the forecast horizons (0–23 h) from the RDPS system. However, the precipitation data were taken from the Canadian Precipitation Analysis (CaPA) (Mahfouf *et al.* 2007) which are available daily at 6-h time intervals at a spatial resolution of 10 km. CaPA is a reliable precipitation product for the Canadian domain (Boluwade *et al.* 2018).

Hydrological forecasting for 2018 was performed using the meteorological products from the Global Deterministic Prediction System (GDPS, Buehner *et al.* 2015). Like RDPS, GDPS is also part of the GEM numerical weather prediction model and is a global operational forecasting system that provides deterministic atmospheric variable predictions with a 10-day lead time (Bélair *et al.* 2009; Charron *et al.* 2012). The forecasts are produced twice a day (00 UTC and 12 UTC) at 3-h temporal resolution and have a spatial resolution of approximately 25 km. Previous studies (e.g., Lindenschmidt *et al.* 2019; Rokaya *et al.* 2020) have found GDPS to provide reasonable results. All the forcing datasets (CaPA, RDPS and GDPS) were downloaded from the Canadian Surface Prediction Archive (CaSPAr) platform (Mai *et al.* 2020) (https://caspar-data.ca/caspar).

Winter ice processes information

Historical winter breakup information was obtained from the Cold Regions Research and Engineering Laboratory (CRREL) ice database (https://icejam.sec.usace.army.mil/ords/icejam/r/icejam/home). The information from this database such as breakup dates, jam locations, and a brief description of the breakup and ice-jams from this database was used to examine the winter breakup phenomenon and modelling setup. Moreover, the study site's visual history of river ice processes is recorded by the Department of Environment and Local Government, New Brunswick. The winter breakup and associated ice-jam location data were analyzed from these visual history records. Furthermore, the progress of ice cover formation during the freeze-up was captured using Sentinel-1 satellite imagery from the sentinel hub through the EO browser (https://www.sentinel-hub.com/explore/eobrowser/). EO browser is an open-source database that provides an image every 7 days, allowing us to capture the ice cover progress along the river.

MESH hydrological model

MESH (Modélisation Environnementale Communautaire – Surface Hydrology) is a semi-distributed hydrological land surface model developed by Environment and Climate Change Canada (ECCC) (Pietroniro *et al.* 2007). The hydrological processes represented in MESH consist of three components: (i) vertical exchange of water between soil, plants and atmosphere within a grid cell using CLASS (Verseghy 1991; Verseghy *et al.* 1993), (ii) generation of surface and subsurface runoff within a grid cell, and (iii) routing of lateral fluxes within the stream network using WATROUTE (Kouwen 2016).

In the soil profile, the moisture content and its vertical movement in the soil layers are calculated by solving Richard's equation. As a result, CLASS estimates overland runoff, interflow, and baseflow for each computational grid cell. The horizontal flow for each Grouped Response Unit (GRU) consists of overland flow, interflow, and baseflow. Overland flow is calculated using Manning's approximation of the kinematic wave propagation. Interflow, which accounts for the downward hill slope flow, is estimated from the bulk saturation of each soil layer, calculated at each time step. Baseflow is treated as any water that percolates out of the bottom of a soil column in a GRU and is immediately added to two interconnected hydrological reservoirs that slowly release water towards streams. The total amount of surface runoff is then calculated for each grid cell by the areal average of GRUs within that grid cell. More details on MESH, including the recent advances, is available from Wheater *et al.* (2022).

Streamflow forecasting system setup

Figure 2 shows the schematic view of a MESH operational streamflow forecasting system. The streamflow forecast involves two major steps. First, running the model in the hindcast mode and saving the hydrological state variables until the previous day and then performing the flow forecast from the current day, for the next 10 days. The basin's hydrological condition and state variables are saved every day before each forecast is made, so that the initial hydrologic condition is always correct. GEM-CaPA + RDPS forcing is used during hindcasting, whereas GDPS forcing dataset are used for the forecasting. MESH was run at an hourly time step in the hindcasting mode and 3-hourly in the forecasting mode to match the temporal resolution of the meteorological data.

Stochastic modelling framework

The stochastic modelling approach can simulate hundreds of probable scenarios under many conditions using a set of random variables. In this study, the RIVICE hydrodynamic model was embedded into the Parameter Estimation Software (PEST) program to perform the Monte-Carlo (MOCA) method. The RIVICE model is able to simulate various river ice processes, such as frazil ice generation, transport, juxtaposition and hanging dam formation, shoving and ice cover melting and ablation using a set of river ice and hydraulic parameters and boundary conditions (EC 2013b; Lindenschmidt 2017). The boundary conditions include upstream discharge (Q), downstream water level elevation (W), location of the ice-jam toe (x), and volume of inflowing ice (V_{ice}). Key parameters include porosity and thickness of rubble pans (PS and ST, respectively), porosity and thickness of the ice cover at its front (PC and FT, respectively), thickness of the intact ice cover (h)

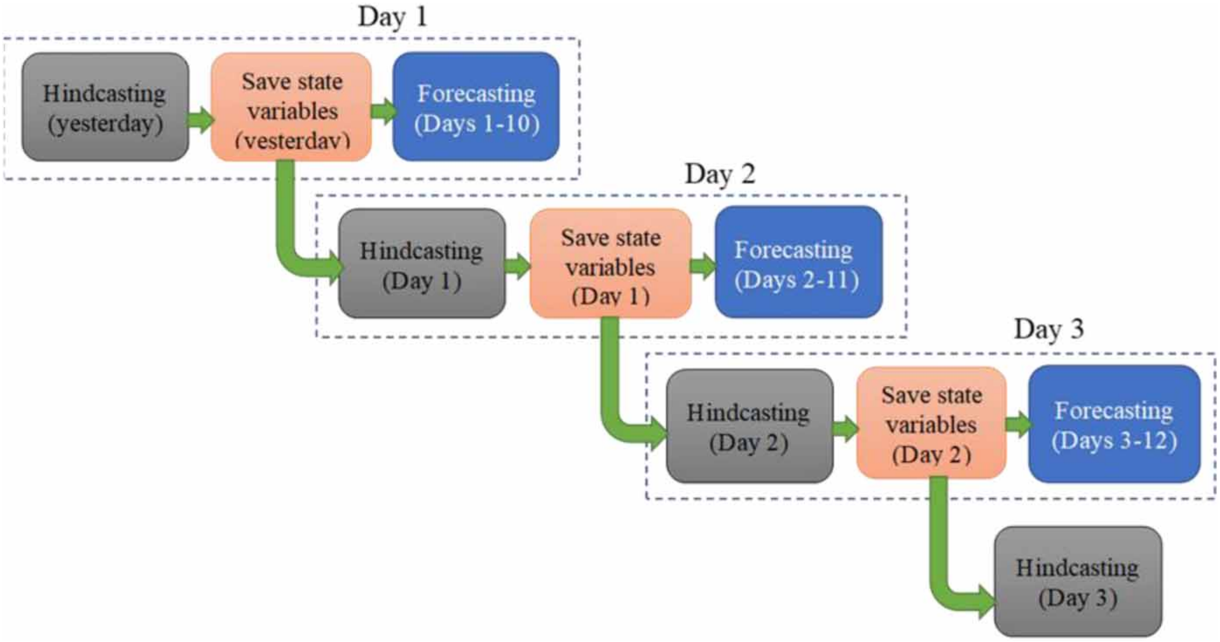

Figure 2 | Schematic view of MESH operational streamflow forecasting setup (adapted from Rokaya *et al.* 2019).

downstream from the ice-jam, depositional and erosional velocity thresholds (v_d and v_e, respectively), ice and river bed roughness (n_{8m} and n_{bed}, respectively), and longitudinal to lateral and longitudinal to vertical stress distributions within the ice-jam cover (*K1TAN* and *K2*, respectively).

Using MOCA, the model was able to simulate hundreds of ice-jam water level scenarios using a range of randomly selected river ice parameters and boundary conditions (Figure 3). The random values of hydraulic and river ice parameters and ice-jam

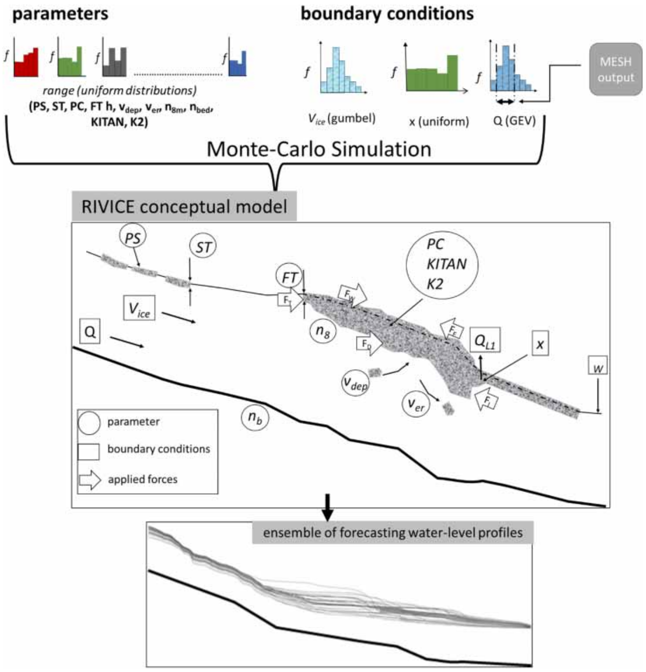

Figure 3 | Stochastic modelling framework for ice-jam backwater level forecasting.

toe locations were selected using a uniform distribution, while extreme value distributions, generalized extreme value (GEV), and gamma were used for obtaining river discharge and cumulative ice volume selections. Figure 3 illustrates the overall stochastic framework of the study. Previous studies and survey results were used to select the maximum and minimum ranges of the parameters' values (EC 2013a, 2013b; Lindenschmidt & Chun, 2013; Lindenschmidt 2017). The toe of the ice-jam location was selected based on the selected river stretch where the impacts of the ice-jam backwater level could be determined. This study selected the toe of ice-jam locations downstream of Edmundston to simulate the ice-jam backwater level impacts at Edmundston.

For the upstream discharge, the GEV distribution of the maximum daily flows at Grand Falls from 1981 to 2020 was used to select the random values (Figure 4). MESH hydrological model outputs (3-day daily forecasts) were then used to constrain the historical GEV distribution (Figure 4). The maximum and minimum range from the 3-day daily forecast were used to select the hundreds of discharge values for the stochastic framework.

The volume of ice, an important boundary condition, was also obtained from the extreme value distribution from the study by Das & Lindenschmidt (2021). This study used stochastic processes to simulate freeze-up conditions along the study reach. From that study, a cumulative distribution was developed to select the total volume of ice that could contribute to an ice-jam for a particular toe location. Based on a toe location, random values of the ice volumes were selected using a gamma distribution (Figure 5). A range of the parameters and boundary conditions values are given in Table 1.

RESULTS AND DISCUSSION

MESH set up and calibration

ECCC's Green Kenue software (EnSim Hydrologic, 2014) was used to prepare the drainage database required for MESH. For this, the Digital Elevation Model (DEM) was retrieved from the hydrologically adjusted elevation of MERIT Hydro database (Yamazaki *et al.* 2019). The landcover and vegetation parameters were retrieved from the Commission for Environmental Cooperation (CEC) North American landcover (30 m resolution) and CLASS manual (Verseghy, 2009), whereas the soil texture information for different soil depths were retrieved from the Unified North American Soil Map (UNASM) (LIU *et al.* 2014). The model was set up with the spatial grid resolution of 0.125° resulting in 373 grid cells and having a drainage area of 41,000 km^2 with the outlet at the Mactaquac Dam station (long./lat.: –66.672, 45.951). Further details on the model setup are available from Budhathoki *et al.* (2022).

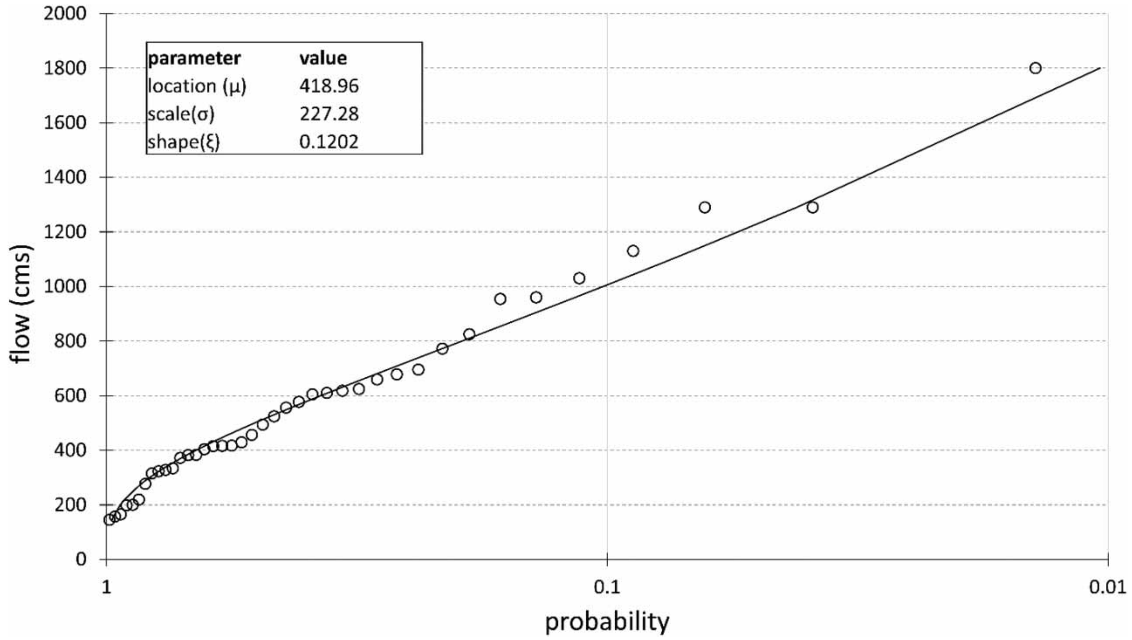

Figure 4 | GEV distribution of the maximum daily flows at Grand Falls from 1981 to 2020.

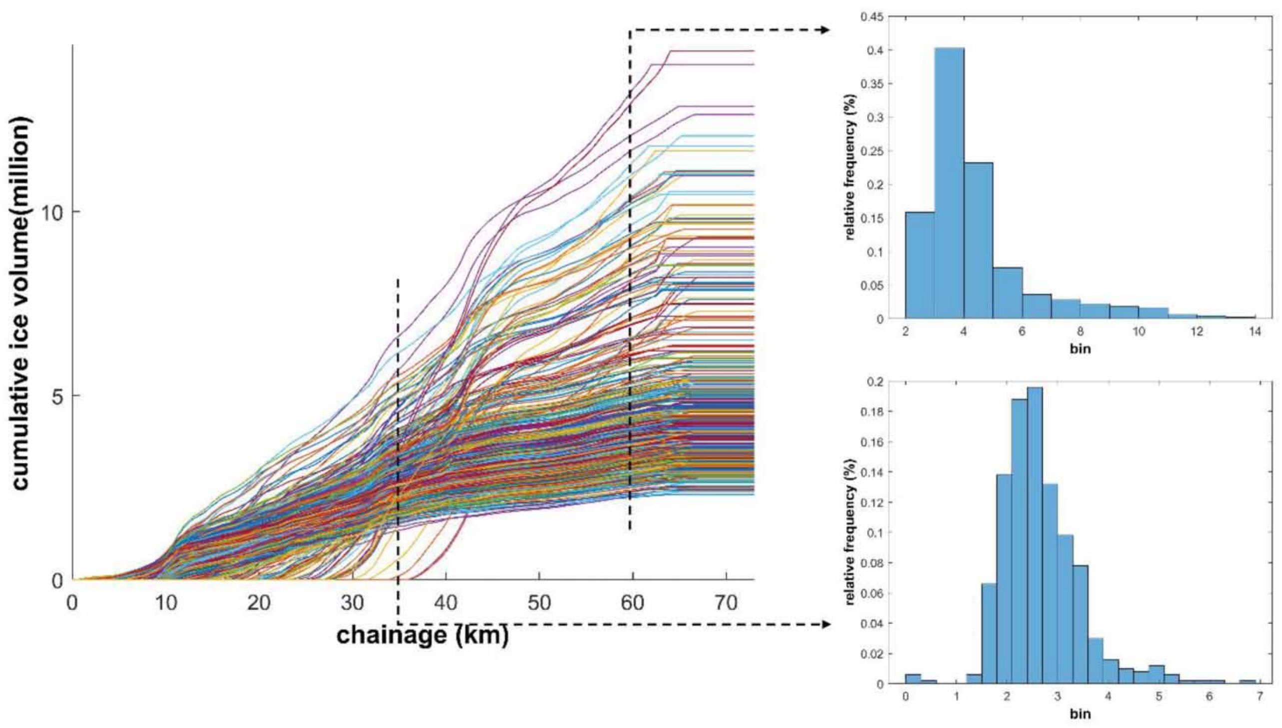

Figure 5 | Cumulative ice volume distribution during freeze-up along the Saint John River from Fort Kent to Grand Falls.

Table 1 | Description of RIVICE parameters and boundary conditions

Inputs	**Description**	**Units**	**Range (maximum–minimum)**
Boundary conditions			
Q	Upstream river discharge	m^3/s	MESH output
Q_L	Lateral flow	m^3/s	MESH output
V_{ice}	Inflowing volume of ice	m^3	Calibration
x	Toe of the ice-jam location	km	50–75
Parameters			
PC	Porosity of ice cover	none	0.4–0.6
FT	Thickness of ice cover	m	0.5–0.7
PS	Porosity of slush pans	none	0.4–0.6
ST	Thickness of slush pans	m	0.4–0.6
v_{dep}	Ice deposition velocity	m/s	1.1–1.3
v_{er}	Ice erosion velocity	m/s	1.7–1.9
n_{bed}	Riverbed roughness	$s/m^{1/3}$	0.028–0.03
n_{8m}	Ice roughness	$s/m^{1/3}$	0.11–0.115
$K1$	Longitudinal-to-lateral force ratio	none	0.14–0.26
$KITAN$	Longitudinal-to-vertical force ratio	none	7.3–7.7
H	Thickness of ice downstream of jam	m	0.48–0.68

OSTRICH (Optimization Software Toolkit for Research Involving Computational Heuristics) (Matott 2005), an open sourced auto-calibration optimization software, was used for model calibration. Ten parameters of six dominant GRU's were calibrated for the period of 2002–2010 (model spin-up from Oct 2002 to Oct 2003) using the Nash–Sutcliffe efficiency (NSE) and its logarithmic value (LogNSE) as objective functions.

Figure 6(a) and 6(b) shows the result of the MESH calibration and validation, respectively, for the gauging station 01AF002 (Saint John River at Grand Falls). The observed and simulated flows are in good agreement with each other. The NSE value of 0.89 and log (NSE) value of 0.84 were achieved for the calibration period, whereas for the validation period, values of NSE and log(NSE) were 0.88 and 0.85, respectively.

Refined MESH calibration for the winter period

In the second step, the calibrated and validated model parameters were further fine-tuned for the winter period, i.e., 2014–2015, 2015–2016, 2016–2017, 2017–2018, and 2018–2019. Only the streamflow data from 1 December to 28 February were input to the model to improve the mid-winter flow simulations. Figure 7 shows the model results compared with the observed mid-winter flows at Grand Falls. The results show that the model can simulate the mid-winter flows well ($\mathrm{NSE} = 0.7$).

RIVICE calibration and validation

The RIVICE hydrodynamic model was calibrated and validated using two winter ice-jams events in 1995 and 1996. Figure 8 illustrates the maps of these winter breakup and ice-jamming events. The information on these maps is acquired from the study by Beltaos *et al.* (2003). In the winter of 1995, the breakup occurred in mid-January. The river from Dickey to Grand Falls was fully covered with solid ice during this time. A series of mild days (air temperatures > 0 °C) and high river flows resulted in ice cover breakup and ice-jamming in several locations along the study area. Field and aerial surveys revealed ice-jamming in three locations – Saint Basile, St. Hillaire, and Allagash. In 1996, two breakup events occurred in

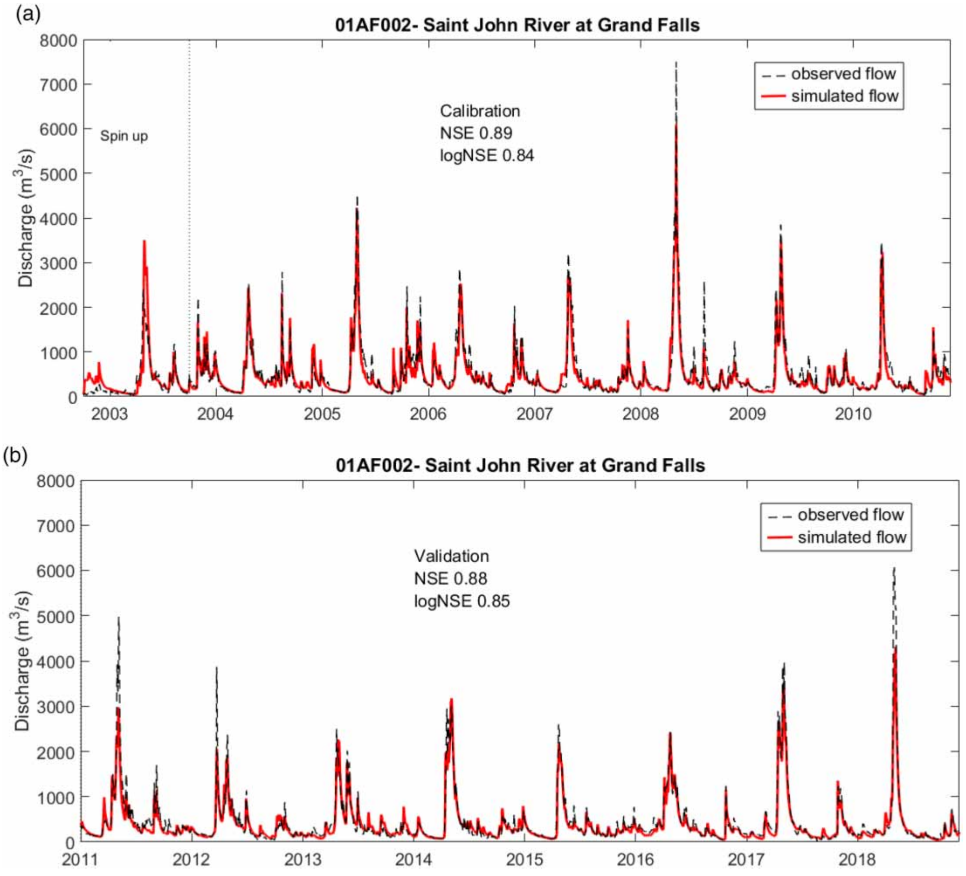

Figure 6 | Observed and simulated flows at Grand Falls for the (a) calibration and (b) validation periods.

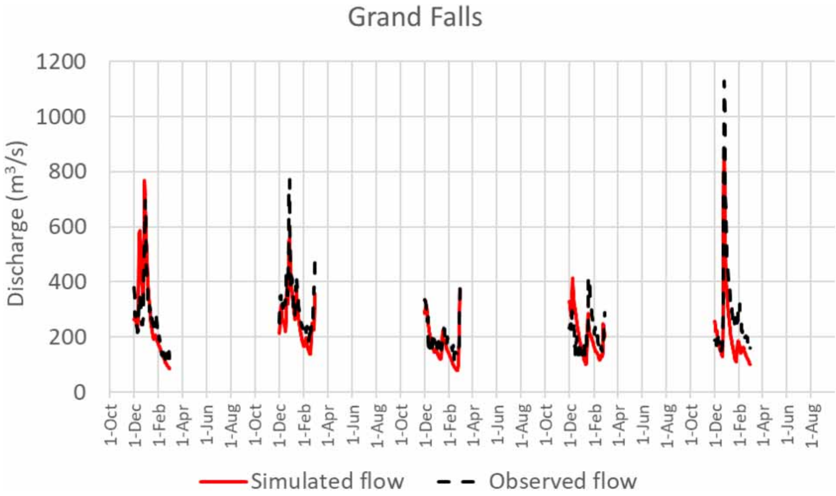

Figure 7 | Observed and simulated mid-winter flows at Grand Falls.

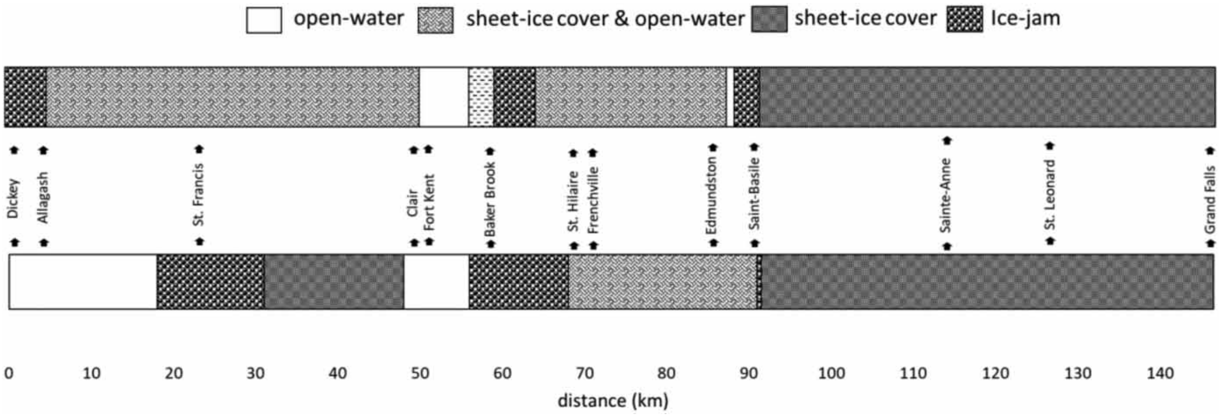

Figure 8 | Winter breakup and ice-jam map along the Saint John River in 1995 (top level) and 1996 (bottom level) (source: Beltaos *et al.* 2003).

January and February. This study only modelled the first breakup event. The breakup and ice-jamming occurred due to mild weather conditions and rainfall, which increased the river discharge significantly. The ice cover broke with ice-jamming at several locations – Saint Basile, St. Hillaire, and St. Francis. For calibration, the 1996 ice-jam that occurred at St. Hillaire was used, while the two jams in 1995 that occurred in Saint Basile and upstream of St. Hillaire were used for validation. Figure 9 shows the model calibration and validation results. The model is calibrated based on ice-jam length and backwater level elevation at Fort Kent and Edmundston. The results show the model successfully captured the ice-jam length and water level elevation.

Freeze-up and winter breakup in 2018

The progress of freeze-up in 2018 was captured using Sentinel-1 imagery from 1 November to 30 December (Figure 10). The freeze-up started mid-November when air temperatures were consistently below 0 °C. By 19 November, solid ice cover formations were observed at Sainte-Anne and downstream of the Fort Kent gauge station (Figure 10). There was an open water section from Edmundston to just upstream of Fort Kent. The ice cover in both locations progressed upstream due to consistent cold weather conditions (air temperatures below 0 °C). By mid-December, the ice cover at Sainte-Anne progressed to Fort Kent, while the ice cover downstream of Fort Kent had advanced to Dickey (Figure 10).

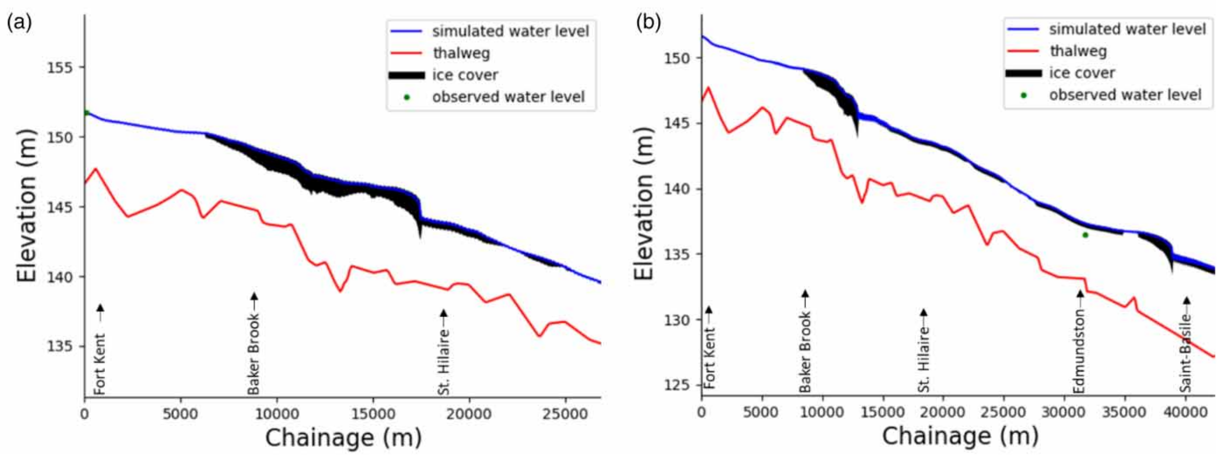

Figure 9 | The calibration and validation of the RIVICE hydraulic model using the winter ice-jam event at St. Hilaire in January 1996 (a) and ice-jam at Baker Brook and Saint Basile in January 1995 (b), respectively.

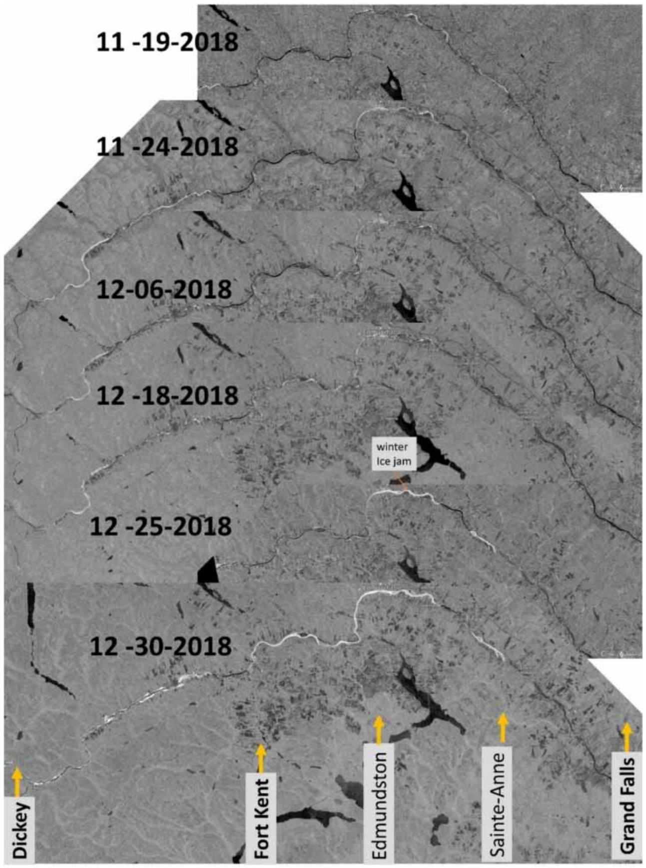

Figure 10 | Ice cover progress observation using Sentinel-1 imagery.

On 25 December, as a result of mild air temperatures and rainfall, river discharge significantly increased. The river flows were recorded to the season maximum of 202.1 and 1,100 m^3/s at the Fort Kent and Grand Falls gauge stations, respectively (Figure 11). A breakup ice-jamming occurred downstream of Edmundston, and a large volume of ice from upstream was juxtaposed to form a long ice-jam. The maximum water level was recorded to be 141.233 m a.s.l above the flood level at the Edmunston gauge station.

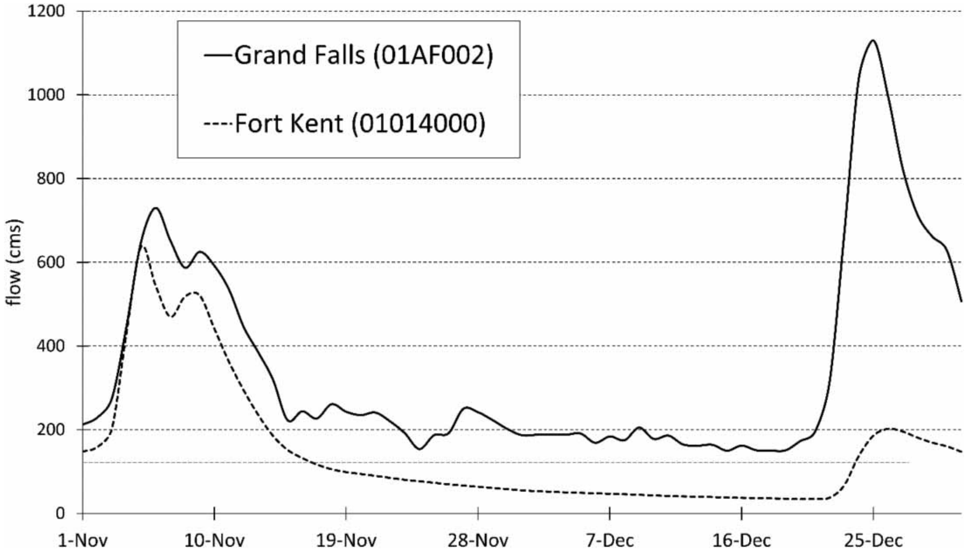

Figure 11 | Streamflow conditions at Fort Kent and Grand Falls during freeze-up in 2018.

Real-time forecasting for 2018 winter breakup

Figure 12 shows the 10-day streamflow forecasts at the Grand Falls station for the mid-winter period of 2018. MESH was able to forecast the timing of the mid-winter rise in the flows with some underestimation in the magnitudes of the maximum flow. The forecasted mid-winter flows from these events are used as a boundary condition for river ice-jam forecasting.

The stochastic modelling framework generates hundreds of ice-jam scenarios for the next 3 days using the set of randomly selected parameters and boundary conditions. The forecasting simulation for the case study started on 22 December and the winter breakup and jam occurred on 25 December. A stochastic modelling outcome for 24 December is illustrated in Figure 13. The result shows that it was able to capture the maximum water level that occurred on 25 December due to winter ice-jam formation. The stochastic approach is able to simulate maximum water level between 50th and 95th percentile. Overall, forecasting results are shown in Figure 14. At the beginning of the forecasting, the stochastic outcome overestimated

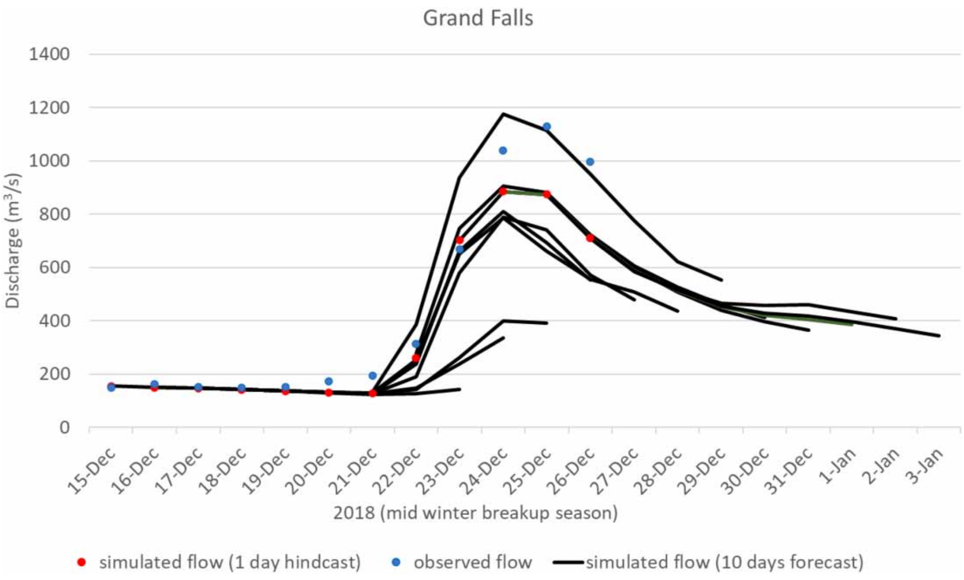

Figure 12 | Flow forecast at Grand Falls (01AF002) for the mid-winter breakup event in 2018.

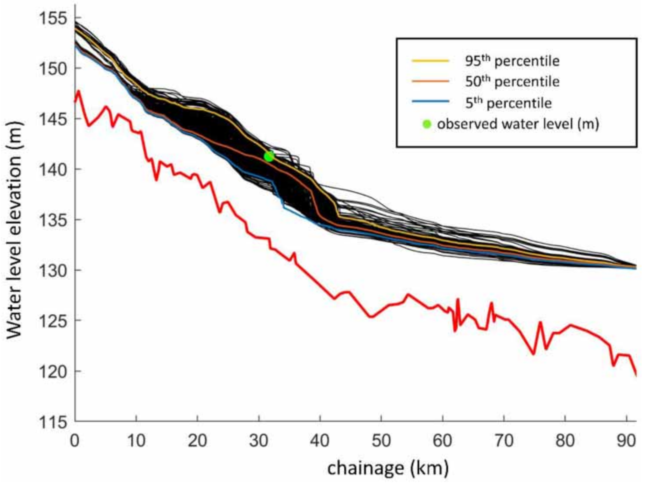

Figure 13 | The ensemble of backwater level profiles from the stochastic model framework.

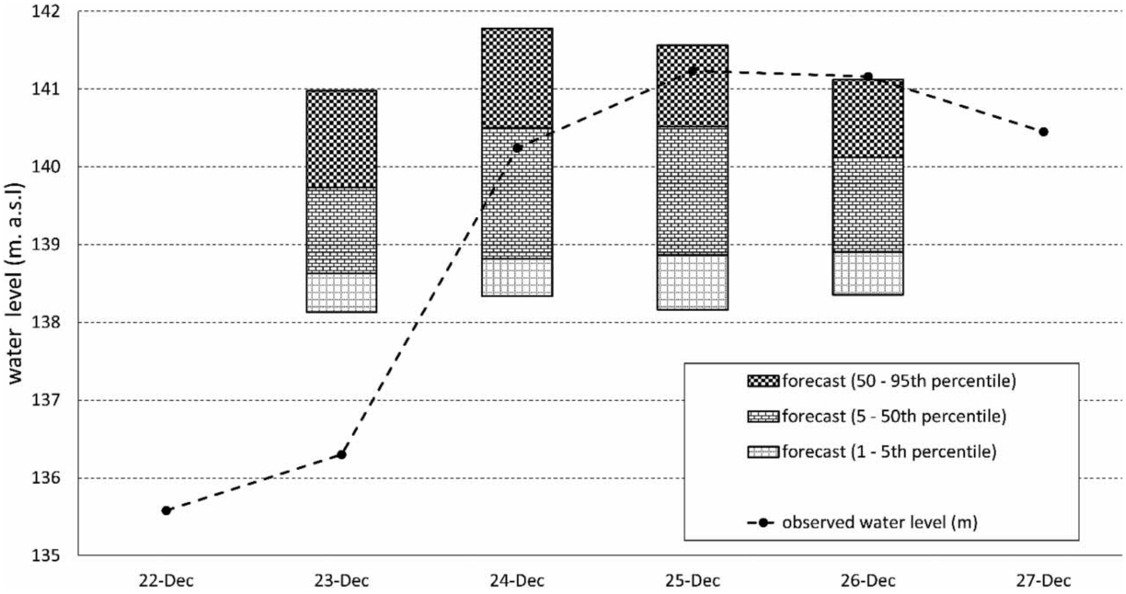

Figure 14 | The performance of the forecasting model for the winter breakup in 2018.

the water level because no breakup and jamming occurred between 23 and 24 December along the study reach. On 25 December, jamming occurred and produced a maximum backwater level elevation at the Edmundston gauge station.

Uncertainty in the modelling framework

The modelling framework still requires many assumptions and is based on historical observation data, which may create some uncertainty in the results. For example, the locations of the ice-jam toe locations may not always be in the right stretch; therefore, it may create some level of overestimation or underestimation in the results. To overcome this limitation, real-time monitoring data or field observation can be used to select the probable toe location during freeze-up. Moreover, the study only simulates ice-jam scenarios; therefore, the framework can only produce accurate water level elevation when there is an ice-jam along the river. The ice volume was used from the simulation results; however, more robust study and field data are required to estimate the total volume of ice cover for a freeze-up or winter periods. Furthermore, the hydrological model did not consider the ice processes along the river; therefore, there is some uncertainty in the forecasting flow results.

SUMMARY AND CONCLUSION

In this study, a first attempt was carried out to develop a framework to forecast ice-jam flooding along the Saint John River. The stochastic modelling framework was developed to forecast the severity of mid-winter breakup along the Saint John River. The study combines the hydrological and hydraulic models and multi-sources of data such as satellite, gauge, and historical studies to develop the stochastic framework. The MESH hydrological model provides the forecasted flows, and river ice modelling results provide another important boundary condition, the volume of ice cover. Overall modelling results were applied to a real case study or mid-winter breakup in December 2018. The framework was successfully able to model the ice-jam scenarios and backwater level elevation along the river.

This stochastic modelling framework can be used to forecast mid-winter breakup severity in an operational context. This can help to make appropriate management decisions and emergency measures before the breakup. The stochastic outcomes allow the assessment of hundreds of probable scenarios that could be used in decision-making during emergency situations. The percentile results from these hundreds of forecasts could be used to determine the level of ice-jam flood risk for the study area. For example, if most of the simulated water level profiles between 50th and 95th percentile exceed the historical flood water level elevation, it could be marked as a high risk/emergency. While the 50th percentile water level profile is below the historic flood level, it can be indicated as a low-risk situation. However, further studies are required to make the framework more robust in changing climate. To do this, real-time time freeze-up observation and hydrological forecasting model for each river basin are needed to obtain the forecasting modelling data.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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