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Preliminary development of a geospatial model to estimate a river channel's predisposition to ice jams

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When dynamic breakup occurs on rivers, ice moving downstream may eventually stop at an obstacle or when the volume of moving ice exceeds the transport capacity of the river, resulting into an ice jam. The morphological and hydrological factors controlling where and how the ice will jam are numerous and complex. Therefore, the goal of this work is to develop a simplified geospatial model that would estimate the predisposition of a river channel to ice jams. The question here is not to predict when the ice will break up but rather to know where the released ice would be susceptible to jam. This paper presents the preliminary developments and results of the proposed approach.

The initial step was to document the main factors identified in the literature, as potential cause for an ice jam. First, six main factors identified in the literature, as potential cause for an ice jam have been selected: 1) presence of an island, 2) narrowing of the channel, 3) sinuosity, 4) presence of a bridge, 5) confluence of rivers and 6) slope break. The second step was to spatially represent, in 2D, the physical characteristics of the channel and to translate these characteristics into potential ice jamming factors. The Chaudiere River, south of Quebec City (Canada), was chosen as a test site. Tools from the GIS-based FRAZIL system have been used to generate these factors from readily available geospatial data the and calcutate the "ice jam predisposition index" over 250m segments along the entire channel. The resulting map was validated upon historical observations and local knowledge.

1. Introduction

Ice jams are the accumulation of fragmented ice on a specific section of a river, obstructing the channel and restricting flow. They happen mainly during the breakup season but can also form at freeze-up or even in winter, if precipitations cause a sudden increase of water levels and a partial dismantlement of the ice cover. Ice jams are frequent in Canada and in northern United-States and the resulting floods are socio-economically costly as well as life threatening. 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, 2002). However, the triggering meteorological, hydrological and morphological factors are numerous and complex and their analysis is difficult and often site-specific (White, 2002). Moreover, when breakup occurs and ice starts to move downstream, another unknown remains: Where would the released ice be susceptible to jam?

The goal of this study is therefore to provide some answers to that 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 and of the watershed. It was developed on the Chaudière River south of Quebec City (Province of Quebec, Canada) (Figure 1), which flows south to north from Megantic Lake to the Saint-Lawrence River. This river has a history of ice jams and frequent flooding of riverside municipalities. This paper presents the preliminary developments of the approach on the Chaudière River and the first results.

2. Methodology

2.1 Background

The initial step of the methodology was to document the main factors identified in the literature, as potential causes for an ice jam. According to White (2002), ice accumulation and jam occur when the volume of ice exceeds the transport capacity of the river. We therefore conducted a literature review to highlight the parameters having an impact on that transport capacity. The following parameters were the most often mentioned: presence of islands in the channel, presence of a bridge across the channel, narrowing of the river channel, meandering, tributaries, sudden slope changes, shallow waters and estuaries. Some authors worked more closely on some of these factors. For example, Kalinin (2008) conducted a qualitative and quantitative study of the first five parameters mentioned above while Dutton (1999) established classes of sinuosity, Jasek (1995) looked at the influence of the length of islands and Saint-Laurent et al. (2001) studied the shape of the tributaries watersheds. Based on the available documentation, six factors have been selected at this stage: 1) sinuosity, 2) narrowing of the channel, 3) presence of an island, 4) presence of a bridge, 5) confluence of rivers and 6) slope breaks. In this first version of the model, we have discarded dynamic parameters such as flow, ice cover or tides as well as bathymetry, which is not often available.

2.2 Geospatialisation of the selected parameters

Geospatialisation is the spatial representation of a physical characteristic of the channel and its transformation into a hazard factor for ice jam. This was done using a standard Geographical Information System (ArcGIS) and some specific tools developed in ArcObject through the FRAZIL project (Gauthier et al., 2008) for the support of winter hydraulic modeling and ice-jam early warning systems. These tools enable the determination the river channel center line, its

segmentation into equal length sections and the calculation of the width, the calculation of channel curvature radius and sinuosity along the axis. In this work, calculations were integrated along 250m long segments. Input data come from the National Hydrographic Network (NHN), the National Topographic Database (NTDB) and the Quebec Topographic Database (BDTQ). Relevant files include river channel, watershed, islands, bridges, rapids, towns and elevations.
To address sinuosity, we have retained some of the classes from Dutton (1999), mainly through the standardized sinuosity coefficient S in equation 1.

$$S = \sqrt{1 - \left(\frac{1}{SV^2}\right)} \qquad [1]$$

Where SV is the coefficient of sinuosity (Equation 2):

$$SV = \frac{\text{Curvilinear distance}}{\text{Euclidean distance}} \qquad [2]$$

We then compared the value of S to 0.34 and 0.66, which are thresholds for a medium and high sinuosity, as specified by Dutton. Proposed classes are then:

- 0 (no hazard): $S < 0.34$
- 1 (low hazard): $0.34 < S < 0.66$
- 2 (high hazard): $S > 0.66$

For the second parameter, we established the percentage of narrowing (*Wn*) by comparing the main channel width from one river segment to its upstream neighbour. Classes were established empirically as no reference was found in the literature.

- 1: *Wn* < 66% of *Wn-1* (medium change)
- 2: *Wn* <50% of *Wn-1* (strong narrowing)

Dealing with islands is far more complex, as shown in Figure 2. Based on Jasek (1995), which stipulates that the upstream point of an island presents a higher risk for ice jamming (due to shallow water), we have first identified all island heads. However, if an island is farther to the main channel than another island (islands #2 vs #1 in Figure 2) within the same segment we consider that it won’t alter the main flow and therefore, it was discarded. Then, considering that small islands (relative to the channel width) would also have a lower impact on ice jam risk (case #3 in Figure 2), we’ve isolated them using two criteria:

- *Lis/B < 1*, from Jasek (1995). *Lis* is the length of the island and *B* is the total width of the channel.
- And/or: when both upstream and downstream points are within a single segment.

All remaining upstream points are considered in the analysis. In this model, segments with one or more upstream points are considered equally (islands #1 and #4 in Figure 2). Therefore, classes would be:

- 0: No island or island not in the main channel
- 1: Presence of a small island
- 2: Presence of a larger island in the main channel

However in future versions, segments with several islands could be considered more at risk.

Bridges also constitute obstacles for ice flows. In this version of the model, we simply considered the absence or presence of such a structure, notwithstanding the type of pillars. Classes are then:

- 0: Absence
- 2: Presence

To weight the impact of tributaries, we have used the Horton index, which characterize the shape of a watershed (St-Laurent, 2001). We make the hypothesis that a sub-basin with a large drained area and a short respond time would break more easily and the released ice would increase the risk of a jam at the junction of the main river. To calculate the Horton Index (Rf), we started from the Hydro Junction layer of the NHN. For the Chaudiere River, we calculated the distance between the outlet and the far most point of each tributary (Lm, in km). Then, we calculated the area of each sub-basin (A, in km²). Therefore:

$$\mathrm{Rf} = \frac{\mathrm{A}}{\mathrm{Lm}^2} \quad [3]$$

A round sub-basin (large A, small Lm) would drain more water and increase ice jam hazards. So the selected classes are:

- 0: $0 < Rf < 0.2$
- 1: $0.2 < Rf < 0.3$
- 2: $Rf > 0.3$

Finally we used the "rapid" layer from the NHN as an indicator. In fact according to Michel (1986), rapids act as a cruncher of ice and ice jams do not occur in these areas. The slope break criteria might be ideally made with bathymetry data, but it was not available for the Chaudiere River. So when a rapid intersects with a segment, the risk is set to zero. However, in a future version of the model, rapids should also be considered as frazil producers and the impact downstream should be evaluated. It should be noted that proposed classes for all parameters are within 0 and 2 in order to keep similar extreme values.

2.3 Conceptual model

The conceptual model then integrates the predefined parameters to establish the potential occurrence of ice jams for each 250m segment along the river. The class value attributed to each parameter is first multiplied by a weight factor, according to its estimated importance in the process of ice jam formation. Firstly we used mainly the study of Kalinin, then some weight factors were adapted depending on the river response to the model. The ice jam predisposition index (IJPI) is then calculated from the ratio of the sum of the weighted values by the sum that would be obtained if all hazards were maximal (equation 4):

$$\mathrm{IJPI} = \frac{\sum_{k=1}^{5} \mathrm{Vk\,Pk}}{\sum_{k=1}^{5} \mathrm{Vmax\,Pk}} \quad [4]$$

Where:
V_k : class value [0-2]
P_k : attributed weight
V_{max} : Maximum class value (V_{max}= 2).

3. Results and validation

The model was tested on a representative section of the Chaudiere River (from Saint-Georges to Beauceville), containing islands, bridges, tributaries and rapids. It is also the section containing the most validation data, which come from a study by Petryk et al (1995) and a series of interviews that we have conducted with the directors of public safety and fire departments of all municipalities along the river. The obtained values for IJPI were categorized as:

IJPI $\in$ [0 ; 0.2[: low risk of ice jam at that location
IJPI $\in$ [0.2 ; 0.3[: medium risk of ice jam at that location
IJPI $\in$ [0.3 ; 1] : high risk of ice jam at that location

The first results of the model are presented in Figure 3. According with validation data, the areas that were correctly classified (forecasted) appear in green stars (7) and those incorrectly classified appear in red stars (5). According to White (2002), multivariate models have a tendency towards positive errors (false ice jam prediction). The validation data were therefore used to recalibrate and improve the model in order to decrease false predictions.

Some of the errors were related to bridges. It appeared that some structures have pillars that do not cause obstruction to floating ice. Some cases of multiple islands were not properly taken into account and adjustments were made. The tributaries seem to have a higher impact than expected or that the Horton index was not sufficient to estimate the impact. A new condition was therefore added to the model:

$$A_{sb}/A_{tot} > 10\% \qquad [5]$$

Where A_{sb} is the drainage area of the sub basin and A_{tot} is the total drainage area of the Chaudiere watershed.

Finally, the importance of sinuosity was also underestimated and the problem was corrected by keeping only two classes (0: S <0.34 and 2: S >0.34). The adjusted conceptual model is presented in Figure 4 and improved results are presented in Figure 5.

4. Conclusion

A model to estimate a river channel's predisposition to ice jams would be useful when planning a housing development along a river or the construction of a bridge. This preliminary geospatial model produced interesting results that encourage us to pursue his development. However, it still present certain limitations, as positive errors could not be resolved. We will work to refine every aspects of the model in terms of parameters, classes and weight. We will take into account the succession of sedimentary links. The problem with the pillar of bridges has to be quantified, maybe including pillar spacing and river width at the bridge reach. The problematic of islands has also to be refined in order to deal with reaches where more than one island appears. Indeed most of the positive errors occur with the presence of islands on the main channel. Finally, we will also look at the model's transposability by testing it on a different river...

Acknowledgments

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Figures and Tables:

Figure 1 : Location of the Chaudière river watershed, Southern Quebec, Canada.

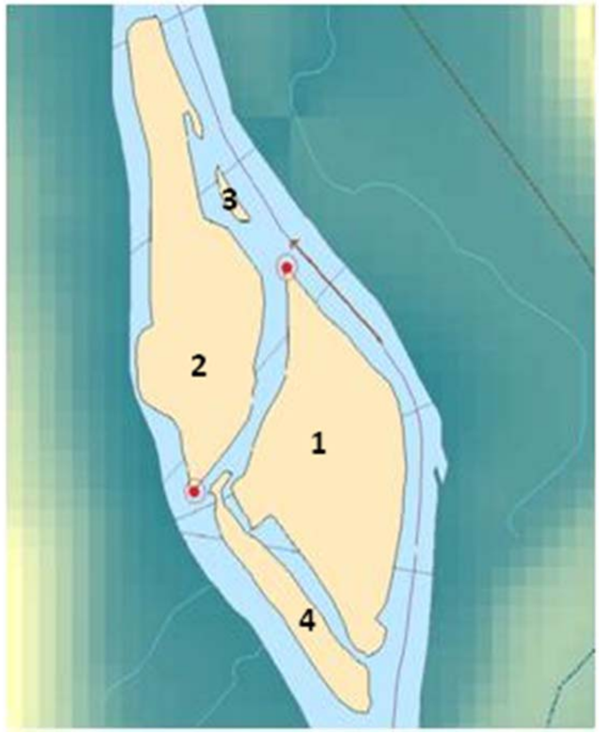

Figure 2 : Complex case of islands. The upstream point of an island presents a higher risk for ice jamming (due to shallow water), then all island heads must be identified. However, if an island is farther to the main channel than another island (islands #2 vs #1) in the same segment, it won't alter the main flow and therefore, it was discarded. Then, considering that small islands (relative to the channel width) would also have a lower impact on ice jam risk (case #3), they are isolated using two criteria: 1) $Lis/B < 1$, from Jasek (1995). *Lis* is the length of the island and *B* is the total width of the channel. 2) And/or: when both upstream and downstream points are within a single segment.

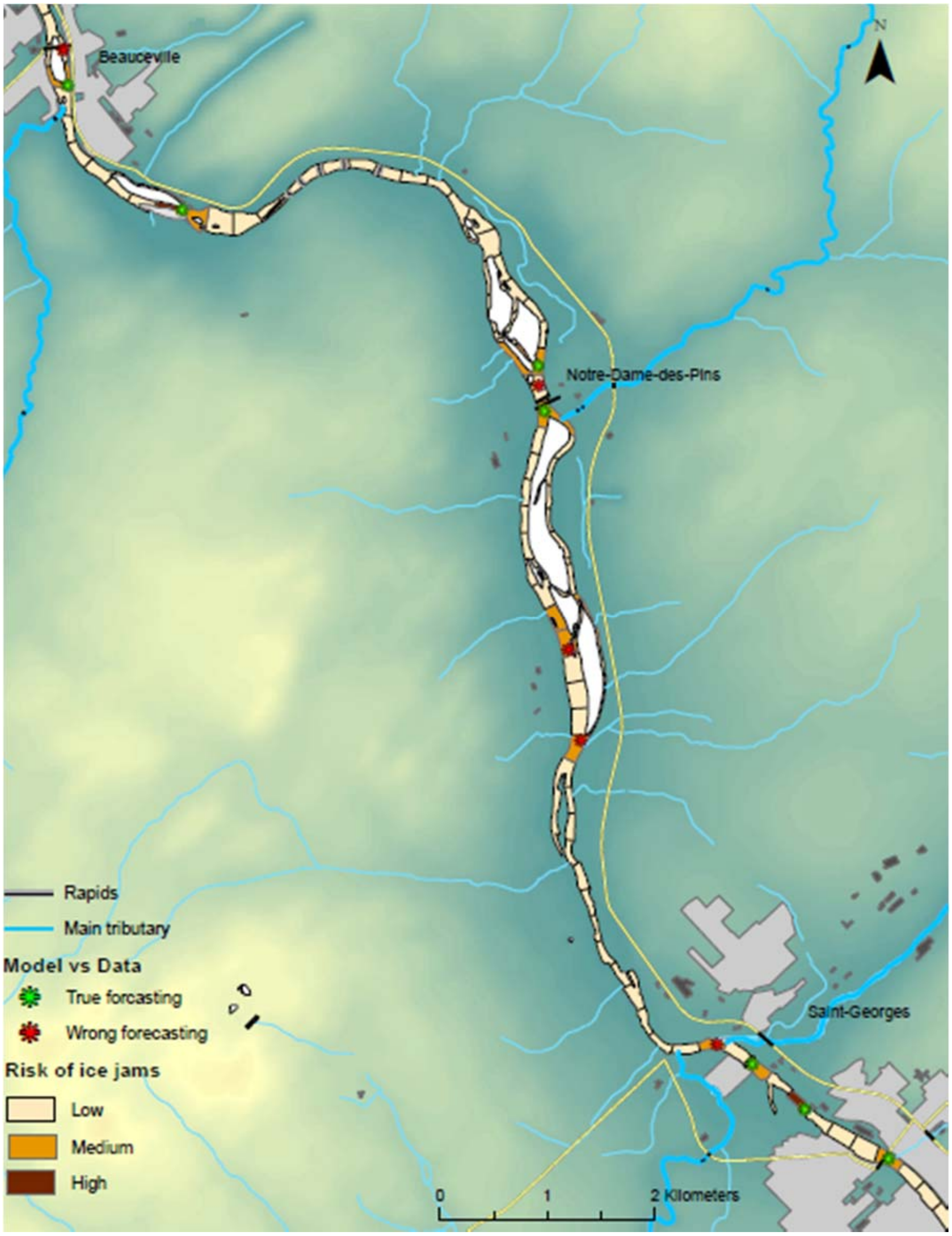

Figure 3 : First results of the model for a 30 km river reach the Chaudière River. The low risk segments are in pale yellow, the medium risk segments are in orange and the only high risk segment is in brown. According with validation data, the areas that were correctly forecasted appear in green stars (7) and those incorrectly forecasted appear in red stars (5).

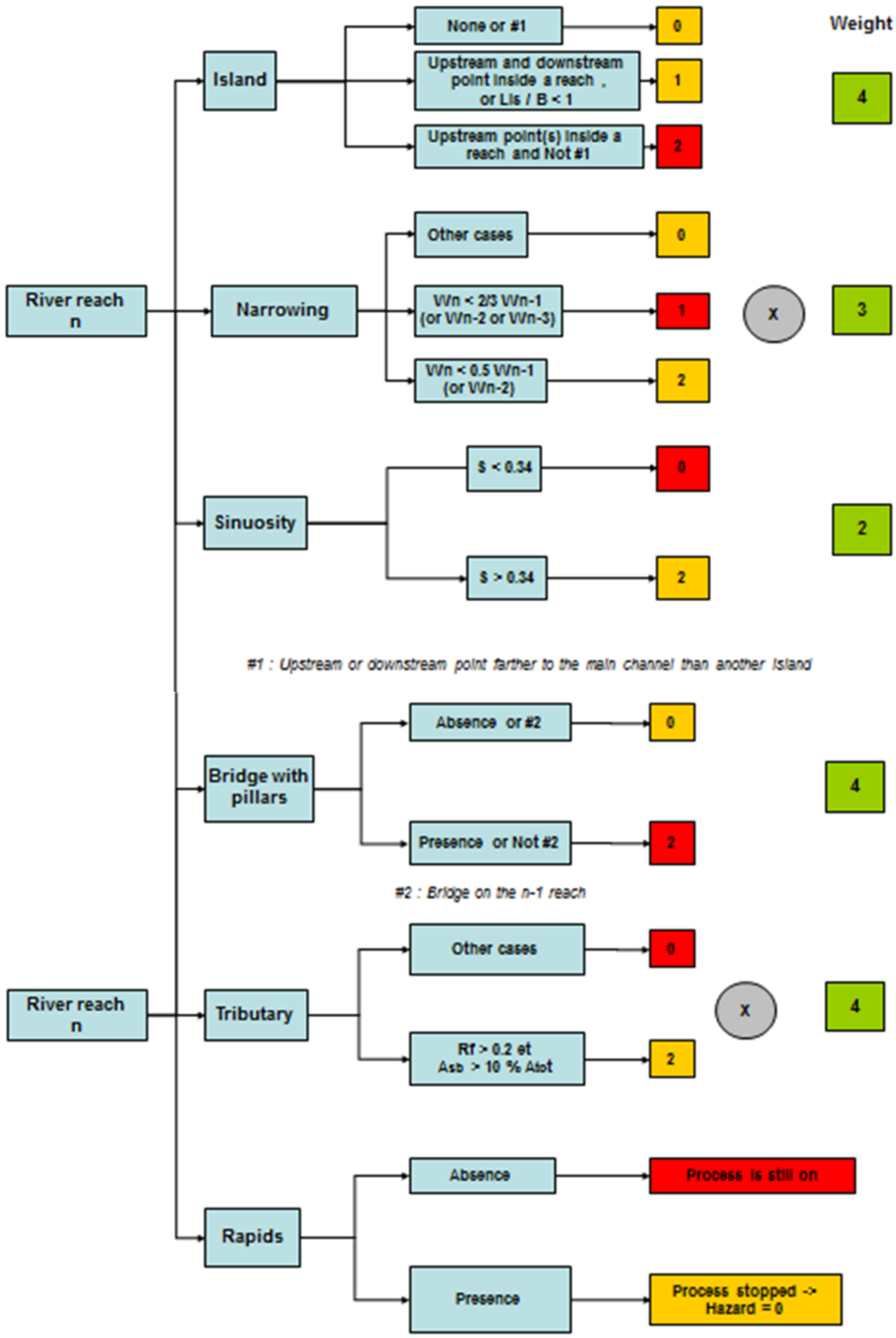

Figure 4 : Adjusted conceptual model. The green squares are the relative weight gives to each parameter except the rapids: island (4), narrowing (3), sinuosity (2), bridge with pillars (4), tributary (4). The red squares represent values taken in a case study. Here the ice jam predisposition index IJPJ gives 19 / 34 = 0.56.

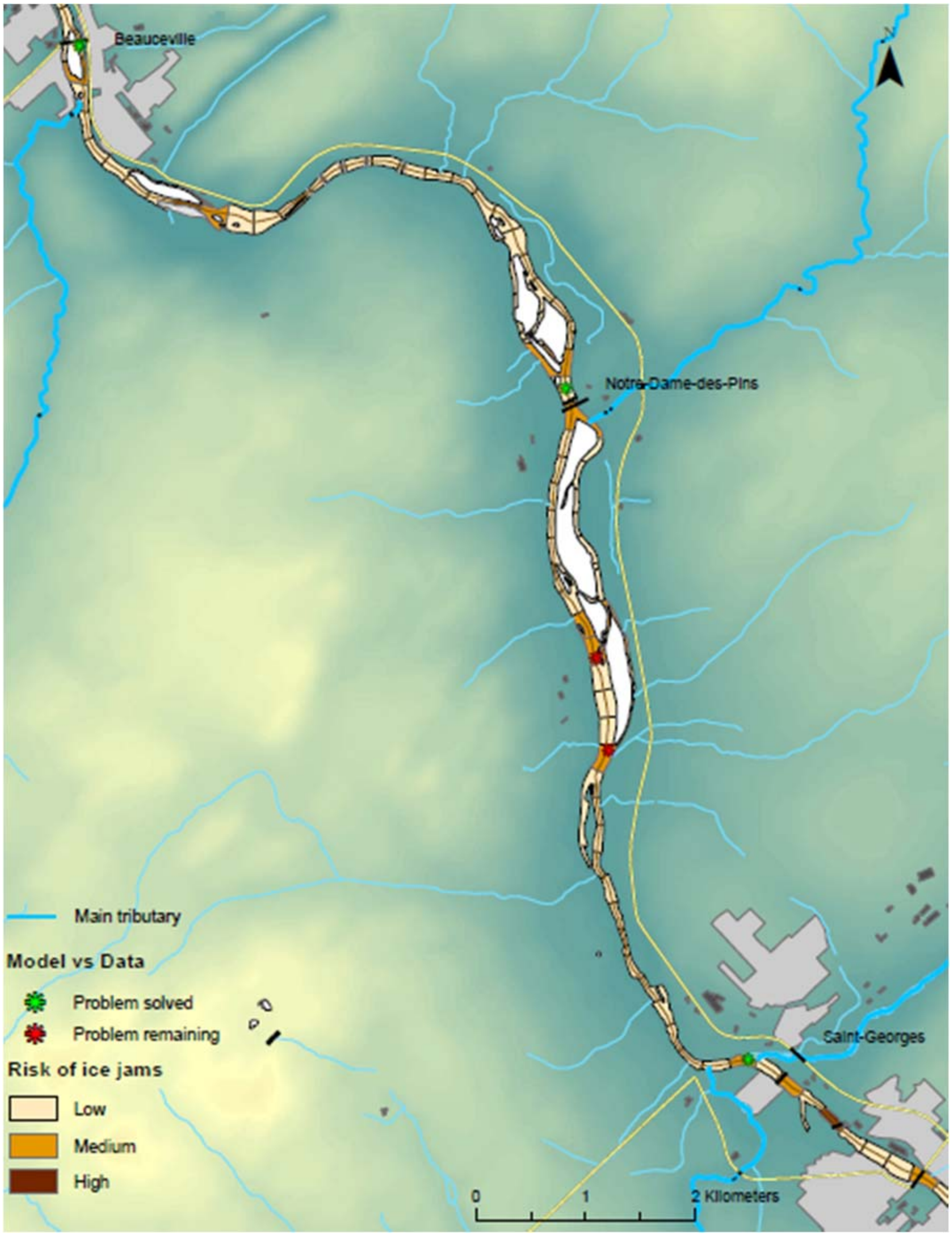

Figure 5 : Improved results for the same 30 km river reach of the Chaudière River (Figure 2) The adjusted conceptual model solves the problem for three segments incorrectly forecasted by the initial version of the model (green stars). However, the wrong detection remains for two segments over the five areas previously incorrectly forecasted. Further, there are more medium risk segments (orange) of ice jams with the adjusted model but no high risk segment (brown).