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Estimating frequency distribution of volumes-of-ice of mid-winter ice jams

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Abstract

Mid-winter breakup and associated ice jams occur along many northern rivers. Modelling such events is helpful for planning flood damage reduction programs, designing waterway structures, and protecting the riverine environment. Ice-jam modelling requires the calibration of hydraulic and river ice parameters and the setting of boundary conditions. These parameters and boundary conditions are often estimated from typical values found in previous studies, field data collection, and gauge records. One of the most important boundary conditions, the volume of ice forming ice jams, is very challenging to estimate. During freeze-up, frazil slush pans are the primary source of this ice. They form along the open water stretch upstream of the ice cover front when the air temperature is below freezing. Methods which have already been developed to estimate ice volumes include: modelling their frequency distributions, direct field measurement, remote sensing imagery, and using the simple empirical Stefan's equation. However, most of these studies have been carried out to estimate ice volume during spring breakup and estimation of freeze-up ice volume has not been attempted. The main objective of this study is to develop a stochastic framework to simulate freeze-up events that can then be used to estimate ice-volume distributions for mid-winter ice jams to aid flood forecasting. The Saint John River, from Dickey to Grand Falls, was used as a test site to develop the framework. First, the heat transfer coefficient was calibrated using available observed freeze-up data. Second, long-term historical river discharge and air temperature data were clustered to select model inputs for the stochastic framework. Finally, frequency distributions of the inflowing volume of ice were developed for various locations along the study site.

1. **Introduction**

Ice processes in cold region rivers can induce multiple detrimental impacts. These include flooding leading to property and infrastructure damage, disruption to hydropower generation and ship navigation, loss of human life, and disturbances to the aquatic environment (Beltaos, 1995). The general sequence of river ice processes during the course of the winter is freeze-up, solid ice-cover formation and breakup. The freeze-up period occurs first with initial ice-cover formation. During freeze-up, frazil ice begins to form in supercooled water, and accumulates to form frazil slush/pans which flow downstream until they lodge at and extend an existing ice cover (Hicks and Beltaos, 2000). As time progresses, the initial ice cover thermally thickens and forms a completely solid ice cover. In the spring, when the temperature rises above zero degrees and snowmelt runoff increases, the ice cover starts to decay and break up in many locations. During the breakup, fractured or rubble ice is transported downstream, and eventually melts or is flushed out of the river (Beltaos, 1997). Many other complex river ice processes are involved within this sequence and all of these processes have significant impacts on the river hydraulics.

Ice jams are a common occurrence during spring breakup but can also occur in mid-winter due to brief thaws and sudden increases in runoff due to significant rainfall and snowmelt events (Beltaos, 2008). Winter ice-jam conditions can be more severe both socio-economically and ecologically since winter jams occur very quickly, leaving little time to implement emergency measures. The flood water freezes when cold conditions resume and the ice persists throughout the rest of the winter. In addition, the disturbance to the aquatic environment due to dynamic mid-winter breakup and jamming can destroy spawning grounds and other aquatic habitats and significantly increase fish mortality (Prowse, 2001).

Although there are significant detrimental impacts of mid-winter jamming, very few studies have been carried out to investigate this jamming process (e.g. Garver, 2018, 2019; Beltaos et al., 2003). Since hydraulic modelling is a crucial process to understand the jamming mechanisms and associated flood intensity, research should be carried out to model this dynamic mid-winter phenomenon. However, modelling mid-winter jamming can be a very challenging task, as very little information related to this dynamic process is documented and available. Hydraulic modelling requires many river ice and hydraulic parameters (e.g. roughness coefficients, ice-cover porosity and thickness) and boundary conditions (e.g. discharge, the volume of inflowing ice) as input to obtain an optimum simulation of a specific event (White, 1999). Many of these parameter values can be extracted from previous studies and observation records, expert knowledge, and model calibration, while boundary conditions can often be obtained from nearby gauge records. However, one of the important boundary conditions, the inflowing volume of ice that forms the jam, is very challenging to predict and difficult to estimate (Lindenschmidt, 2017). The ice in mid-winter jamming can be frazil slush and ice pans (particularly along the Saint John River in recent times) that accumulated and consolidated as an ice cover during freeze-up. As it is not safe to measure ice thicknesses during freeze-up, estimating the total volume of frazil ice is difficult. Moreover, the dynamic behaviour of ice and uncertainties in the thicknesses of frazil slush limit the total ice-volume calculation using other methods, such as remote sensing techniques (Lindenschmidt and Li, 2019).

This study aims to develop a stochastic modelling framework to estimate the frequency distributions of inflowing volumes of ice accumulating in jams during freeze-up along the Saint

John River from Dickey to Grand Falls. The specific objectives are: i) to provide freeze-up ice volume distributions for different locations along the model domain, and ii) to present a global sensitivity analysis (GSA) to understand the impact of model parameters and boundary conditions on the inflowing volume of frazil ice. The GSA provides greater insight into the impact of model parameters and boundary conditions on model results, particularly backwater levels and ice-cover extents. Furthermore, the GSA identifies sensitivities within the entire parameter and boundary condition space.

2. Methodology

2.1 Study Site

This study focuses on a long segment, approximately 157 km in length, of the upper Saint John River from Dickey, Maine, USA to Grand Falls, New Brunswick, Canada, (Figure 1). During at least half of the year, the river is affected by ice. Freeze-up starts between mid-November and January, after which a solid ice cover is in place from January to March, followed by breakup between late March and April. The study stretch of the river is characterized by a steep river slope and numerous rapids, islands and sandbars. During freeze-up, frazil ice usually accumulates in different locations along the river to form a solid ice cover. Historically, the river is prone to ice-jam formation and associated flooding during spring breakup. However, more recently, mid-winter breakup events have been observed in 1995, 1996, 2018 and 2020. This was mainly due to brief thaws and significant rain-on-snow events after freeze-up.

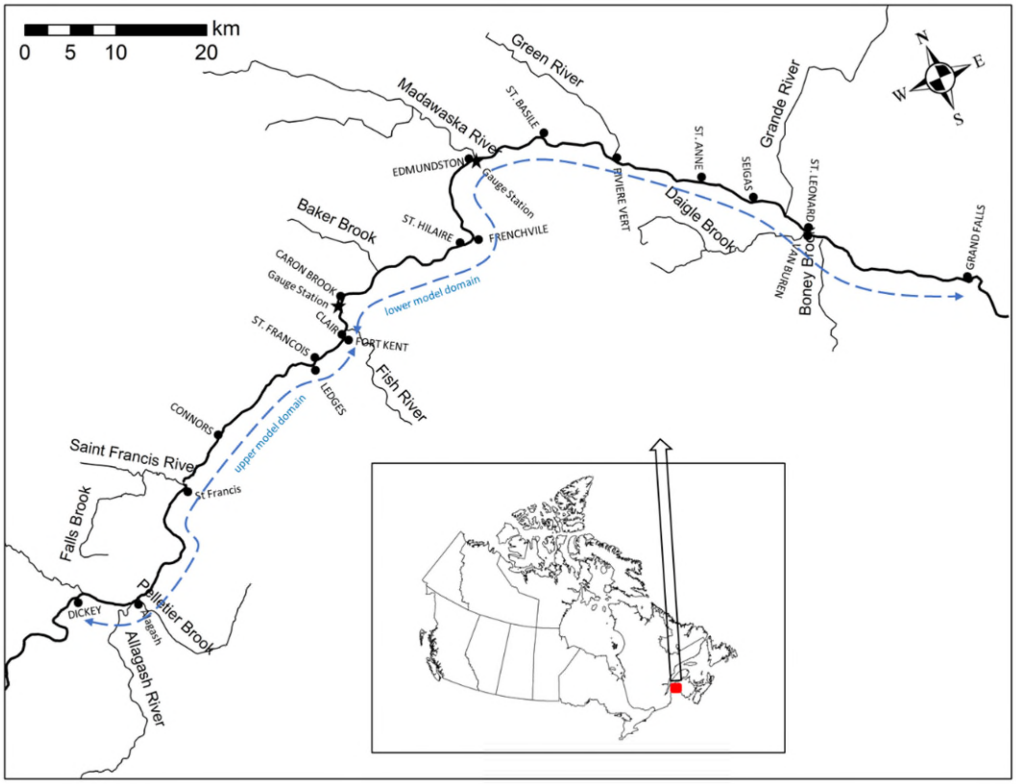


Figure 1: The study reach along the Saint John River from Dickey to Grand Falls.

The hydraulic model domain was divided into two segments: the upper model domain, extending from Dickey to Fort Kent, and the lower model domain extending from Fort Kent to Grand Falls (Figure 1). When necessary, the two models can run separately to avoid lengthy computation times during forecasting. There are several United States Geological Survey (USGS) and Water Survey of Canada (WSA) gauge stations along the river (Figure 1), providing a historical record of flow and water level data available for public download. The Allagash, Saint Francis and Fish rivers are major tributaries that flow into the upper river domain, whereas the Madawaska, Green and Grande rivers empty into the lower domain. Historical records of river discharge were also collected from the gauge stations along these tributaries. The air temperature data for the study site was extracted from climate stations in Edmundston, consisting of a long record of climatic data (Figure 1).

2.2 Remote sensing data

A general overview of river freeze-up within the study stretch was acquired from space-borne remote sensing data available publicly as an online source, specifically the Sentinel Hub EO Browser (SHEB). Since 2017, the SHEB has been providing Sentinel-1 imagery with a 10 m pixel resolution. From this data source, the freeze-up ice-cover initiation and progression were visually observed and analyzed for the studied reach. In addition, visual inspection of the satellite imagery allowed calculation of the approximate timing of freeze-up and the locations of freeze-up ice lodgments along the river.

2.3 River ice modelling

The river ice hydrodynamic model RIVICE was used to simulate freeze-up along the Saint John River. RIVICE is a one-dimensional, fully dynamic hydraulic model that simulates frazil ice formation, ice cover development, border ice formation, breakup, and ice jams. The necessary parameter and boundary condition inputs for RIVICE are shown in Figure 2. During freeze-up, frazil slush pans are generated in the open-water sections when the water temperature (T_w) drops to a few tenths of a degree below zero (supercools) with freezing air temperatures (T_a). In the RIVICE program, heat loss is calculated using the following equation:

$$q = H\,(T_w - T_a) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

where H is the heat transfer coefficient. The typical range of this parameter is between 15 and 25 W/m^2/°C depending on the location. The heat transfer between water and air can also be affected by wind speed and longwave radiation. Besides air temperature (T) and the heat-transfer coefficient (H), the RIVICE model requires some boundary condition and other parameter inputs. The model boundary conditions are upstream river discharge (Q), latereral flows (Q_L) from tributaries connected to the modelled domain, and the toe of the ice lodgement location (x). Parameters include the porosity and thickness of the ice-cover front (PC and FT), the porosity and thickness of slush pans (PS and ST), the erosion and deposition velocity thresholds of transported ice (V_{er} and V_{dep}), riverbed and ice (n_{bed} and n_{ice}) roughness coefficients, and longitudinal to lateral force ratio ($K1$) and longitudinal to vertical force ratio ($K2$) of the ice-jam cover strength.

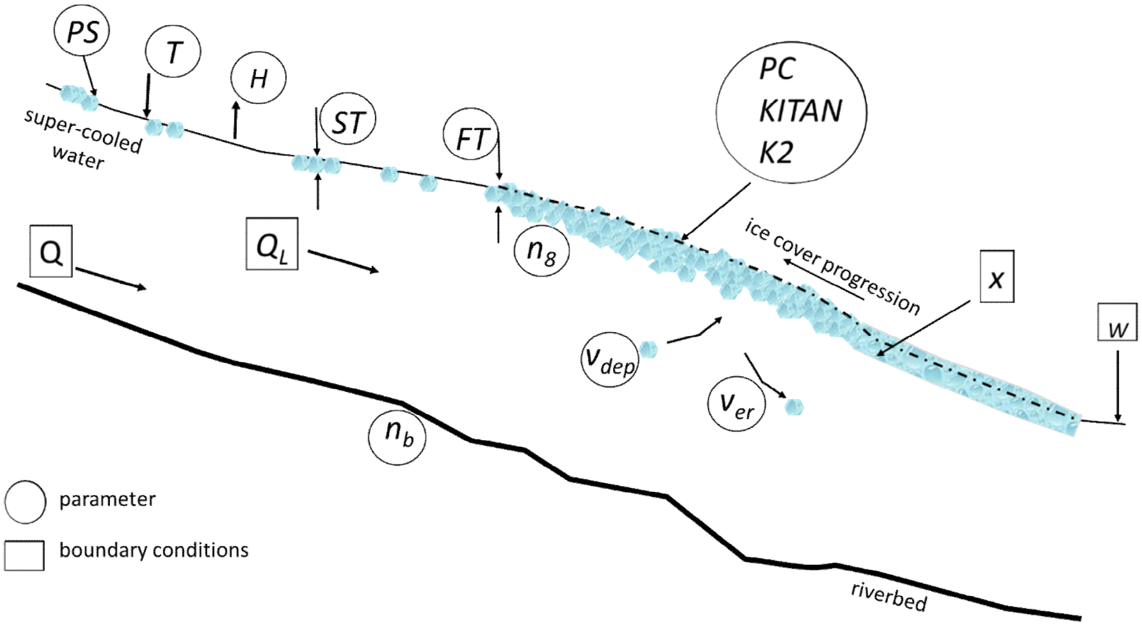


Figure 2: Conceptual diagram of freeze-up ice cover simulation using the RIVICE hydrodynamic model.

2.4 Stochastic modelling framework and data preparation

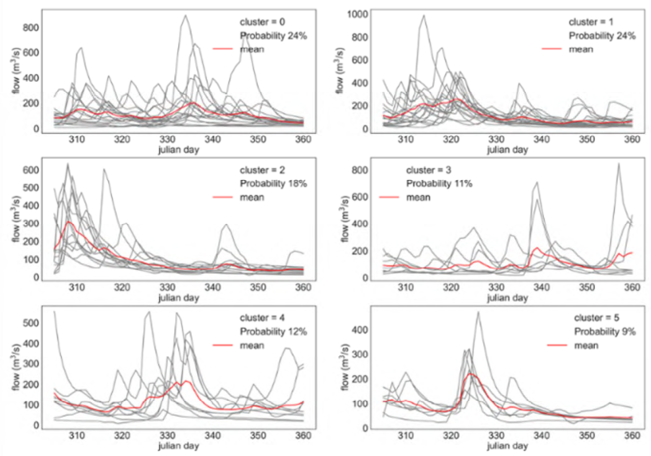
RIVICE was placed into a stochastic framework to simulate river freeze-up using a Monte-Carlo Analysis (MOCA) approach. In this approach, a total of 500 sets of parameter and boundary condition values were selected randomly from uniform probability distributions to repeatedly simulate daily freeze-up (frazil ice cover) profiles from 1 November to 24 December. The ensemble of frazil ice cover profiles was then used to estimate the total volume of ice distribution along the river. The typical range of parameter and boundary condition values of the MOCA analysis were extracted from previous studies and observation records.

Additionally, typical shapes of the daily river hydrograph and air temperature were selected using a clustering analysis. Data for the upstream river discharge boundary condition was collected from the USGS gauge at Dickey for the upper model domain and Fort Kent for the lower model domain. Linear relationships of river discharge between these upstream and tributary gauge stations were developed to estimate lateral flow inputs in each model domain.

In order to select the daily discharge for MOCA for both model domains, a cluster analysis was applied to historical records of river discharge from 1930 to 2020 for Dickey and Fort Kent using a hierarchical clustering approach. A Euclidian distance and ward-linkage method was applied to identify six clusters of the hydrographs at Dickey and ten clusters of the hydrographs at Fort Kent, from 1 November to 24 December. All clusters of the hydrographs from Dickey and Fort Kent are shown in Figure 3.

Similarly, the air temperatures recorded at the Edmundston climate station, from 1930 to 2018, were clustered to simulate freeze-up events (Figure 4). For each simulation, one of the mean profiles was selected randomly from the clustered profiles as input to the MOCA simulations.

a. Dickey



b. Fort Kent

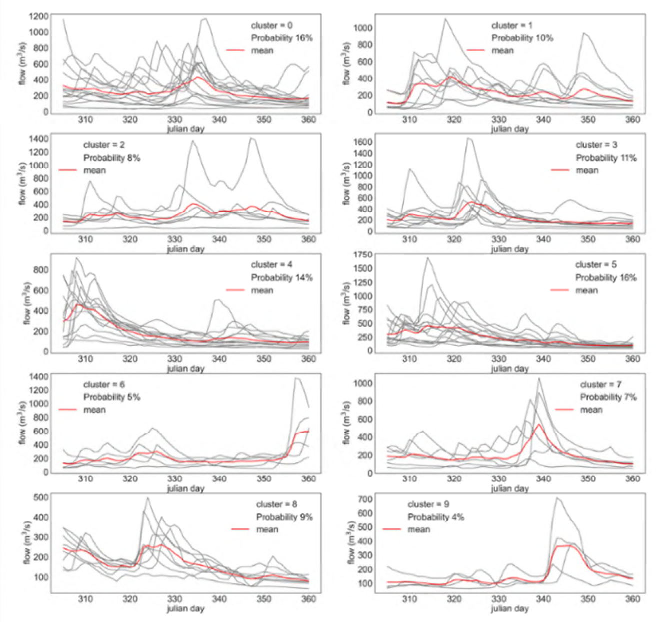


Figure 3: Clustered hydrographs recorded at Dickey and Fort Kent.

2.5 Global Sensitivity Analysis using the inflowing volume of ice

A global sensitivity analysis was carried out using the Regional Sensitivity Analysis (RSA) approach (Hornberger and Spear, 1981). In RSA, an objective function is selected to create two distinct parameter sets called behavioural and non-behavioural groups using a specific threshold value. Many studies have already applied this approach to diagnose the impact of parameters on model output using different objective functions (Lindenschmidt and Chun, 2013; Sheikholeslami et al., 2017; Lindenschmidt, 2017; Das and Lindenschmidt, 2021). Since the goal of the GSA in this study is to understand the impact of the input parameters on frazil ice production during freeze-up, the objective function applied here is the difference between observed and simulated total ice cover extent from ice lodgment to ice cover front locations. An average observed ice cover extent along both model domains was estimated using satellite imagery during the freeze-up from 2016 to 2021. The observed ice cover extent was then compared against each simulated ice cover extent to estimate behavioural and non-behavioural sets. Since a smaller difference between observed and simulated ice cover extent represents a better performing simulation, the top 10% of the better performing parameter and boundary condition sets were selected as the behavioural set, while remaining simulations were chosen as the non-behavioural set. Cumulative distributions of the behavioural and non-behavioural values were then plotted to evaluate the degree of influence of each parameter and boundary condition. A greater dissimilarity between two cumulative distributions indicates a greater influence of the parameter or boundary condition on the model output, which in this case is the extent of the ice cover front from the ice lodgment location.

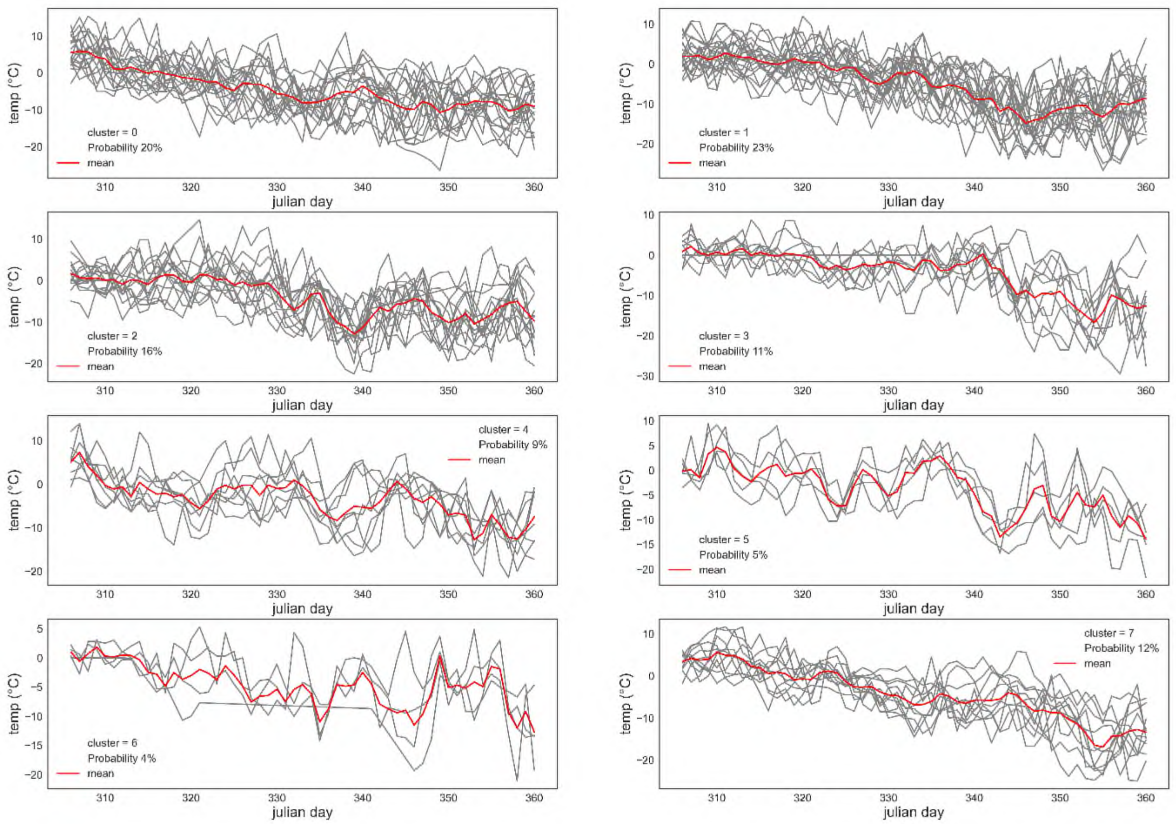


Figure 4: Clustered profiles of air temperature recorded at the Edmundston climate station from November 1 to December 24.

3. Results and Discussion

3.1 Freeze-up along the Saint John River

The air temperature along the study site drops below 0 ° C in early November and the freeze-up ice cover starts to progress in mid-November. Frazil ice begins to form in supercooled water, which leads to frazil flocs and the production of slush pans. Their flow is eventually arrested at different locations along the river and they juxtapose to form consolidated ice covers. Satellite images reveal potential ice lodgment locations, such as at the confluence of the St. Francis River, Kennedy Island, Saint Basile and Sainte-Anne-de-Madawaska, from which frazil flocs start to juxtapose in the upstream direction.

3.2 Modelling Freeze-up in 2018

In order to set up the MOCA simulations, the river ice model RIVICE was calibrated by simulating the freeze-up ice cover in 2018. The freeze-up started in mid-November and ice-cover formation started to progress from Sainte-Anne-de-Madawaska in the lower model domain (Fort Kent to Grand Falls) (Figure 5). The progress of the juxtapositioned frazil slush was observed using Sentinel-1 imagery from 19 November to 6 December in 2018. Figure 5 shows the juxtapositioned ice cover passing upstream of Edmundston on 24 November and reaching Frenchville on 6 December 2018. As the freeze-up progresses further upstream, the rate of juxtapositioning decreases due to the reduction of open-water sections along the model domain. Figure 6 shows the modelling results of the ice cover progression and backwater staging along the lower model domain. The RIVICE hydraulic model successfully simulated the rate of ice cover progression and backwater level staging at the Edmundston and Fort Kent gauge stations. In this domain, the heat transfer coefficient H (Equation 1) was calibrated to be 22.5 $W/m^2/^oC$ during the freeze-up of 2018.

Similarly, RIVICE successfully modelled ice-cover progression and backwater level staging along the upper model domain from Dickey to Fort Kent (Figure 7). In this stretch, an ice lodgment formed approximately 10 km upstream of Fort Kent at Kennedy Island and frazil slush started to juxtapose during mid-November. By 24 November, the ice cover progressed to the Allagash River. The RIVICE hydraulic model was calibrated to have the same heat transfer co-efficient value of 22.5 $W/m^2/^oC$ to simulate the ice cover progression along the upper model domain. Once the model was calibrated, a MOCA simulation was carried out for both model domains separately to simulate ice-volume distributions along the river from 1 November to 24 December.

3.3 Ice-volume distribution

The two model domain results were combined to estimate the total volume of freeze-up ice along the whole studied reach from Dickey to Grand Falls. Figure 8 presents a histogram of the ice volume distribution along the entire study site. The result shows that the total inflowing volume of ice distribution ranges between 3 and 20 million m^3, with a mean of 10 million m^3.

Figure 9 presents the total volume of ice generated in two separate model domains. While the volume of ice ranges between 2.5 and 13 million m^3, with a mean of 6.1 million m^3, for the upper model domain from Dickey to Fort Kent, it varies from 2 to 14 million m^3, with a mean of 4.6 million m^3, for the lower model domain from Fort Kent to Grand Falls.

The distribution of the ice volume simulated in this study can be used as a boundary condition in river ice hydraulic modelling to forecast mid-winter ice jam severity. Within a forecasting framework, the results of this study can be used to develop ice volume distributions for any location along the model domain, based on the winter ice-cover breakup locations. Figure 10 shows some examples of the different distributions of ice volume at different locations along the river.

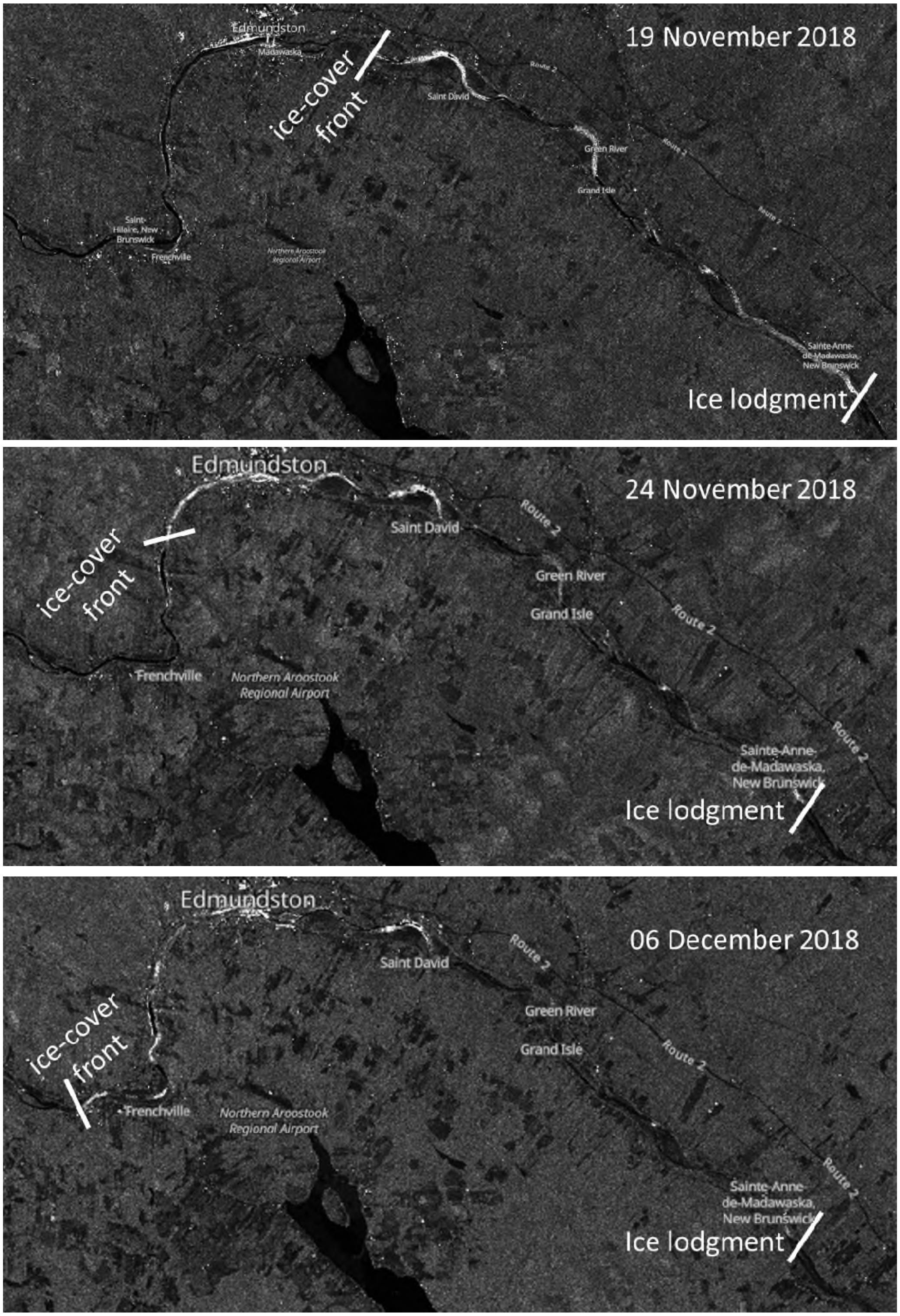


Figure 5: Ice cover progression along the lower model domain during freeze-up 2018 (imagery source: EO Browser, https://apps.sentinel-hub.com/eo-browser/, Sinergise Ltd.).

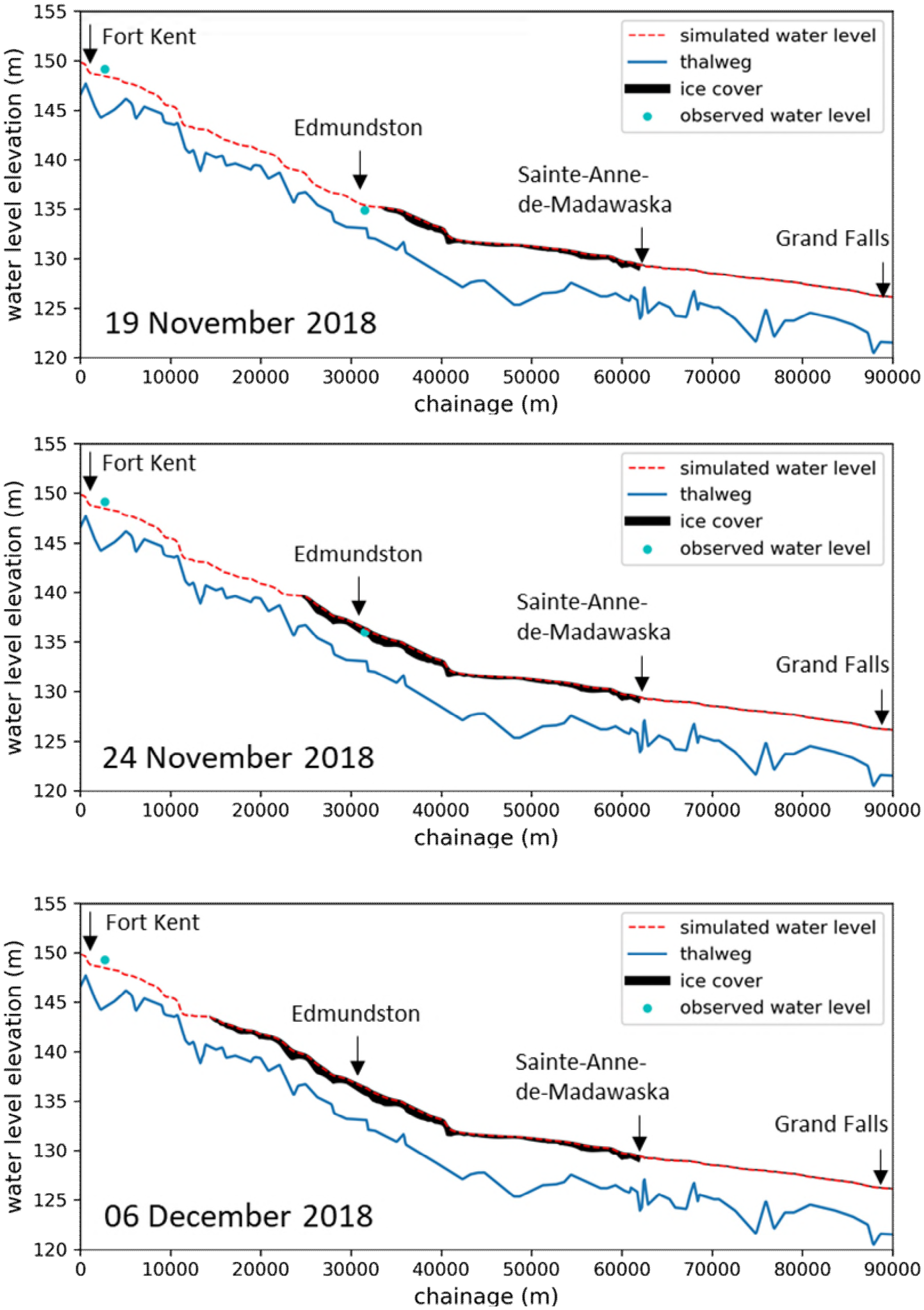


Figure 6: Freeze-up event simulations in 2018 along the lower model domain.

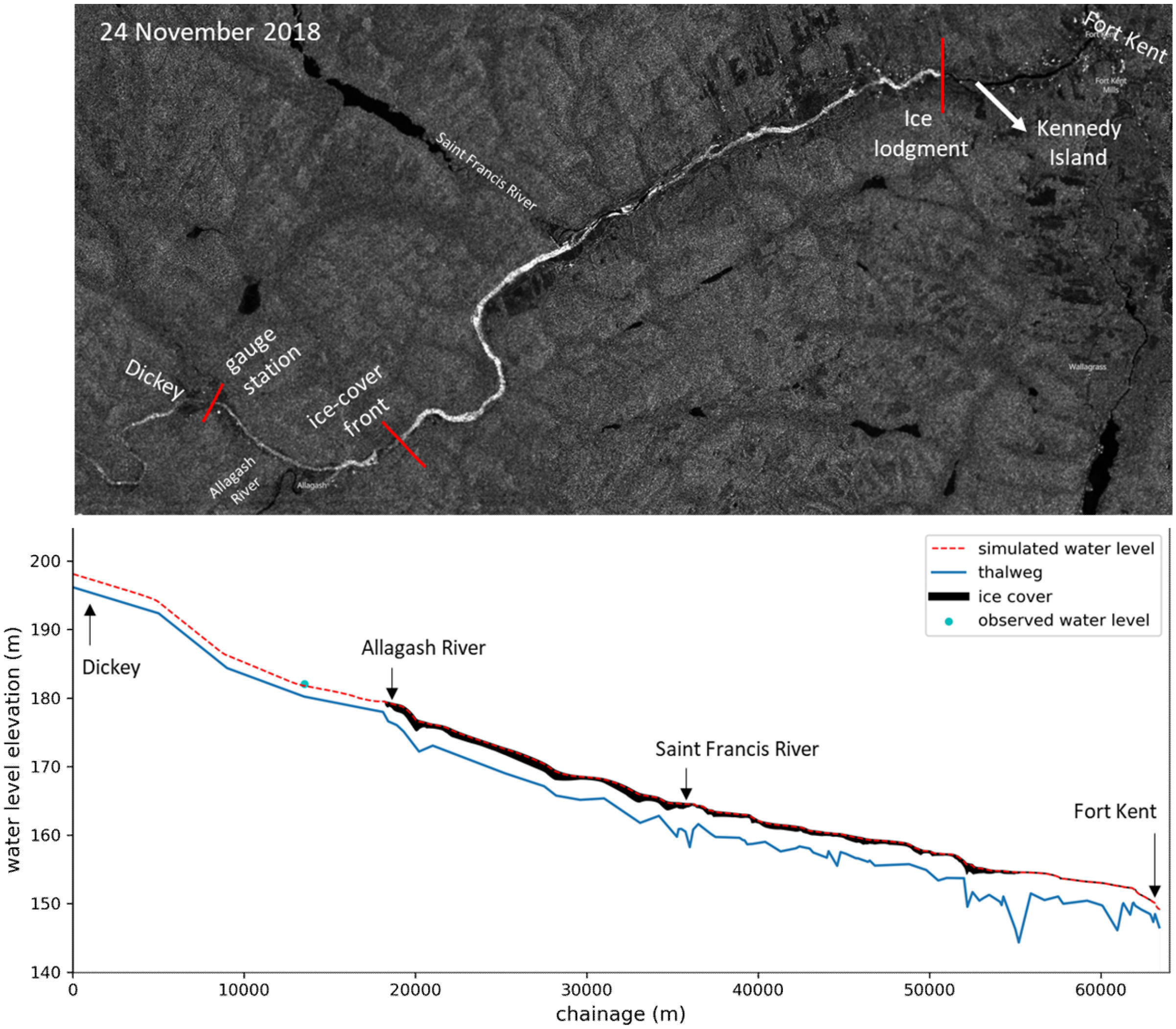


Figure 7: Sentinel-1 images *(top panel*) and simulation of the freeze-up event (*bottom panel*) on 24 November 2018 (source: EO Browser, https://apps.sentinel-hub.com/eo-browser/, Sinergise Ltd.)

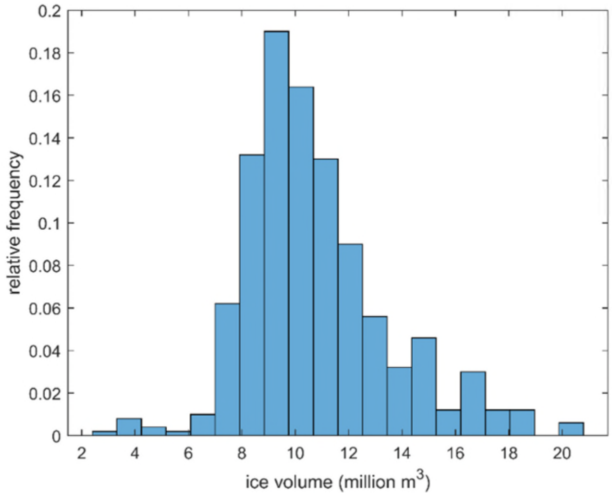


Figure 8: Total ice volume distribution along the Saint John River from Dickey to Grand Falls.

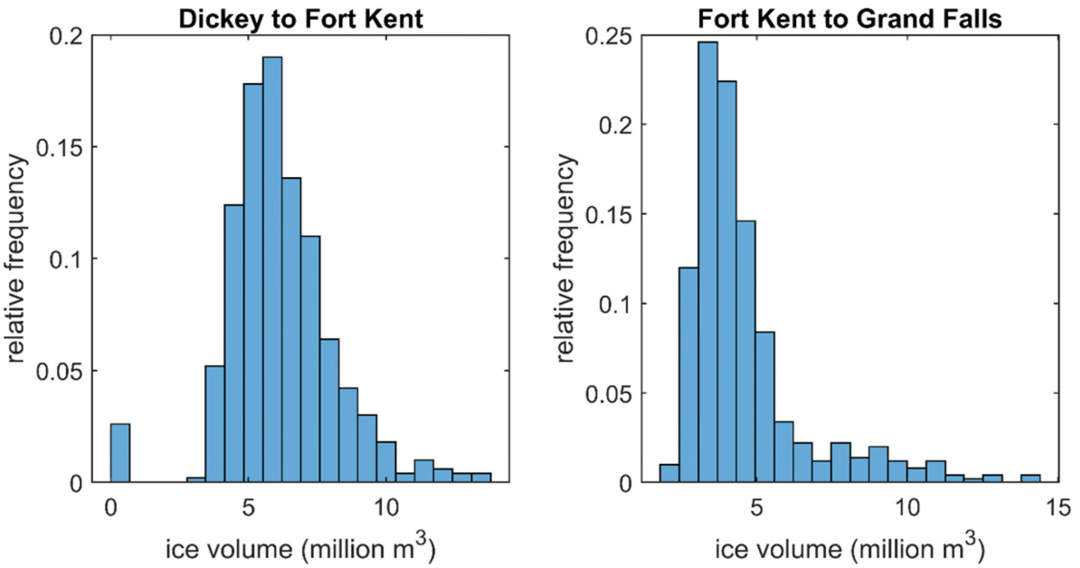


Figure 9: Ice volume distribution along the two model domains – i) Dickey to Fort Kent and ii) Fort Kent to Grand Falls along the Saint John River.

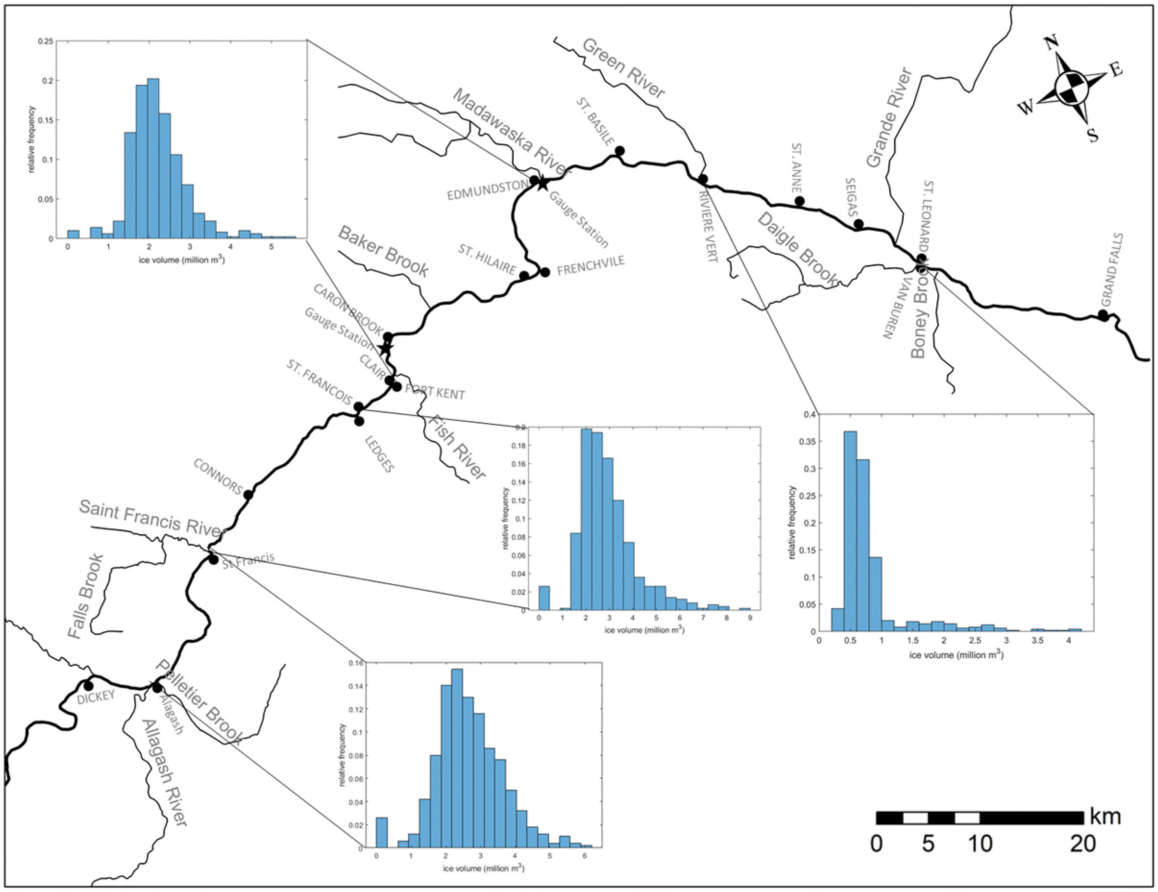


Figure 10: Ice volume distributions in different sections along the Saint John River.

3.4 Parameter and boundary condition sensitivities

The global sensitivities of all input parameters and boundary conditions used to model the inflowing volume of ice are shown in Figure 11. The amount of divergence between the behavioural and non-behavioural cumulative distributions illustrates the impact of each parameter and boundary condition on the model output. Moreover, the Kolmogorov-Smirnov (KS) test, which estimates the maximum distance between the two cumulative distributions was also determined to serve as a proxy for the impact of each parameter and boundary condition value on model output. The result shows that the cumulative distributions of the heat transfer coefficient and porosity of the ice cover are highly dissimilar, and the KS values are relatively large in both model domains, indicating the model output being highly sensitive to these parameters. While most of the other model parameters and boundary conditions are moderately or less influential in both model domains, the toe of ice lodgment is highly influential on model output in the lower model domain.

4. Conclusion

Frequency distributions of the volume of inflowing ice at freeze-up were developed using a stochastic modelling framework. The flow hydrograph and air temperature for the freeze-up period can be classified using a clustering technique. The cumulative distributions of the inflowing ice volume at different locations along the river can be used as a boundary condition to simulate mid-winter ice jams along the Saint John River. Moreover, a global sensitivity analysis identified that model output is highly sensitive to the heat transfer coefficient and porosity of the ice cover. Therefore, future research efforts could be focused on how these highly influential parameters control the ice volume contribution during an ice-jam event.

Since several approaches (e.g. using stage frequency distributions and remote sensing) have already been applied to estimate inflowing ice volume during spring breakup, this stochastic framework to estimate freeze-up ice volumes is another step forward in advancing river ice-jam flood forecasting research. Moreover, this approach to estimating the volume of inflowing ice is easily transferable to other river systems. The overall approach and the simulation of the daily rate of ice-cover advancement could also be used to implement an emergency measures management plan or to manage specific ice control structures along the river.

5. Acknowledgement

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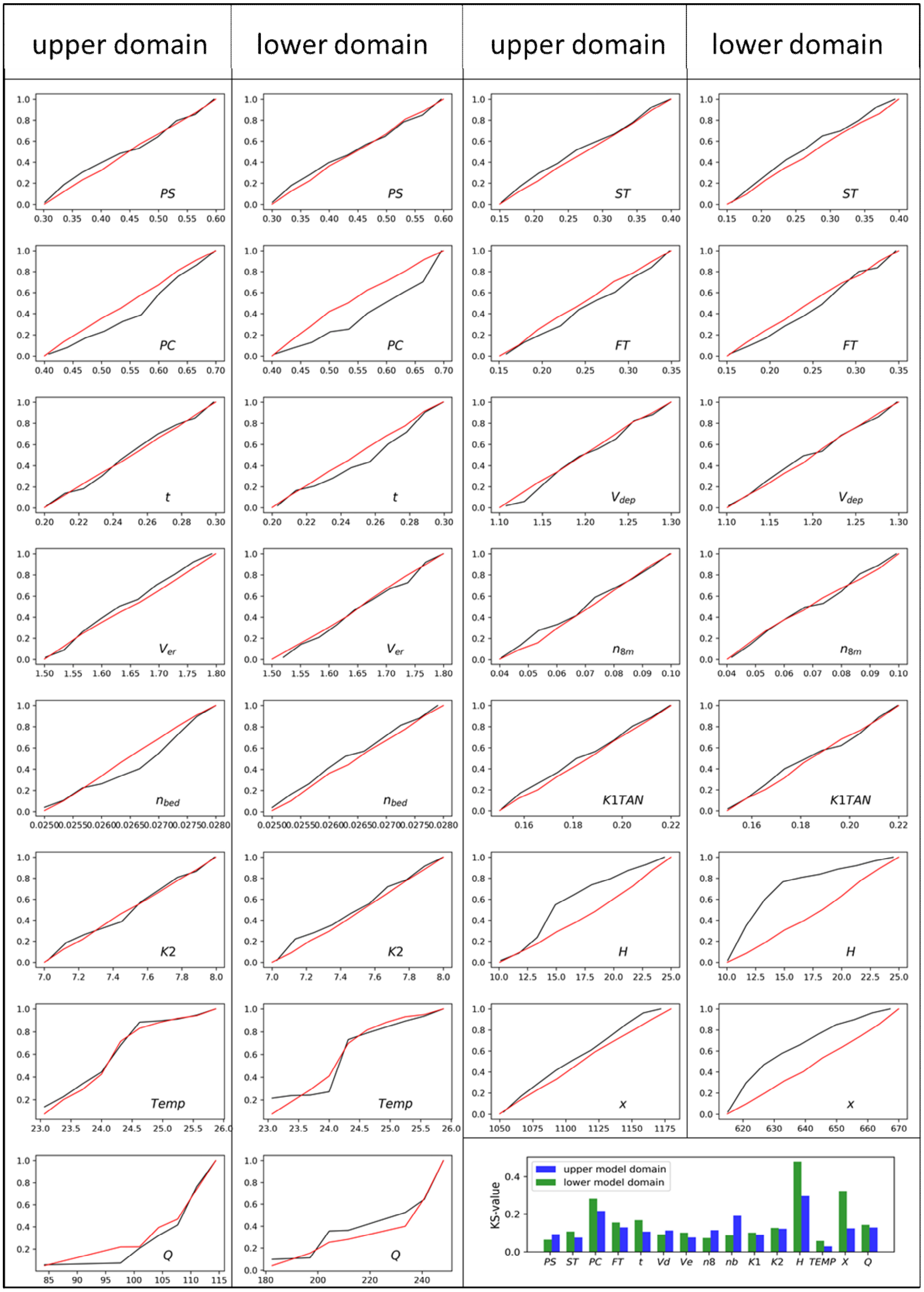

Figure 11: Behavioural (black line) and non-behavioural (red line) cumulative distributions and their KS values for the model parameter and boundary condition values.

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