



Developing a geospatial model to predict locations of higher propensity to ice jamming along the Saint John River

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Abstract

During spring breakup, ice-jam related flooding is a dangerous threat to many riverine communities in cold regions. Ice-jam floods can be relatively severe and often more damaging than open-water floods since they often occur suddenly and are associated with much faster and higher staging. Moreover, various geomorphological characteristics can be responsible for severe ice-jam formation. Therefore, it is necessary to identify the propensity of a river channel to ice-jam formation in order to develop an effective flood mitigation strategy that could reduce potential flood damages. Although several geospatial models have already been developed for various rivers across Canada, a geospatial model precisely focused on the Saint John River has not been developed. The main purpose of this work is to introduce an advanced Machine Learning Approach (MLA) that has been used to develop a geospatial model based on geomorphological parameters (e.g. sinuosity, slopes and depths) and features (e.g. islands or sandbars, narrow channels, tributaries, bridge piers). A hydraulic model (RIVICE) was used to simulate both solid ice cover slopes and longitudinal profiles of riverbed elevations (depths). The remaining geomorphological parameters were derived from spatial data using a Geographical Information System (GIS) tool. Based on observed ice-jam data, a data-driven machine learning model was applied to the aforementioned factors to cluster geomorphological parameters. First, the trained model was used to identify the most probable ice-jam locations and then the results were applied in the test model domain to determine the accuracy of the model.

1 Introduction

Ice jams occur when the amount of floating ice in the river surpasses the channel's transport capacity (Beltaos 1995). The process usually happens in the spring when the river ice cover begins to break up. This breakup and eventual ice-out take place as a result of several hydro-meteorological processes, including a rise in air temperature above zero degrees which melts ice in the stream, and precipitation and snowmelt that increase the overall runoff, leading to rises in river water levels. These result in hydraulic forces acting on the ice, leading to the dislodgment of ice covers from the river banks. Spring breakup is often accompanied by ice-jam formation, however; mid-winter thaws and rain-on-snow events can also break the winter ice cover and create mid-winter ice jams (Beltaos, 2003).

Ice-jam floods can be more devastating than open-water floods as they are difficult to predict. Ice-jam related floods are a key concern of many riverine communities and government and non-government agencies in Canada as they can result in human casualties and millions of dollars in property damages (Beltaos, 2003; Hicks, 2009). They also significantly impact aquatic environments since they can disturb aquatic habitats and destroy spawning locations of aquatic animals. However, ice-jam floods can also be necessary to replenish wetlands areas with river water and sediments in many inland deltas in Canada (Prowse et al. 2007). Therefore, identifying ice-jam locations is one of the prerequisites for developing ice-jam flood mitigation strategies (Kovachis et al. 2017). Several geospatial models have already been developed for various rivers across Canada (Gauthier et al. 2020) but a geospatial model precisely focused on the Saint John River in North America has not yet been developed.

The main goal of this study is to develop a preliminary geospatial model to identify potential ice-jam locations along the Saint John River by exploring the influence of geomorphological parameters and features of the river. The specific objectives are: i) to introduce a simple machine learning tool to cluster geomorphological parameters along the upper part of the Saint John River, ii) to identify the probable ice-jam locations along the river and iii) to evaluate the impact of geomorphological parameters and features on ice jamming.

2 Methodology

2.1 Background

Geomorphological factors have a strong link to ice-jam occurrences and locations. Kalinin (2008) identified six geomorphological features of the river (e.g. islands, bridges, sharp bends, narrow meander loops, tributaries, and narrowing river sections) that can strongly influence ice-jam formation. Based on the geomorphology, several studies have focused on geospatial modelling to determine the predisposition of particular river reaches to ice jamming (De Munk et al., 2011, 2017; Lindenschmidt and Das, 2015; Lindenschmidt and Chun, 2014).

A geospatial model is usually based on the assumption that geomorphological characteristics can control the ice-jam occurrences along rivers. Therefore, the statistical correlation between these geomorphological factors and ice jamming locations can be estimated and presented by developing a geospatial model.

2.2 Study Site

The study site focuses on the Saint John River between Dickey and Grand Falls, a river length of approximately 157 km (Figure 1). It is one of the largest rivers in Atlantic Canada and historically prone to ice-jam formation due to its geomorphological characteristics. Almost 70% of the total flood damages in the province of New Brunswick are attributed to ice-jam flooding along the Saint John River (Humes and Dublin, 1988). The river from Dickey to Grand Falls is relatively shallow with occasional islands and a series of rapids. The upper part of the study site from Dickey to Edmundston is steeper than the lower part of the river stretch from Edmundston to Grand Falls.

The study reach was divided into two stretches to develop a geospatial model. The stretch from Dickey to Edmundston was taken as a training domain and the stretch from Edmundston to Grand Falls was selected to test the model (Figure 1).

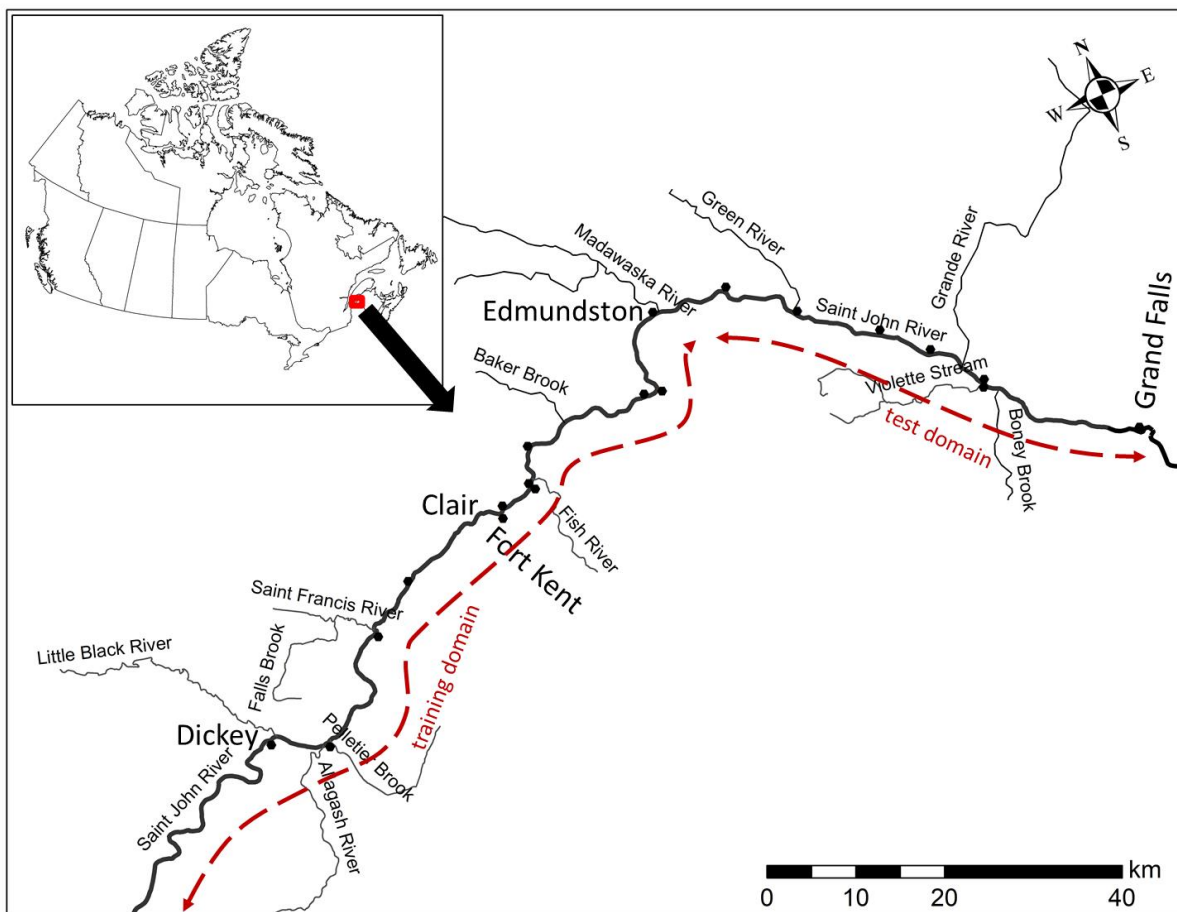


Figure 1: The Saint John River from Dickey to Grand Falls indicating the stretch of the training and test domains.

2.3 Geospatialisation of the selected parameters

A river polygon shapefile was created to develop a geospatial model using GIS software (ArcGIS). The geospatialization of the physical characteristics of the river was placed into a machine-learning algorithm to identify the cluster of various geomorphological features that had the most influence

on ice-jam formation. To derive various geomorphological variables, a centerline was constructed along the river to create stationary points at 100 metre intervals. Then, a parameter value was calculated for each stationary point. The river width was determined at each point by creating bank-to-bank transects (Figure 2).

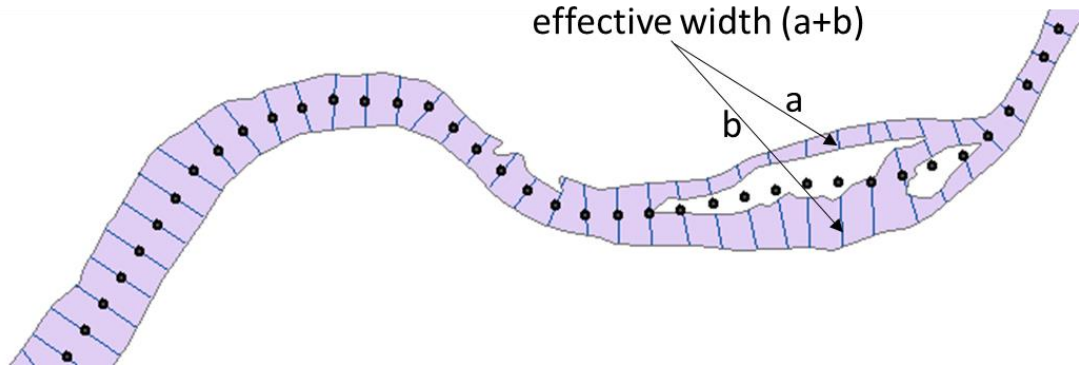


Figure 2: Extraction of the channel width from the river shapefile using the GIS tool.

For river sinuosity, a 200×200 m moving window at each 100 m segment was selected to capture the channel bend. The 200 m window was moved along each centerline point to calculate the channel sinuosity using:

$$\text{Sinuosity} = \frac{\text{actual flow path}}{\text{shortest path length}}$$

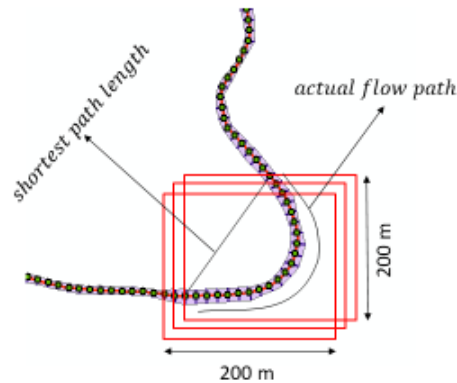


Figure 3: The estimation of the channel sinuosity.

River islands and bridge piers have a great influence on ice-jam formation. Since both of these features could split river channels into multiple sub-channels, they were incorporated using a shedding parameter index. For example, if an island splits a river channel into two sub-channels, the shedding factor was noted as 2 and if there was no island or bridge and the river channel was not divided, the shedding parameter index was marked as 1 (Figure 4).

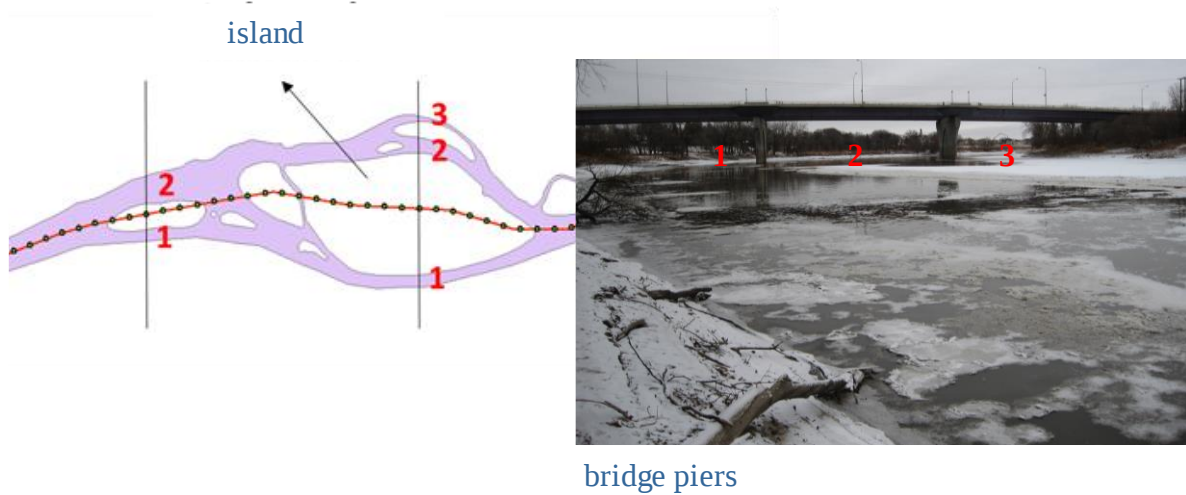


Figure 4: Indexing the shedding parameter (island and bridge) along the river channel
(photo taken by Karl-Erich Lindenschmidt, 4 December 2009)

Tributaries of a river can be a significant influential factor for ice-jam formation since they may contribute additional flow and broken ice at the confluence to form severe ice jams along the river during spring breakup. The tributary index was marked as 0 for no tributary and 1 for the existence of a tributary along the river (Figure 5).

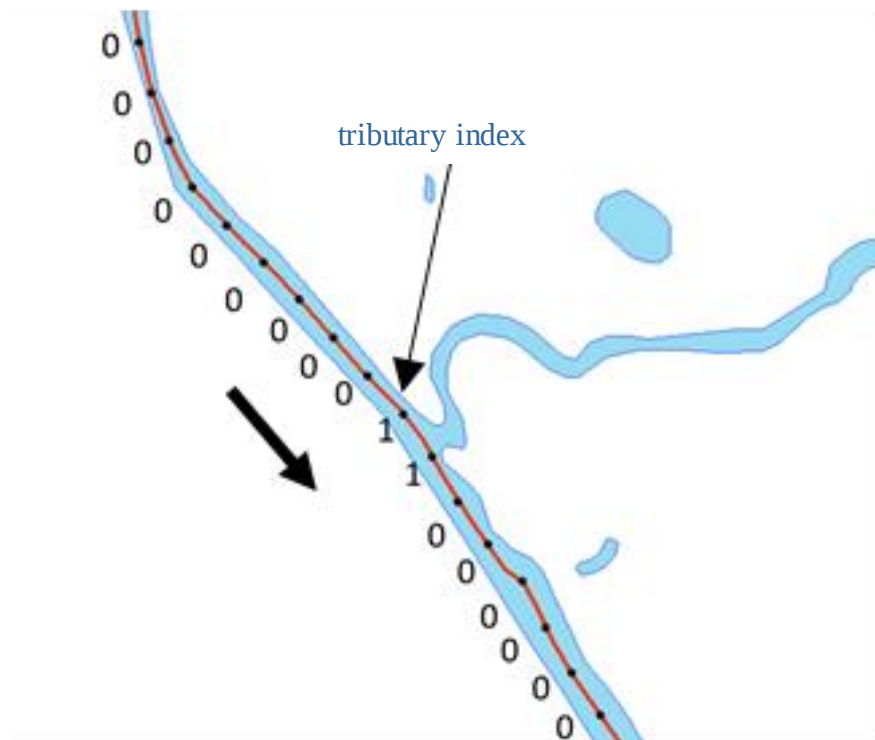


Figure 5: Allocating the tributary index.

A sudden drop in riverbed slope accelerates the tendency of consolidated ice covers to form jams, especially when the bed slope changes from steep to mild. For this particular model, river slope was estimated from the water profile with a solid ice cover surface simulated with the hydraulic model, RIVICE, which also provided interpolated maximum depths at 100 m intervals along the river (Figure 6). The solid ice cover was simulated using an average flow during the breakup.

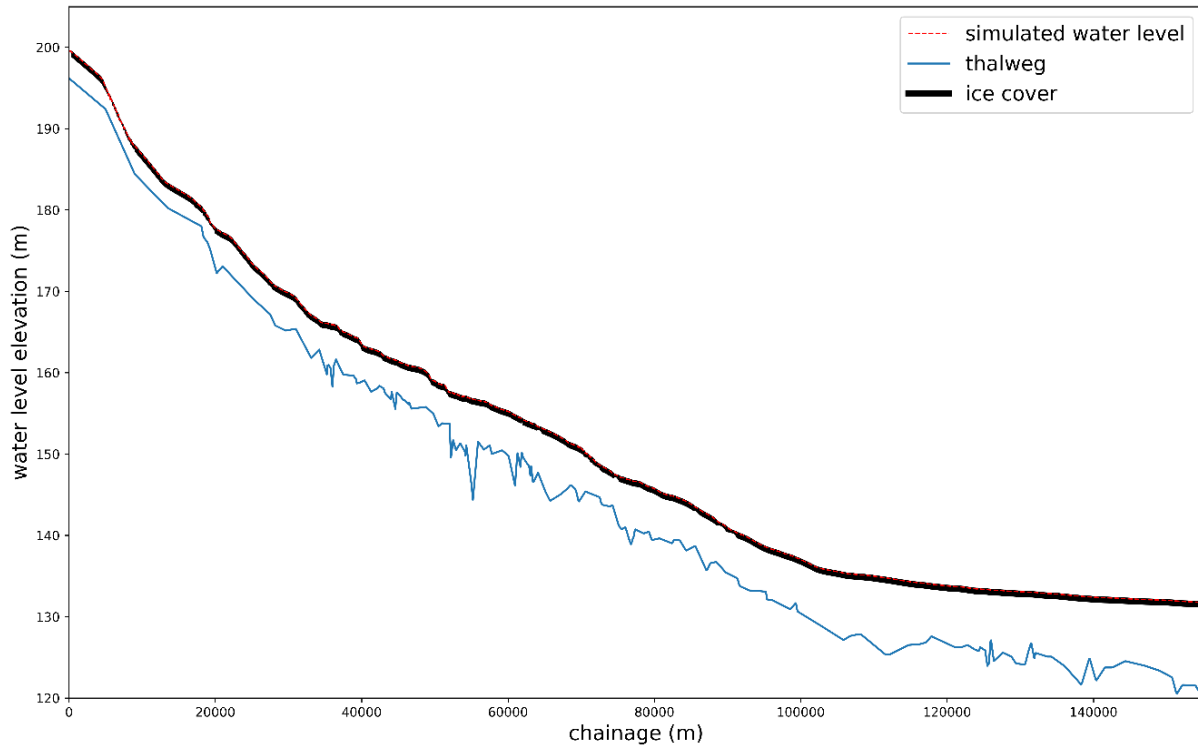


Figure 6: Simulated solid ice cover and riverbed elevation (thalweg) using the RIVICE model along the Saint John River.

2.4 K -means clustering algorithm

Once all the geospatial parameters were determined at centerline points, the dataset was divided into 2 subsets: the training set containing the data from Dickey to Edmundston and the test set containing the rest of the dataset from Edmundston to Grand Falls. Then, a simple machine learning tool was applied to both of the datasets to cluster the parameters using scikit-learn, a free machine learning library for the Python programming language. From this library, K-means clustering was used to analyze each parameter and identify the ice-jam predisposition index based on historical ice-jam locations. K-means clustering is one of the simplest and most popular unsupervised machine-learning algorithms that classify the dataset into K pre-defined distinct non-overlapping clusters (subgroups). The goal of the K-means clustering algorithm is to find clusters in the given input dataset, where K denotes the number of clusters, which is determined using the elbow method. The elbow method is a heuristic approach to calculating distortion score, the sum of square distances between each data point and its designated centroid.

2.5 Historical ice-jam locations and frequency

Historical ice-jam locations and frequencies are necessary to validate the geospatial model. Once we developed the preliminary model, the ice-jam predisposition index (e.g. high, medium and low) was identified based on these historical data. The historical ice-jam locations and their frequencies are available from the New Brunswick Department of Environment and Local Government (Mioc et al., 2014).

3 Results and validation

A K-means clustering algorithm was applied to estimate the optimal number of geomorphological clusters along the training stretch of the Saint John River from Dickey to Edmundston using the elbow method. Figure 7 demonstrates the elbow curve for the training dataset. The curve reaches an optimum minimum value at cluster 5, as there is no significant change in distortion score after this cluster number. Therefore, a total of five clusters was chosen to be optimal for this stretch.

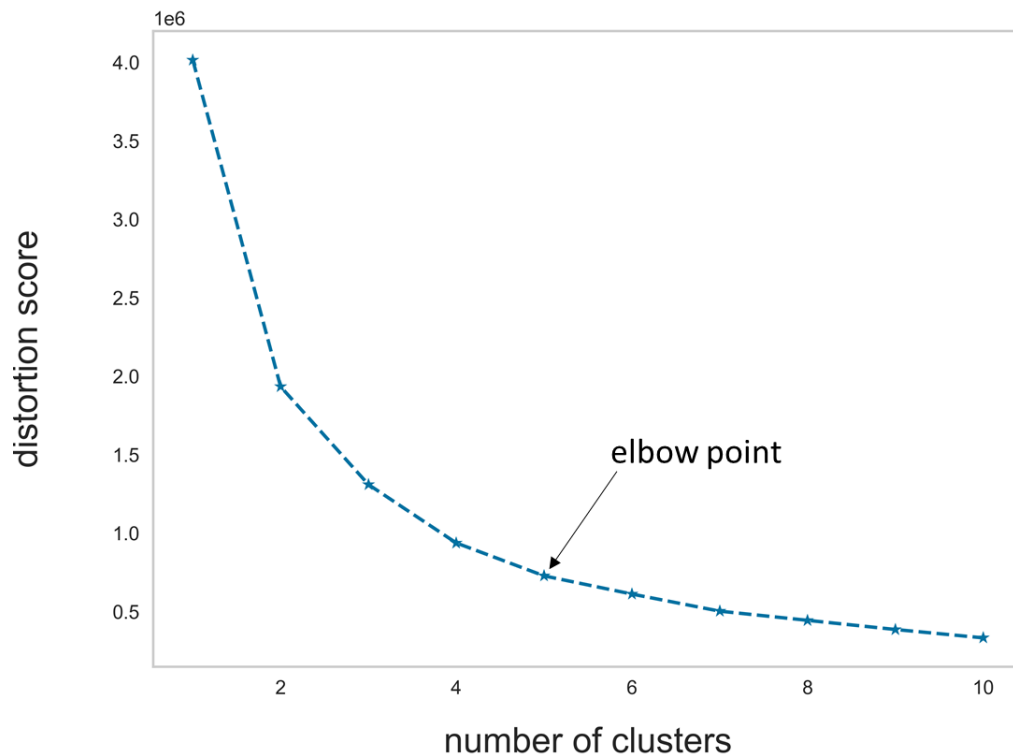


Figure 7 The elbow curve for the training dataset to select the number of optimum clusters.

Figure 8 illustrates the training model and the ice-jam predisposition indices of the different geomorphological clusters along the Saint John River from Dickey to Edmundston. Based on the historical ice-jam observation records, the distribution of clusters 1 and 4, coloured in yellow and purple, respectively, are the most susceptible to ice jams along this training stretch. Therefore, they were marked with a high ice-jam predisposition index for the river. Relatively fewer ice jams were found in clusters 0 and 3, coloured blue and red respectively, and they were designated with medium and low predisposition indices, respectively.

Figure 9 illustrates a simple analysis of the characteristics of different clusters based on normalized mean values of the geomorphological features. The result shows that the locations with clusters 1 and 4, where most of the historical ice jams were formed, are areas that are relatively narrow and shallow. Moreover, the locations of cluster 4 are also highly sinuous compared to the other clusters. The locations with clusters 0 and 3, where fewer ice jams occurred in the past, consisted of moderately narrow channels with quite a number of shedding indices. Although cluster 2 has a high number of shedding indices and tributaries, these locations are very deep and wide. Therefore, in these locations, the probability of ice-jam formation is very low.

Although a clustering approach equally combines and correlates all the geomorphological parameters and features to classify the river stretches, specific parameters or features may have large impacts on the ice-jam predisposition indices. For example, cluster 4 (high ice-jam predisposition index) combines the relatively narrow, shallow and highly sinuous river reaches, which are historically the most probable ice-jam formation locations (Figure 9). However, the same cluster 4 also combines relatively steeper reaches with fewer islands and tributaries leading to a lesser propensity for ice-jam formation. Therefore, three parameters (narrow, shallow and highly sinuous river reaches) play key roles in forming high ice-jam predisposition clusters.

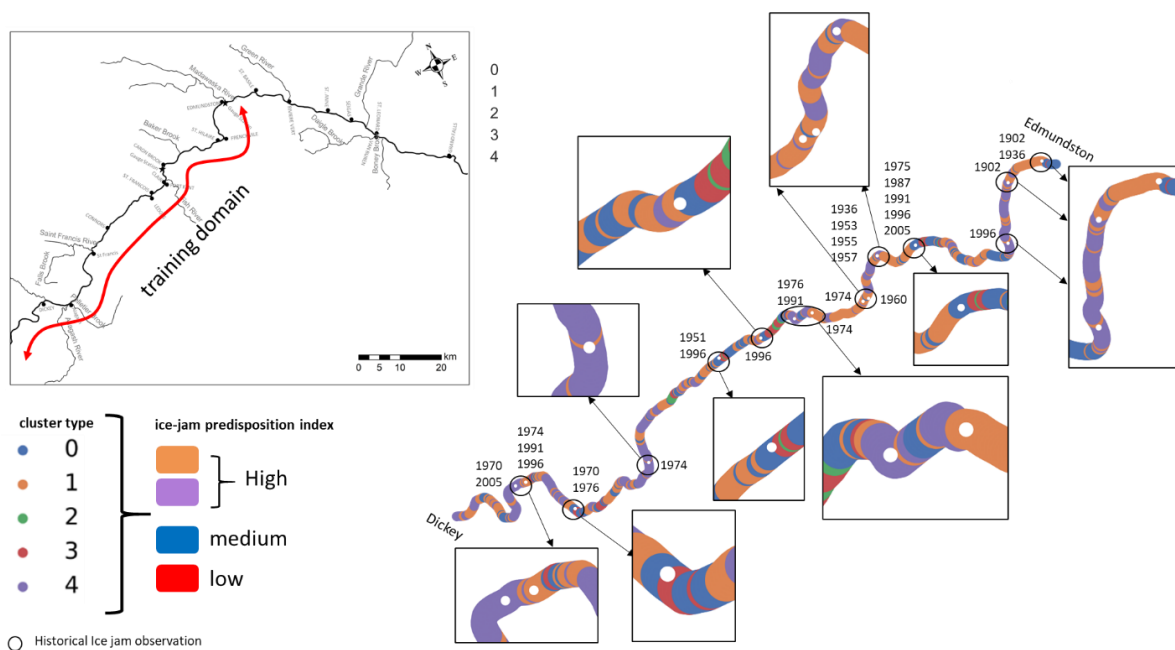


Figure 8 Training model domain along the Saint John River from Dickey to Edmundston.

Figure 10 illustrates the test model domain and its ice-jam predisposition indices. In this model domain, most of the historical ice jams occurred either in the yellow or purple clusters which were marked as high predisposition ice-jam locations in the training domain. Therefore, the model provides an accurate means of identifying the high predisposition locations along the study site. The accuracy of the test model was estimated to be 93%, as the model gave a false negative prediction for only 1 event out of 16 historical ice-jam events. Though the current model provides a high level of accuracy, it needs to be validated on other rivers with a larger number of observations.

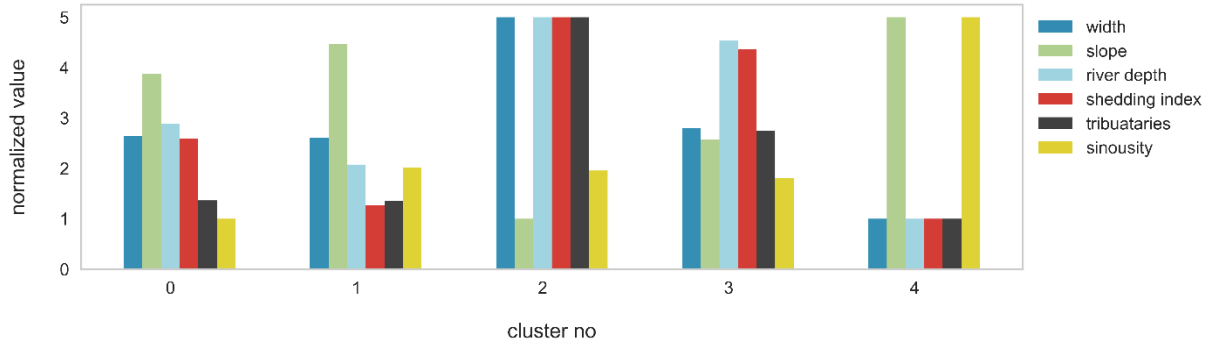


Figure 9 Geomorphological characteristics of the different clusters in the geospatial model.

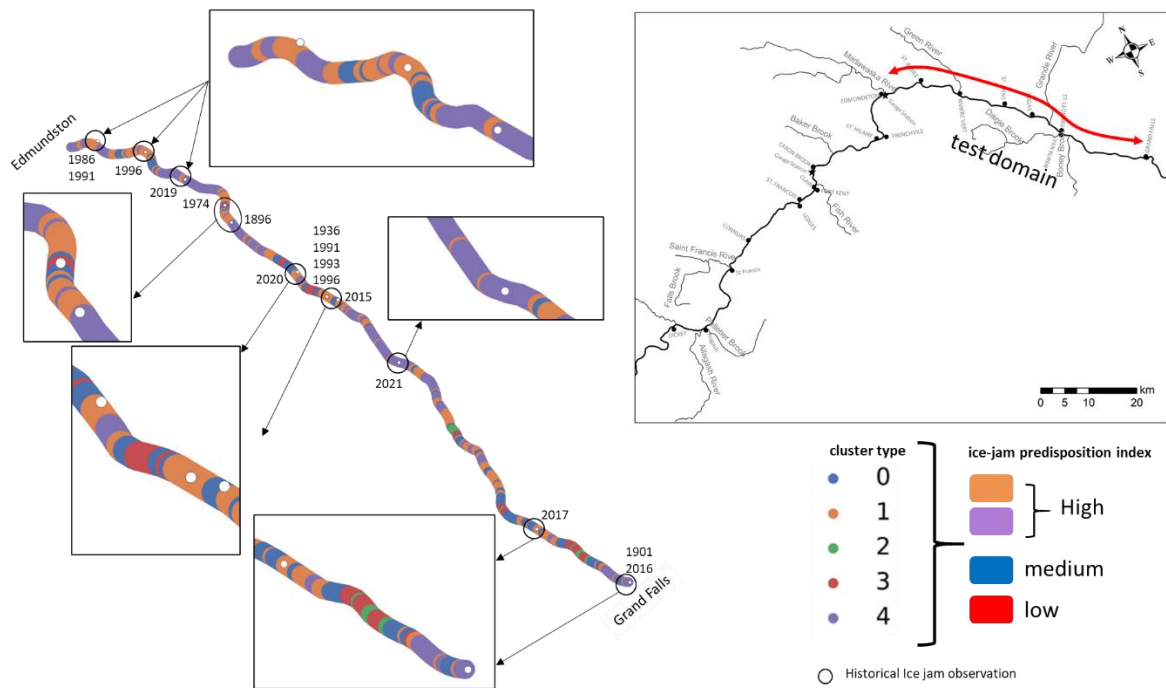


Figure 10 Test domain of the geospatial model along the Saint John River from Edmundston to Grand Falls.

4. Conclusion and Future Direction

A preliminary geospatial model based on various geomorphological parameters and features along the Saint John River was developed using the K-means clustering technique. The geospatial model is able to identify probable ice-jam locations along the river. Similar to previous studies, it is also notable that various common geomorphological parameters, such as narrow and sinuous channels with a relatively milder slope and the existence of islands, are conducive for most of the ice-jam formation.

Although the current geospatial model is able to identify the most potential locations of ice jams along the Saint John River from Dickey to Grand Falls, it is necessary to improve its capability to identify the real-time ice-jam locations for a given breakup season. To carry this out, hydraulic and river ice parameters can be incorporated into the model. Moreover, this study shows the potential of using a hydraulic model to develop a geospatial model by incorporating two parameters from the RIVICE hydrodynamic model. The future research goal is to incorporate many other river ice parameters (e.g. ice cover types, flow, velocity) to dynamically predict high propensity ice-jam locations in real-time.

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