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A Stochastic Modelling Approach to Forecast Real-time Ice Jam Flood Severity Along the Transborder (New Brunswick/Maine) Saint John River of North America

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Abstract

Ice jam floods (IJF) are a major concern for many riverine communities, government and non-government authorities and companies in the higher latitudes of the northern hemisphere. Ice jam related flooding can result in millions of dollars of property damages, loss of human life and adverse impacts on ecology. Ice jam flood forecasting is challenging as its formation mechanism is chaotic and depends on numerous unpredictable hydraulic and river ice factors. In this study, Modélisation environnementale communautaire – surface hydrology (MESH), a semi-distributed physically-based land-surface hydrological modelling system was used to acquire a 10-day flow forecast, an important boundary condition for any modelling of river ice-jam flood forecasting. A stochastic modelling approach was then applied to simulate hundreds of possible ice-jam scenarios using the hydrodynamic river ice model RIVICE within a Monte-Carlo Analysis (MOCA) framework for the Saint John River from Fort Kent to Grand Falls. First, a 10-day outlook was simulated to provide insight on the severity of ice jam flooding during spring breakup. Then, 3-day forecasts were modelled to provide longitudinal profiles of exceedance probabilities of ice jam flood staging along the river during the ice-cover breakup. Overall, results show that the stochastic approach performed well to estimate maximum probable ice-jam backwater level elevations for the spring 2021 breakup season.

1. Introduction

Ice jam related floods are a key concern for many riverside communities during freeze-up and spring breakup in Canada. Ice jam floods can be more devastating than open-water floods, as their occurrence can be extremely rapid and suddenly, allowing very little time to implement an emergency measure. Ice related floods can cause millions of dollars of property and businesses losses, damaging homes and infrastructure, death of human life and various detrimental impacts on the aquatic environment (e.g. fish mortality).

The Saint John River is one of the ice-jam prone rivers in Canada. The majority of flood damages in the province occur due to ice-jam flooding within the Saint John River basin (Humes and Dublin, 1988). Some studies indicate that the severity of the flooding would continue to rise due to climate change (Beltaos, 2002, 2004). Flow forecasting is carried out by the Hydrology Centre at the Environment Department of the New Brunswick Government using a hydrological model. However, the model is based on an open-water case and cannot consider the ice effects on the river staging. Therefore, this forecasting cannot reflect the actual severity of flooding, as ice jams can significantly increase river stages above those during open-water floods. To reduce this limitation, Beltaos et al. (2012) attempted to forecast ice-jam water levels along the Saint John River from Dickey to Grand Falls using the HEC-RAS model in steady-state mode in an operational context. The results show that the calibrated model could simulate probable ice jam scenarios and associated flooding severity. However, this type of forecasting greatly depends on real-time data availability and a clear understanding of the dynamic behaviour of ice cover during spring breakup. Moreover, there is still no publicly available model that could predict the timing and locations of ice jam formation.

In recent years, a stochastic modelling approach has been applied to several Canadian rivers (e.g. Athabasca, Peace and Red rivers) to predict ice jam water elevations (Lindenschmidt et al., 2019; Rokaya et al., 2019; Williams et al., 2021). In this approach, many probable scenarios of ice jams are simulated using a set of randomly selected variables to predict the potential severity of flooding (Lindenschmidt, 2020; Das, 2021). One of the advantages of this approach is it can provide a range of maximum and minimum values to select modelling parameters instead of a specific or single parameter value. Therefore, different distributions of modelling parameters and boundary conditions can be used to simulate hundreds of probable ice jam scenarios. For example, as the location of ice jams are difficult to predict during spring breakup, a range of ice jam locations can be used as model input. Lindenschmidt et al. (2019) applied this approach in an operational flood forecasting context to predict maximum probable ice jam water level elevations along the Athabasca River at Fort McMurray, Canada.

The main purpose of this study is to develop a stochastic modelling framework for an operational real-time ice-jam flood forecasting system along the Saint John River, Canada. The specific objectives are i) to provide an ice-jam flood outlook for spring ice-cover breakup and ii) to forecast probable maximum ice-jam backwater level elevations.

2. Methodology

2.1 Study Area

The hydrological model setup to simulate flows along the Saint John River extends across the Saint John River Basin. This basin is situated in northeastern North America (Fig. 1), covering more than 55,000 km^2 across the United States and Canada. While a major portion of the basin is located in Canada (51% and 13% in the provinces of New Brunswick and Quebec, respectively), the remaining portion (36%) is situated in the State of Maine, USA (Kidd et al., 2011). The Saint John River is more than 700 km long, flows from northern Maine, USA to western New Brunswick, Canada, before draining into the Bay of Fundy at Saint John, Canada. The total elevation drop of the river is about 480 m (Beltaos et al., 2012).

The Saint John River basin has mixed humid continental and maritime climates (Kidd, Curry and Munkittrick, 2011). The average annual precipitation is measured to be 1100 mm, in which 30% is snowfall (Beltaos et al., 2012). The mean annual discharge is approximately 1100 m^3/s with a peak flow condition in later spring. The soil type in the basin is dominated by “forest soil” - humo-ferric podzols and gray luvisols. The land cover mostly consists of forests (70%), with some patches of cropland (6%) and wetlands (6%). There are three large hydroelectric reservoirs in the basin, impounded by the Grand Falls, Beechwood and Mactaquac dams. Since there is currently no active hydrometric station in the main river channel downstream of Fredericton hence the outlet station for the hydrological model of the basin was taken to be at the Mactaquac Dam, which reduces the hydrological model domain area to 41,000 km^2.

The hydraulic model domain extends from Fort Kent to Grand Falls, an approximate 94 km long river reach. This portion of the river is prone to ice jam formation during spring breakup due to its geomorphological settings. The reach from Fort Kent to Edmundston is relatively steep with a series of rapids. The strech from Edmundston to Grand Falls has a relatively milder slope, shallow riverbed, and many islands and sandbars that splits the main river channels into multiple sub-channels.

Some hydraulic gauge stations record daily river flows and water levels along the study site. The United States Geological Survey (USGS) operates the gauging stations at Dickey and Fort Kent, ECCC’s Water Survey of Canada operate the gauge at Edmundston and New Brunswick Power own the gauge at Grand Falls. The hydrological model is calibrated and validated using streamflow records from Dickey and Grand Falls. Since the hydraulic model was calibrated and validated using the water levels recorded at the Edmundston gauge station and the model simulates ice jam backwater level profiles, the model framework was developed to forecast the severity of ice jams downstream of Edmundston.

2.2 MESH hydrological model

MESH is a physically-based hydrological land-surface model from Environment and Climate Change Canada (ECCC) (Pietroniro et al., 2007) and has been widely used in different parts of Canada, from small to large catchments (Mengistu & Spence, 2016; Haghnegahdar et al., 2017; Yassin et al., 2017; Lindenschmidt et al., 2019; Budhathoki et al., 2020; Rokaya et al., 2020). MESH uses a grouped response unit (GRU) approach to capture basin heterogeneity. It has a grid-based modelling system which is composed of three major components (i) a vertical exchange of water within a grid cell between the land surface and the atmosphere (ii) the routing of lateral fluxes and (iii) the generation of surface and sub-surface runoff. MESH uses the Canadian Land Surface Scheme (CLASS) (Verseghy, 1991) for the vertical generation and exchange of lateral fluxes. WATROF (Soulis et al., 2000) and PDMROF (Mekonnen et al., 2014) are the two scheme used to account for lateral fluxes. The routing of surface and subsurface runoff is performed using WATROUTE (Kouwen, 2016).

2.3 Meteorological Input for MESH

MESH requires seven meteorological forcing inputs: precipitation, wind speed, air temperature, specific humidity, incoming longwave radiation, barometric pressure and incoming shortwave radiation. For model calibration and validation, all inputs except precipitation were taken from combined gridded datasets of Global Environmental Multiscale (GEM) model (Côté et al., 1998; Yeh et al., 2002) which is available at an hourly temporal resolution and at the spatial resolution of 15 km. The precipitation inputs were taken from the Canadian Precipitation Analysis (CaPA) (Mahfouf et al., 2007) datasets which are available at 6 hour time intervals at a spatial resolution of 10 km. CaPA is found to be a reliable precipitation product for the Canadian domain (Boluwade et al., 2018).

For streamflow forecasting, all the meteorological forcing data were retrieved from Global Deterministic Prediction System (GDPS). GDPS is an operational forecasting system, based on the GEM model from ECCC which provides deterministic predictions of atmospheric variables with a 10-day lead time (Bélair et al., 2009; Charron et al., 2012). The forecasts are produced two times a day (00 UTC and 12 UTC) at 3-hourly temporal resolution and has an approximate 25 km spatial resolution.

2.4 MESH set up and calibration

“The topographic data for SJRB were obtained from the hydrologically adjusted elevation of MERIT Hydro which is at a resolution of 3 arc-second resolution (~ 90 m at the equator) (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/) (Yamazaki et al., 2019).The landcover data were derived from the Commission for Environmental Cooperation (CEC) land cover database in 30 m resolution (http://www.cec.org/north-american-environmental-atlas/land-cover-2010-landsat-30m/). The vegetation parameters were obtained from literature (Kidd et al., 2011) and the CLASS manual (Verseghy, 2009) and the soil texture information was obtained from the Unified North American Soil Map (UNASM) (LIU et al., 2014) for different soil depths.” (Budhathoki et al., submitted). Six vertical soil profile layers of 10 cm, 35 cm, 120 cm, 260 cm, 310 cm and 410 cm were defined from the surface boundary in MESH. The model was built with a grid resolution of 0.125 deg. (approx. 10 km), resulting in 373 grid cells. Nine GRUs were created based on the landcover variability in the basin. The preprocessing of the spatial data was conducted using ECCC’s Green Kenue software (EnSim Hydrologic, 2014) to generate drainage networks and other topographically driven basin characteristics such as slope and channel length. The discharge data were retrieved from ECCC’s database HYDAT and the reservoir inflows and outflows were retrieved from the New Brunswick Power company.

The calibration was performed using parallel DDS algorithm in OSTRICH (Matott, 2005) with the Nash Sutcliffe Efficiency (NSE) as the objective function. The sensitive parameters were selected based on Haghnegahdar et al. (2017) and ten parameters of six dominant GRU's were calibrated. The model was calibrated for the period 2002–2010 considering the first year (Oct 2002 - Oct 2003) as the model spin-up period. The validation was then performed using the subsequent six years (2011–2018).

2.5 Streamflow Forecast

Forecasting the basin's streamflow involves a two-step process, first running the MESH model in hindcast mode, which saves the state variables until the previous day (yesterday) of the forecast period and then performing the flow forecast for the next 10 days (from today) with the saved state variables. It is important to save and update the basin state variables and hydrologic conditions everyday so that the initial hydrologic conditions for running the model are always accurate. Figure 2 shows the schematic view of the MESH operational forecasting setup for the SJRB.

In the hindcasting mode, the forcing data for precipitation were obtained from CaPA and other meteorological forcing data were retrieved from the GEM system. In the forecasting mode, all the meteorological forcing data were retrieved from the GDPS system. 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.

2.6 RIVICE hydraulic model

RIVICE is a one-dimensional hydrodynamic model that simulates various river ice phenomena, including the formations of frazil ice, border ice, solid ice covers and ice jams. RIVICE solves the Saint Venant equations for transient flows and water levels using an implicit finite difference scheme. A user usually calibrates the time steps and appropriate lengths of the simulation based on specific sites and purposes. Surveyed cross-sections are the primary inputs to set up the model structure along a river. Moreover, the model requires various hydraulic and river ice parameters and boundary condition inputs to simulate these processes. A conceptual diagram of ice jam simulations and their require variables is shown in Fig. 3. Some of these parameters and boundary conditions are user-defined or calibrated based on historical events along the model domain. Table I briefly describes all of the parameters and boundary conditions. For further details about the RIVICE the reader may refer to the online manual (http://giws.usask.ca/rivice/Manual/RIVICE_Manual_2013-01-11.pdf) and to Lindenschmidt (2017).

Table I Description of RIVICE parameters and boundary conditions

Inputs	Description	Units
Boundary Conditions		
Q	Upstream river discharge	m^3/s
W	Downstream water level	m a.s.l
V_{ice}	Inflowing volume of ice	m^3
x	Toe of the ice-jam location	none
Parameters		
PC	Porosity of ice-cover	none
FT	Thickness of ice-cover	m
PS	Porosity of slush pans	none
ST	Thickness of slush pans	m
v_{dep}	ice deposition velocity	m/s
v_{er}	ice erosion velocity	m/s
n_{bed}	Riverbed roughness	s/m$^{1/3}$
n_{8m}	ice roughness	s/m$^{1/3}$
K1	Longitudinal to lateral force ratio	none
K2	longitudinal to vertical force ratio	none
h	Thickness of ice downstream of jam	m

2.7 Stochastic framework for forecasting

In the stochastic framework (Fig. 4), the RIVICE hydrodynamic model is placed within a Monte-Carlo Analysis (MOCA) framework to simulate hundreds of ice jam scenarios using randomly selected sets of parameters and boundary conditions. To select random values of the parameters and boundary conditions, minimum and maximum values of the inputs were extracted from gauge records and the calibration data of previous studies along the model domain. While the uniform distribution of most of the parameters and toe of ice jam location are used to select the random values for the MOCA, an extreme value distribution (Gumbel) was implemented for two important boundary conditions – river discharge and the inflowing volume of ice.

An extreme value distribution was developed for river discharge using observed flows recorded at the Fort Kent gauging station during spring breakup. The location and scale parameters of the distribution were then used to select the random values from the maximum and minimum range of forecasted flows. The 3-day probable streamflow data from the MESH hydrological model was used to select the maximum and minimum range of the flows. The lateral flow inputs from various major tributaries along the model domain were also estimated by establishing linear relationships between the Fort Kent discharge and tributary flows.

The observed flow frequency distribution during spring breakup was used as an input in the MOCA framework. The volume-of-ice frequency distribution was then calibrated by comparing (i) the frequency distribution of the ensemble of stages simulated at Edmundston and (ii) the frequency distribution of the water level elevations recorded at the Edmundston gauge during ice-jam events. If the two distributions did not coincide, the volume-of-ice frequency distribution was adjusted and the MOCA repeated to yield a new “simulated” frequency distribution of stages at Edmundston for comparison, again, with the “observed” frequency distribution of the water level elevations recorded at Edmundston. The process is repeated until the “simulated” and “observed” frequency distributions of the volume of ice consistently coincided. A more detailed description of this process can be obtained from Lindenschmidt (2020; p. 181–183).

Once all the parameters and boundary conditions distributions were established, the framework was used to produce a seasonal outlook (before the breakup initiation along the model domain) of the severity of ice jam from 22 March 2021. The 3-day forecasting simulation began on 24 March 2021. Additional information was updated using the New Brunswick government’s daily interactive map of ice observation, especially important to track the toe of ice jam location.

3. Result And Discussion

3.1 MESH calibration and validation

The results of the MESH calibration and validation for the gauging station 01AF002 (Saint John River at Grand Falls) is shown in Fig. 5. 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 = 0.88 and log(NSE) = 0.85 were obtained.

3.2 MESH 10-day flow forecasts

10-day flow forecasts were simulated using MESH. Figure 6 shows the flow forecast at the Fort Kent station during the spring of 2021. MESH was able to forecast the timing of the rise in the flows with a Pbias of + 15 % (based on the average of a seven-day daily forecast). The forecasted flow data from these events are used as an important boundary condition to assist parallel ice-jam forecasting.

3.4 RIVICE calibration and validation

The RIVICE model is calibrated and validated using historical ice jam events in 1991 and 2008 along the Saint John River. Observed water level and related data of these events were obtained from the study by Beltaos et al. (2012). First hydraulic and river ice parameters were calibrated until good agreement was obtained between simulated and observed water level profiles. Figure 7 (left panel) shows the RIVICE calibration result for the ice jam event of 1991 that occurred upstream of St. Leonard. To validate the model, the same calibration data were used to simulate the ice jam that occurred in 2009. Figure 7 (right panel) shows a good agreement between observed and simulated water levels of the 2009 ice jam event.

3.5 Ice cover breakup in spring 2021

Spring ice cover breakup in 2021 was triggered by consistent warm air temperatures (above 0ºC) from 20 to 25 March 2021. During this period, river discharge increased significantly from 124 to 1241 m^3/s due to rapid snowmelt (Fig. 8). By 24 March 2021, ice covers began to crack and melt out forming open-water leads in the ice cover. On 25 March 2021, a long open-water section with intermittent fragmented ice was observed from downstream of Frenchville to Grand Isle. The ice cover from Fort Kent to Edmundston completely broke up with ice moving downstream of Edmundston by 26 March 2021. On 27 March 2021, an ice jam formed immediately upstream of Sainte-Anne-de-Madawaska, which extended upstream for more than 20 km by 28 March 2021. On this day, the water level elevation at Edmundston gauge station increased to the season maximum of 138.126 m a.s.l.

3.6 Ice jam flood outlook for spring 2021

The main goal of the ice jam flood outlook is to provide a preliminary forecast for the breakup period. Since MESH usually simulates 10-day flow forecasts, the outlook results present the potential maximum ice-jam water level profiles for the next 10 days. Figure 9 shows the ice-jam flood outlook from 22 to 31 March 2021. The outlook predicted the maximum water level elevation due to ice jam formation to be lower than the flood level (140.5 m a.s.l according to the New Brunswick Government river watch website). The comparison between observed water level and simulated water level profiles shows that the simulated outlook (90th percentile) was fairly accurate to predict maximum water level elevations.

3.7 Ice jam flood forecasting during spring 2021

The 3-day ice jam flood forecasts began on 24 March 2021. Each day a total of 250 ice jam scenarios were simulated in the stochastic modelling framework to predict the severity of ice jam flooding along the study site. Figure 10 shows the forecasting results from 24 to 27 March 2021, indicating the 10th, 50th, and 90th percentiles of the ice jam water level profiles. As the ice cover was still intact on 24 March, the simulations slightly overestimated the water level elevations along the river. The forecasting results started to improve when the ice cover broke up from 25 to 27 March 2021. The ice jam flood forecast from 27 March 2021compares well with the observed water level elevations at the Edmundston gauge. The results show that the mean and maximum observed water level elevations at Edmundston were within the 50th and 90th percentiles of the forecasted water level profiles. Overall, the 3-day flood forecasting was effective to estimate the backwater level conditions during breakup.

4. Potential Sources Of Error

Although the stochastic approach for ice jam flood forecasting provides a reasonable outcome to predict the severity of flooding, there are still some limitations and uncertainties associated with the assumptions and parameter selection.

- the volume of inflowing ice has been calibrated and selected as an independent parameter, which may not always be the case, as this variable depends on streamflow conditions. For example, low spring flow conditions may result in thermal breakup and significant ice melt, leading to relatively small ice volumes to form ice jams. The opposite is true for the high spring flows, however in this stochastic approach the model simulation can be incorporated with high flows with low volumes to mimic under-developed ice jams. Moreover, these uncertainties can also be associated with the errors in the selected parameter distributions.

- the toe of the ice-jam location is not always uniformly distributed along the river and there are some preferred ice-lodgment sites. Although the study was used observed ice breakup and potential ice jam toe locations, there are still some discrepancies between forecasting setup and observed information. Hence the incorrect selection of toe location range can create an additional error in the forecasting results.

- tribuatary inflows in the model domain were considered as a mean flow, which may not reflect the actual river flow condition. Since the hydrological model forecasting setup only provides the upstream flow conditions of the main model domain, providing tributary flows dynamically would not decrease the overall error.

- the study considered the peak breakup water level due to ice-jam formation along the river stretch downstream of Edmundston; therefore the results were only validated using the observed water level recorded at the Edmundston gauge station. Therefore, there are maybe some biases that should be considered to assess the forecasting results.

5. Conclusion

A stochastic modelling framework was developed to forecast the severity of ice jam flooding along the Saint John River from Fort Kent to Grand Falls. The framework loosely coupled a hydrological land-surface model MESH with a hydrodynamic river ice model RIVICE to simulate hundreds of probable ice jam scenarios using a Monte-Carlo analysis.

Within this stochastic framework, an outlook was provided at the beginning of the breakup to assess the 10-day ice jam severity along the study site. This is one of the novelties in the field of ice jam flood forecasting. This outlook may help to provide early warning and extra preparation time to improve mitigation strategies. The 3-day ice jam flood forecasting was also able to simulate maximum water levels more accurately. Overall, the framework can be used in real-time mode for operations ice-jam flood forecasting and mitigation management and planning.

6. Declarations

Ethical Approval

Not Applicable

Consent to Participate

Not Applicable

Consent to Publish

Not Applicable

Authors Contributions

AD carried out all the data analyses and wrote most of the sections of the manuscript. SB provided hydrological model results and wrote some sections of the manuscript. KEL conceptually helped to develop the paper and reviewed the manuscript throughout the process.

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Competing Interests

None

Data Availability Statement

The historical hydrometric and meteorological data are available from Environment and Climate Change Canada and Unites State Geological Survey (USGS). The model simulated data and code are available from the corresponding author upon reasonable request.

Conflict of Interest

None

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Figures

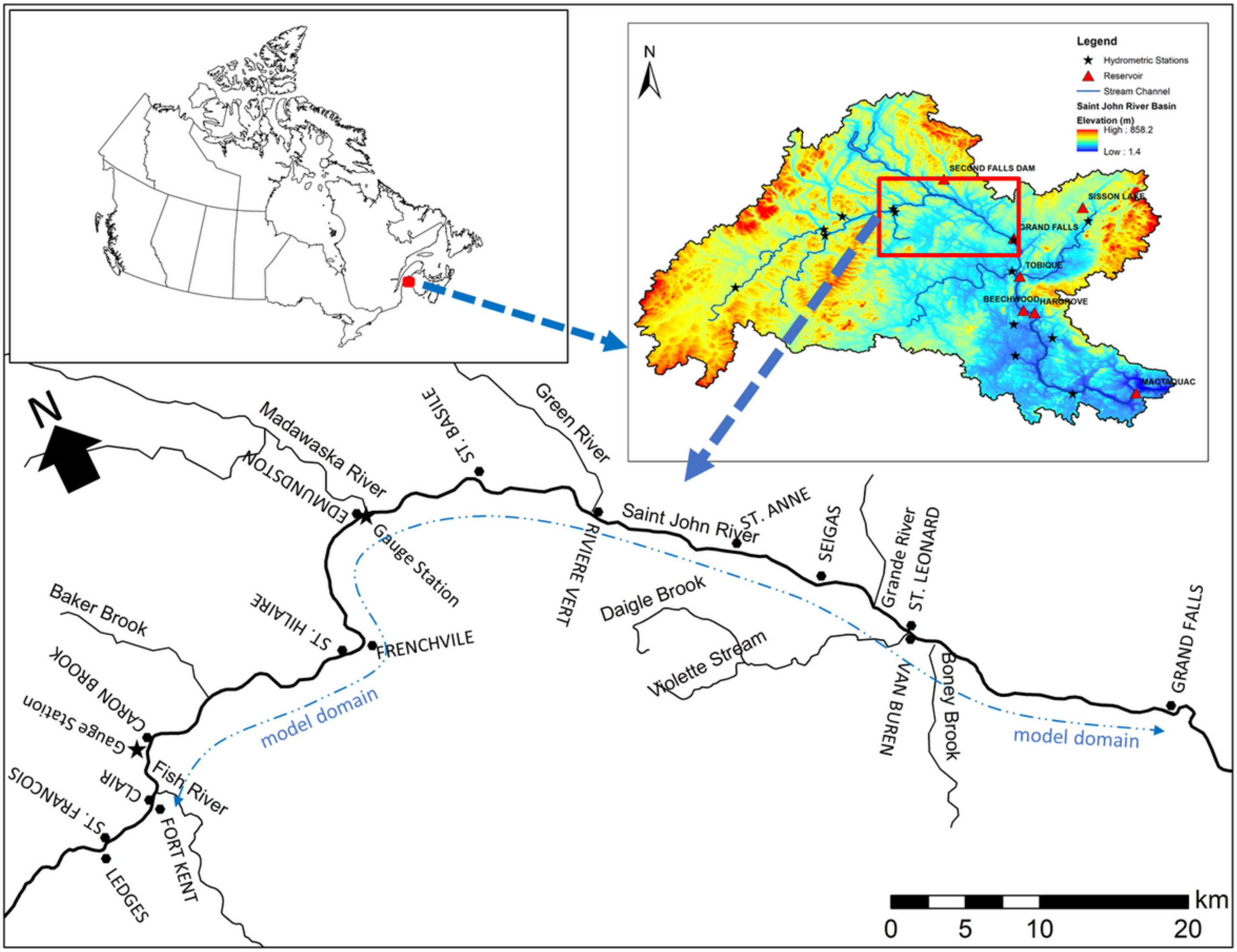

Figure 1

Study site including hydrological and hydraulic model domains of Saint John River and its basin.

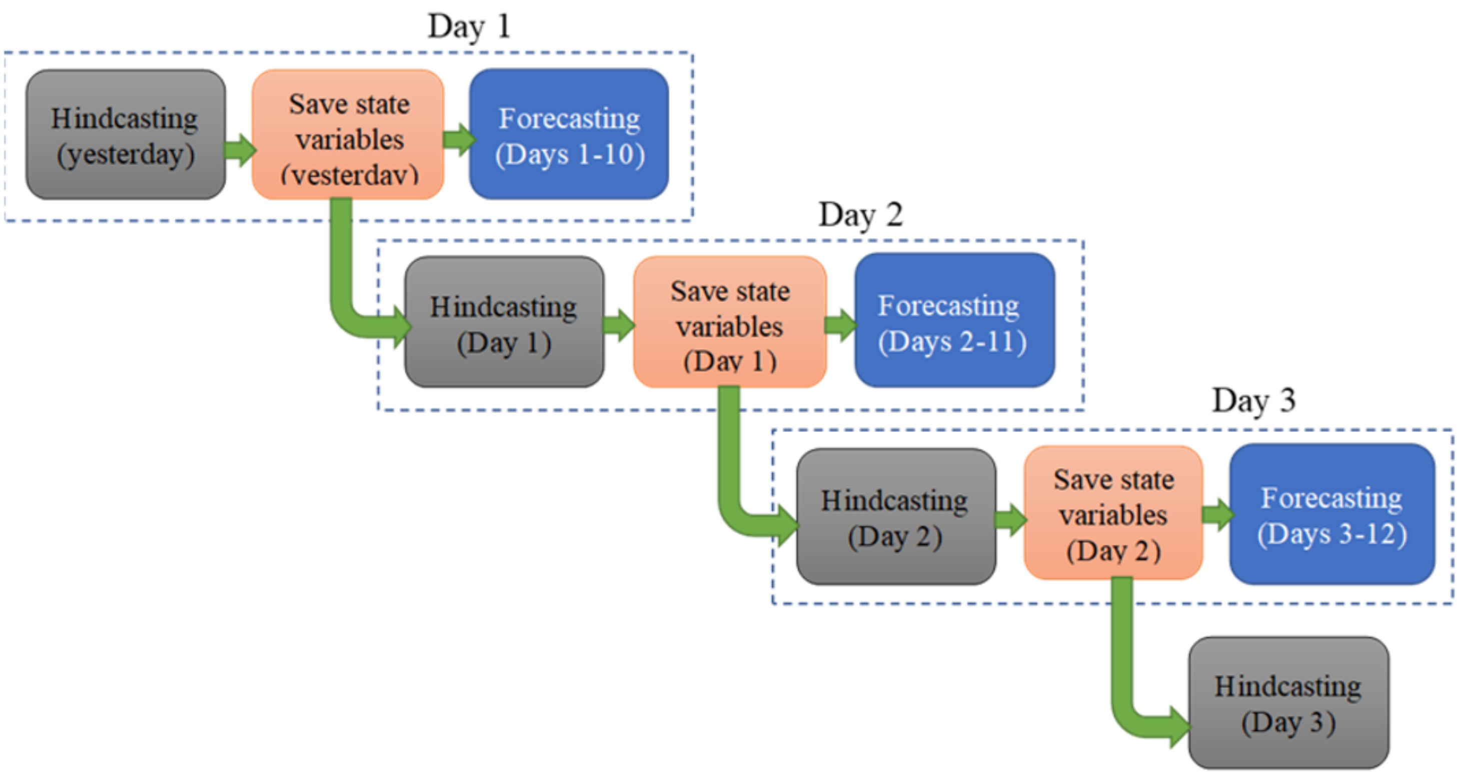

Figure 2

Schematic view of MESH operational streamflow forecasting setup

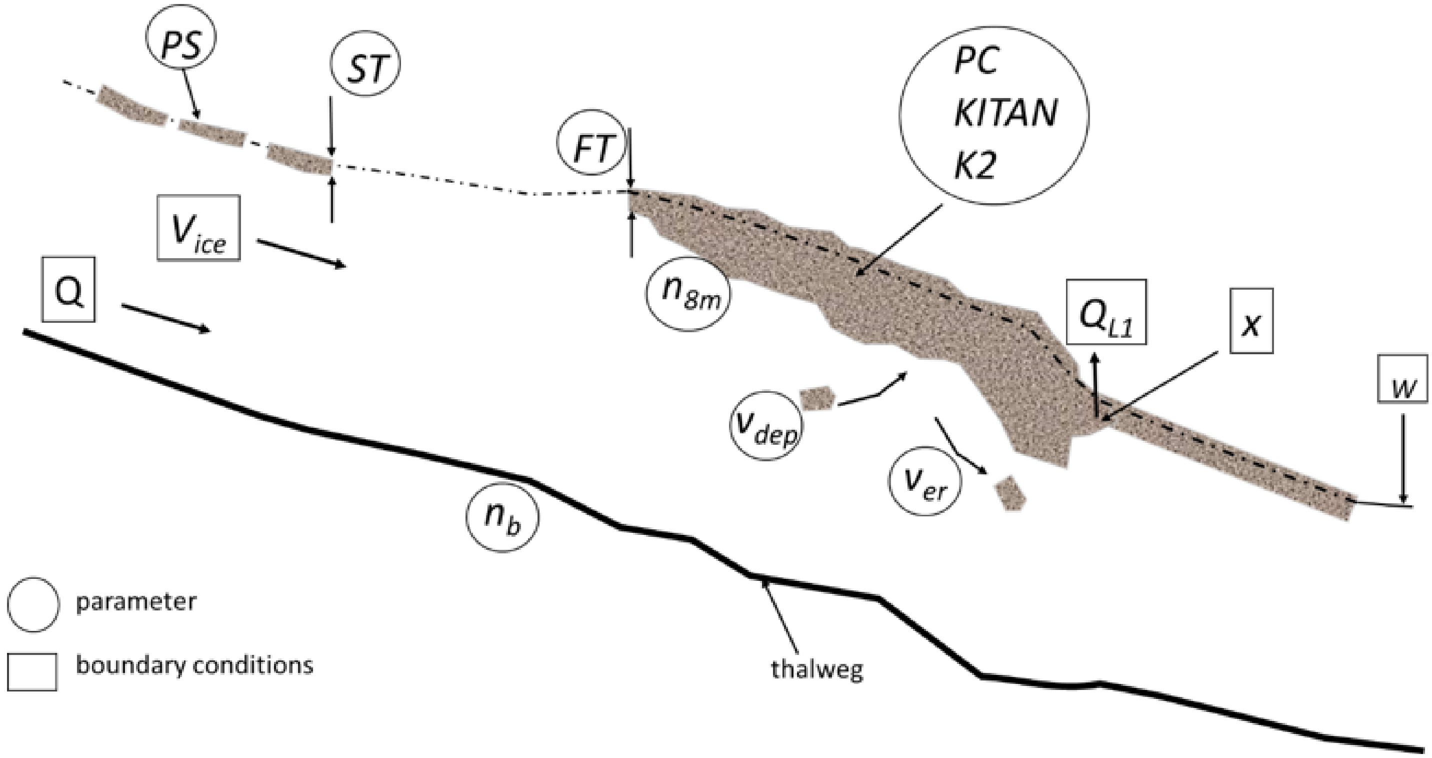

Figure 3

A conceptual diagram of the ice jam modelling using RIVICE.

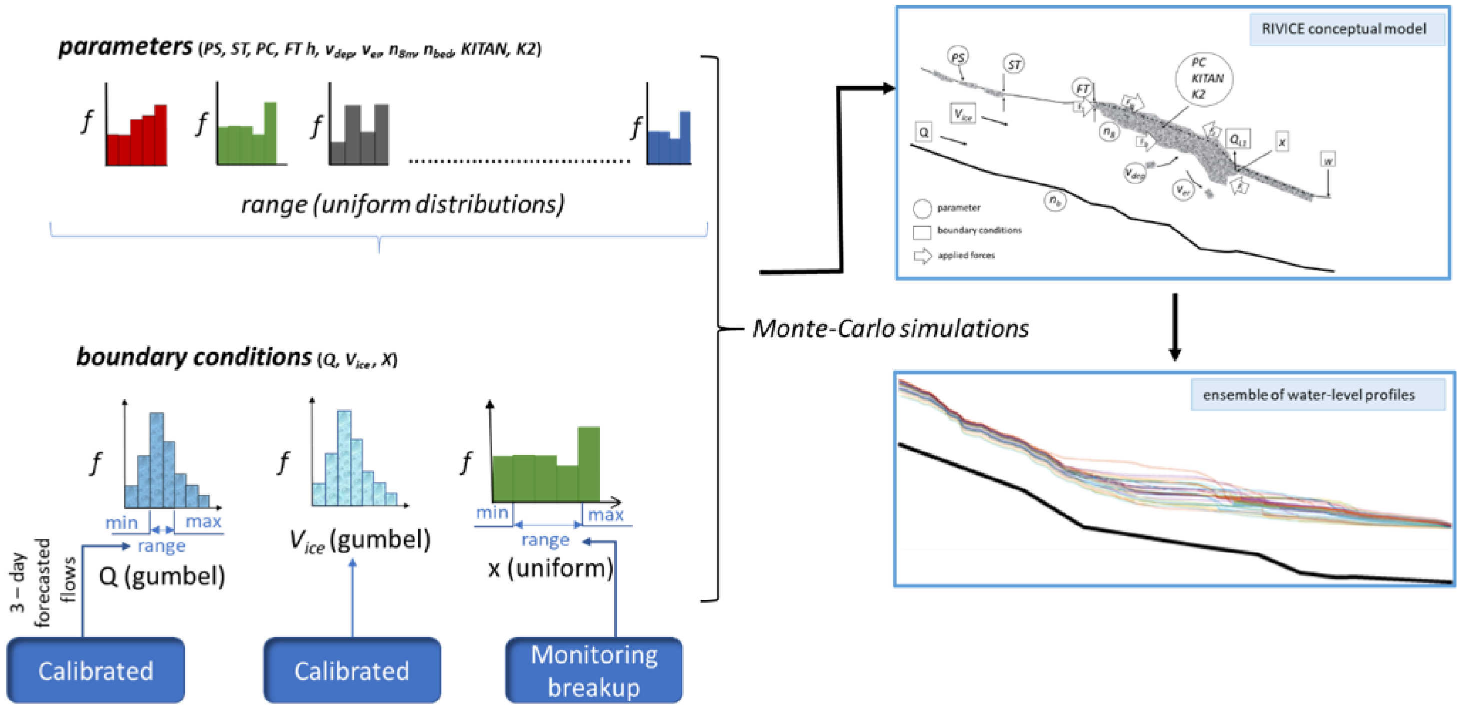

Figure 4

Stochastic framework for ice jam flood forecasting.

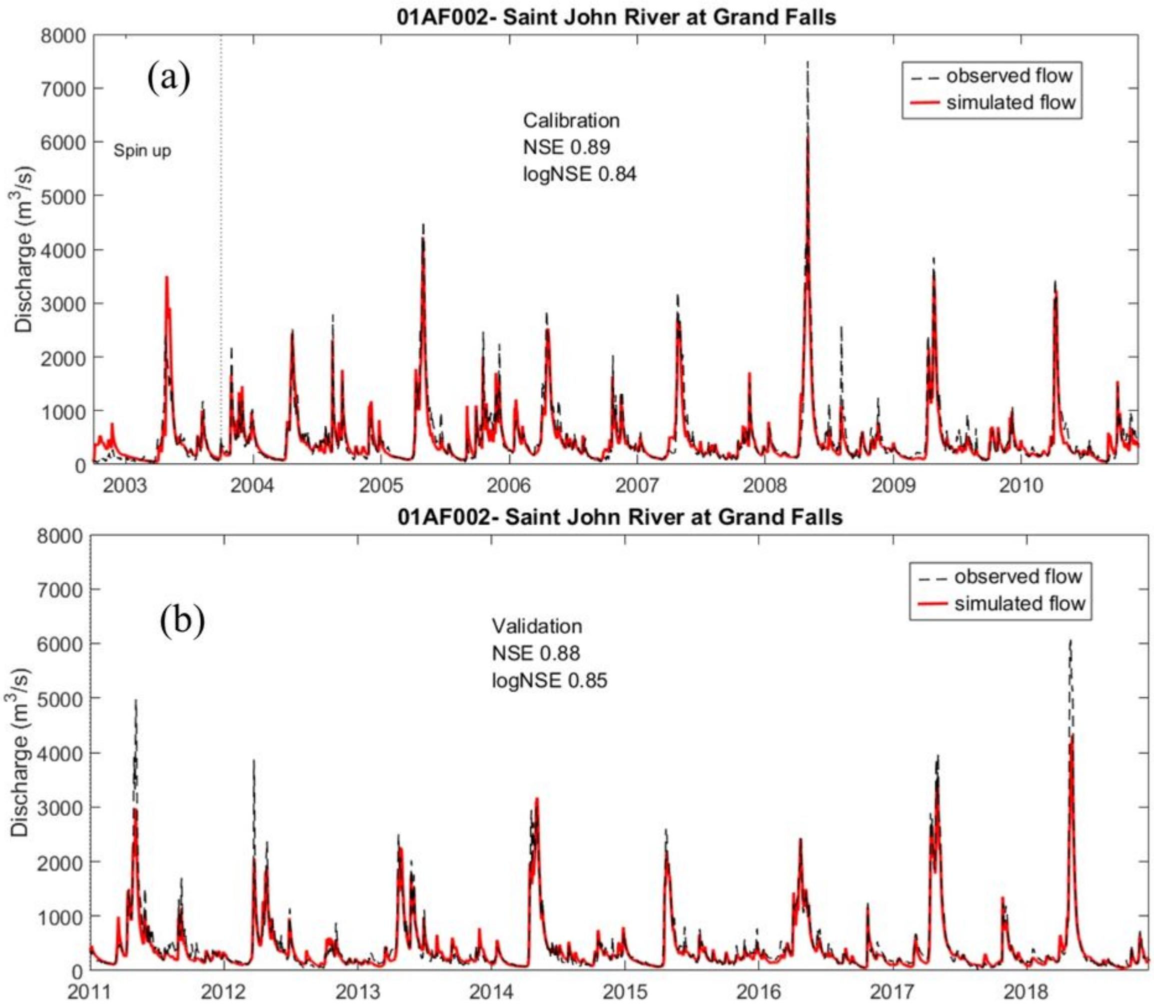

Figure 5

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

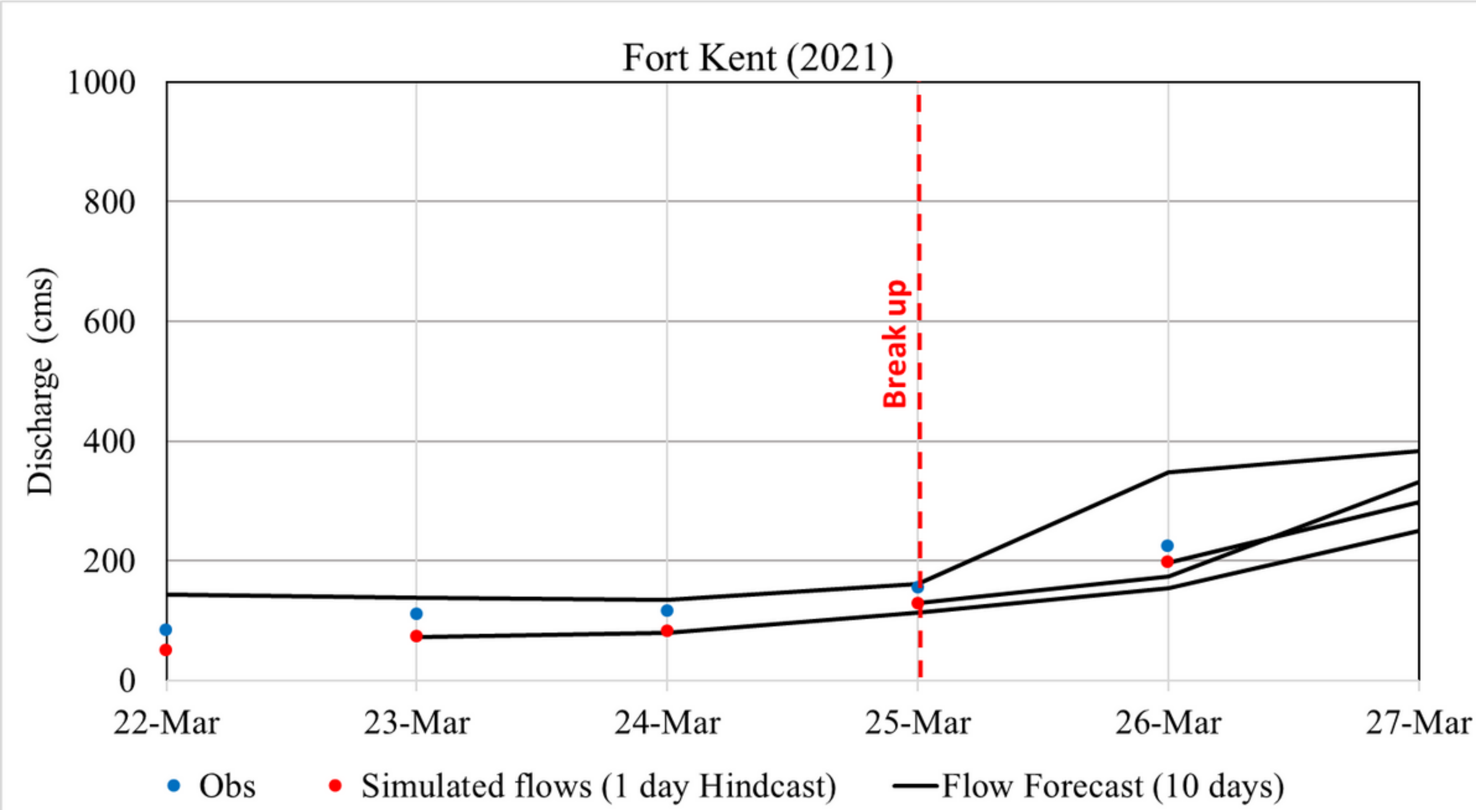

Figure 6

Forecast at Fort Kent (01AD002) for the spring breakup event in 2021.

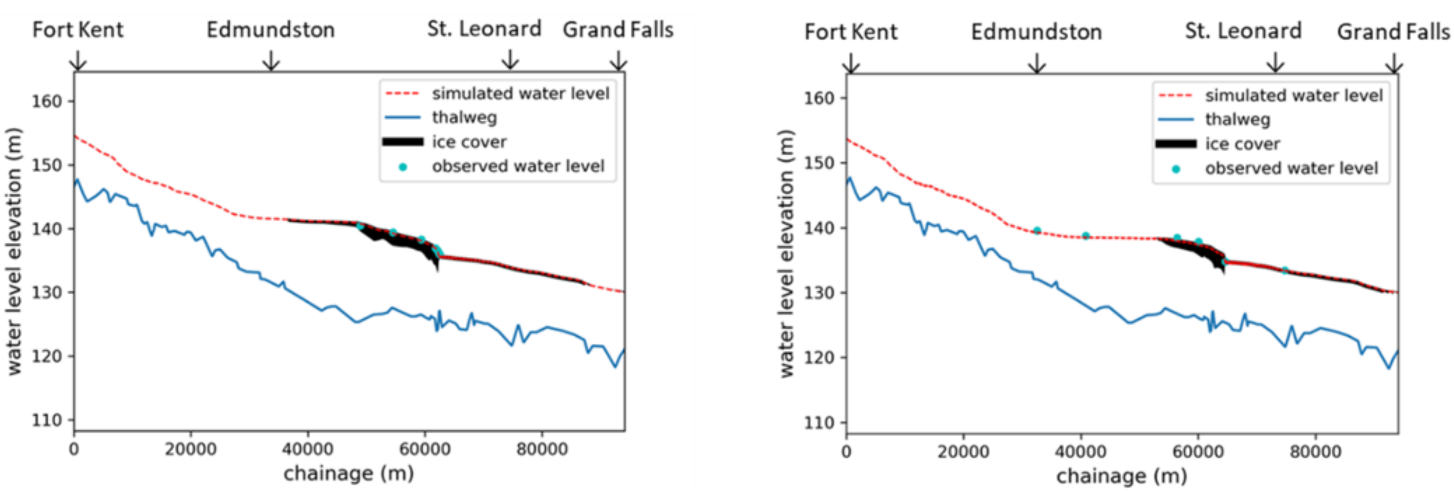

Figure 7

RVICE calibration (left panel) and validation (right panel) results using historical ice jam events in 1991 and 2009 along the model domain (data sources: Beltaos et al. 2012)

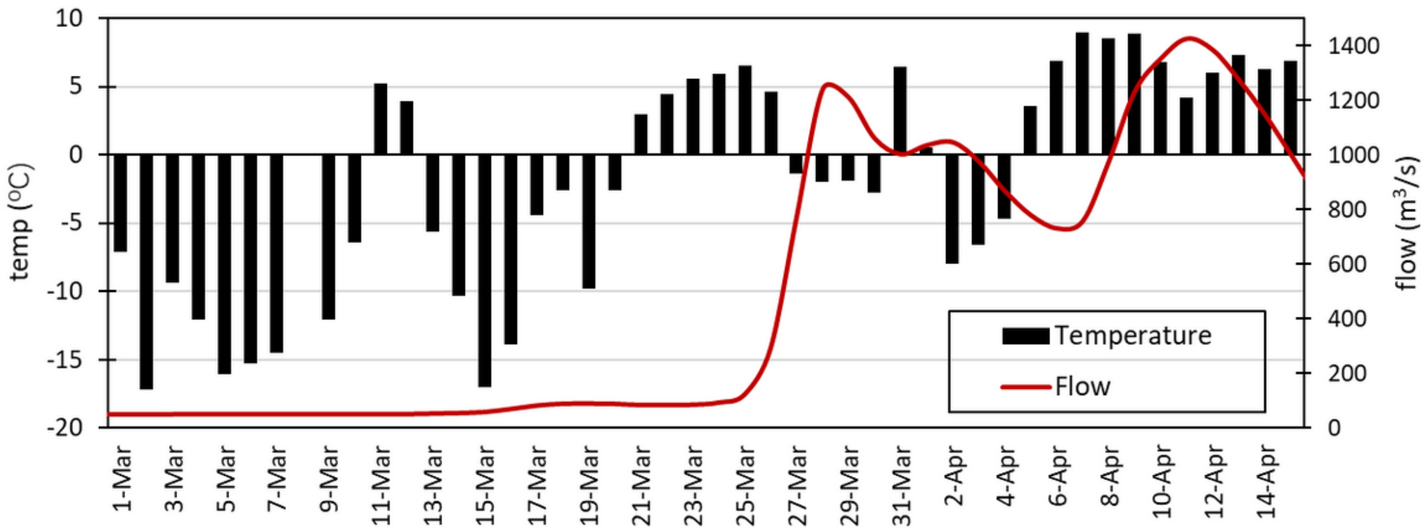

Figure 8

Daily mean streamflow at Fort Kent gauging station and air temperatures at the Edmundston meteorological station.

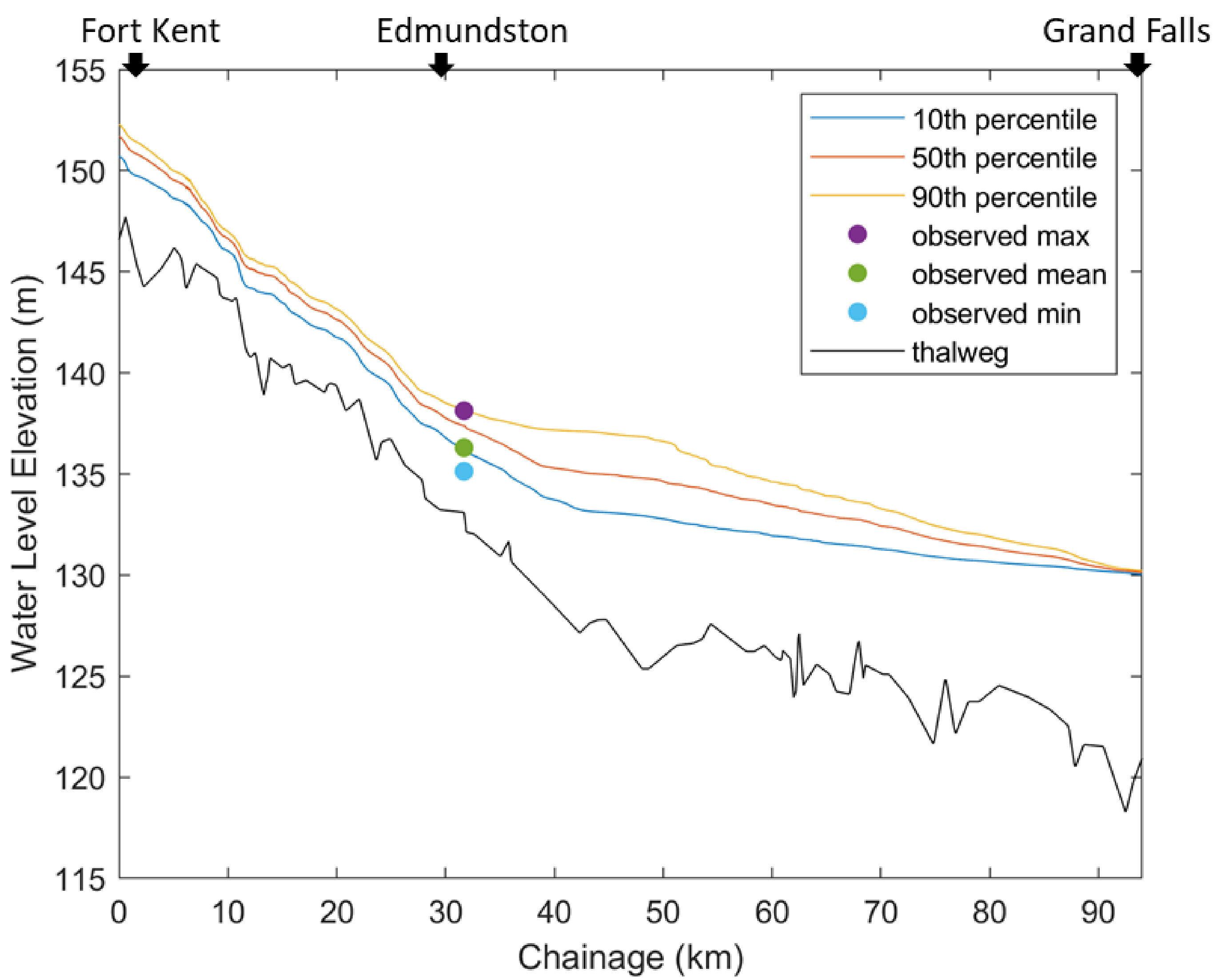

Figure 9

Ice jam flood outlook from 22 to 31 March 2021.

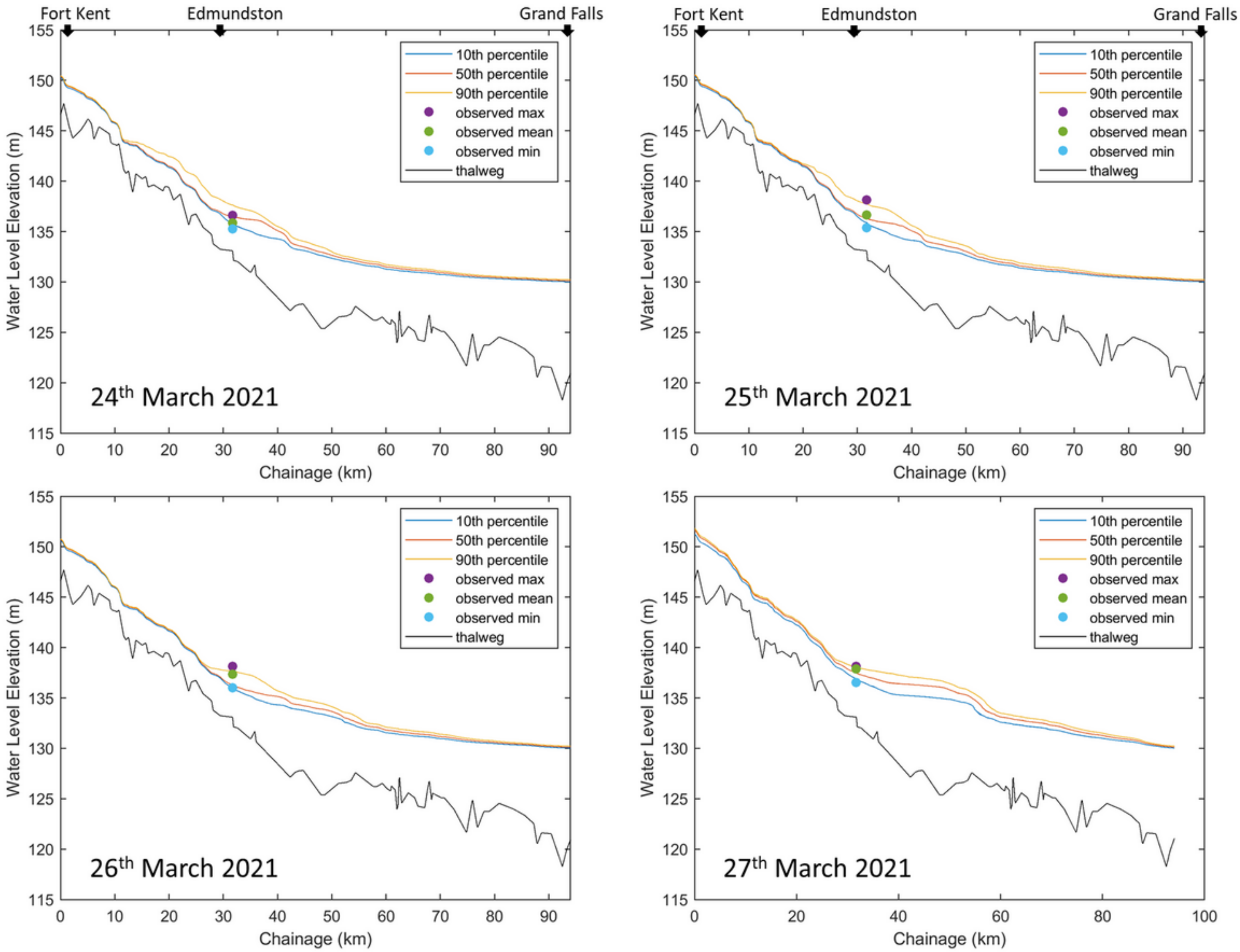

Figure 10

The 3-day ice jam flood forecasts from 24 to 27 March 2021 along the Saint John River from Fort Kent to Grand Falls.