River predisposition to ice jams: a simplified geospatial model

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Abstract. Floods resulting from river ice jams pose a great risk to many riverside municipalities in Canada. The location of an ice jam is mainly influenced by channel morphology. The goal of this work was therefore to develop a simplified geospatial model to estimate the predisposition of a river channel to ice jams. Rather than predicting river ice break up, the main question here was to predict where the broken 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 initially 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 was 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) were 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 cases). Results, limitations and potential improvements are discussed.

1 Introduction

Ice jams result from the accumulation of fragmented ice on a 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 rain events cause a sudden increase of water levels and a dismantlement of the ice cover. The resulting floods can be socio-economically costly as well as life threatening (Beltaos and Prowse, 2001; 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; Mahabir et al, 2007; White, 2009). However, existing forecast models are often site-specific: they combine numerous and complex triggering meteorological, hydrological and morphological factors (White,

Commentaire [GY1]: All corrections were made.
All comments from reviewers have been addressed.
Sections: Background, Method and Conclusion have been rewritten accordingly.
All figures have been improved

To follow the nature of the changes: Highlighted text is where/how we addressed specific comments from reviewers. When not specified, Comment refers to reviewer #2.

Detailed comments and replies are at the end of this document.

Commentaire [GY2]: Comment 14

Commentaire [GY3]: Comment 15

Commentaire [GY4]: Comment 16

2003; Beltaos, 2009; Bergeron et al, 2011). Moreover, when breakup occurs and ice starts to move downstream, another key question is: where would the released ice be susceptible to jamming? 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. This is not a physical model simulating the processes of ice jamming but rather an approach based on some common knowledge about the general causes of ice jams and their relationship to the morphological characteristics of the channel, within a 2D spatial representation (De Munck et al., 2011). Being developed for an eventual application over large areas and multiple rivers, the geospatial model uses simplifications and provide a “first level” assessment of the predisposition to ice jam along the river channel. 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 each have a history of ice jams and relatively 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 Canadian Shield and the Saint-Lawrence lowlands. It drains a 4220 km² watershed.

2 Background

According to Shen and Lianwu (2003), the key mechanism of the initiation of an ice jam at a river section is the convergence of ice motion, or when the incoming ice discharge exceeds the outgoing ice discharge. The convergence of ice flow can be produced by the reduction in driving forces and the increase in resistance forces to the ice motion when the ice run is not impeded by an intact ice cover. Both changes in driving and resistance forces are governed by the river geometry. In the literature, there is a consensus about the channel characteristics which can result in a reduction of ice transport capacity. Shen and Lianwu (2003) say that a reduction in channel slope or an increase in channel cross-section area, that is, a reduction in current velocity, will reduce the driving forces. On the other hand, a reduction in channel top width, the existence of meandering and braided sections, and shoals or islands in the channel will increase the resistance to the ice flow. According to US Army Corp of Engineers (2002), any river section where the slope decreases is a possible location for ice jamming. During freeze-up, the slower moving reaches freeze first and so will have a thicker ice cover come breakup. Another possible location might be a constriction in the channel, either natural, such as at a bend or at islands, or at man-made features, such as bridges. A third typical location is a shallow reach, where the ice can freeze to bottom bars or boulders and will not be lifted and moved by the increased water flow. According to Beltaos (1995; 2008), theoretical analysis and experience suggest that sharp bends, sudden reduction in slope, or constrictions, are frequent ice jamming sites, along with areas where the ice cover may be relatively thick and strong. According to Environment Canada (2011), there are

Commentaire [GY5]: Comments 6, 19, 20
Section rewritten, added references

Commentaire [GY6]: Comment 25

Commentaire [GY7]: Comment 26

locations which are more susceptible to ice jam formation than others. These include the confluence of two rivers, channel constrictions, sharp bends, islands, bridge piers, shallow river reaches, the edge of a solid ice cover, and at sudden changes in the slope of the water surface. Often ice jams are caused by a combination of two or more of these factors. According to Ettema et al (1999), by virtue of their role in connecting channels and thereby concentrating ice within a watershed, confluences are perceived as locations especially prone to the occurrence of 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.

We can therefore summarize the key parameters leading to ice congestion and ice jam as:

- Reduction in channel slope or slope break
- Reduction in channel top width (naturally or due to border ice)
- Constriction in the channel from bends, meandering, islands, bridges
- Presence of shallow reaches and bottom bars
- Presence of an intact ice cover.

We should add that although ice congestion is the key parameter that leads to ice jams, an ice run can also simply be stopped by an obstacle, such as an intact ice cover, a bridge or an island.

Kalinin (2008) conducted a qualitative and quantitative study of several parameters mentioned above. On the rivers of the Votkinsk reservoir catchment (Russia), 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.

To estimate a channel predisposition to ice jam, we will therefore consider: narrowing of the channel, sinuosity, presence of an island, presence of a bridge, confluence of rivers and slope breaks. These parameters are based on simple and relatively stable morphological characteristics and can be derived from easily available geospatial data. Shallow reaches and bottom bars are linked to water depth, which is variable throughout the year. The presence of an intact ice cover is also variable through time. For this reason, and because that bathymetry and ice maps are not available on a large scale, these two parameters will not be considered in this study. However, they are often linked to the morphological characteristics of the river channel (Turcotte and Morse, 2013).

Commentaire [GY8]: Comments 10
18, 26

Commentaire [GY9]: As requested

Commentaire [GY10]: Comments 2
26

Commentaire [GY11]: Comment 2

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 centerline, 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 channel characteristics vary and the size of ice jams (hundreds of meters to kilometers (Beltaos, 2008)). Shorter sections overestimate narrowing and underestimate sinuosity. Long sections tend to underestimate narrowing and the impact of small features (islands, bridges). A variable length based on the homogeneity of the channel morphology could be an interesting avenue but it would have to be developed as a separate study.

Therefore, for the Chaudière, Saint-François and L’Assomption rivers, 444, 861, and 508 sections of 250m were created respectively. Input data came 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). The planimetric accuracy of these dataset is better than 2m. Shapefile layers include river channel, watershed, vegetated islands, bridges, rapids and elevations.

Note that for some rivers, when the upstream channel becomes very narrow, data representation can change from a polygon to a line and hence, we do not apply the model pass this point. Metadata do not indicate the minimal channel width represented by polygons in the dataset. But for the three rivers in this study we calculated that all sections in a polygon format were over 20m wide, which would be the limitation of the model if using this data source. Therefore, for the Chaudière River, the model was applied over the last 110 km to the St-Lawrence River. For the L’Assomption River, it was applied over the last 127km.

3.1.1 Narrowing Index (NI)

Considering that an ice jam formation is often due to a combination of different factors, our model proposes to combine and weight different parameters. Four parameters are first considered: 1) natural changes in the channel width, 2) presence of bridges, 3) presence of islands and 4) presence of an incoming tributary. They are linked to ice jamming processes for distinct physical reasons. However, for simplification, we consider in the model that they are all contributing to congestion through narrowing of the channel section available for ice transit.

Commentaire [GY12]: Comment 2
30

Commentaire [GY13]: Comment 3

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Commentaire [GY15]: Comment 3

Commentaire [GY16]: Comment 9

Commentaire [GY17]: Comment 3
(+Entire section rewritten)

For example, 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. The model would therefore consider this section as predisposed to ice jamming. The drawback of this generalization is that the model assumes 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. We did try to consider the specific location, type, size and shape of the islands but the complexity of dealing with these combined parameters was generating more uncertainties in the model results. We should also mention that with this approach, the model does not take into account the potential release of some pressure when ice is pushed into secondary channels.

Commentaire [GY18]: Comments 2
37
(+Entire section rewritten)

Commentaire [GY19]: Comment 3
(+Entire section rewritten)

The need for simplification also applied to bridges. A bridge is an obstacle which disturbs the natural flow of ice moving downstream, specifically when pillars are close 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. The interaction between ice and bridges is a balance between ice-driving and ice-resisting forces (Beltaos, 2006). Bridges can act as an obstacle or a constraint. 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. Again, considering the presence of a bridge as a narrowing of the channel enables the model to infer some predisposition to ice jamming on this specific section. And specifying a certain width reduction permits to adjust the impact of the bridges. Here, we consider that a half reduction of the channel width when a bridge is crossing the river would give a substantial weight to bridges in the final predisposition model. The available datasets in this study do not specify the characteristics of the bridges (type of bridge, number and shape of pillars). Therefore, the drawback of this generalization is that all bridges are considered equal. However, a user could adjust the width reduction parameter to better fit a specific river. And bridges which characteristics do not pose a risk of ice jamming could simply be removed from the input layer.

Commentaire [GY20]: Comments 2
38
(+Entire section rewritten)

And comment #2 and #3 from reviewer

The final parameter that has to be generalized is the tributary. Small rivers usually respond more quickly to rising run off compared to large rivers. A quick hydrological response in tributaries may trigger an early breakup and send an ice run into the main channel. Since the ice cover of the main channel is likely to still be intact, the ice run can stop at the confluence, become an immediate ice jam or initiate an ice jam during the breakup to come on the main channel. Literature considers that the major impact of a tributary is the potential input of ice (or even sediment) into the main channel that would also result in reducing the available space or would create an obstacle for ice transport in that main channel. Again, conceptualizing the tributary as a narrowing of the main channel allows the model to infer a predisposition for ice jamming on this section while the specified width reduction determines the importance of the impact. Here, the width reduction is equal to the minimal width of the tributary at the outlet (Figure 3). This gives more importance to large tributaries.

Commentaire [GY21]: Comment 3
(+Entire section rewritten)

Even if we fit many parameters into a unique narrowing index, each parameter is calculated independently and its relative importance can be adjusted. In the end, the Narrowing Index is calculated from the natural or adjusted channel width of each 250m section. When the width of the preceding section is smaller than that of the actual section (sections 5 and 6 in Figure 4) the index has 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 closer upstream maximum width. A value tending towards 0 will indicate a stronger narrowing of the channel. It should be noted that although a narrowing of the channel can in some instances concentrate energy and favor transit of ice runs, the model only considers it as an aggravating factor.

Commentaire [GY22]: Comment 9

Commentaire [GY23]: Comment 8

3.1.2 Sinuosity Index (SI)

Bends and loops are known to increase resistance to the ice flow (Shen and Lianwu, 2003). Due to preferential flow, ice is deported towards the concave bank and may start accumulating there, gradually reaching the opposite bank and creating a jam (Zufelt, 1988). Here it should be noted that the simplified model do not consider the fact that the first bend of a meandering reach is more likely to initiate an ice jam.

Commentaire [GY24]: Comment 2

The Frazil toolbox (Gauthier and al., 2008) is used to obtain a standardized sinuosity coefficient. It uses the *Sinuosity4* equation proposed by Dutton (1999) to express the sinuosity coefficient (SV) in values ranging between 0 and 1 (Eq. (1)).

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

where, SV is the curvilinear distance between two points divided by the direct linear distance between the same two points. Calculations of SV are based on inflection points, which separate two curves going in opposite directions. A 0-value for *Sinuosity4* means that there is no sinuosity in the section. The distance between two inflexion points can cover adjacent 250m sections. The calculated sinuosity is applied to all sections it overlays. If a section was overlaid by two different values of sinuosity, the mean value was calculated and retained.

Commentaire [GY25]: Comment 4
43 (section rewritten)

3.1.3 Slope Break Index

A change of the river bed slope from steep to mild is the typical case involved in ice jams. Since gravity is the driving force, the ice can lose its energy when it reaches a milder slope, and can stall or arch across the river and initiate an ice jam (Wuebben and Gagnon, 1995). Such a change of slope is also present at the estuary of a river or at lakes and reservoirs, where ice jams often form (Saint-Laurent et al., 2001). On a technical point of view, this parameter should be easy to integrate to the model. A slope break index would be calculated based on the approximate channel surface altimetry from a Digital Elevation Model (DEM) (Eq. (2)).

$$\text{Slope Break Index} = \Delta\,\frac{\Delta\,Height}{\Delta\,Length} \qquad (2)$$

Initially, we did consider this parameter in the model. The data from the 1:20 000 Quebec Topographical database are built over contour lines with a ±5 meter resolution. This coarse resolution resulted in shaky slope break index values, giving an inadequate 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 did not integrate the slope break index. However, an accurate LIDAR model could be used if available. If a future version of the model integrates the slope parameter, it should also include rapids, since ice jams almost never initiate in rapids but often, at the end. It is nonetheless possible to force a low predisposition to sections with rapids.

Commentaire [GY26]: Comments 2
44
(section rewritten)

Commentaire [GY27]: Comment 3

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 ice jams reported in the province of Quebec from 1985 to 2016, with approximate geolocation since most jams are longer than a single coordinate and because this geolocation does not refer to the toe where the jamming process is initiated. The database is not "validated" in the sense that each event has not been compared to corresponding hydrographs, that a few observed ice jams could be related to anchor ice or frazil, and that reported locations do not necessarily refer to the toe where the jamming process is initiated. Therefore, validation of the model from this database is not absolute. But it is nonetheless a unique source of information in Canada. Although proceeding to a complete validation of the database was out of the scope of this study, we have discarded observations that could not be located with enough accuracy. Furthermore, the analysis will consider not only the sections directly coinciding with an ice jam observation, but also neighbouring sections where the toe could have formed. In this study, we focused on 118 historical observations: 61 ice jam reports for the Chaudière River, 33 for the St-François River and 24 for 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.

Commentaire [GY28]: Comments 5
45, 47
(section rewritten)

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. The model was developed mainly with the data from the Chaudière River. However, to determine the thresholds for the classes of Narrowing and Sinuosity index using K-means, we used the entire range of values from the three rivers in this study in order to provide a more robust and representative model. Four clusters were created with squared Euclidian distances, replicated 5 times. Table 1 shows the thresholds established from the K-Means approach.

Commentaire [GY29]: Comment 4

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 compared 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 also obtain a ratio of 1.5 in favor of the Narrowing Index. A multi-criteria analysis (Saaty, 1990) then assigns a weight of 0.60 to the Narrowing Index, and a weight of 0.40 to the Sinuosity Index.

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).

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

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 magenta (false-negative error) when the reported ice jam falls into a section with a low predisposition. Again, we have to keep in mind that there may be a difference between the initiation site (higher predisposition) and the observation site (anywhere along the jam). In contrast, a false-positive error would give a high value of predisposition in a section where no ice jam was observed. 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 or non-vulnerable 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.

Commentaire [GY30]: Comment 4

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 predisposition to ice jamming was underestimated.

Table 4 also shows that of these 18 cases, 3 are related to the presence of a major tributary in the section. This could indicate that the value applied for channel width reduction underestimates the actual impact of a tributary on ice jamming.

Commentaire [GY31]: Comment 5

However, we also have to look at these results in the context of the uncertainty related to the geolocation and length of the ice jam reported in the historical database. Considering that an ice jam may have a length of a few hundred meters to a few kilometers, one could have reported the sighting upstream from the toe of the jam, where it was initiated. Therefore, the geolocation of the point in the database may lie upstream of the predisposed section. It is interesting to see that for 10 of the

18 false-negative errors on the Chaudière River, the ice jam is reported less than 1km upstream from a section with a high or medium predisposition. So we may even underestimate the performance of the simplified model, although it is impossible to confirm without more accurate data.

Commentaire [GY32]: Comments 5
54

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. As mentioned earlier, these are not necessarily errors. But it is also probable that the model is overestimating predisposition in some areas. For example, when looking at the false-positives cases (32 sections of high predisposition), 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 confirm that all bridges are not equal and that the model could be easily improved at the local level with specific information about the bridge characteristics.

Commentaire [GY33]: Comment 5

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. As can be seen in Table 5, the percentage of sections respectively 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). Here we notice that three false-negative errors occurred on sections with at least one island.

The number of sections with false-positive results is similar to the Chaudière River 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.

In Figure 8, 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 could be caused by a parameter not considered in the model (e.g. slope break), by the simplification approach, or by an inaccurate geolocation of the observation. In site A (Figure 8) the shape of the channel and the presence of islands are probably enough to trigger an ice jam. But the islands are small and do not seem to impact on the mean narrowing calculated over the sections. The problem is then related to generalization and scale. In A', we can see that the area has shallow waters (not considered in the model), which could also support ice jamming. In site B, the model sees the bends upstream and downstream but again, misses the islands. Here they are located in a wider section of the channel, cancelling the narrowing effect. In site C, the first island causes a sudden narrowing well detected by the model. But the main channel width remains stable over the next sections, again cancelling the potential narrowing impact of the islands. However, the changes in direction of the main channel should have increase predisposition. In site D, the land strip going into the channel could have caused the ice jam. But the feature is so localized compared to the section's length that it may not sufficiently affect the mean width to register as a narrowing. Thus, the error here could be related to scale. Finally, let's note that if we can't identify with certainty the cause of a false-negative error, either from channel characteristics, model generalization or scale, 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 time dependent parameter, which is not considered by the model. Again, there is also the possibility that the observation point did not correspond to the ice jam toe.

Commentaire [GY34]: Comments 55, 56, 57, 58, 59, 60 (section rewritten, figure improved)

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 has a much higher sinuosity in its lower portion. Figure 9 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 to 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 (meandering channel) and a smaller ice jam dataset, false-positive errors are naturally higher (31%). As expected, more false-positive errors are on sections where the Sinuosity Index is greater than the Narrowing Index. Finally, as for the other rivers, the bridges seem to create some overestimation of the risk as 8 false-positives are at sections where a bridge is present (on a total of 14 bridges over the study area).

5 Conclusions

Commentaire [GY35]: Comment 3 Section improved

A geospatial model for estimating a river's predisposition to ice jams was proposed based on the key morphologic parameters leading to ice jams. 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 also calculated. 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 setup using 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. This database presents a certain degree of uncertainty, particularly concerning the location of some of the reported ice jams (toe and length). It is nonetheless a great tool to document areas at risk of ice jams and to assess the reliability of the proposed model.

Commentaire [GY36]: Comments 4

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 occurred on low predisposition areas are called false-negative errors. The uncertain geolocation of the reported ice jams may account for part of these. A majority of false-negative errors are located less than 1 kilometer from sections with a higher predisposition. However, results tend to show that the model underestimates the role of islands and tributaries in the initiation of an ice jam. Some errors left unexplained could be related to time dependent parameters not integrated into the model such as water depth or the presence of an intact ice cover, although both are indirectly related to channel morphology.

Commentaire [GY37]: Comment 6

River sections that are categorized with a predisposition to ice jam but where no ice jam was reported are called false-positive cases (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 bridges.

Overall, the results of this geospatial model are very promising. Even in a conceptual form and by using only parameters that are mostly stable over time, the model seems to correctly represent the nature of the river and the areas where the morphology has an impact on ice jam occurrence. Having applied the model over three different rivers also ensures a certain degree of transferability to the approach.

However, it is important to understand some limitations of the model. First, it is not developed for freeze-up ice jams occurring from frazil accumulation or hanging dams. It addresses ice jams following a breakup event. Also, it is a simplified model, intended to work with data easily available for most rivers. It does not simulate the physical processes of ice jams but rather locate areas where the morphology of the channel presents some characteristics known to initiate ice jams. The model gives a first level assessment of the ice jam potential of rivers. Some fine tuning could have to be done if high resolution data or local knowledge is available on a specific river, in order to better take into account some local and more complex causes of ice jams.

Commentaire [GY38]: Comment 2

Commentaire [GY39]: Comment 5

Commentaire [GY40]: Comment 4

Commentaire [GY41]: Comment 1 from reviewer #1

Even in its present 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 potential ice jam flooding sites, an improved version of the model could bring information for land planning, zoning, bridge construction or insurance evaluation. In the province of Quebec, the historical database is a great tool to document areas at risk of ice jams. The geospatial model is now a complementary tool to map these areas, as well as others for which no ice jam has yet been reported. And the model is a valuable tool for provinces or countries where no ice jam database exists.

For a future version of the model, potential developments could be:

- To consider attenuating factors, such as a section located immediately downstream a reservoir or directly within a rapid;
- To consider the width, shape and length of the contributing reach upstream from a predisposed section (is there potentially enough incoming ice to produce a jam?);
- To consider sudden channel widening (dissipation of the energy and ice run stalling);
- To take into account the presence of hydraulic structures (weirs, dams, dam reservoirs, etc.);
- To test the model using the US Ice Jam database (Carr et al, 2015)
- And certainly to use the slope index, upon availability of accurate elevation data.

The authors are presently starting the application of the model on all rivers prone to ice jams in the province of Quebec. They are also planning the work on a new version that will be integrated within an ice jam vigilance and alert system, combining spatial predisposition, temporal forecasting and ice status.

Commentaire [GY42]: Comment 1

Commentaire [GY43]: Comment 1

Commentaire [GY44]: Comment 1
52

Commentaire [GY45]: Comment 7

Commentaire [GY46]: Comment 6

Commentaire [GY47]: Comment 3

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

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Table 1: Threshold values for the Narrowing (NI) and Sinuosity (SI) indices, as determined by the K-Means approach.

	Narrowing Index (NI)	Sinuosity Index (SI)
Class 0		
	0.56	0.24
Class 1		
	0.77	0.46
Class 2		
	0.92	0.69
Class 3		

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

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.

Narrowing Index / Sinuosity 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

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	No specific feature		
-	-	3	15		
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%	

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	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%	

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%	

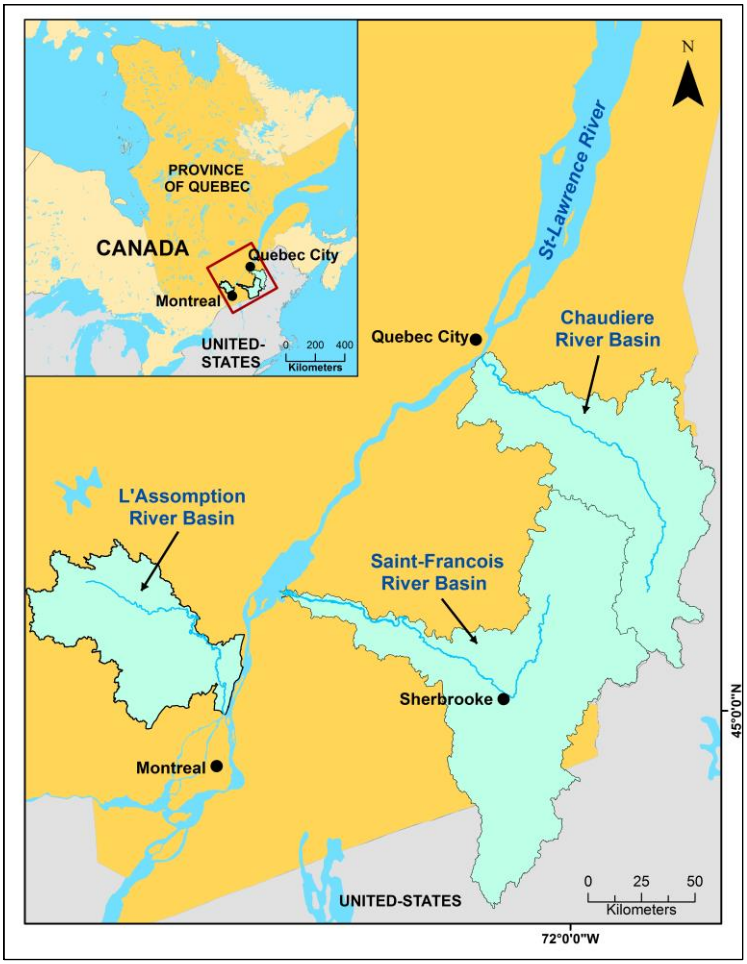


Figure 1: Location of the Chaudière River, Saint-François River and L'Assomption River (Province of Quebec, Canada).

Commentaire [GY48]: Comment 1
Figure improved

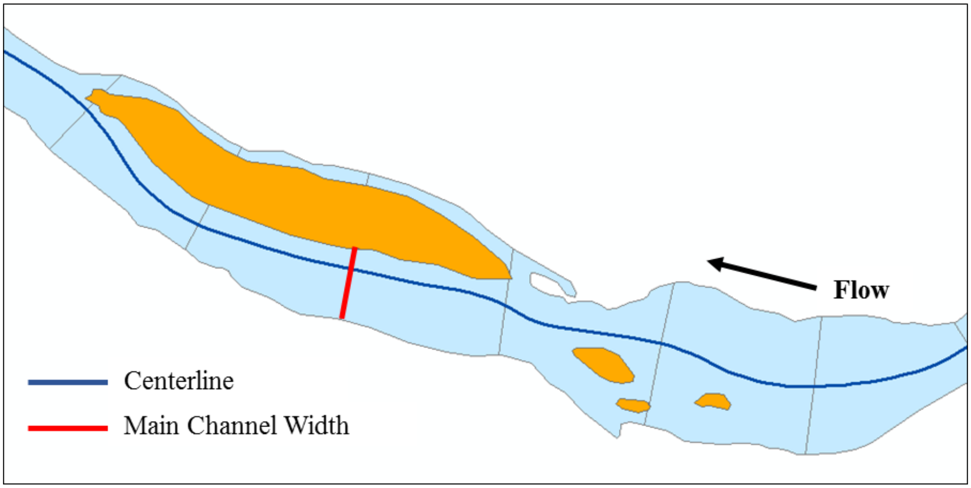
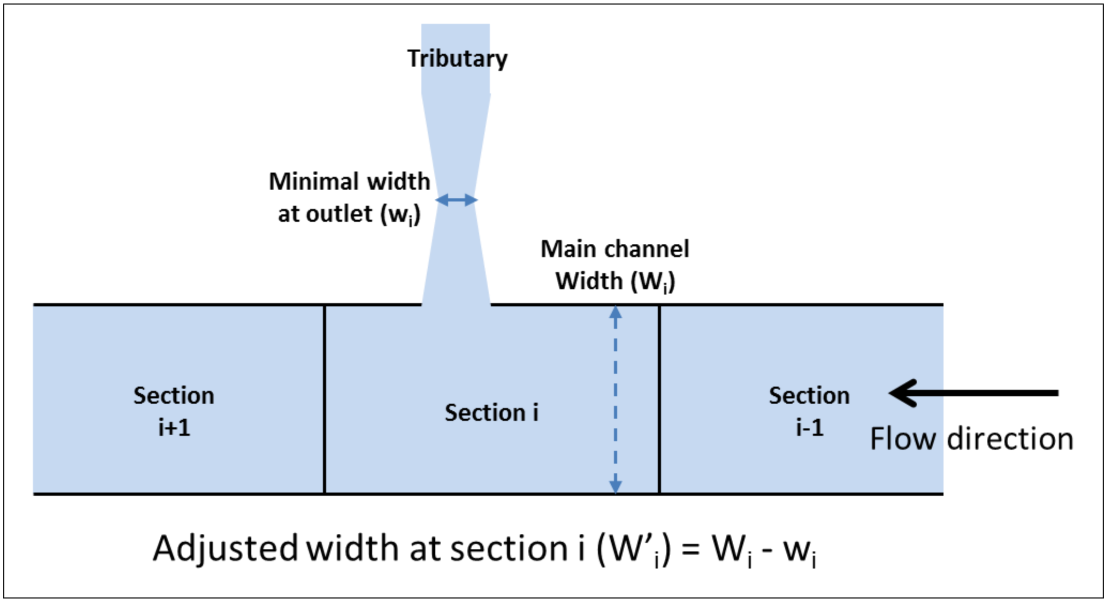
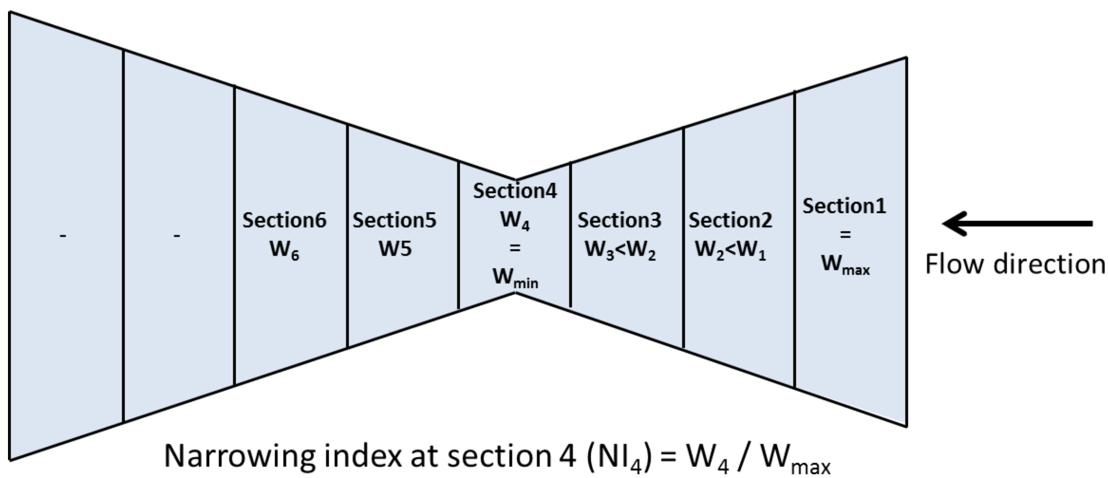


Figure 2: Spatial representation of the channel centerline, channel width and channel 250m sections in presence of islands (from the FRAZIL tools).



455 **Figure 3: Modification of the channel's width due to incoming tributaries. For segment i, the adjusted width (W'_i) is obtained by subtracting the minimal width of the tributary at the outlet (w_i), from the main channel width (W_i).**

Commentaire [GY49]: Comment 4
Figure improved



460 **Figure 4: Approach used to calculate the Narrowing index, dividing the section's width (W) by the upstream maximum width (W_{max}).**

Commentaire [GY50]: Comment 4
Figure improved

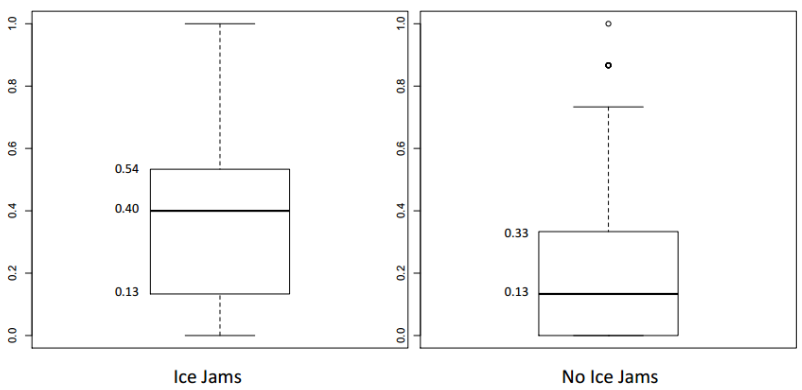


Figure 5: Boxplot of the IJPI values on the Chaudière River. Graph on the left is for 250m river sections where ice jams were reported. Graph on the right is for river sections with no ice jam listed. Numbers represent the median, first and third quartiles.

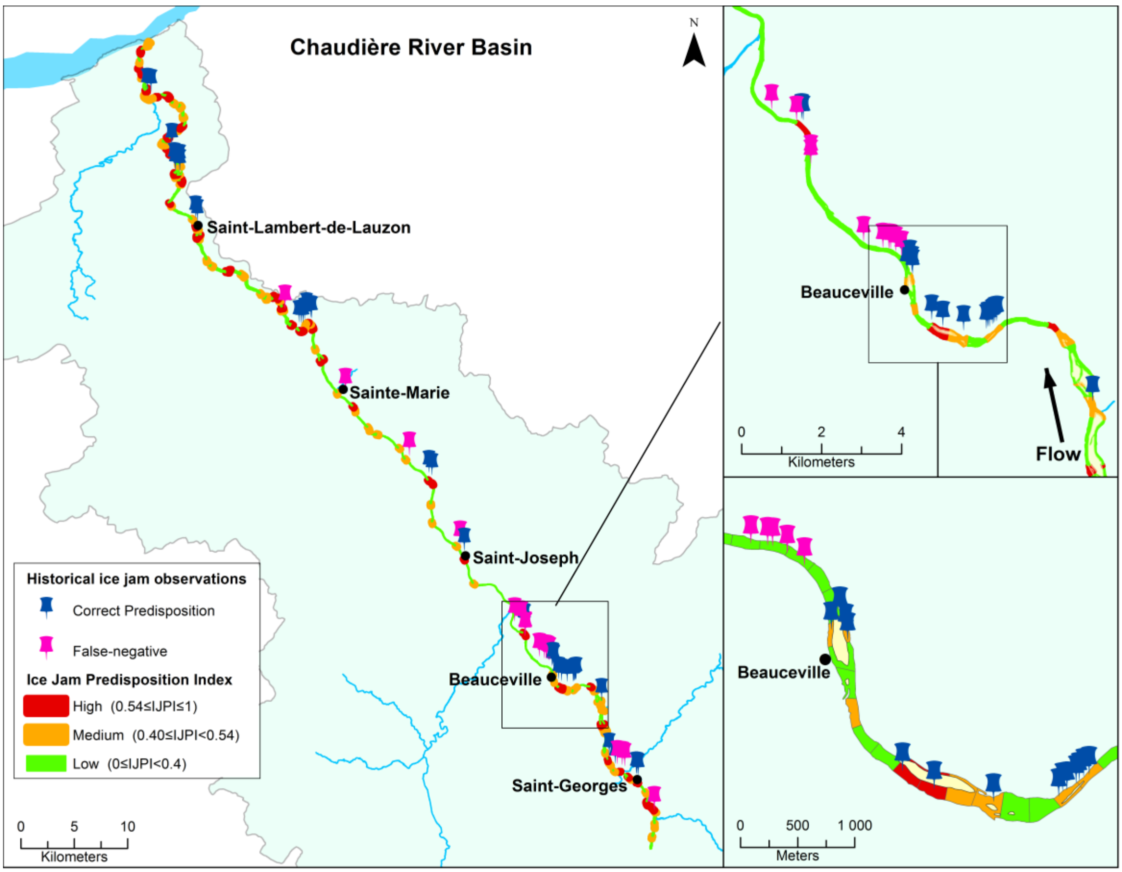


Figure 6: Map of the model results on the Chaudière River, over 250m sections. Thumbnails are the locations of reported ice jams. Blue is used when the ice jam falls on a section with a moderate to high predisposition (correct assessment). Magenta is used when the ice jam falls on a section with a low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

Commentaire [GY51]: Figure improved

475

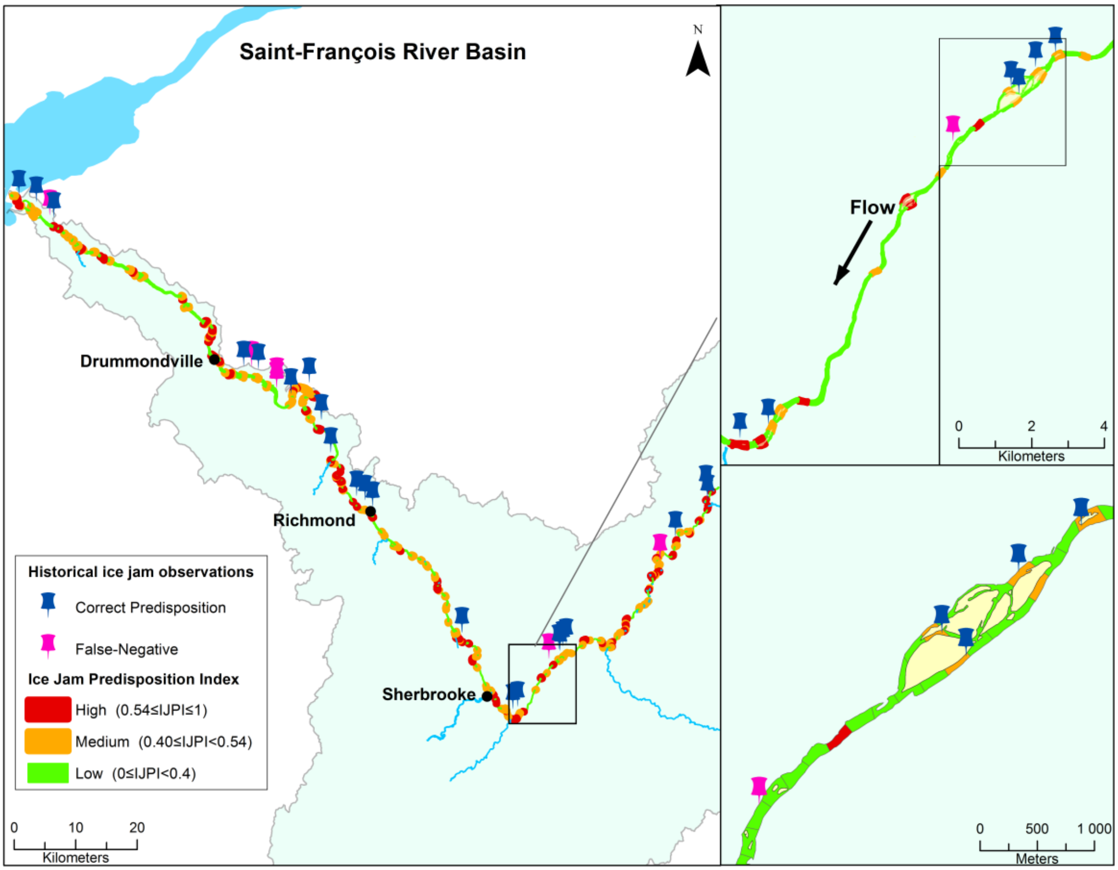


Figure 7: Map of the model results on the St-François River, over 250m sections. Thumbnails are the locations of reported ice jams. Blue is used when the ice jam falls on a section with a moderate to high predisposition (correct assessment). Magenta is used when the ice jam falls on a section with a low predisposition (false-negative error).

Commentaire [GY52]: Figure improved

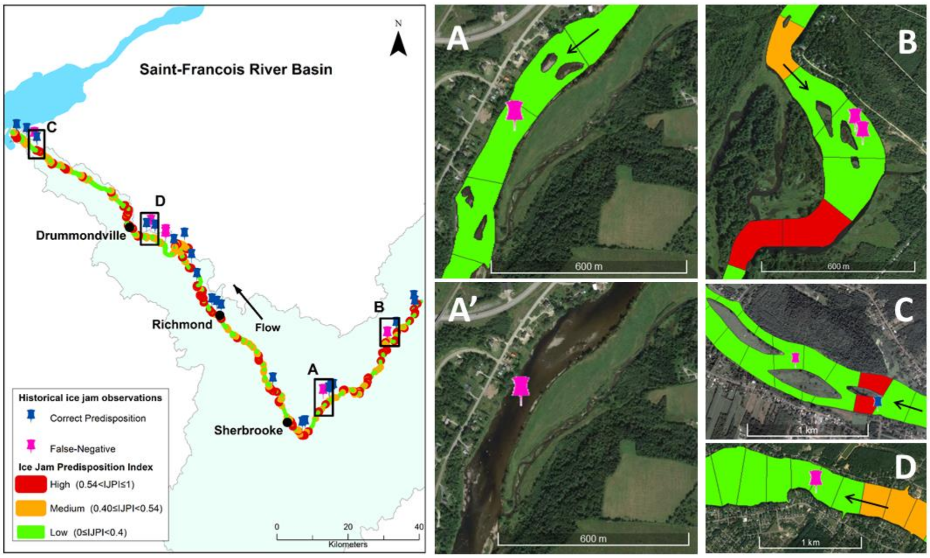


Figure 8: Examples of false-negative errors on the St-François River for site A, B, C and D.

Commentaire [GY53]: Figure improved

485

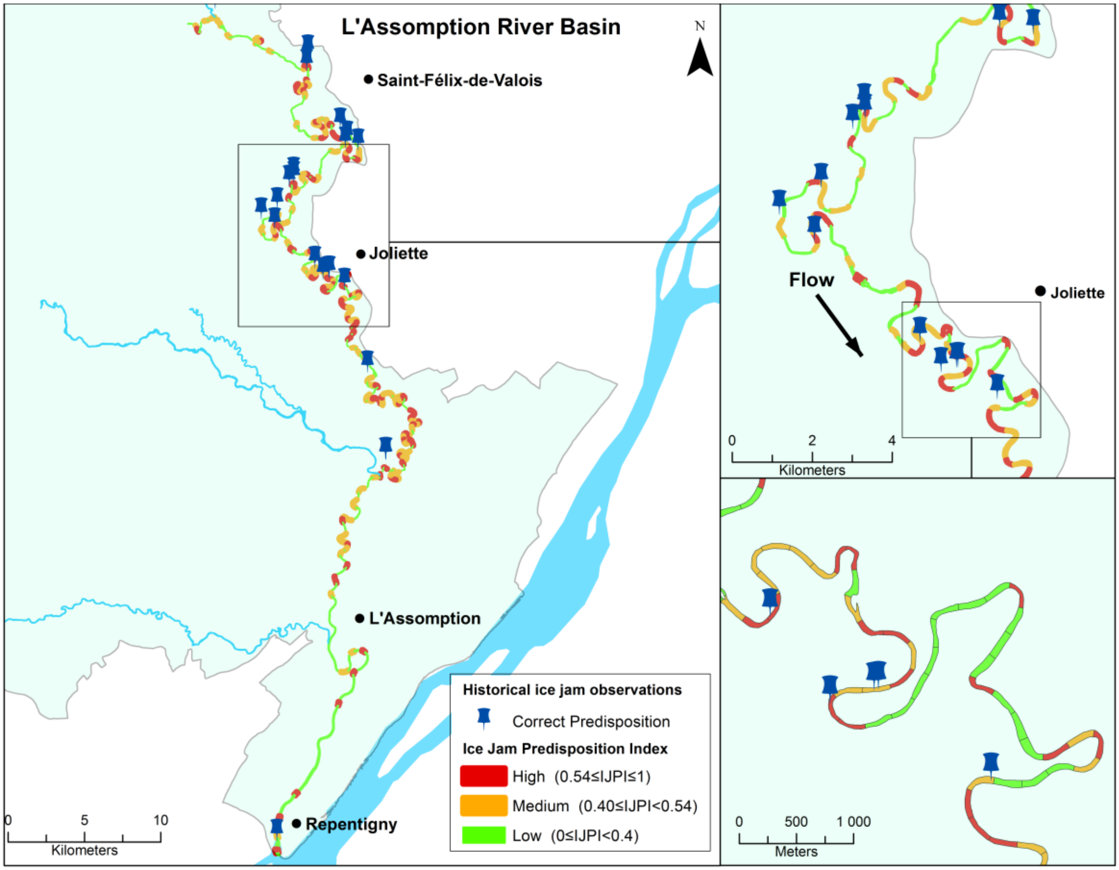


Figure 9: Map of the model results on the L'Assomption River, over 250m sections. Thumbnails are the locations of reported ice jams. Blue is used when the ice jam falls on a section with a moderate to high predisposition (correct assessment). Magenta is used when the ice jam falls on a section with a low predisposition (false-negative error).

Commentaire [GY54]: Figure improved

Summary of comments from Reviewer #1 with initial reply from Authors

General comment

This paper explores ice jam predispositions along northern rivers using a geospatial modelling approach in which sets of fluvial geomorphological parameters are compared with ice jam occurrences. There is a high success rate of predicting ice jam locations, however some errors do occur due to the presence of sand bars and low water depths, variables not considered in the model The approach does give a first assessment of the ice jam potential of rivers, hence, the paper is deemed publishable if the following minor revisions are considered.

Authors' response

We thank the reviewer for his comment. It is true that the simplified model presented here gives only a first assessment of the ice jam potential of rivers. Hence, the paper shows that even with limited data, it is possible to get a good sense of the areas at risk for ice jamming. This work can then be further used to build a version of the model that would better take into account some local and more complex causes of ice jams. This was better explained in the text.

Specific comments

The narrowing index (NI) for bridge peers is rather arbitrarily derived that can lead to over- or under-estimation of their effect on ice jamming. No consideration was given to the number of peers spanning across the bridge. Hence, the NI of a suspended bridge would have the same NI value as a bridge with many closely spaced peers. Could you please give an explanation of why this wasn't considered?

Authors' response

This aspect was of course considered in the development of the model. However, the information about the different characteristics of the bridges is not always available or easily accessible. Therefore, to maintain the objective of a simplified model that can be quickly deployed on many rivers, we have decided in this version, to consider all bridges equal. On a local scale, one could easily take a bridge out of the analysis if he considers that the structure is not a factor of ice jamming. An improved version of the model would certainly have to take bridges characteristics into account. This was better explained in the text.

Specific comments

Also on the subject of bridges, I find that bridge peers do not necessarily stop an ice run to create an ice jam but reduce the inertia of the ice run enough for it to slow down and stop at a location further downstream from a bridge peer. Would such a consideration improve the predictability of the model?

Authors' response

In its present version, the model considers a bridge to be an "aggravating factor" (coming either from obstacle or constraint). It uses "narrowing" as a strategy to apply this aggravating factor on a geospatial point of view.

Summary of comments from Reviewer #2 with initial reply from Authors

Comment 1: "This paper presents a very interesting and original model that uses qualitative, geospatial information to quantitatively identify channel locations where ice jams could form. Its development and calibration is supported by an ice jam database. Overall, it seems that there is a great potential for the development of a model that could be used to identify potential ice jamming sites and this could be combined with a river ice breakup forecasting model. However, the model overlooks or simplify a number of key ice jamming parameters, factors, processes, and information that may limit its reliability and the paper really presents what appears to be the early development stage of an acceptable model. "

Reply 1: We really thank Dr Turcotte for the thorough review of our paper. Here we address every comment, suggestion or correction.

Comment 2: "It seems that the authors globally lack in experience and confidence (a lot of sentences seem defensive) and the following points (below) should be considered to improve the next versions of the model (the actual knowledge about river ice processes has only be partially considered). I consider that the actual version of the model is almost dangerous to use by public security services or for flood insurance purposes. "

Reply 2: The authors of the paper are specialized in geomatics and remote sensing and have worked for many years on developing tools to support river ice and ice jam monitoring and characterization. However, they do not pretend to be experts in ice jam processes. This may explain the cautious (rather than defensive) tone of the paper. As for its "potentially dangerous" nature, we had better explained the limitations of the model in order to avoid any misinterpretation of the results.

Comment 3: "At this point, I am not sure if I recommend (1) that the authors should make multiple technical changes to the paper and include a discussion that mentions the many limitations of the model in its actual form or (2) that the authors should present a new paper with a more advanced version of the model that would address and include most of the following points. I would tend to vote 1 because I consider that the model is original and represent a step forward in the field of river ice and flood forecasting. In this case, I would encourage the authors to present an improved version of the paper with a serious discussion and to present, in the years to come, an improved version of the model that would potentially include a completely new model structure."

Reply 3: We understand the ambivalence of the reviewer and we appreciate the opportunity he offers. Indeed, we think that the approach presented in the paper is innovative and that it produces very promising results. Its publication at this stage could help improve and validate the model within the river ice and public safety community. Discussion and conclusions sections were improved.

Comment 4: "1. The authors do not mention that they have observed ice jams and do not refer to any experience in the field (e.g., to verify the sites presented at Figures 8 – 10 or to look under bridges if pillars can be pointed out for ice jamming) . Therefore, this research is only based on theory and the authors cannot really confirm that the model is reliable. "

Reply 4: Here we need to clarify a point (and it was done in the paper as well). The proposed model is not a physical model simulating the processes of ice jamming. Yes it is theoretical, in the sense that it is based on some common knowledge expressed by experts in the literature, about the general causes of ice jams. The model tries to express these causes in terms of channel morphology, within a 2D spatial representation. Being develop for a wide application, the model uses simplifications and provide what we could name "first level" results. Although it could certainly be helpful, we do not think that going in the field was essential to this work at this point. But the model could certainly be fine-tuned for a specific river, with high resolution data and knowledge of local phenomena. Finally, the validation of the model is based on real events, not theoretical events, even if the historical database may contain some uncertainties. Therefore, we can certainly assess the model's reliability.

Comment 5: "Beyond the government ice jam data base, the authors should have conducted a complete historical research and confirmed that the mentioned ice jam dates corresponded to specific hydro-meteorological events. This type of data base often confuses ice jams with other ice processes that generate winter or spring flooding (e.g., anchor ice and hanging dams). Moreover, at locations where observation is not easy, where there is no societal vulnerability, or where the jamming and release occur at night year after year, ice jams may have gone unnoticed (as somewhat mentioned in the paper). "

Reply 5: We agree that the historical database is not perfect. We will better explain its limitations right from the start, in section 3.1.4. But it is nonetheless a unique source of information. The first author of the paper has worked with the government on the transfer and integration of historical observations within the database for the 3 rivers under study.

Comment 6: "2. The authors refer to particular factors influencing ice jamming, but do not seem to understand all the physics that link these factors with ice jam processes. The authors never refer to the distinction between the toe and head of an ice jam and they barely mention something about their potential length (that can be much greater than 250 m and therefore extend in sections that have nothing to do with the initiation of the jam). It is crucial to point out that the parameters influencing ice jamming sites refer to the toe (initiation site), which can be hundreds of meters or even kilometers away from the ice jam observation site. This can influence the results of the research positively or negatively. "

Reply 6: We agree that we put the emphasis of the paper more on the geospatialization aspect than on the explanation of the ice jam physical processes. We have given some justification for this in Reply 4. Background section improved.

Comment 7: "3. A number of parameters such as channel widening (dissipation of the energy and ice run stalling), the presence of hydraulic structures (weirs, dams, dam reservoirs, etc.), and the presence of a tight, single bend (not a meander) have not been mentioned in the study and could help reducing false-negative errors."

Reply 7: From the literature, these were not found to be part of the major factors causing ice jams. Added as potential developments.

Comment 8: "On the other end, it seems that channel narrowing is assumed to generate ice jamming but in some cases, the concentration of energy actually favors the transit of an ice run."

Reply 8: Again, the narrowing of the channel is mentioned in all references, as a major factor favoring ice jams. Thus the importance it is given in the model.

Comment 9: "From my point of view, trying to fit many parameters in a "narrowing equivalent" will limit the potential development of the model."

Reply 9: Even if we fit many parameters into a unique narrowing index, each parameter is calculated independently and its relative importance can be adjusted. Also, representing each parameter as a narrowing equivalent simplifies the geospatial calculations. The final Narrowing Index is not just about a physical narrowing of the channel. It can also be viewed as a way to take into account, different aggravating factors.

Comment 10: "4. Obstacles and gradient variations could explain a significant ratio of ice jams. This may require a more sophisticated spatial analysis that may become tedious to automatize. "

Reply 10: Introduction and background improved.

Comment 11: "5. One important parameter affecting ice jamming is the potential quantity of ice, i.e., the contributing reach. If there is not enough ice to produce an ice jam that can affect the floodplain, the jam may remain unnoticed. The most critical jamming sites are located downstream of long sections where an ice run would simply not stop. This has to be mentioned here and potentially included in a future version of the model."

Reply 11: We agree. Added in the discussion. Technically, long sections could be spatially identified.

Comment 12: "6. The model could consider factors that prevent the formation of an ice jam (e.g., immediately downstream of a reservoir) and the model could gain in accuracy and reliability. "

Reply 12: In a future version, we can certainly consider some attenuating factors for some river sections, not just aggravating factors. Added in discussion/conclusion.

Comment 13: "7. In the end, at this development stage of the model, for Quebec, the data base itself could represent a more reliable tool to identify potential ice jamming sites than the model calibrated with the data base."

Reply 13: This may be partly true because in any domain, if you have all the data, you do not necessarily need a model to replace the data. But here, we know that the model will identify sections potentially predisposed to ice jams, even if no ice jam has been observed or reported yet. Also, the historical database does not cover all rivers in the province of Quebec. And such a database is not yet available in other provinces or in many countries. Hence, this shows the usefulness of the model, on top of the database. Added in discussion/conclusion.

Comment 14: "There is no introducing context in the abstract."

Reply 14: Added.

Specific comments

Comment 15: "Line 7: "any" should be moderated. The model has been tested on three rivers only and a number of parameters and factors are not considered."

Reply 15: This is the goal (to develop a model that can be applied on any river), not necessarily the end. Changed.

Comment 16: "Lines 16-17: I am not sure that talking about "false positives" is pertinent here. These are not really errors. "

It is true, as we mention in the paper, that "false positives" are not really errors. We could change the term to "potentially false alarm" or "false positive cases".

Comment 17: "Figure 1: Second part of the Figure may not be necessary. There is a lot of empty space in the map north of Quebec City that could be used to increase the size of the legend or to rearrange the ratio of each sub-Figure. Please confirm that the L'Assomption River watershed is the right one. It seems that it is in contact with the St. Lawrence along 80 km. The southern part of the St-Francois River could be indicated approximately."

Reply 17: Figure 1 improved.

Comment 18: "Background: This section should be reorganized: The authors should mention that an ice jam can form because of congestion or because of an obstacle. The use of a transport capacity in the literature only represents one simplified interpretation that has been overused here. Most of this section refers to congestion processes as if an ice jam could only be the result of an unimpeded ice run (Jasek 2003) that slows down and stop. Indeed, an important portion of ice runs encounter a physical obstacle (such as an intact ice cover mentioned at the end) and suddenly stop. This has nothing to do with congestion or a "reduction in the ice transport capacity". "

Reply 18: As mentioned in reply 10, background section modified accordingly.

Comment 19: "Line 39: I am not sure if Beltaos would refer to "volume of ice". I believe that it would be the "ice discharge". "

Reply 19: No. the term used by Beltaos is "ice volume".

Comment 20: "Line 41: Authors should seek additional references. The books "River ice Jams" or "River ice Breakup" are potential sources of complementary information. "

Reply 20: We have used these two books. More references were added.

Comment 21: "Lines 43-44: The authors should mention that there are different types of islands. They can be naked bars, vegetated bars or emerging rock outcrops (vegetated or not) and not all of them are associated with a break in the channel gradient. From my point of view, the presence of an island is associated with ice jam in part because the flow can bypass the congested channel and release the pressure on the impeded ice run, therefore leaving an ice jam on one side of the island. The authors only mention "narrowing" as the basic process to identify potential ice jamming sites. "

Reply 21: We didn't want to infer that the only ice jam related physical process involved in the presence of an island was narrowing. But "narrowing" is how we "conceptualize" the impact of islands in our simplified model. Clarifications were made.

Comment 22: "Lines 45-47: Not all bridges present pillars and pillars are often profiled to minimize to effect on flow conditions and ice transport capacity. Also, bridges are often build at natural (or artificial) narrows that already represent a limitation for ice mobilisation.

This may affect the result of the study. Also, the flow often accelerates under a bridge because of the smaller river width and ice runs could easily transit that these locations. "

Reply 22: This was acknowledged in reply to reviewer #1. Here the bridges are considered equal because for application of the model on a large area, the information about individual bridges is not always available. But at the local level, one could simply take individual bridges out of the analysis if he knows it is not an aggravating factor.

Comment 23: "Lines 48-50: Not well explained. The basic process may be that the flow along the concave bank drowns while the ice floats. Also, the authors mentioned that sinuosity may "initiate" a jam. This is correct, but it would mean that the first bend of a meandering reach is more likely to cause jamming that the last one. The authors could include this (or mention that this has been or should be considered) in their study. "

Reply 23: Clarification was made.

Comment 24: "Lines 57-59: This is one of the most important parameters explaining ice jamming. "

Reply 24: Agree. But as we will see later, it requires accurate elevation data.

Comment 25: "Lines 60-62: There are many types or gravel bars in gravel bed rivers. The authors only mention two types here (point bars or side bars). I am not sure that I agree with the reasoning presented: gravel bars are usually mobilized when the flow increases and stabilize when the flow decreases. How could they form and migrate if there was never a potential for transport? The first part of these lines does not need a reference as most people know about bars. It is really the second part of the sentence that needs the support of a reference."

Reply 25: Clarification was made.

Comment 26: "Lines 65-66: The authors should refer to the concept of an impeded ice run here (Jasek ,2003, or Jasek and Beltaos, 2008). This is the only parameter that does not directly refer to the morphology, but it is very important. This is why I would reorganize this entire section. "

Reply 26: The entire section was strengthened. However, we should again keep in mind that we do not prepare the reader for the development of a physical model. We only want to give him a basic understanding of how morphology can play a role in ice jam formation.

Comment 27: "Line 69-70: This is important because the authors use this single idea of the combination of two ice jamming factors for their model. I understand the need to simplify reality, but I am not sure that one publication can justify this choice. "

Reply 27: The idea here is that an ice jam formation is often due to a combination of different factors, as seen in the literature. The study from Kalinin presents numbers that reinforce this idea. Thus, our model combines and weight different parameters (natural narrowing, convergence with a tributary, presence of a bridge, presence of an island, sinuosity). Clarification was made.

Comment 28: "Line 77-78: I would express this differently. The word "dynamic" in the river ice literature usually refers to processes such as ice runs, ice jams and ice dams. Note that the depth can be linked to the morphology and the cover characteristics as well (e.g., Turcotte and Morse, 2013). If the authors believe that the presence of bars is important, well their emergence is completely linked to the depth and discharge!"

Reply 28: Dynamic has been replaced by variable. As for bars, refer to Reply 25 and 26. Here, the comment from the reviewer is correct. Bars are dependent on the water level and discharge. Which are variable throughout the year and more so during the spring. This is why we do not consider the bars in this model.

Comment 29: "Line 87: How does the 250 m in length compares with the channel width? Why not using a variable length that depends on the width of the channel or the homogeneity of the morphology and alignment? I guess that this would be complex for automatic interpretation to be performed and it would not fit with the title of the paper."

Reply 29: The width of the channel was not a factor when deciding the length of the river sections used for the model. It had more to do with the resolution of the input data and the scale of the parameters we were calculating. For example, we could average the channel width every 5 meters if we wanted to. But we would get micro narrowing. And the sinuosity must also be estimated over a certain distance to be significant. On the opposite, an ice jam can run on several hundreds of meters or even several kilometers. This would be too coarse for the scale of the model. We decided to compromise with 250m sections.

Comment 30: "Line 88: What can be said here about the size of ice jams if the data base does not include such information?"

In the historical database, ice jam length is only mentioned on some occasions. But from observations and from literature we know that ice jam length can vary from hundreds of meters to kilometers.

Comment 31: "Line 89-91: Is this precise enough to document parameters such as narrowing?"

Yes. The planimetric accuracy of these dataset is better than 2m. Clarification was made.

Comment 32: « Line 92: Islands: Does the model differentiate bars and stable islands?"

Reply 32: Metadata from the data provider do not mention what was digitized as an island. But looking at the island vector over Google Earth clearly shows that for the three rivers of this study, islands correspond to "vegetated islands". Clarification was made.

Comment 33: "Line 92: rapids: This is very important and has not been mentioned before. Ice jams almost never initiate in rapids but often at the end of rapids. Does this include riffles or just rapids?"

Reply 33: Again, metadata do not inform about the types of rapid. But overlaying this layer to Google Earth seems to indicate that it concerns rapids, not small riffles that may disappear with higher water level. We will add a word on rapids in the improved background section, when discussing slope changes. It would also be possible to force a low predisposition to sections in a rapid. Clarification was made.

Comment 34: "Line 93: This is not very reassuring: The authors should mention that a width less than X m could not be included in the model for spatial information accuracy limitations. Then, it means that the model is actually not adaptable to small rivers. "

Reply 34: Metadata from the data provider do not mention the minimal channel width for which they use a polygone. We have checked the three rivers in this study and all sections in polygon format are at least 20m wide. The text was clarified accordingly.

Comment 35: "Lines 100-102: I understand that the model is simplified for practical reasons. However, as noted in the general comments and as the authors mention at the end, these four factors are linked to ice jamming processes for distinct physical reasons. "

Yes, the physical reasons are different. But the model only needs to know where it occurs (where is the natural narrowing, the bridge, the tributary, etc…) and what aggravating factor to apply at this place.

Comment 36: "Line 104-105: About the secondary channel presenting a more competent ice cover: I do not agree and the authors do not refer to any study to support this. From my point of view, there could be less (or no) ice in the secondary channel and at some location, the secondary channel plays a determinant role in the ice jamming initiation process. "

Reply 36: The assumption was that the main channel (here the more direct route) is the one with the maximum discharge. Hence, the secondary channels would freeze earlier. This section was modified.

Comment 37: "Line 105-107: Every island site is different and I am not sure that the simplification proposed by the authors is the most adequate one. Food for thought."

Reply 37: Initially, we tried to consider in our analysis, the position of the island in the channel as well as the shape of the island. This proved to be complex and hard to calibrate. This is why we went for such a simplification. Clarification was made.

Comment 38: "Line 108: Do you have any information about the pillars? What is the assumption here? If the bridge is located downstream of rapids, ice blocs may be small and easily pass under. If large is slabs come in contact with wide, rectangular pillars, yes, they might be stopped right there. This would be a serious engineering error that as no real link with a channel narrowing. Line 109: What do you mean by "initially"? I believe that this factor should have been calibrated more accurately or considered differently (not a narrowing). Line 112-113: I believe that this is a major mistake made by the authors: Presenting an assumption in the methodology, mentioning that it could be improved before the results are presented and not doing anything later despite this could have been better calibrated."

Reply 38: As mentioned before, there is no physical assumption here, other than that the presence of a bridge may increase the possibility of an ice jam (either as an obstacle or a constraint). Again, bridges that do not pose such a risk should be taken out of the analysis. The weight of the remaining bridges could be adjusted like for instance, one could adjust the manning coefficient when trying to better fit a hydraulic model to a specific river. On the Chaudière River, there are 18 sections with a bridge. Due to the weight applied to bridges, all sections are classified as having high (15) or medium (3) predisposition. Of these 18 sections, 7 report ice jams. So this indicates that the model is right to consider bridges as an aggravating factor but at the same time, that not all bridges are equal and that fine tuning should be done at the local scale. Clarification was made..

Comment 39: "Line 116: Specify that this gives more importance to large tributaries. Again, this has almost nothing to do with channel narrowing."

Reply 39. Again, it is true that the impact of the tributary is just indirectly related to the concept of narrowing. The strategy of considering it as a narrowing is a scheme to apply a predisposition weight at this spot.

Comment 40`"Figure 3: Does not explain well how the tributary is considered"

Reply 40: Figure improved.

Comment 41: "Figure 4: The flow direction should be the same than in Figure 3. A narrowing index (equation) should be presented for each presented section."

Reply 41: Figure improved.

Comment 42: "Line 131-132: This definition refers to SV, not the Sinuosity4. . . The authors should mention that SV is always larger than 1."

Comment 43: "Line 133: I am not sure that "several" will satisfy the reader. Can you present a range? Can this take into account single bends and not only meanders?"

Reply 42-43: This part was correctly rephrased.

Comment 44: "Line 139-142: Did the authors try to use the 5 m resolution? I am sure that some governmental agencies have data concerning river profiles and hydraulic models. This would probably not be precise enough to determine changes between 250 m sections, but it could very well identify slope breaks that are so important in jamming processes. As a reader, I am disappointed about this ending and this introduces a difficulty acceptable omission in the model. "Luckily" for the authors, a change in slope is normally characterized by a change in morphology and pattern and therefore slope breaks are somewhat indirectly covered by the model. Including gradient data would probably improve the model's result."

Reply 44: Yes, in the development phase, we used the 5m elevation data to detect slope breaks. A DEM was created by interpolating contour lines. Then, altitude was extracted at the upstream and downstream limit of each 250m section to calculate slope. However, due to accuracy of the data and to the interpolation process, this would result in a longitudinal profile showing big steps. At the time, river ice experts advised us to take out the slope index. If lidar data were to become available over an entire river, it should be possible to reintegrate the slope index. The link between slope and channel morphology may be a reason why even without a slope index, we can obtain very promising results. Clarification was made.

Comment 45: "Line 146: I would say "approximate" since most jams are longer than a single coordinate and because this geolocation does not refer to the toe where the jamming process is initiated. In some instances, the toe could be kilometers away from the observation point. Also, as mentioned in the general comments, some reported ice jams could be intense anchor ice or frazil jam events and these *processes could take place at locations where ice jams are not likely to form. A validation with a corresponding rising Q should be performed.*

Reply 45: Clarification done. Concerning the possible anchor ice or frazil jams, it is out of the scope of this study to validate the historical database.

Comment 46: "Line 157: This is the Chaudière River section but this sentence refers to the three rivers."

Reply 46: The model was developed mainly with the data from the Chaudière River. However, to determine the thresholds for the classes of Narrowing and Sinuosity index using K-means, we have decided to use the entire range of values from the three rivers in this study. This provides a more robust and representative model. Clarification was made.

Comment 47: Lines 163-166: Note here that you use "reported" ice jams to calibrate a model. Taking into account previous comments may improve the calibration result and their reliability.

Reply 47: Clarification was made.

Comment 48: "Table 3: This is a fair analysis tool but note that this version of the model cannot gain a high precision potential in part because it is limited by a 2D IJPI. Also, note that highly sinuous reaches often present a relatively constant width and therefore, the two parameters considered here are not independent. Therefore, a value of 1 may be difficult to obtain in reality."

Reply 48: We do not understand this comment and to what it refers.

Comment 49: "Line 201: About false negative errors: Please consider the potential length of the jam and the difference between the initiation site (predisposition) and the observation site (anywhere along the jam). Line 202: About false positive errors: Not really an error because this is not an ice jam temporal prevision model. Please consider at everywhere in the paper that important ice jams can happen where there is no observation point nor vulnerability.."

Reply 49: We agree. Clarification was made..

Comment 50: "Line 209: I understand that the model can underestimate some factors, but this is your calibration river. This could have been better considered if you were not limited to two indicators and if observations had been made in the field."

Reply 50: The model has two indices but they in fact reflect five factors that can favor the initiation of an ice jam. Tributaries being one of them.

Comment 51: "Lines 210-211: Exactly, and this should be stated clearly in the previous sections. Not only a source of incoming ice, but also a source of incoming runoff and javes."

Reply 51: Clarification was made.

Comment 52: "Lines 221-222: Please eventually consider: The contributing area for ice blocks, the gradient, an increasing width, the absence of observation points along the river, the absence of vulnerability along the river, and finally, ice scars on trees. You should present the potential reasons for false-positive errors in the form of bullets."

Reply 52: Added to the discussion.

Comment 53: "Line 219: Same comment as line 209. Bridges are often located at natural narrows, but there design does not necessarily impede the transit of ice runs."

Reply 53: This point was addressed earlier.

Comment 53b: "Line 224: How short? Please specify a range."

Reply 53b: Clarification done.

Comment 54: "Table 4: You could have further investigated the 6 "no specific feature". This could mean factors that have not been considered.

"Table 5: Same comment as Table 4"

"Lines 259-263: The model may be missing something because there is no info about the gradient. A widening is also a site for ice jams, especially downstream of rapids or riffles. Note also that the analysis assumes that the toe of the jam was correctly located, which may not be true."

Reply 54: This was better stressed out in the discussion.

Comment 55: "Line 245: Note about bridges: Their presence can mean less snow ice and more thermal ice. Their presence can also be associated with de-icing salt falling on the ice surface. Then, what would be the final relative ice resistance at the time of breakup?"

Reply 55: This is a very local consideration and cannot be accounted for in a general model.

Comment 56: "Line 260: Please add a reference that supports that sand bars are associated with ice jams. I do not know any."

Reply 56: Refer to reply 25.

Comment 57: "Line 265-266: Yes. But then, this could be associated with other morphological or areal patterns."

Reply 57: True but still a time dependent parameter.

Comment 58: "Lines 278-280: A lot of sections may be associated with ice jamming, but the contributing area is just too small. The ice jam will most often form in the first (upstream) predisposition area located downstream of a long stretch of relatively fragile ice."

Reply 58: Interesting point. Could be considered in a future version of the model.

Comment 59:

"Figure 8: Potential interpretation (I do not know this site): This is enough narrowing, widening and changing direction to generate an ice jam. The low floodplain on the left bank and the possible secondary channel all support ice jamming. The marker may point a pool between two riffles where ice jams often form (against a small hanging dam. . .).

Figure 9: Potential interpretation: B: The ice run loses energy in the bend and loses further energy in the widening. C: Water evacuation channels and changes in direction, enough to initiate an ice jam.

Figure 10: Potential interpretation: This is an energy concentration area followed by a dissipation area. If there is no info about the jamming scenario (jamming of an impeded or unimpeded ice run), the reason for the ice jam event is hard to certify."

Reply 59: This was considered in the new conclusion section.

Comment 60: "Figures 8 to 10: Note how all these reported jam are located where roads or houses are close to the river, ideal observation points that may not correspond to the ice jam toe."

Reply 60: See reply 47.

Comment 61: "Table 6: You could lower the False-Positives by considering the length of the potential contributing area."

Reply 61: See reply 58.

Comment 62: "Line 300 and Lines 302-303: Yes, but the slope could not be considered and this should be mentioned as a potential development, not as a limitation of the actual model. This should be part of a discussion section. Overall, some sentences could be written more positively and confidently."

Reply 62: Clarification done.

Comment 63: "Line 314: Here, the bathymetry is considered as a dynamic parameter. Why? Why not just considering morphological (pattern, width, gradient, topography) and ice (type, potential thickness, possible processes) parameters?"

Reply 63: By bathymetry, we mean water depth. As with ice, it is a variable parameter that cannot be considered in this simplified model.