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River predisposition to ice jams: a simplified geospatial model

Stéphane De Munck[1], Yves Gauthier[1], Monique Bernier[1], Karem Chokmani[1], and Serge Légaré[2]

1 Centre Eau Terre Environnement, Institut National de la Recherche Scientifique (INRS), Quebec City (Quebec), G1K 9A9, Canada
2 Ministère de la Sécurité publique (MSP), Quebec City (Quebec), G1V 2L2, Canada

Correspondence to: Y. Gauthier (yves.gauthier@ete.inrs.ca)

Abstract. The goal of this work was to develop a simplified geospatial model to estimate the predisposition of any river channel to ice jams. Rather than predicting river ice break up, the main question here was to predict where the broken up ice is susceptible to jam based on the river's geomorphological characteristics. Thus, six parameters referred to potential causes for ice jams in the literature were selected: presence of an island, narrowing of the channel, high sinuosity, presence of a bridge, confluence of rivers, and slope break. A GIS-based tool has been used to generate the aforementioned factors over regular-spaced segments along the entire channel using available geospatial data. An "Ice Jam Predisposition Index" (IJPI) was calculated by combining the weighted optimal factors. Three Canadian rivers (Province of Quebec) have been chosen as test sites. The resulting maps were assessed from historical observations and local knowledge. Results show 77% of the observed ice jam sites on record occurred in river sections that the model considered as having high or medium predisposition. This leaves 23% of false negative errors (missed occurrence). Between 7% and 11% of the highly "predisposed" river sections did not have an ice jam on record (false-positive errors). Potential improvements are discussed.

1 Introduction

Ice jams emerge from the accumulation of fragmented ice on a specific section of a river, obstructing the channel and restricting the flow. Ice jams mainly occur during the breakup season but can also form in the period of freeze-up or even during winter when precipitations cause a sudden increase of water levels and a partial dismantlement of the ice cover. The resulting floods are socio-economically costly as well as life threatening (Environment Canada, 2011). Many attempts have been made to develop reliable forecasting methods in order to provide early warnings and to mitigate the impacts of such events (White, 2003). However, existing forecast models are often site-specific: they combine numerous and complex triggering meteorological, hydrological and morphological factors (White, 2003). Moreover, when breakup occurs and ice starts to move downstream, another key question is: where would the released ice be susceptible to jam?

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The goal of this study is to provide some answers to the aforementioned question by developing a simplified geospatial model that would estimate the predisposition of a river channel to ice jams. The approach is based on the morphological characteristics of the channel (De Munck et al., 2011). It has been developed on three Canadian rivers from the Province of Quebec: the Chaudière River, the Saint-François River, and the L'Assomption River (Figure 1), which all flow to the Saint-Lawrence River. They also have a history of ice jams and frequent flooding of riverside municipalities.

The Chaudière and Saint-François rivers flow mostly northward, through the geological areas of the Appalachians and of the Saint-Lawrence lowlands. Their length and drainage area are comparable: 185 km over 6 682 km² for the Chaudière River and 210 km over 10 230 km² for the Saint-François River. The L'Assomption River flows 200 km southward over the Greenville geological province and the Saint-Lawrence lowlands. It drains a 4220 km² watershed.

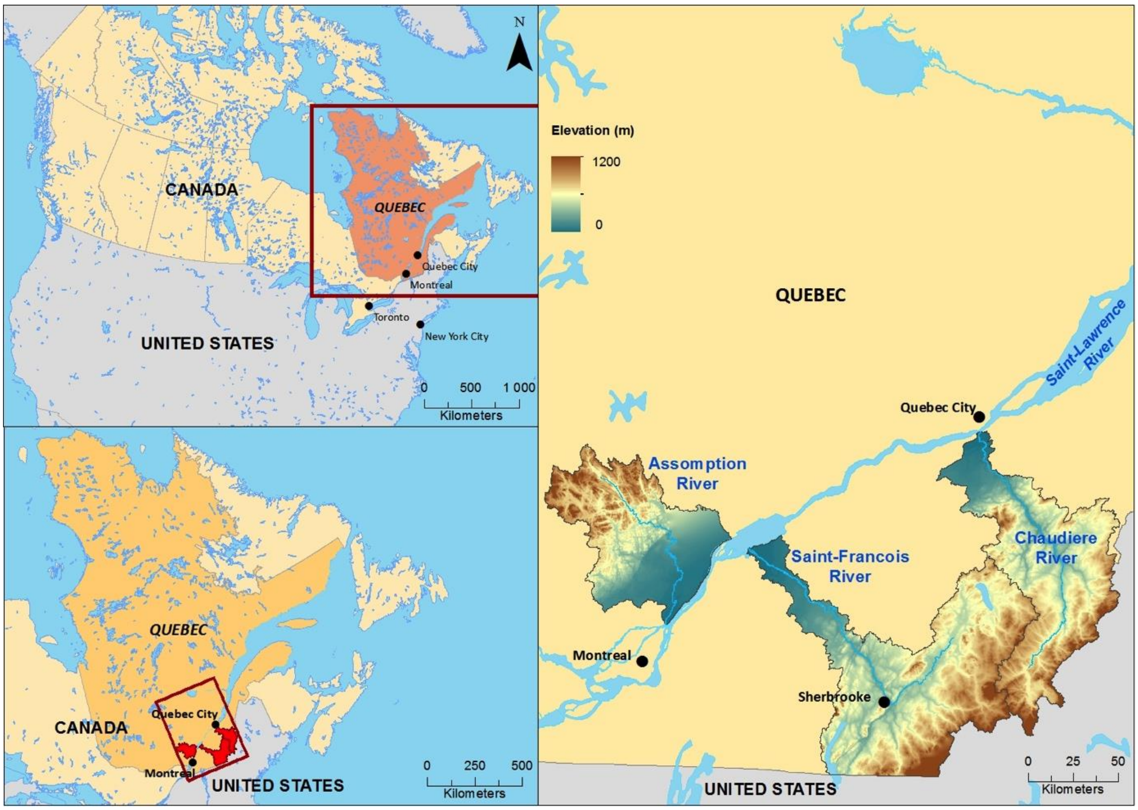

Figure 1: Watersheds of the Chaudière River, Saint-François River and L'Assomption River (Province of Quebec, Canada).

2 Background

According to Beltaos (1995), ice accumulation and jam occur where the volume of ice exceeds the transport capacity of the river. An ice jam is often initiated when at least two physiographic parameters having an impact on that transport capacity are present. The following parameters were the most often referred to (USACE, 1994; Environment Canada, 2011):

- Narrowing of the river channel: caused naturally or due to border ice (Beltaos, 1995);
- Presence of islands in the channel: Islands generally involve a narrowing of the main channel (Banshchikova, 2008) as well as a breaking slope from steep to mild. Thus moving ice is forced to slow down and to obstruct the channel;
- Presence of a bridge across the channel: A bridge is an obstacle which disturbs the natural flow of ice moving downstream, specifically when pillars are closer to each other. According to Urroz et al. (1994), the ratio of the distance between pillars by the channel width has to be high in order to have a smaller impact on the moving ice process;
- Meandering: Due to the centrifugal acceleration, the river flow in a channel that bends and loops have different speeds through the cross-section (Zufelt, 1988). Sinuous sections may initiate ice jams as the moving ice has to change its path toward the outside riverbank that creates increased friction;
- Tributaries: Narrow rivers usually respond more quickly to rising run off from precipitations compared to wider rivers. Quick response in narrow rivers involves a quicker increase of the water level, as well as an early breakup of the ice cover. This ice often moves downstream until reaching the intact ice cover of the wider river in which it flows, where the slope is generally milder. Thus, the ice from the tributary stops at the confluence with the main river, initiating an ice jam (Wuebben and Gagnon, 1995). The jamming may also be caused by merging ice runs or by the presence of a confluence bar (Ettema et al, 1999);
- Sudden slope changes: A change of the river bed slope from steep to mild is the typical case involved in ice jams. Due to the gravity force, the ice can lose its impetus when it reaches the milder slope, and can stall or arch across the river and initiate an ice jam (Wuebben and Gagnon, 1995);
- River bars (Banshchikova, 2008), or gravel bars (Bergeron et al., 2011): They are located on both sides of the sinuous thalweg (Bergeron et al., 2011). The presence of gravel deposits is usually an indication that the transport capacity of the river is reduced for both ice and sediment;
- Estuaries (Saint-Laurent et al., 2001): When the ice reaches the estuary of the river, the mild slope and slow flow can initiate an ice jam;
- Presence of an intact ice cover: When the ice breaks in a river section and encounters the strong resistance of an intact ice cover in a section downstream, ice jam can occur.

Kalinin (2008) conducted a qualitative and quantitative study of the first five parameters mentioned above. For the river he studied, he found that a narrowing of the channel was present in 90% of the ice jams reported, islands were present in 80% of cases and bends were there in 70% as well. He also observed that the simultaneous presence of at least two of these five factors is characteristic of frequent ice jams. According to Lindenschmidt and Das (2015), narrower, steeper and relatively straight channels are more susceptible to initiate breakup along the river. On the opposite, wider and mild slope sections of the river may have a persistent ice cover until the end of breakup. Therefore, the presence of an intact ice cover downstream would increase the risk of ice jams.

However, in this present study, only static parameters (mostly stable over time) will be considered for the geospatial model: narrowing of the channel, sinuosity, presence of an island, presence of a bridge, confluence of rivers and slope breaks. They are based on simple and relatively stable morphological characteristics and are the most documented in literature. They can be derived from easily available geospatial data. Dynamic parameters such as river depth and ice cover characteristics reflect rapidly changing conditions of flow and ice rather than the intrinsic morphological characteristics of the river channel. They are also more complex to obtain and not always available.

3 Methods

3.1 Geospatialization of the selected parameters

In this work, “geospatialization” is the spatial representation of a physical characteristic of the channel and its transformation into a potential ice-jamming factor. This was done using a standard Geographical Information System (ArcGIS software) and some specific tools developed in ArcObject through the FRAZIL project (Gauthier and al., 2008) for the support of winter hydraulic modeling and ice-jam early warning systems. These tools enable the determination of the river channel center line, its segmentation into equal length sections, calculation of the width, and calculation of channel sinuosity along the axis (Figure 2). Calculations were integrated along segments of equal length. Sections of 250m were found to be optimal considering the scale at which we evaluate channel characteristics and the size of ice jams. For the Chaudière, Saint-François and L’Assomption rivers, 444, 861, and 508 sections were created respectively. Input data comes from CanVec, a digital cartographic reference product of Natural Resources Canada (Natural Resources Canada, 2016), and the Quebec Topographic Database (BDTQ) (Énergie et Ressources Naturelles Québec, 2008). Shapefile layers include river channel, watershed, islands, bridges, rapids and elevations. However, for some rivers, the channel’s representation goes at some point, from a polygon to a line. Therefore we only processed the last 110 km of the Chaudière River and the last 127 km of the L’Assomption River. For the St-François River, the entire channel could be processed. From this information, three main ice jamming factors were calculated.

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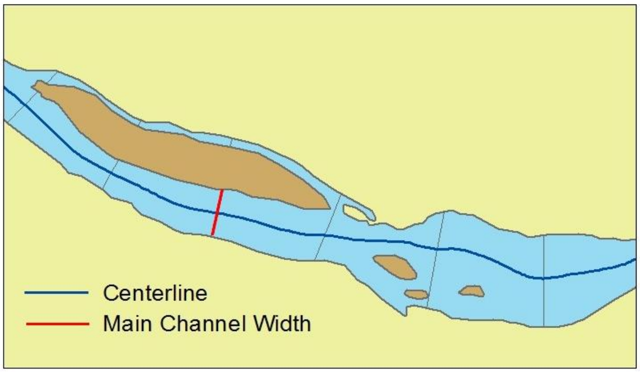

Figure 2: Spatial representation of the channel centerline, channel width and channel sections in presence of islands (from the FRAZIL tools).

3.1.1 Narrowing Index (NI)

The first factor combines four parameters into a single narrowing index: 1) natural changes in the channel width, 2) presence of bridges, 3) presence of islands and 4) presence of an incoming tributary. All are considered resulting in the narrowing of the channel section available for ice transit. However, some generalizations have to be made.

The presence of an island usually splits the river and often results in the narrowing of the main channel. The proposed model will focus on the main channel only. Although secondary channels may serve as outlets for ice being pushed from upstream, they are generally more solidly frozen and not involved as much in the ice jam event. The model will also assume that an island located in the middle of the channel has the same impact on restricting the ice movement than an island closer to the shore.

From a hydraulic point of view, the pillars of a bridge divide the main channel into several narrow channels, where the ice is more susceptible to jam. The proposed model initially considers a half reduction of the channel width when a bridge is crossing the river. An approximation is necessary because the formation of ice jams at bridges is a complex phenomenon, based on the balance between ice-driving and ice-resisting forces (Beltaos, 2006). Keeping half of the main channel width gives a substantial weight to bridges in the final predisposition model. This value could be adjusted later if the model overestimate or underestimate ice jams at bridges.

As discussed earlier, the major impact of a tributary is the potential input of ice (or even sediments) into the main channel that would also result in reducing the available space for ice transiting in that main channel. For approximation of this parameter into the model, the minimal width of the tributary at the outlet is subtracted from the main river width (Figure 3).

At the end, the Narrowing Index is calculated from the natural or corrected channel widths, for each 250m sections. When the width of the preceding section is smaller than that of the actual section (sections 5 and 6 in Figure 4) the index will have a value of 1 (no narrowing). When the width of the preceding section is larger than that of the actual section (sections 2 to 4 in Figure 4), the narrowing index is obtained by dividing the width of the actual section by the most recent maximum width of the upstream sections. A value tending towards 0 will indicate a stronger narrowing of the channel.

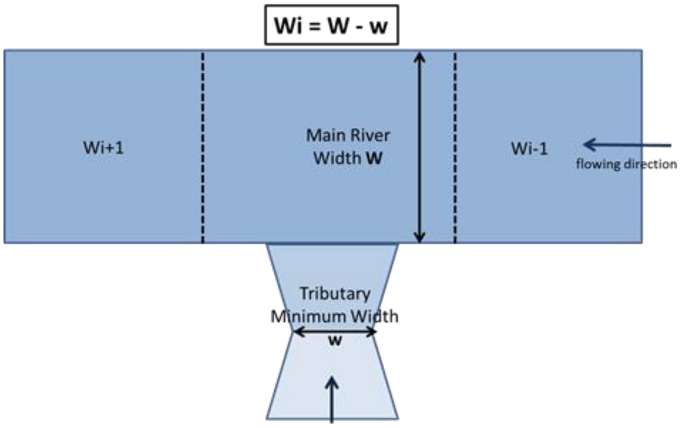

Figure 3: Modification of the channel's width due to incoming tributaries. For each segment the adjusted width (Wi) is obtained by subtracting the main river width (W) from the minimal width of the tributary at the outlet (w).

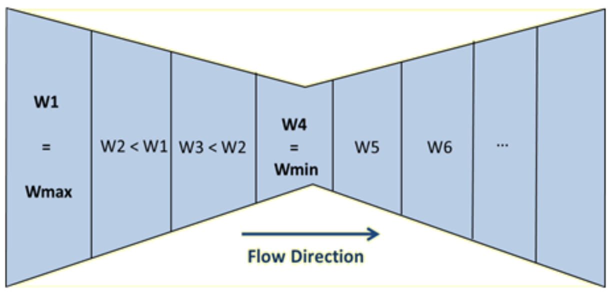

Figure 4: Approach used to calculate the Narrowing index, dividing the section's width by the upstream maximum width.

3.1.2 Sinuosity Index (SI)

The Frazil toolbox (Gauthier and al., 2008) is used to obtain a standardized sinuosity coefficient (Dutton, 1999) (*Sinuosity4* in Eq. (1)),

$$\text{Sinuosity4} = \sqrt{1 - \frac{1}{SV^2}} \qquad (1)$$

where, SV is the classic sinuosity coefficient ranged from 0 to 1. It is the curvilinear distance between two points divided by the direct linear distance between the same two points. Calculations are based on inflection points. A 0-value means that

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there is no sinuosity in the section. The standardized sinuosity of each 250m section is obtained by considering several sections together. If a section was overlaid by two different values of sinuosity, the mean value was calculated and retained.

3.1.3 Slope Break Index

A slope break index can be calculated based on the approximate channel surface altimetry from a Digital Elevation Model (DEM) (Eq. (2)).

$$\text{Slope Break Index} = \Delta \frac{\Delta\, Height}{\Delta\, Length} \tag{2}$$

However, the data from the 1:20 000 Quebec Topographical database are built over contour lines with a ±5 meter resolution. It can be argued that they would not provide a sufficiently accurate representation of the actual river slope. Complete bathymetric data for the rivers under study were not available. For this reason, this version of the model will not integrate the slope break index. However, an accurate LIDAR model could be used if available.

3.1.4 Ice jam dataset

The ice jam dataset is provided by the Quebec Ministry of Public Safety (MSP). The data comes from digital or paper event reports provided by local authorities under the jurisdiction of MSP (Données Québec, 2016). The database contains 950 ice jams reported in the province of Quebec from 1985 to 2016, with accurate or general geolocation. In our study, we focused on 118 historical observations: 61 ice jam reports on the Chaudière River, 33 on the St-François River and 24 on the L'Assomption River. The 61 ice jams listed on the Chaudière River were used as test sites for calibration of the conceptual model. Then validation of the model was performed over the other two rivers.

3.2 Conceptual model on the Chaudière River

The conceptual model proposed here integrates the narrowing index and the sinuosity index to establish the potential predisposition of a river channel to ice jams, the "Ice Jam Predisposition Index", IJPI.

3.2.1 Standardization of the index values

First, we standardized the range of values for each index. Each index was transposed into four classes, 0 to 3, from the weakest to the strongest impact on ice jam predisposition. The thresholds between these classes were determined using a K-Means clustering approach. Four clusters were created with squared Euclidian distances, replicated 5 times. Table 1 shows the thresholds established from the K-Means approach. The data from the three rivers were used in order to cover a larger range of values and to obtain indices that are more representative of the geomorphological diversity of the study areas.

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Table 1: Threshold values for the Narrowing and Sinuosity Indices, as determined by the K-Means approach.

	Narrowing Index	Sinuosity Index
Class 0		
	0.56	0.24
Class 1		
	0.77	0.46
Class 2		
	0.92	0.69
Class 3		

3.2.2 Weighting of the index values

The narrowing and sinuosity indices may contribute differently to the ice jamming process. To determine the weight of each index in the conceptual model, we have used the same approach as Kalinin (2008), which is to cross reference the ice jam occurrence from the historical dataset with the values of both indices at these sites. The ice jam occurrences on the Chaudière River were categorized into three classes: the “frequent” category was assigned to a section where at least two ice jams were listed in the dataset, while the “occasional” category was assigned to sections where only one ice jam was listed. Sections with no ice jam recorded were classified in the “rare” category. We then compare the frequent and occasional occurrences with the values of the narrowing and sinuosity indices at these river sections. As shown in Table 2, the Narrowing Index usually outnumbers the Sinuosity Index, indicating that it should have a more important weight in the model. If we cross reference sections with a frequent occurrence of ice jams with sections where both indices show the maximum value (class #3), we would obtain a ratio of 1.5 in favor of the Narrowing index. If we cross reference all sections where an ice jam was observed, with sections where both indices show a moderate or high value (class #2 and class #3), we would also obtain a ratio of 1.5 in favor of the Narrowing Index. A multicriterion analysis (Saaty, 1990) would then assign a weight of 0.60 to the Narrowing Index, and a weight of 0.40 to the Sinuosity Index.

Table 2: Comparison of river sections with reported ice jam events (frequent and occasional occurrences) with the narrowing and sinuosity indices at these locations. NI/SI is the ratio of the Narrowing Index (NI) on the Sinuosity Index (SI).

	Number of sections with a high Narrowing Index (NI)		Number of sections with a high Sinuosity Index (SI)		Ratio NI/SI	
Ice jams	Class 2	Class 3	Class 2	Class 3	Class 2	Class 3
Frequent	5	3	3	2	1,67	1,5
Occasional	4	4	3	5	1,33	0,8

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3.2.3 Ice Jam Predisposition Index (IJPI)

The final step of the model is the calculation of the Ice Jam Predisposition Index (IJPI). The standardized class value (V) attributed to each index (k) is multiplied by the weight factor (W) for that index. The sum of weighted values is divided by the sum of weighted maximal values (Eq. (3))

$$\text{Ice Jam Predisposition Index (IJPI)} = \frac{\sum_{k=1}^{2} V_k W_k}{\sum_{k=1}^{2} V_{max} W_k} \quad (3)$$

According to the maximum value (Vmax = 3) and the normalized weight factor, equation 3 can be simplified to Eq. (4).

$$\text{Ice Jam Predisposition Index (IJPI)} = \frac{\sum_{k=1}^{2} V_k W_k}{3} \quad (4)$$

The values resulting from the ice jam predisposition index (IJPI) range from 0 (no predisposition to ice jam) to 1 (very high predisposition to ice jam). Table 3 shows the 14 possible IJPI values obtained from equation 4. We used boxplots to study the statistical distribution of the IJPI values, on sections of the Chaudière River with listed ice jams and on sections without ice jam (Figure 5). To simplify the results of the model into three main classes (high, medium and low predisposition to ice jams), we used the median and the third quartiles of IJPI values as thresholds: IJPI≥0.54; 0.40≤IJPI<0.54; IJPI<0.40.

Table 3: Possible results from the Ice Jam Predisposition Index (IJPI). Values highlighted in light grey (IJPI≥0.40) were selected as representing a moderate predisposition to ice jams while values highlighted in dark grey (IJPI≥0.54) would represent a strong predisposition to ice jams.

Sinuosity Index \ Narrowing Index	0	1	2	3
0	0	0.20	0.40	0.60
1	0.13	0.33	0.53	0.73
2	0.26	0.46	0.66	0.86
3	0.40	0.60	0.80	1

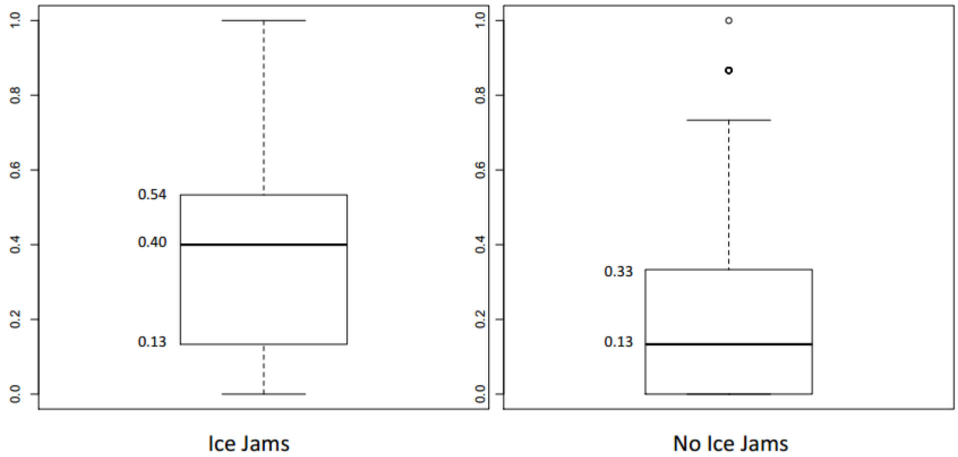

Figure 5: Boxplot of the IJPI values on the Chaudière River. Graph on the left is for 250m river sections where ice jams were reported. Graph on the right is for river sections with no ice jam listed. Numbers represent the median, first and third quartiles.

4 Results and discussion

4.1 Chaudière River

Figure 6 shows the results of the model applied on all 250 m sections of the Chaudière River (calibration site). High predisposition is shown in red, medium predisposition in orange and low predisposition in green. Locations of reported ice jams are indicated with thumbtacks. The symbol is blue (correct assessment) when the ice jam falls into a section with a medium or high predisposition. It is red (false-negative) when the reported ice jam falls into a section with a low predisposition. False-negative errors would arise if the model gives a low predisposition to ice jam in a section where ice jams have been reported. On the opposite, a false-positive error would give a high value of predisposition in a section where no ice jam was observed.

In total (Table 4), the model indicates that 51 of the 444 sections (11%) would have a high predisposition for ice jams, 69 sections (16%) would have a medium predisposition and 324 sections would be at low risk. Of the 61 reported ice jams on the Chaudière River, 20 (33%) are located on sections with a high predisposition, 23 (38%) are on a section with a moderate predisposition and 18 (29%) are on sections with low predisposition. These 18 sightings represent the false-negative results or where the risk of ice jam was underestimated. Table 4 also shows that of these 18 cases, 12 are related to the presence of a tributary in the section. This could indicate that the model underestimate the role of tributaries in the initiation of an ice jam. This might be due to the fact that the model only considers the tributary as a narrowing feature and not as a source of incoming ice runs.

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Table 4 finally shows that over the river, 32 sections (7%) were classified with having a high predisposition to ice jams but without any event reported. For moderate predisposition, it concerns 46 sections (10%). These cases are the false-positive results. This doesn't mean that the model is necessarily wrong. It is possible that ice jams on some of these sections have never been reported. It is often the case in isolated areas. Or, since the model gives a "predisposition", it doesn't mean that an ice jam will automatically occur or as already occurred. So the false-positive results are to be considered objectively. But it is also probable that the model is also overestimating in some areas. For example, when looking at the false-positives errors with a high predisposition index (32 sections), we can determine that in each case the class of the Narrowing Index is greater than the class of the Sinuosity Index. This would indicate that we may overestimate the impact of the narrowing of the channel. The false-positives can be caused by all types of narrowing but we found that 5 of the "faulty" sections have a bridge. Considering that there are only a dozen of bridges in the study area, this number tends to indicate that the model's simplification of bridges could be improved.

However, if we look again at Figure 6 we can also see that almost all false-negative errors (red thumbnails) are only within a short distance of sections with a high predisposition Index. Therefore, even in a conceptual form and by using only non-dynamic parameters, the model seems to correctly represent the nature of the river and the areas where the morphology has an impact on ice jam occurrence.

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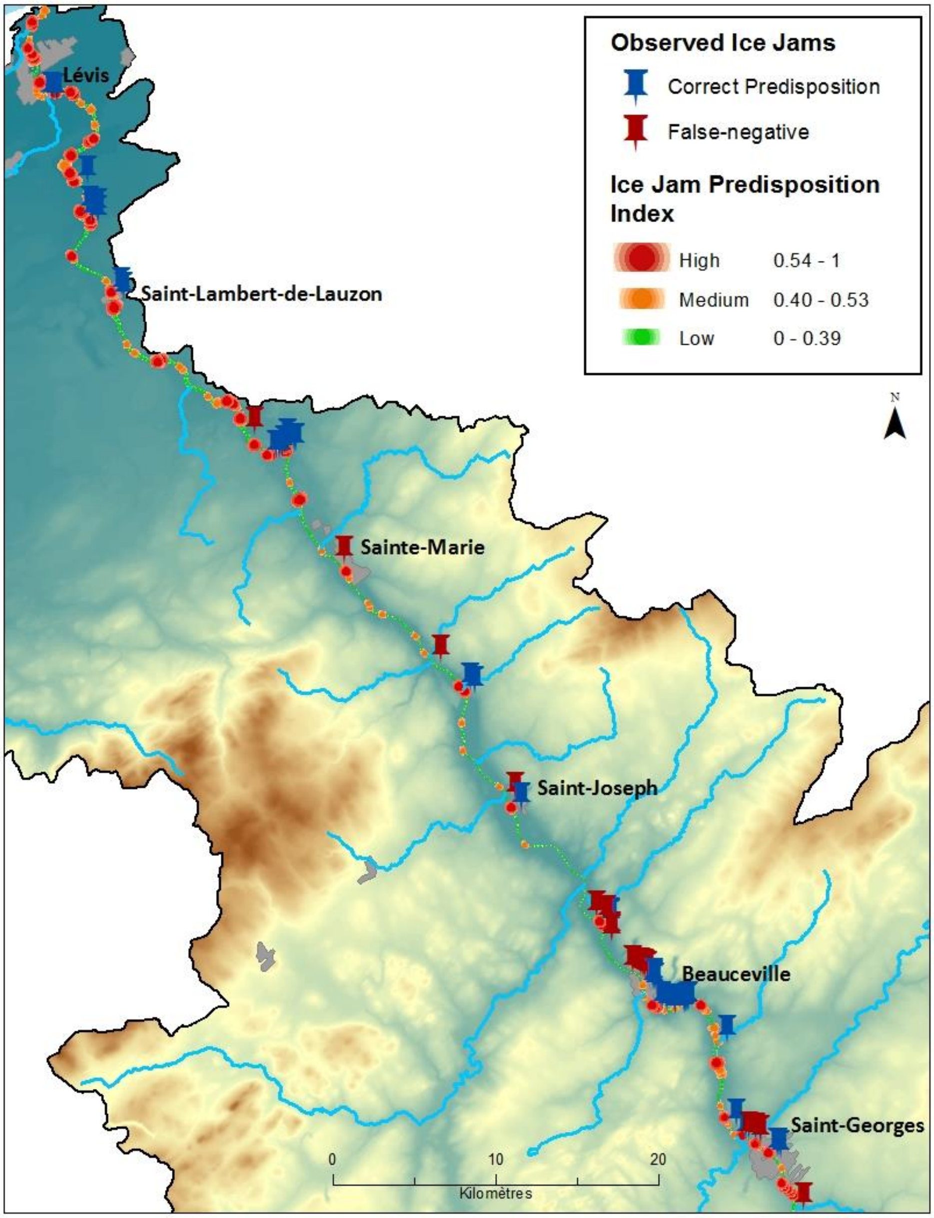

230 **Figure 6: Map of the model results on the Chaudière River, over 250m sections. Flow is from south to north. Thumbnails are the locations of reported ice jams. Blue is used when the ice jam falls on a section with a moderate to high predisposition (correct assessment). Red is used when the ice jam falls on a section with a low predisposition (false-negative error).**

Table 4: Results and accuracy of the IJPI on the Chaudière River

Model results	Number of river sections		Reported ice jams
High predisposition	51/444	(11%)	20 (33%)
Medium predisposition	69/444	(16%)	23 (38%)
Low predisposition	324/444	(73%)	18 (29%)

False negative errors				
Features present on river sections with false-negative errors				
Bridge	Island	Tributary	Natural narrowing	No specific feature
-	-	12	-	6

False-positive errors		
River sections with high predisposition but no ice jam reported	32/444	7%
River sections with medium predisposition but no ice jam reported	46/444	10%

4.2 Saint-François River

As mentioned earlier, the Saint-François River is comparable to the Chaudière River. Both flow mostly northward, through the same geological region, and have similar channel length and drainage areas. Results for the IJPI on the St-François River are shown in Figure 7 with the 33 reported ice jams extracted from the database (thumbnails). As can be seen in Table 5 the percentages of sections classified as high, moderate or low predisposition to ice jams are similar to the Chaudière River. Of the 33 reported ice jams on the St-François River, 11 (33%) are located on sections with a high predisposition, 13 (40%) are on a section with a moderate predisposition and 9 (27%) are on sections with low predisposition (false-negatives). These percentages are similar to the results on the Chaudière River. The number of sections with false-positive results is similar also (17% vs 20%). However, when looking at the false-positives errors with a high predisposition index (79 sections), only 46 show that the Narrowing Index is greater than the class of the Sinuosity Index. But again, the number of “faulty” sections with the presence of a bridge (12) is quite high since there are around 20 bridges on the St-François River.

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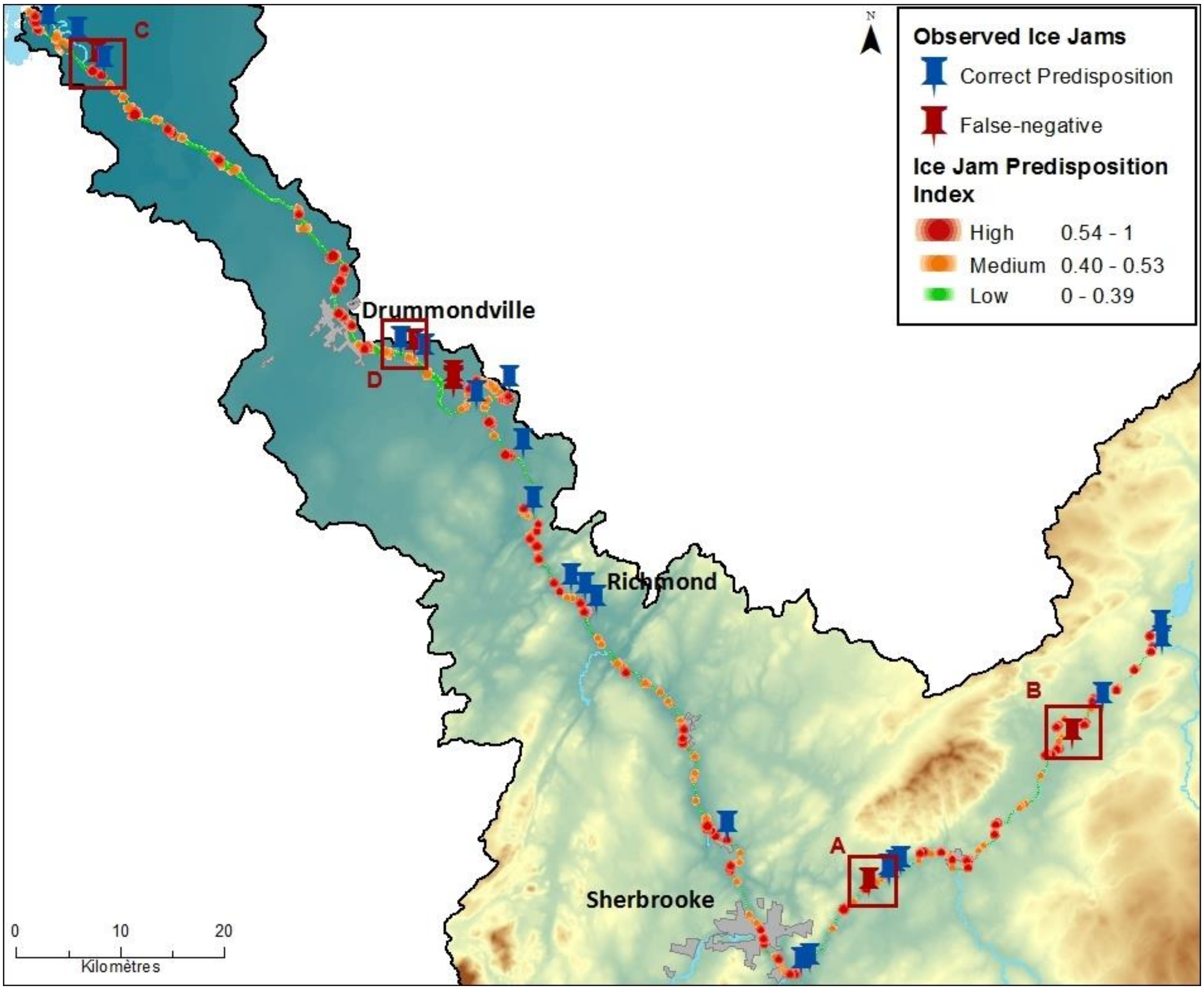

250 **Figure 7: Map of the model results on the St-François River, over 250m sections. Flow is from south to north. Thumbnails are the locations of reported ice jams. Blue is used when the ice jam falls on a section with a moderate to high predisposition (correct assessment). Red is used when the ice jam falls on a section with a low predisposition (false-negative error). Red frames delimit areas zoomed on** Erreur ! Source du renvoi introuvable. **to** Erreur ! Source du renvoi introuvable.**.**

Table 5: Results and accuracy of the IJPI on the Saint-François River

Model results	**Number of river sections**		**Reported ice jams**
High predisposition	93/861	11%	11 (33%)
Medium predisposition	132/861	15%	13 (40%)
Low predisposition	636/861	74%	**9 (27%)**
False negative errors			
Parameters present on river sections with false-negative errors			

Bridge	Island	Tributary	Natural narrowing	No specific feature
-	-	3	-	6

False-positive errors		
River sections with high predisposition but no ice jam reported	79/861	9%
River sections with medium predisposition but no ice jam reported	96/861	11%

In the next figures, we take a closer look at some of the false-negative errors on the St-François River. These omissions are more significant in terms of public safety. They mean that the model is missing something. In site A (Figure 8) there seem to be shallow sections where sand islands might grow bigger during low flow. Sand bars are a common location for ice jams. However, this parameter is directly correlated to the river depth, which is variable during the year. Hence, it is not considered in this model. In sites B and C (Figure 9), the model seems to underestimate the impact of the presence of islands in the channel.

Let's also note that if we can't identify with certainty the cause of a false-negative error, either from channel characteristics or from model generalization (Site D, Figure 10), there is still the possibility that the ice jam was initiated by the presence of an intact ice cover. According to Lindenschmidt and Das (2015), wider and mild slope sections of the river are more susceptible to have a persistent ice cover until the end of breakup. Again, this is a dynamic parameter, which is not considered by the model.

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4.3 L'Assomption River

We could expect to get different results from the L'Assomption River, as it flows southward in a different geological area and it presents a much higher sinuosity. Figure 11 shows the results of IJPI on the L'Assomption River. According to Table 6 the percentage of sections classified as having a high or moderate predisposition to ice jams is higher by about 20% compared with the two other rivers. Of the 24 reported ice jams on the L'Assomption River, 14 (58%) are located on sections with a high predisposition and 10 (42%) are on a section with a moderate predisposition. There are no false-negatives. However, with more sections at risk and a smaller ice jam dataset, false-positive errors are naturally higher. As expected with this meandering river channel, more false-positive errors are on sections where the Sinuosity Index is greater than the Narrowing Index. And again, the bridges seem to create some overestimation of the risk as 8 false-positives are on sections where a bridge is present (on a total of 14 bridges over the study area).

Figure 8: A false-negative error on the St-François River and its potential link to the presence of sand bars. On the left, results from the predisposition model (see legend on Figure 7). The arrow indicates flow direction. On the right, background image from Google Earth.

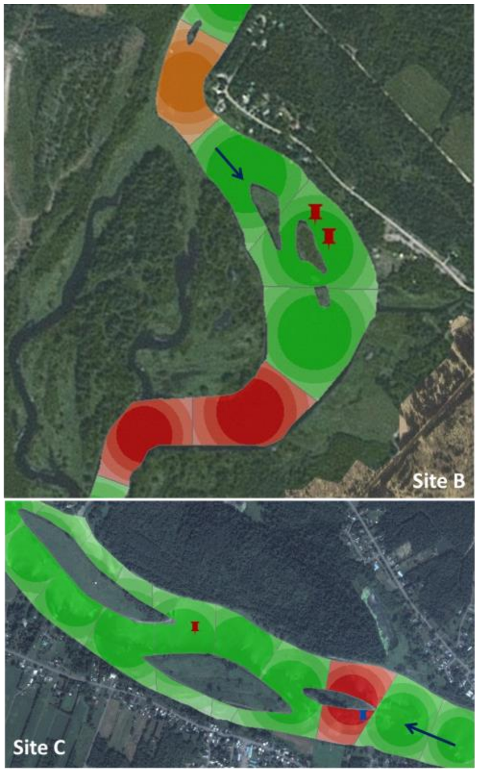

Figure 9: False-negative errors on the St-François River and their potential link to the presence of islands. The arrow indicates flow direction.

Figure 10: False-negative error on the St-François River with no apparent explanation. The arrow indicates flow direction.

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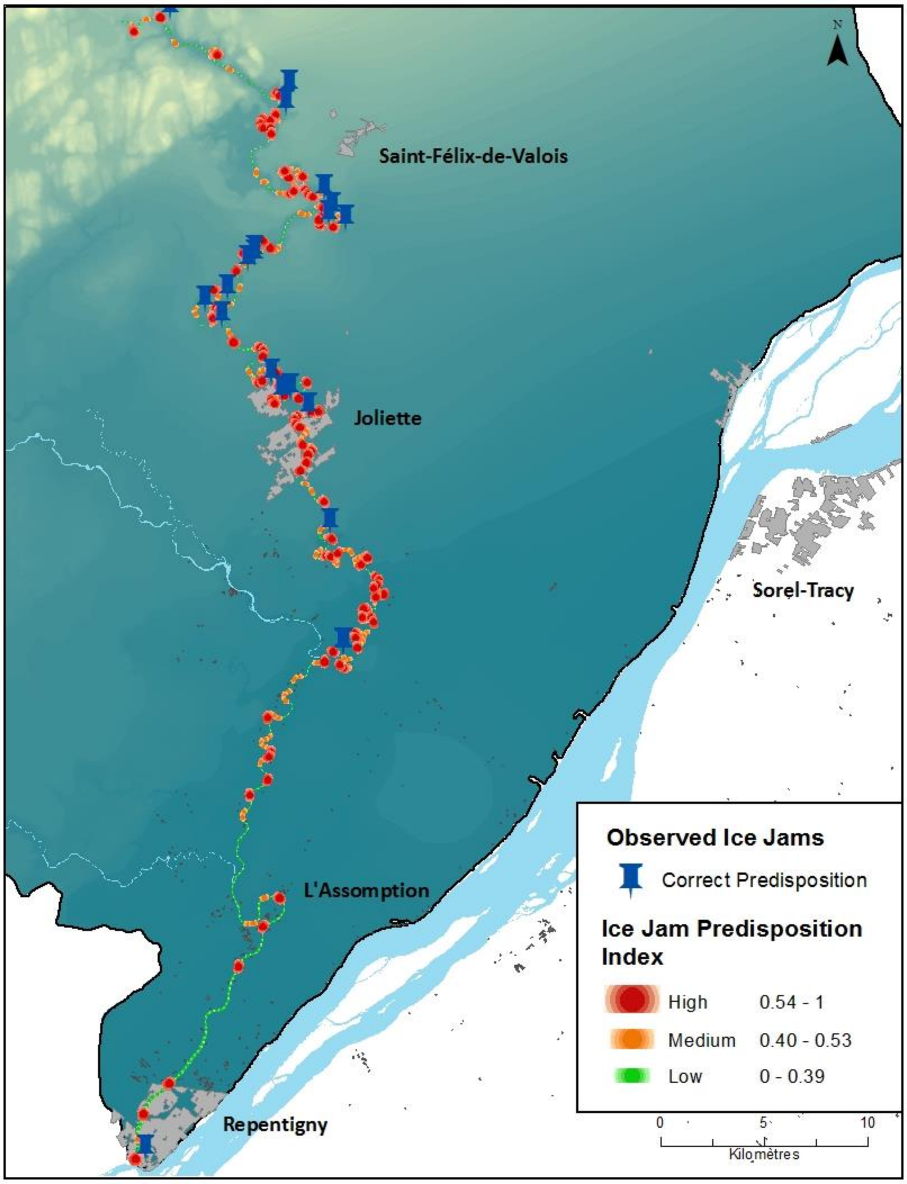

295 **Figure 11: Map of the model results on the L'Assomption River, over 250m sections. Flow is from south to north. Thumbnails are the locations of reported ice jams. Blue is used when the ice jam falls on a section with a moderate to high predisposition (correct assessment). Red is used when the ice jam falls on a section with a low predisposition (false-negative error).**

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Table 6: Results and accuracy of the IJPI on the L'Assomption River

Model results	**Number of river sections**		**Reported ice jams**
High predisposition	98/508	19%	14 (58%)
Medium predisposition	133/508	26%	10 (42%)
Low predisposition	277/508	55%	0
False-positive errors			
River sections with high predisposition but no ice jam reported	55/508	11%	
River sections with medium predisposition but no ice jam reported	100/508	20%	

5 Conclusions

A geospatial model for estimating a river's predisposition to ice jams was proposed. Only static parameters such as channel width, sinuosity and slope were considered as key features for the model. For simplification of the model, four factors were integrated into a single Narrowing index: natural narrowing, presence of islands and bridges and incoming tributaries. A Sinuosity index was calculated. A slope break index was proposed but had to be discarded in this version of the model due to the accuracy of the available elevation data. Each index was standardized and given a weight. Calibration was done on the Chaudière River and validation was performed on the Saint-François and L'Assomption Rivers in Quebec, Canada. The model was applied on 250m long river sections. The development and validation phases were supported by the ice jam database of the Quebec Ministry of Public Safety, with historical observations from 1985 to 2016. The model or Ice Jam Predisposition Index (IJPI) was applied over the three rivers under study.

The model produced between 11 and 19% of river sections classed as having a high predisposition to ice jams and between 15 and 26% of river sections presenting a moderate risk. When compared to the historical observations, most reported ice jams fall into these sections (71% on the Chaudière River, 73% on the St-François River and 100% on the L'Assomption River). Ice jams that happened on low predisposition areas are called false-negative errors. A majority of these errors are nonetheless located very close to sections with a high predisposition. However, results tend to show that the model underestimate the role of tributaries in the initiation of an ice jam. Some errors left unexplained could be related to dynamic parameters not integrated into the model such as bathymetry and the presence of an intact ice cover.

River sections that are categorized with a predisposition to ice jam but where no ice jam was reported are called false-positive results (17% for the Chaudière River, 20% for the St-François River and 31% for the L'Assomption River). They are not necessarily errors since the historical dataset is not exhaustive and because a predisposition is not a certainty. However, the results show that the model could overestimate the impact of the Narrowing Index, particularly in the way it deals with the presence of bridges.

Overall, the results of this geospatial model are very interesting, considering its level of simplification. Having applied the model over three different rivers ensures a certain degree of exportability to the approach. However, it must be noted that the model is not developed for ice jams occurring from frazil accumulation, without a breakup event

In view of these results, the next step will be to build an automated version of the model in order to easily vary all the parameters and evaluate the impact of such adjustments on reducing the false and positive errors. Afterward, it will have to be tested on more different environments and types of rivers - for example using the US Ice Jam database, as no such database is yet available in other provinces in Canada. Even in its actual version, the model is already providing valuable information to the Quebec Ministry of Public Safety and to the municipalities located along the studied rivers. In addition to forecasting ice jam flooding, such a model could also bring information for land planning, zoning, bridge construction or insurance evaluation. Future work would include the integration of the model within an ice jam vigilance and alert system, combining predisposition, meteorological conditions and ice status.

Competing interests

The authors declare that they have no conflict of interest.

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