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# Using the FRAZIL system in support of winter river flow modelling

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## Abstract

The purpose of the FRAZIL Project is to develop a GIS-based system in support of winter river flow modelling and ice-related flood forecasting. Usually, *in situ* measurements and simulation models are used to characterize the state of the river and to foresee its future behaviour. The advantage of using GIS in hydraulic modelling is the potential for extracting topographically correct cross-section data from a DTM that can be used to determine river stage and floodplain extent as calculated in hydraulic modelling software package. However, such applications require a detailed description of the channel geometry and do not deal specifically with winter flow modelling and the presence of an ice cover. *River1D*, a one-dimensional unsteady flood routing model has been developed to study ice-related events and has been successfully used to adequately predict flood hydrographs over long river reaches, based on relatively limited data. The FRAZIL GIS-based system is well adapted to provide some of the physical characteristics of the river channel. It proposes tools to assist in building the channel geometry, partitioning the river and preparing data for the hydraulic model, while taking advantage of the database and other functions of the ArcGIS software. It is also developed to take advantage of the river ice information which can be derived from a radar image. This component provides an ice map, ice coverage for reaches along the river, relative ice roughness and the location and length of ice jams. This paper presents the approaches used in the development of the FRAZIL tools for *River1D*. The demonstration is made on a section of the Athabasca River (Alberta).

## Introduction

This work is part of the FRAZIL project: *Integrated expertise towards the development of an ice jam related flood warning system*. This initiative is funded in Canada by GEOIDE (GEOmatics for Informed DEcisions) through the Networks of Centers of Excellence (NCE). The purpose of the FRAZIL Project is to develop a GIS-based system in support of winter river flow modelling and ice-related flood forecasting. Hydroelectric companies and government instances need to take considerable measures in order to mitigate potential flooding problems, to optimize hydroelectric revenue and to enable safe navigation on rivers, particularly during winter time, when ice related processes are harder to predict. Usually, *in situ* measurements and simulation models are used to characterize the state of the river and to foresee its future behaviour. However, to develop, calibrate and validate such models, flood forecasters need many parameters, which are not always easily available. This is more so with hydraulic flood routing models, which through their deterministic approach, often require a more detailed description of the channel geometry and of the ice cover (for winter flood routing).

The use of a Geographical Information System (GIS) in support of flood forecasting is now routinely applied with distributed hydrological models [1]. In such applications, a digital terrain model (DTM) is used to assess the terrain variability and determine the drainage network, plus the watershed and subcatchment areas, in support of runoff simulations [2]. Application of GIS to hydraulic modelling is also developing and the most significant example is the HEC-GeoRAS package [3, 4], which is an ArcGIS extension specifically designed to process geospatial data for use with the Hydrologic Engineering Center's River Analysis System (HEC-RAS). The advantage of using GIS in hydraulic modelling is the potential for extracting topographically correct cross-section data from a DTM that can be used to determine river stage and floodplain extent as calculated in hydraulic modelling software packages [5]. But the main required data, which is a complete digital terrain model that includes the bottom of the river channel, is not always available, particularly for long river reaches.

However, it has been consistently shown that one can adequately predict flood hydrographs based on more limited data using hydraulic flood routing models, such as *River1D* [6, 7]. This one dimensional deterministic model has been developed to study ice related events and employs a limited geometry approach (rectangular channel) for flood routing over long reaches [8]. In such a case, the FRAZIL GIS-based system is well adapted to provide some of the physical characteristics of the river channel and to assist in data preparation prior to hydraulic flood routing. Furthermore, FRAZIL being specifically developed for winter conditions, it includes some tools designed to extract ice cover information from satellite radar images, which can also be fed to the model. This study presents the FRAZIL tools that are being developed or adapted to provide some of the necessary inputs to the *River1D* model. This demonstration is made for a section of the Athabasca River, near Fort McMurray, Alberta (Figure 1).

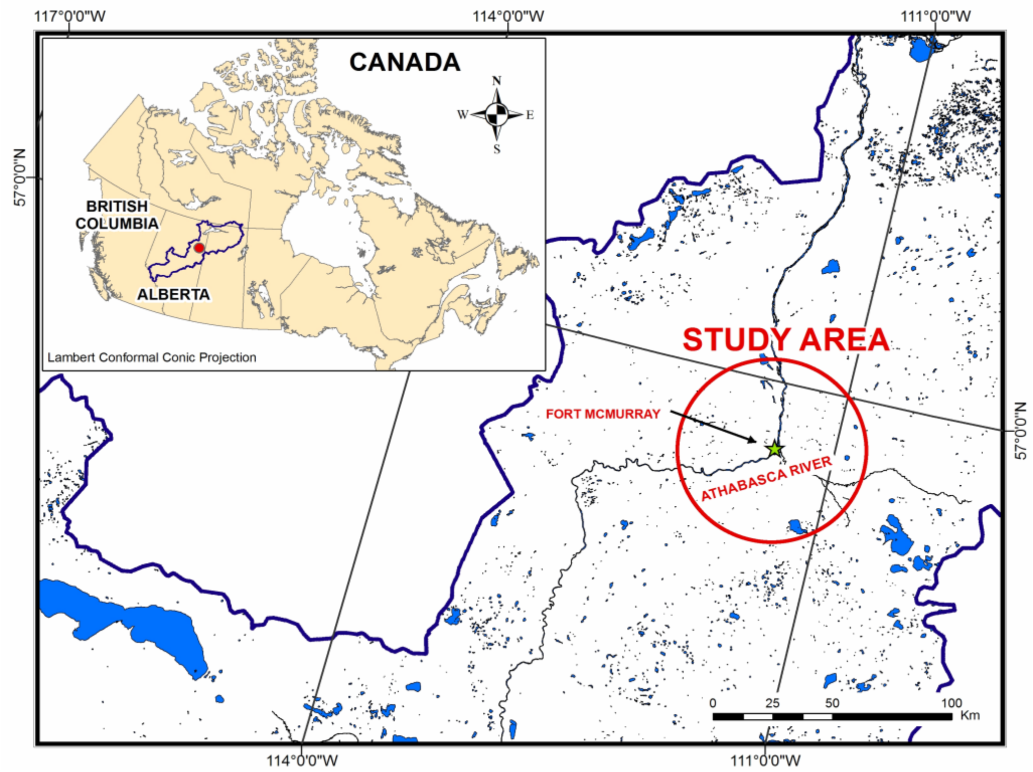


**Figure 1: The Athabasca River near Fort McMurray**

# RIVER1D

*River1D* is a one-dimensional unsteady hydraulic flood routing model which solves the St.Venant equations, for a primary dimension extending in the longitudinal direction [6, 7]. Therefore, it computes values of stage and flow for a series of nodes extending along the channel length. Unsteady flow modeling deals with how these parameters change with time and distance downstream. Therefore, both the temporal and spatial discretization (the length of the computational segments between nodes) affect the accuracy of the model output.

The first step in hydraulic modelling with *River1D* is to define the study reach (upstream and downstream boundaries) and to partition this reach in suitable segments. Between each segment is a computational node. Typically for large rivers, such as the Athabasca River example here, equal 1 km node spacing are used, though smaller discretizations may be employed in the vicinity of rapids. Usually, the origin of the study reach is assigned a station value of 0 (in km) and each subsequent node is assigned a station corresponding to the distance downstream (or upstream) of this origin.

To predict hydrological events, *River1D* requires five types of input parameters:

1. **Geometry of the reach**

   When using a rectangular channel approximation, the channel top width is the only information required. The top width is the horizontal width of the channel at the water surface.

2. **Bed elevation**

   This is the channel invert, or elevation at the bottom of the channel. For the rectangular channel approximation, this represents the mean bed elevation.

3. **Channel roughness**

   The channel roughness is a measure of the resistivity offered by the material constituting the channel, to the flow of water. Apart from the bed material, obstructions, vegetation and meandering, there are other factors affecting roughness. Therefore, this is the parameter with the most uncertainty, and therefore calibration is generally required to define this parameter. Manning's $n$ values or roughness heights ($k$, in m) are used to represent channel roughness.

4. **Boundary conditions**

   These are the hydraulic conditions at the upstream (from inflow hydrograph) and downstream (from stage hydrograph) boundaries of the simulation reach. Lateral inflows from tributaries also have to be taken into account.

5. **Initial conditions**

   For unsteady flow simulations, the initial stage and discharge are needed at every node. The model can be run in steady flow mode to determine these initial conditions.

In winter hydraulic modelling, a sixth parameter is necessary:

6. **Ice cover characteristics**

   On any river, the presence of ice has a significant effect on water levels. It increases the wetted perimeter (by a facto of about two for wide shallow rivers) and decrease channel conveyance, since the ice floats with about 92% of its thickness submerged). Therefore, ice cover thickness and roughness are the two parameters required by the model.

   If there is an ice jam, the *River1D* model can computer a thickness profile using steady ice jam stability theory. However, the location of the jam toe (downstream end) and ice jam length must be known. Ice jam roughness must be specified as an input.

   *River1D* can also model thermal ice processes and ice jam release [9].

## The FRAZIL system

The FRAZIL system includes two major components. The first one is a set of GIS tools developed in ArcObject language, for use with ArcGIS (ESRI).These tools will assist in building the channel geometry, partitioning the river and preparing data for the hydraulic model, while taking advantage of the database and other functions of the ArcGIS software.

The second component is a series of image processing routines developed in Geomatica, an image processing software from PCIGeomatics. These routines use information layers from the GIS to assist radar image processing. The resulting ice maps are then transferred back to the GIS, where other tools will process the new information.

The system is developed with three principles in mind: 1) the input data should be easily available, 2) the tools should be mostly automated and 3) the system should make an optimal use of the radar images.

## FRAZIL - GIS component

This section presents some of the tools of the GIS component, which can be used to assist *River1D*. These specifically designed tools are: 1) Create the channel centerline, 2) Partition the river, 3) Calculate channel width, and 4) Export data.

### *Required data*

Geographic data commonly used in Geographic Information System (GIS) can be of two categories: vector and raster data. The vector data are represented by point, line and polygon features. The raster data are represented as a regularly spaced grid, each cell containing a specific value. Topographic maps usually come as vector information, while radar images and ice maps are of the raster type. Geographic data providers such as governments and private companies, follow rigorous and pre-established standards. These conventions ensure standardized data production and quality products. Numerical data can come from various sources, be produced with different techniques and have their own constraints, limitations and accuracy. Metadata documents usually provide this information. The choice of input datasets directly affects the accuracy of the final results and should be done carefully.

The basic input required by the FRAZIL GIS tools is the vector for the right and left bank of the river. For the development of the FRAZIL GIS tools, we have used the 1:20 000 hydrography base feature maps (planimetric accuracy: 5m) from the National Topographic System (NTS) of the Government of Alberta. Larger scales are possible but it will affect the result's accuracy. At the 1:20 000 scale, rivers larger than 20m are represented as polygons while the smaller ones are represented as single polylines [10]. Other necessary information layers included in the hydrography base feature maps are islands, dams and rapids. From the communication base feature maps, roads, bridges, railways, pipelines and power lines are useful for interpretation purposes.

### *Creating the channel centerline*

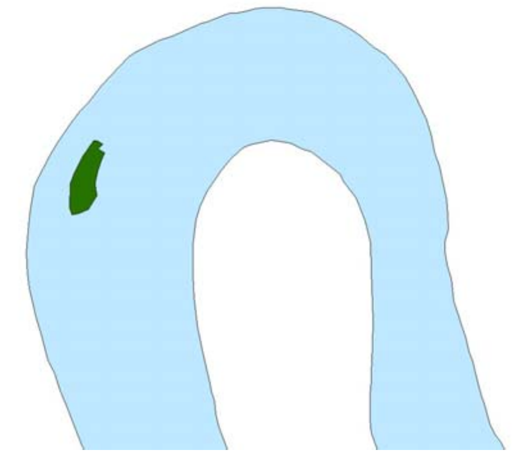
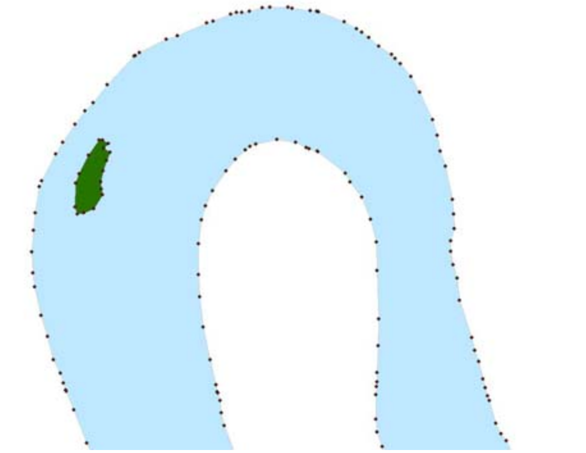
Defining the longitudinal axis of the river of the channel is the initial and most fundamental step before any channel geometry can be achieved. But this longitudinal axis can have different definitions and, depending on the selected approach, it may vary in shape and length. Ideally, the longitudinal axis should follow the channel's thalweg, or the line following the deepest points along the river bed [11, 12]. However, this can be difficult to define unless a dense series of cross-sections are available. Also, with scour and deposition and/or bedform migration, the thalweg location can shift over time. For hydraulic simulations over long reaches, this approach is not practical.

Most commonly, the longitudinal axis is simply defined as being the centreline median of the channel. This approach is often used as a way to generalize a river with a single polyline. Many flood simulation studies use it, by hand drawing an arbitrary line between the two channel banks [3]. However, when automated, this method is time consuming and the resulting centerline contains many anomalies due to the uneven nature of a river channel.

A more accurate centerline can be achieved by skeleton extraction [13]. A voronoi diagram is first created for the channel, to express the proximal regions of each object and to provide adjacency relationships [14]. Then, only the resulting medial axis is kept and smoothed, providing a centerline that adequately follows the channel shape. This method allows the creation of an automatic tool which can manage almost any river geometry. When adding the islands to the channel layer, this method will create a centerline dividing around the islands. Although useful, this information is more complex to process. So in this present version, FRAZIL do not consider islands for the creation of the centerline. Figure 2 presents the required steps for generating a centerline with this approach. The channel bank polylines are first segmented into points, which become the objects used to create the voronoi diagram. As referred in [15], the Voronoi lines are placed such that:

- Only one point falls within each polygon
- The location of any intersection is equidistant to the same number of points as the number of lines intersecting at that location (i.e. An intersection of three lines is equidistant to three points).
- Any location on a given inner line (other than at an intersection) is equidistant to exactly two points.
- Any location within a given cell is closest to the point within that cell.

The medial axis is then isolated and smoothed, creating a centerline for the main channel as well as for the back channels.

| | |
|---|---|
|  |  |
| Step 1. Initial polyline of the channel banks | Step 2. Transformation of the polyline into points |

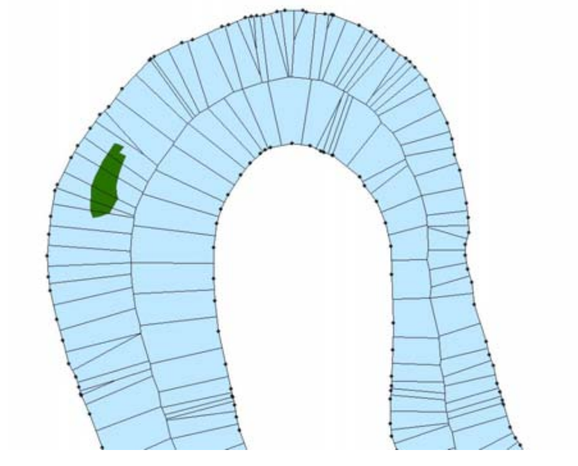
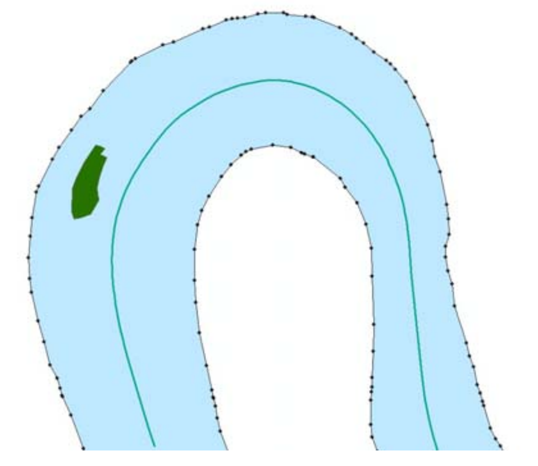
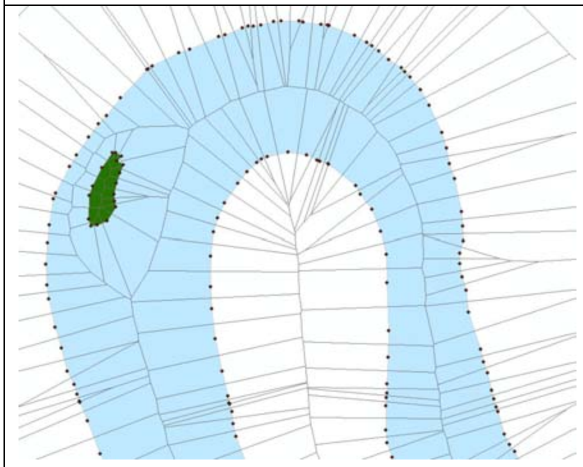
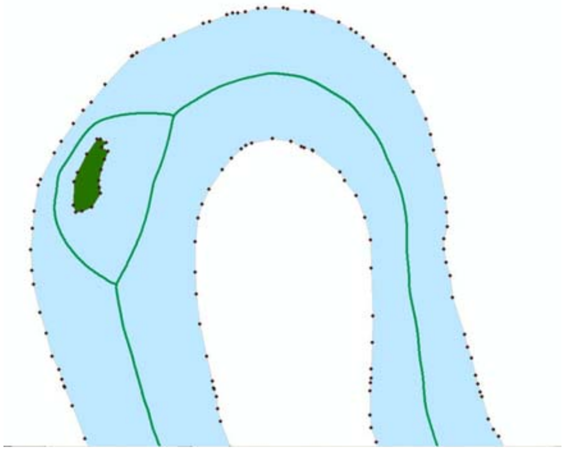
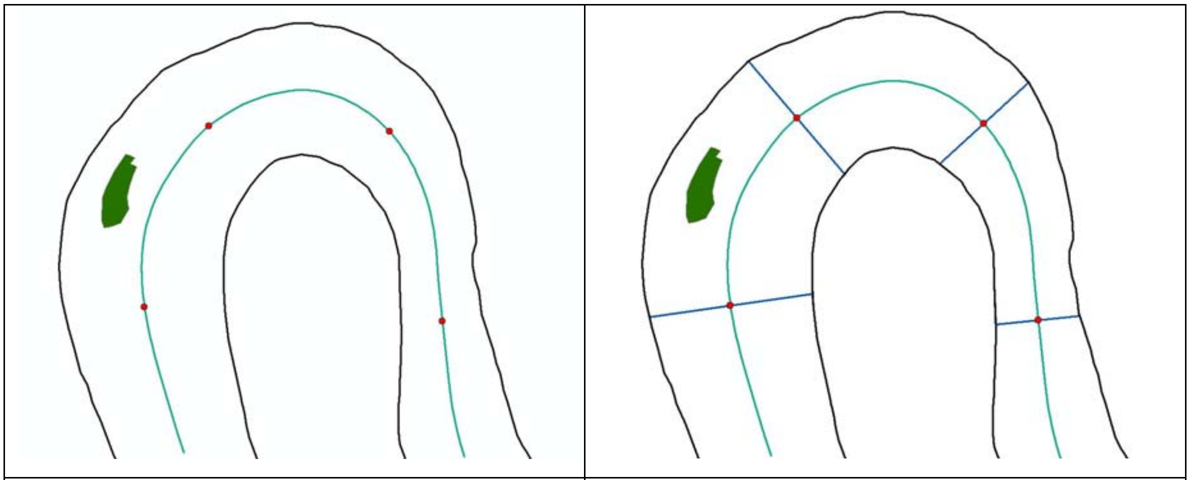
| | |
|---|---|
|  |  |
| Step 3. Creation of voronoi diagram | Step 4. Extraction and simplification of the centerline |
|  |  |
| Creation of voronoi diagram considering islands | Extraction and simplification of the centerline considering islands |

**Figure 2 : Centerline extraction steps with skeleton approach**

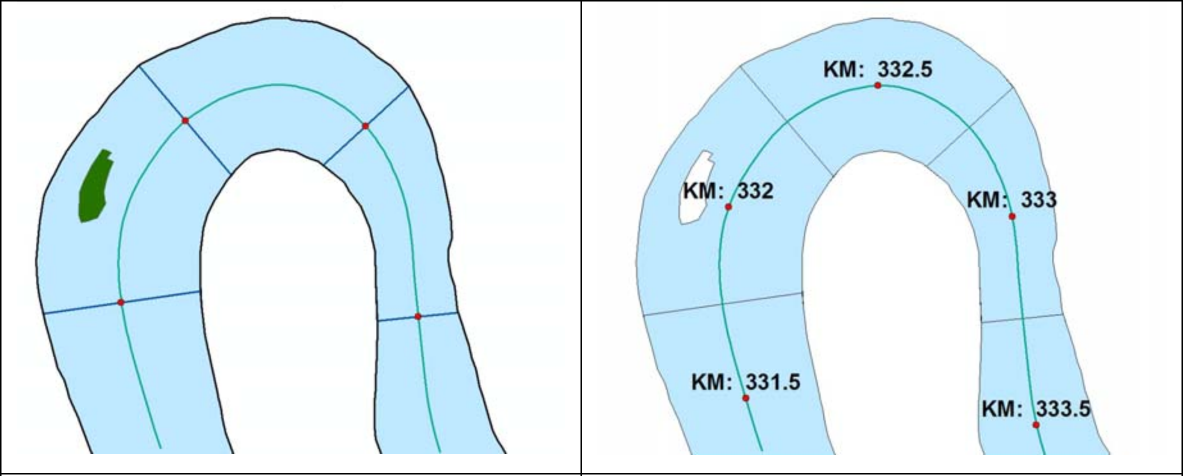
### *Partitioning the river channel*

The achieved centerline can now be used for partitioning and stationing of the river. This tool allows the user to determine the starting point (upstream boundary) and endpoint (downstream boundary) by entering coordinates or by clicking on the map. The system reads the user coordinates and finds the nearest point on the centerline. This point on the centerline is saved as the starting (or ending) point. The user can now enter the desired length for the segments. Starting upstream (Figure 3), temporary nodes are assigned on the centerline at the specified interval. Then, perpendicular lines are drawn from the centerline at each node and extended to both banks. By closing the resulting vectors, polygons are created. From these polygons, islands are extracted by using spatial intersection and deletion. Finally, the computational nodes are created along the centerline, at mid-point of each polygon-reach. At the same time, stationing is done giving each node a km attribute, which is the distance from the origin, measured along the defined centerline. With this feature, it is possible to obtain an averaged value for the area around a node and to assign it to the node. For example, this will be used for extracting ice concentrations.



Step 1. Creating temporary nodes

Step 2. Drawing perpendicular lines



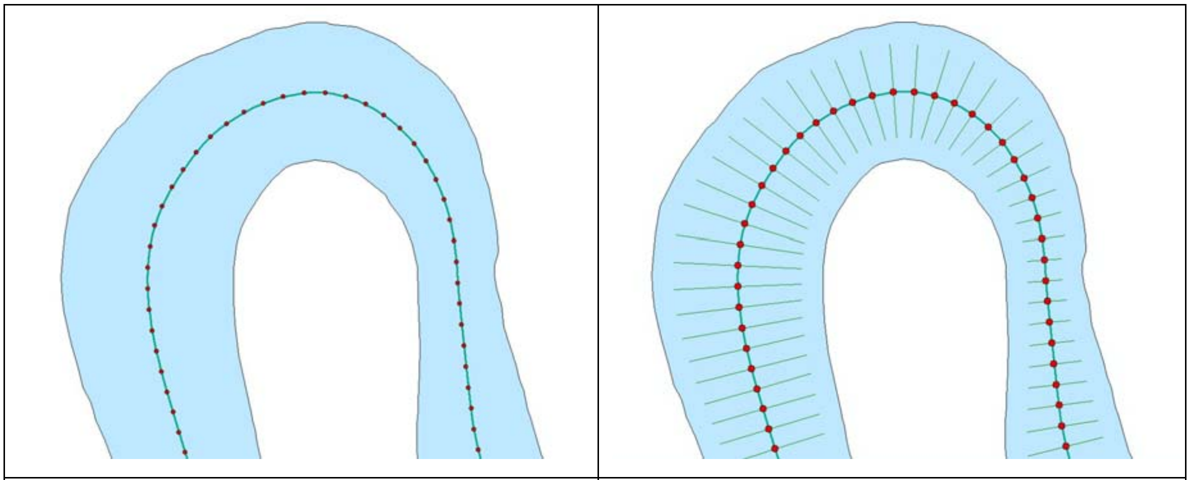
Step 3. Creating polygons

Step 4. Removing islands, creating computational nodes at 500m intervals and assigning km

**Figure 3 : Partitioning and stationing steps**

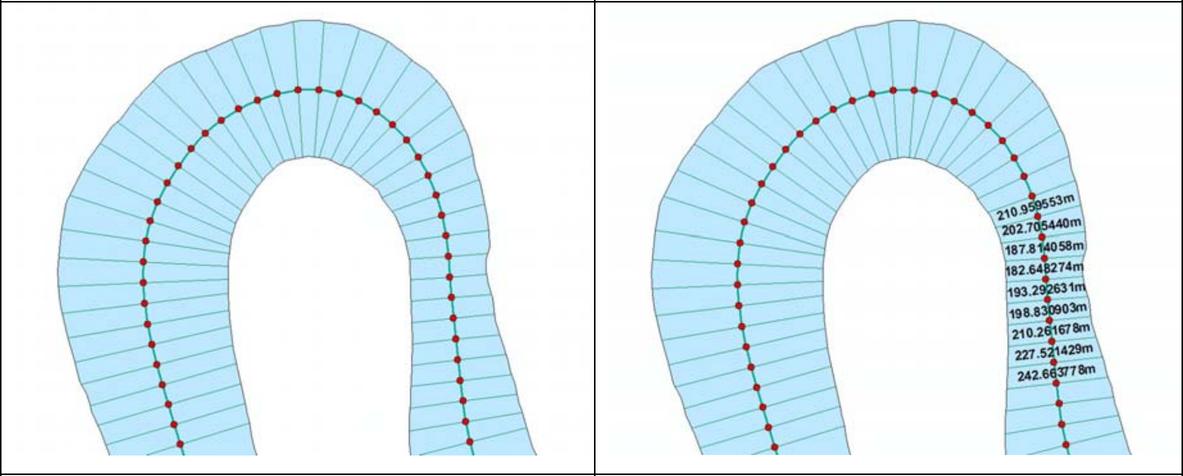
### *Calculating the channel width*

In this study we consider that the vectors of the 1:20 000 hydrography layer are a good representation of the channel banks and thus, of the water surface. Therefore, in terms of GIS, we can define the river top width as being the smallest distance between the right and left bank. To achieve this width calculation, we start again from the centerline (Figure 4). The first step is to segment the centerline into points at close intervals (e.g. 50m). Then, the same approach used for polygon-reaches is applied, constructing perpendicular lines at each point and extending the lines to both banks. The length of each line is then calculated and corresponds to the channel width.



Step 1. Segmenting river centerline

Step 2. Creating perpendicular lines



Step 3. Extending perpendicular lines to banks

Step 4. Calculating length

**Figure 4 : Channel width calculation steps**

### *Exporting data*

Any information layer in the GIS (vector or raster) can be overlaid with the polygon-reaches, the centerline and the computational nodes. This enables the exportation of data under different forms. The FRAZIL export tool enables the exportation of information for each node. The value transferred to the node can be either: the value under the node, the mean for the polygon, or the mean along the centerline within the polygon. For *River1D*, we create a text file in the format required by the model, with a unique identifier, the assigned km and the channel top width. Blank spaces are introduced into the text file to allow the user to add the remaining parameters that are not provided by the FRAZIL tools. Other useful information can also be added, such as the water surface elevation and the water surface slope. We simply overlaid the polygon-reaches over the 1:20 000 Digital Elevation Models (DEM) (planimetric accuracy: 5m; altimetric accuracy: 3m) and calculated the mean water surface elevation in each polygon. The ArcGIS Spatial Analyst tools were then used to calculate the surface slope from the DEM and the value under the node was exported. This surface slope can eventually be used to interpolate the bed slope between cross-sections.

## FRAZIL - Image processing component

The FRAZIL system is developed to take advantage of the spatial information on river ice information which can be derived from a synthetic aperture radar (SAR) image, acquired in all weather conditions, day or night. The FRAZIL project is also improving our knowledge of the interaction between the radar signal and the river ice [16, 17], as well as the development of river ice classification algorithms [18].

The image processing process in FRAZIL is based on [19] and [20] but has been evolving. The raw radar image is first transformed into backscattering coefficients (power) and then orthorectified. This latter step still necessitates the user intervention. Once the image is georeferenced and can be overlaid with the GIS information, an automated routine proceed with texture calculations and ice classifications.

Then, two ice tools have been developed: 1) ice coverage and 2) ice jam locator

### *Required data*

Several radar satellites are operational today and images are commercially available. These active microwave systems (ERS, RADARSAT-1, ASAR, PALSAR), and some others to be launched soon (RADARSAT-2, TerraSAR-X), operate in different wavelengths (C-band, L-band, X-band), frequencies and polarizations (VV, HH, multipolarization, polarimetric). Furthermore, images can be acquired with various resolutions and incidence angles.

RADARSAT-1 has been successfully used for sea ice mapping since its launch in 1995 [21] and its 5cm wavelength has also proved to be adequate for freshwater ice mapping [22]. With a fine spatial resolution of 8 to 9m, it is also well suited for the study of rivers, which are generally narrow features. Finally, with a revisiting rate of 2 to 3 days in the northern latitudes [23], RADARSAT-1 offers good monitoring capacities of dynamic ice events. Therefore, the FRAZIL ice tools have been developed using RADARSAT-1 fine mode images (Table 1).

**Table 1 : RADARSAT-1 Fine mode characteristics**

| Incidence angles (5 beams) | Spatial resolution | Coverage | Processing look |
|---|---|---|---|
| 37º-48º | 8-9m | 50km x 50km | 1 |

To achieve classification of the channel area only, a mask of the channel is extracted from the GIS hydrography layer and used in the routine.

### *Creating an ice map*

This processing routine first creates texture images from the raw radar image. It then proceeds with a first unsupervised classification with the Fuzzy K-mean algorithm [24] to obtain 7 classes related to the type of ice. The lower classes correspond to water and a predominance of columnar ice. The higher classes correspond to a predominance of consolidated frazil ice. The highest class is further split into two, using backscattering, to discriminate heavily consolidated ice, which can often, but not always, be related to ice jams. The lowest class is also split into two, from a set of three texture measurements, to better discriminate water and floating pans of different concentrations. The resulting ice map provides a spatial distribution of 9 classes (Table 2)

**Table 2 : Ice map classes**

| | |
|---|---|
| Class 1 | Water |
| Class2 | Presence of floating pans |
| Class 3 | Border ice |
| Class 4 | Ice sheet – Dominance of columnar ice |
| Class 5 | Ice sheet – A mix of columnar and frazil ice |
| Class 6 | Juxtaposed ice |
| Classes 7 to 9 | Slightly to heavily consolidated ice |

### *Calculating ice coverage*

The ice map is transferred to the GIS component. The first tool will use the polygon-reaches to extract four levels of information. The first one is a simple ice/no ice layer (Figure 5). Therefore, a node will get the value 1, if ice is present in the polygon and 0 if there is none. The second level is the percentage of ice coverage in the polygon. For km 216.5, there was 81.5% of ice.

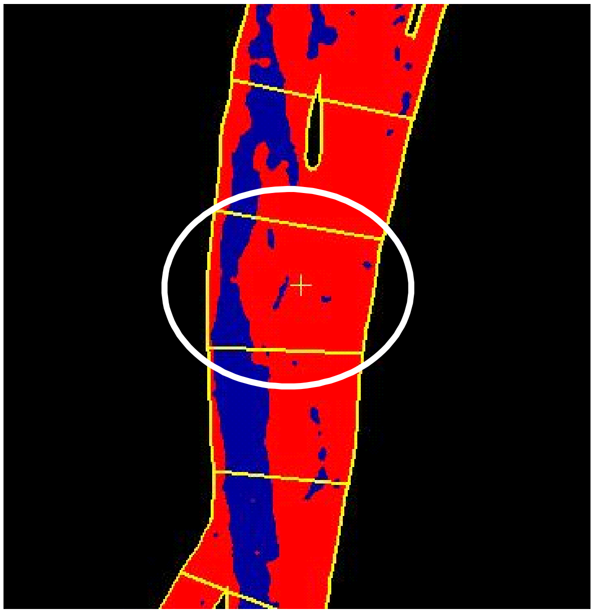


**Figure 5 : Ice / no ice map, Athabasca River, Km 216.5, November 5, 2006**

The third level of information is the percentage of ice coverage for each of the 9 classes (Figure 6). We can also calculate for each polygon-reach the proportion of the open channel which is covered by moving ice.

| Ice type | % | Legend |
|---|---|---|
| Water | 8.3 | 🟦 |
| Presence of floating pans | 10.2 | 🟦 |
| Border ice | 16.6 | 🟦 |
| Ice sheet – Dominance of columnar ice | 20.8 | 🟦 |
| Ice sheet – A mix of columnar and frazil ice | 18.3 | 🟪 |
| Juxtaposed ice | 11.9 | 🟪 |
| Slightly consolidated ice | 8.8 | 🟫 |
| Moderately consolidated ice | 4.0 | 🟥 |
| Heavily consolidated ice | 1.1 | ⬜ |

Moving ice in open channel

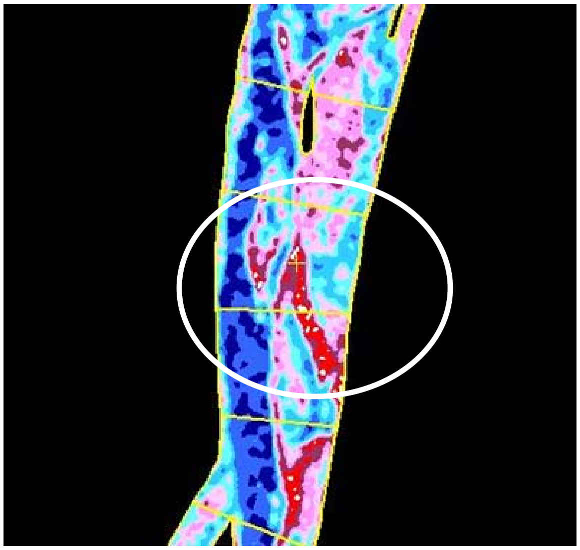


**Figure 6 : Ice map with 9 classes, Athabasca River, Km 216.5, November 5, 2006**

The fourth level of information is simply obtained by associating each class to a certain roughness. This information can be used to help determine the ice roughness parameter in *River1D*.

| Class | % | |
|---|---|---|
| Water and floating pans | 18.5 | 🟦 |
| Smooth ice | 55.7 | 🟦 |
| Rough ice | 25.8 | 🟥 |

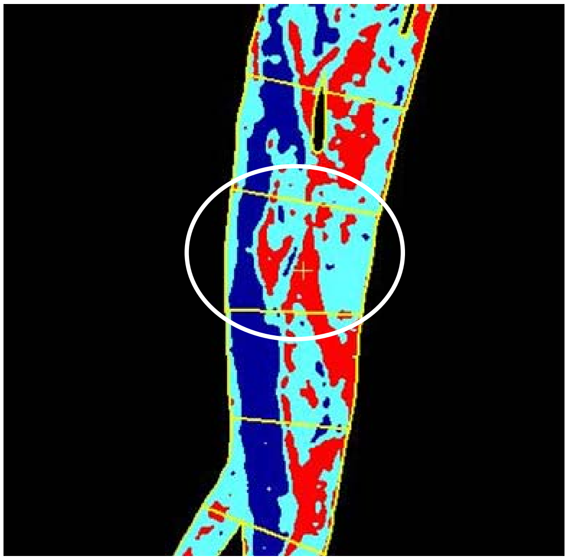


**Figure 7 : Roughness map, Athabasca River, Km 216.5, November 5, 2006**

## *Ice jam locator*

An ice jam is a stationary accumulation of fragmented ice or frazil that restricts flow. Therefore, it can cause sudden massive increases in the water level resulting in severe flood damages. Jams occur at locations where the river's transport capacity is exceeded. This can happen with an intact ice cover, sharp bends, decreases in channel slope, constrictions of the channel, in the presence of islands and bridges or confluences with other rivers [25]. Often ice jams are caused by a combination of two or more of these factors. They usually happen during break-up (spring) but can also be seen during freezeup (fall). When a jam suddenly lets go, a steep water wave moves rapidly down river and can cause serious damage with little warning. To predict the speed and magnitude of released waves, the *River1D* model proposes an ice jam release component [26]. Therefore, one mandatory input is the location and characteristics of the ice jam.

The FRAZIL tool was developed to locate an ice jam and extract the coordinates of the toe and the length of the jam (Figure 8). In its present version, the user first determines which class or classes could be an ice jam. On the selected pixels, we use a distance transform (Chanfrein de Borgefors) [27] to eliminate small clusters and isolated pixels, keeping only the possible ice jam. The polygon is then smoothed by a morphometric technique [28].

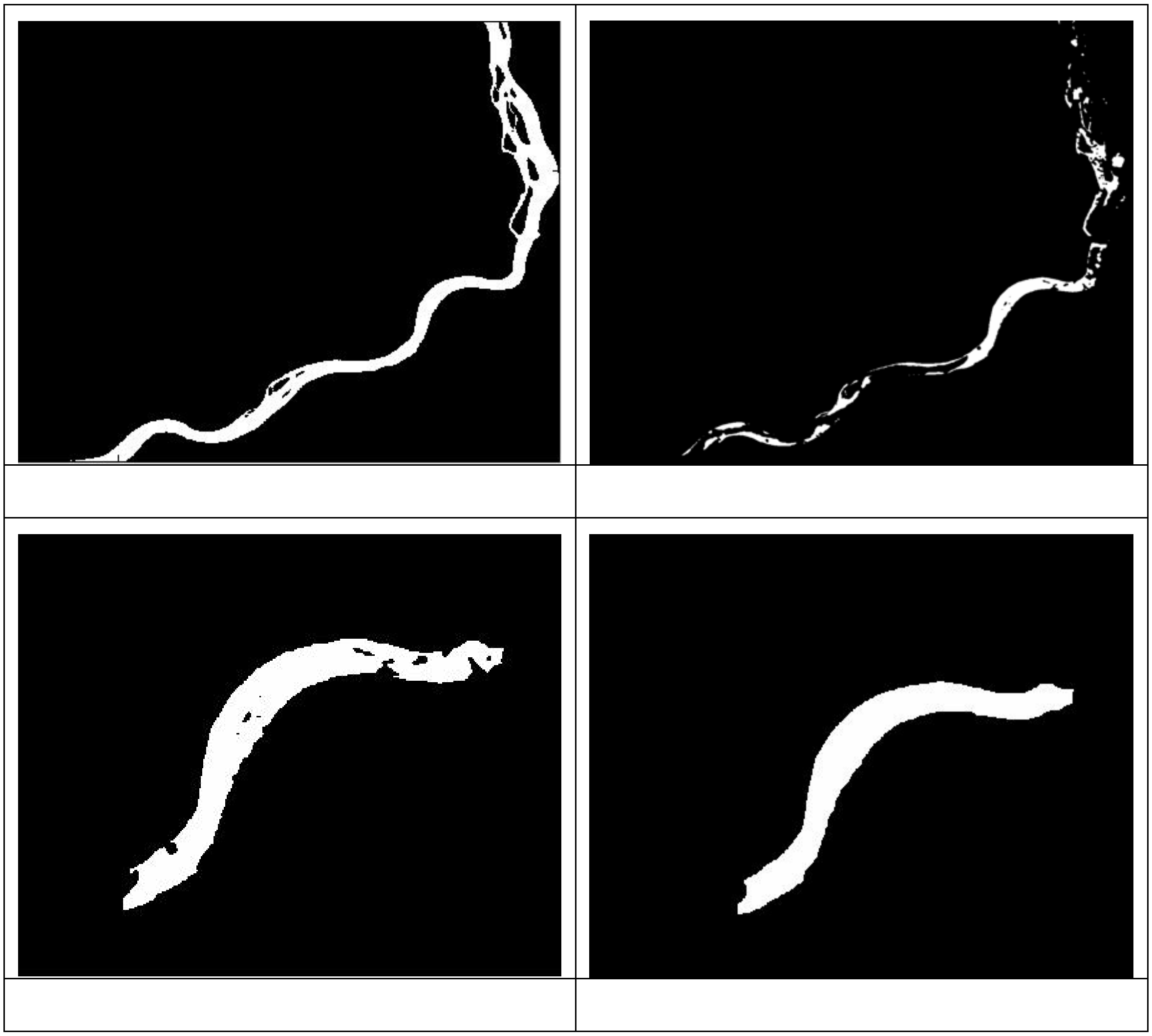
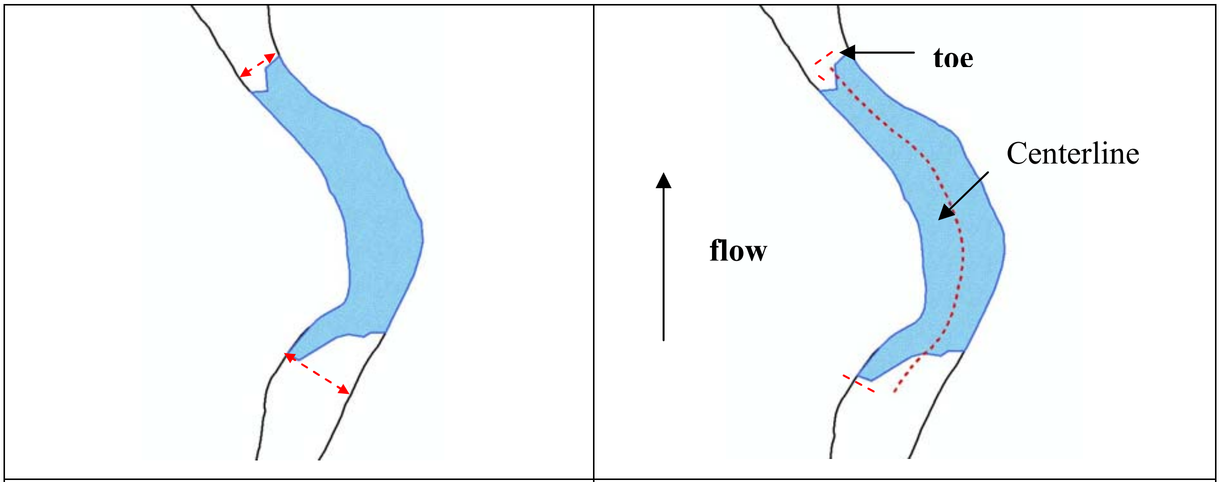


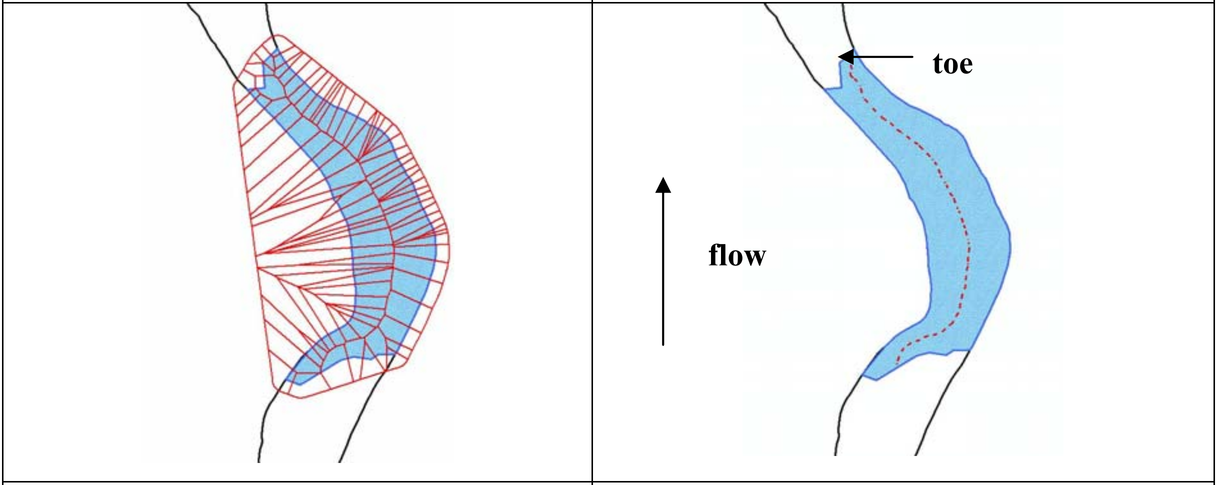
**Figure 8 : Ice jam detection, Near Fort McMurray, April 19, 2006**

The ice jam polygon is then processed to identify the jam toe and to calculate the length of the jam. There are three approaches to identify the jam head and toe (Figure 9).



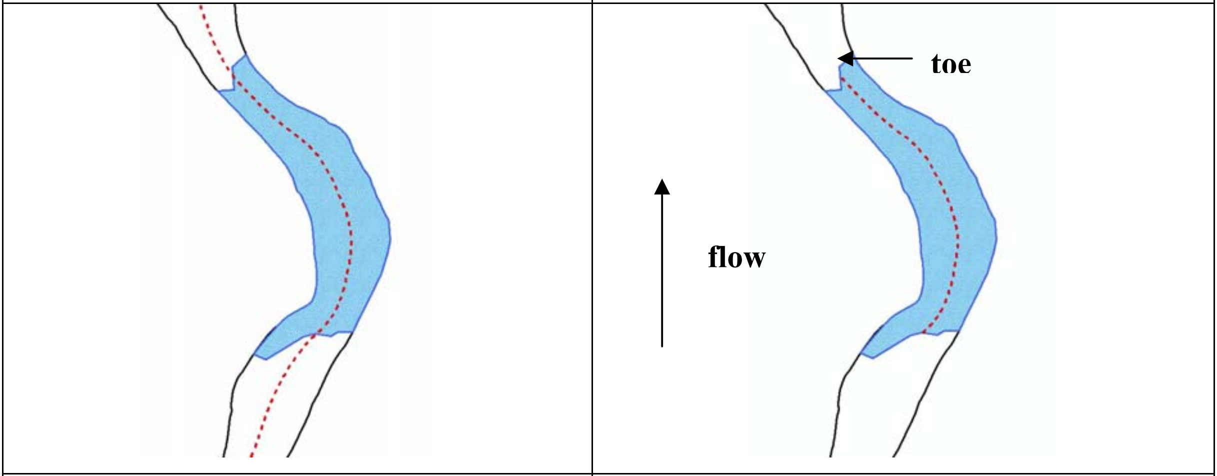
Perpendicular line approach – Detecting head + toe

Perpendicular line approach – Measuring jam length



Squelettization approach – Detecting head and toe

Squelettization approach – Measuring jam length



Centerline approach – Detecting head and toe

Centerline approach – Measuring jam length

**Figure 9 : Various approaches to detect the head and toe of a jam for length calculation.**

The first one is to consider the maximum extent of the jam, which would be done by detecting the first and last perpendicular lines intersecting the jam and measuring the distance between them along the centerline. The second one would be to extract the skeleton of the jam and measure the length of the medial axis. The third one, which is for now implemented in FRAZIL, is to consider the first and last intersection of the centerline with the jam and to measure the length of this segment.

## Conclusion

This paper has presented the tools that are being developed within the FRAZIL project and their adaptation to assist flood forecasting with *River1D*. We have showed that much automation can be achieved in the tedious task of obtaining channel geometry and preparing data for hydraulic flood routing (one dimensional, rectangular channel approximation). We have also shown that relevant ice information can be extracted from a radar image. However, as the FRAZIL project being only at mid-point of its existence, the system is constantly evolving. With this first set of tools, testing of their use with *River1D* can now begin. Improvements will be made and new tools will be developed. For example, a function should detect lateral inflows and assign its ID code to the closest node. Also, the complex problem of dealing with islands, for centerline creation, partitioning and width calculation, will be addressed. Integrating existing cross-sections for automating the estimation of the channel invert is also a possibility. For the radar image component, the classification process will also improve in the near future. Ice thickness estimation should also get much of our attention.

## Acknowledgements

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