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How Ice Mapping Can Help Manage and Prevent Ice Jams: Remote Sensing Monitoring of the Saint-François River, Québec

Apport de la cartographie de la glace par télédétection dans la gestion et la prévention des embâcles: cas de la rivière Saint-François, Québec

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ABSTRACT

We focus on the Saint-François River (Quebec), which is known for recurrent ice jam-induced floods. This study addresses monitoring deficiencies and proposes solutions by presenting a comprehensive large-scale ice cover monitoring approach using diverse remote sensing tools for managing ice-jam risks effectively on this watercourse. We achieved three sub-objectives: (1) gathering spatial characteristics of the ice jam by acquiring images during the ice jam with an RGB camera-equipped drone; (2) mapping river ice using radar and optical images; and (3) river segmentation based on the dominant ice process. The methodological approach integrates data remotely sensed before and during the ice jam event, employing various tools. By comparing remote sensing methods with traditional monitoring, we underscore the importance of spatial data acquisition in ice-jam risk management. Orthomosaic and summary maps illustrate ice evolution processes, highlighting remote sensing efficacy in discerning hydro-meteorological events and emphasizing the need to target specific areas for risk mitigation. River segmentation based on the dominant ice process provides insights into freeze and thaw sequences, thereby illustrating ice evolution processes.

RÉSUMÉ

Cette étude aborde les lacunes en matière de surveillance et propose des solutions en présentant une approche de suivi du couvert de glace à grande échelle à l'aide de divers outils de télédétection pour gérer efficacement les risques d'embâcles de glace à l'aide d'une étude de cas de la rivière Saint-François au Québec, connue pour ses inondations récurrentes provoquées par les embâcles de glace. La recherche comporte trois sous-objectifs: (1) déterminer les caractéristiques spatiales d'un embâcle de glace par l'acquisition d'images par drone équipé d'une caméra RGB, (2) cartographie de la glace de rivière à l'aide d'images optiques et de cartes radars du type de glace, et (3) segmentation de la rivière en fonction du processus glaciaire dominant. L'approche méthodologique intègre des données de télédétection obtenues avant, pendant et après l'événement d'embâcle de glace, en utilisant divers outils. En comparant les méthodes de télédétection avec la surveillance traditionnelle, l'étude souligne l'importance des données spatiales dans la gestion des risques liés aux embâcles de glace. Elle utilise des orthomosaïques et des cartes de synthèse pour illustrer les processus d'évolution de la glace, mettant en évidence l'efficacité de la télédétection pour discerner les événements hydrométéorologiques et soulignant la nécessité de cibler des zones spécifiques pour la mitigation des risques. La segmentation de la rivière en fonction du processus glaciaire dominant fournit des indications sur les séquences de gel et de dégel, illustrant les processus d'évolution de la glace.

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Introduction

River ice jams are serious hazards that can lead to extensive flooding in areas surrounding watercourses. Their high spatial and temporal variability makes it difficult to implement operational tools (Beltaos 2008). Therefore, civil security authorities must often wait until the ice jam is in place before taking action to protect riparian communities and infrastructure. Various combinations of hydro-meteorological and geomorphological factors

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can lead to the breakup and jamming of the transported ice. The most important condition in cold fluvial environments, however, remains the presence of an ice cover and its cohesive strength.

Manual *in situ* data collections involve various methods that provide quasi-instantaneous information regarding the ice cover. They require moving onto the ice with equipment for each measurement, thereby limiting their use to formed ice covers for safety reasons, while excluding periods of growth or degradation. Apart from georadar (i.e., ground-penetrating radar, GPR), which distinguishes ice types, point-collection tools can measure the thickness, determine the type, and assess the structure of the cover. Georadar detects the ice-water interface, distinguishes ice types, and measures their thicknesses (Best et al. 2005; Kämäri et al. 2017). Manual drilling measures thickness, thereby enabling its estimation across the entire cover through interpolation (Lagadec et al. 2015). Sherstone et al. (1986) sought to find alternatives to manual drilling, but these remain unsafe and time-consuming. A recent approach uses passive seismic standing wave to obtain *in situ* data on the ice cover (Fedin et al. 2022) while locating the transitions between ice, water, and the riverbed.

Field data collection tools, such as gauges, ground cameras, hydrometric stations, and under-ice sonars currently enable automated monitoring of ice cover. These sensors typically cover strategically important or high-risk portions of rivers, which require multiple installations for comprehensive coverage. They record data throughout the ice season, are deployable before ice formation, and are retrievable post-melt. One approach for non-disruptive, continuous monitoring, which has been considered by researchers, involves gauge installations. Sherstone et al. (1986) introduced two-gauge types for thickness measurement, yet recent articles employing this method have yet to be identified. De Rham et al. (2020) utilized a national network of hydrometric stations to establish a Canadian river ice database, incorporating ice thickness measurements. Under-ice sonar deployments, such as Ice Profiling Sonar (IPS) or Shallow Water Ice Profiler (SWIP), offer continuous data on ice presence, growth, and absence, primarily tracking under-ice frazil ice, albeit at high cost (Richard et al. 2011). Their deployment requires a team that potentially includes divers on boats, depending upon river depth. Monitoring ice cover from shore using cameras is a cost-effective and user-friendly alternative, and regularly provides high-resolution data depending upon weather conditions and infrastructure quality (Bourgault 2008; Ansari et al. 2017). Captured images help determine ice formation and breakup times, support photogrammetry for cover modeling, and assist in ice type and transport detection (Bourgault 2008; Vuyovich et al. 2009; Ansari et al. 2017). In cases, such as the Chaudière River, which originates near Lac-Mégantic (southeast Quebec), some cameras serve civil safety purposes, accompanying hydrometric stations, with publicly accessible online photos for community consultation (COBARIC 2019).

Many investigations also rely on hydro-meteorological or ice observation stations to establish rating curves from water heights, even though a significant decline in the deployment of monitoring tools was observed a decade ago (Duguay et al. 2014). Collecting data on riverbanks or directly on the ice cover is unsafe during freeze-up, thaw, or ice-jam events (Andrishak and Hicks 2015). The most frequently used proxy for determining ice cover conditions is freezing degree-days (Morse and Turcotte 2018). With this method, temperatures below zero degrees Celsius are cumulated as positive values; values ≥0 °C do not contribute to the annual or seasonal sum of FDD.

Characterization methods for river ice using remote sensing can help overcome limitations to ground-based data collection. Various sensors on different platforms provide information regarding the ice cover, including crucial aspects, such as ice thickness. Remote sensing methods for ice monitoring can be categorized into two main types: satellite-based and airborne. Remote sensing is a reliable technology that enables comprehensive data collection for the entire river simultaneously, with repeated measurements at regular intervals throughout the winter season. Multiple sensor types (radar, optical, infrared, LiDAR) and platforms (satellites, airplanes, helicopters, drones) can be employed. Different indicators and variables are monitored in river ice studies through remote sensing, including ice phenology (Pavelsky and Smith 2004; Chaouch et al. 2014; Das et al. 2015; Cooley and Pavelsky 2016; Łoś and Pawłowski 2017; Muhammad et al. 2016; Beaton et al. 2019), spatial distribution metrics like ice cover area, volume, or thickness (Mermoz et al. 2014; Chu et al. 2015; Kraatz et al. 2017; Zhang et al. 2017), detection of winter floods (Sakai et al. 2015), and ice type classification (Weber et al. 2003; Unterschultz et al. 2009; Łoś et al. 2019). These studies typically focus on local monitoring of specific rivers, addressing various subjects, such as flood prevention, hydraulic condition simulations, ice-front tracking, protection of hydroelectric infrastructure, and safe winter transportation.

Optical images enable precise temporal monitoring and extraction of data on ice's temporal and spatial patterns. Widely used satellites with varying resolutions include Sentinel-2 (10–60 m), Proba-V (100 m), Landsat (30 m), MODIS (150, 500, or 1000 m), and Planet (3–5 m). Some less frequently used satellites, such as VIIRS, AVHRR, NOAA, and GOES-1, remain relevant for historical tracking or model validation. Their spatial resolutions, despite exceeding those that have been mentioned earlier, range from 375 m for VIIRS to 5 km for certain NOAA spectral bands. Long-standing satellites like Landsat, which has been operational globally for decades, facilitate studies on large spatial and temporal trends (Gatto 1990). Temporal resolutions vary widely, from daily for Planet images to 5–6 days for Sentinel satellites.

In river ice monitoring, optical satellite images are valuable for determining the onset of melting and freezing processes (Yang et al. 2020). They effectively distinguish ice from water due to distinct colors, thereby making their interpretation more intuitive and engaging for those individuals who are less familiar with geomatics. Yet, optical sensors have limitations, such as sensitivity to weather conditions like clouds, which can affect classification quality, together with their inability to use entire images in the presence of cloud cover (Kraatz et al. 2017). Efficient filters can partially address these problems. Nevertheless, the variability in revisiting times and sensitivity to weather conditions make it challenging to precisely target specific events, such as mechanical breakup of ice cover or ice-jam formation.

Radar imaging enables tracking of ice cover, given that radar can penetrate snow, directly reflecting ice characteristics (Yang et al. 2020). Yet, a snow cover that is saturated with water may affect the signal differently from fresh, dry snow, thereby causing variations in the spring signal compared to that of the freezing period. The radar signal is sensitive to ice roughness and different textures, facilitating distinctions between various covers, including smooth ice, floating ice, open water, and consolidated frazil rafts. Depending on the season and radar incidence angle, distinguishing different ice types can be challenging (van der Sanden et al. 2021). Remote sensing is an effective means of monitoring and tracking ice cover development over extended periods, together with estimating breakup timing. Radar imaging offers tracking capabilities that are similar to those of optical methods, but often with finer spatial resolution and greater consistency in image acquisition, which is also unaffected by weather conditions. Detailed information that is captured by meter-scale pixels allows further texture analysis and identification of the ice type *in situ* (Chu and Lindenschmidt 2016).

Many optical satellite datasets are currently available online for free or for research and monitoring purposes; some of these data are realized almost in real time. In Quebec (Canada), river-ice type maps are made from radar images and made accessible by the provincial government throughout winter for ice-jam prone rivers. Civil security advisors or waterways managers can utilize this information to monitor the rivers at risk, together with their surroundings. The recent democratization of drone use can also allow this technology to be added to surveillance strategies at low cost.

The objective of our research is to create a method for monitoring conditions that are related to ice using various remote sensing technologies. Three sub-objectives are carried out: (1) gathering spatial characteristics of the ice jam by acquiring images during the ice jam with an RGB camera-equipped drone; (2) mapping the river ice from radar and optical images before and until the ice jam releases; and (3) segmenting lengths of the river according to the dominant ice process. By doing so, we aim to provide more efficient ways of monitoring ice jams over the short- and long-term that could help limit interventions or do so in a more sustainable manner. The ice jam that occurred in January 2019 on the Saint-François River (Quebec) is being used as a study case to demonstrate the utility of remote sensing in reducing the risk of ice jams.

Methodology

Study site

Originating in the Chaudière-Appalaches Administrative Region of Quebec (i.e., the "Beauce"), the Saint-François River flows through Estrie (the Eastern Townships) for 200 km before it empties into Lac Saint-Pierre, which is widened stretch of St. Lawrence River (Centre-du-Québec Administrative Region). Its 10 230 km^2 watershed includes the City of Sherbrooke (Figure 1). The Saint-François River has been monitored for ice jams for several years. The average annual damage that is related to ice jams on this river has been estimated to be 350 000 CAD per year (Morse and Turcotte 2018). The Quebec ice-jam historical database has 46 events that have been listed on the extent of the river from 1994 to 2019 (Gouvernement du Québec 2022).

Among the sections where ice jams occur most frequently is the confluence of the Saint-François with the Massawippi River near Bishop's University in the Borough of Lennoxville (Sherbrooke). The first entry in the database at this location goes back to 1994 (observation_seq_999920). Two major events occurred there in 2013 and 2017 (Radio-Canada 2013; Bouchard 2017). The work of De Munck et al. (2017) indicates that the predisposition toward ice jams in this area is strong because of the presence of islands, river sinuosity, and human infrastructure (e.g., a bridge). Ice jams in this sector often lead to flooding (Gouvernement du Québec 2022).

Our study focuses on an ice jam that was recorded on January 25, 2019 (observation_seq_no. 32859) by the Ministère de la Sécurité publique du Québec (MSPQ [Quebec Ministry of Public Security], Gouvernement du Québec 2022). It describes an ice jam of minor severity with a length of 5000 m. Comments in the report state that "[a] few gaps are observable in the front of the jam and in the ice cover; otherwise, the ice occupies the entire surface. It is particularly dense in the Bishop's University and Massawippi River area." Another small ice jam was observed and reported on the Massawippi River right next to this one.

Meteorological and hydrometric data were gathered from different governmental measuring stations (Figure 1). Daily mean temperature (°C) measurements were taken at the Lennoxville station meteorological station (7024280; Environment Canada). The hydrological Saint-François hydrometric measuring station (030208) was used to obtain a daily mean flow rate.

Mapping techniques

Our monitoring of the ice conditions that led to the formation of the ice jam in winter 2019 on the Saint-François River uses various remote sensing tools including radar and optical satellite imagery as well as optical imagery, which are acquired by drones (Figure 2). Our first step was, therefore, to list online images, maps, and data that were available to reconstruct the evolution of the ice cover on a section of the Saint-François River during winter. A survey of the ice jam was recorded on February 7th, 2019, using a Sony a6000 RGB camera (24.3 MP), which was mounted on an Observer 6 drone. This drone was specifically developed for research and allows for rapid deployment, such as in the case of an ice jam. Its multirotor system provides good stability, which is essential for capturing images at high altitudes. The gimbal accommodates various types of sensors, making it versatile. It does not have unique functions and can be used in various situations depending on the deployment objective. The camera is equipped with a 16 mm focal length lens, which allows for wide coverage

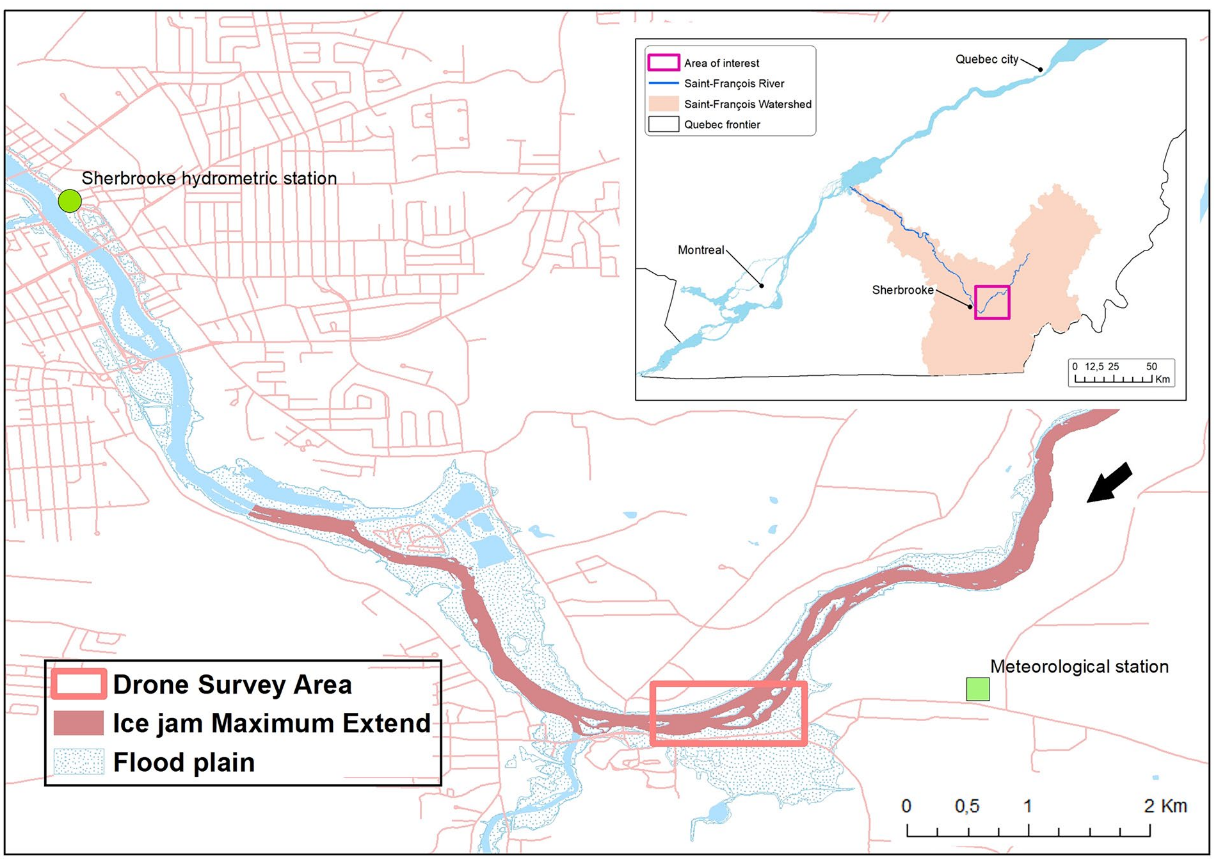

Figure 1. Study area of Saint-François River including ice jam maximum extent location, drone survey area and measuring stations.

and good overlap between successive images. The survey covered 6.30 km, achieving a resolution of 2.25 cm. The lateral overlap of the images was 70%, and the entire flight duration was 17.5 min. One thousand two hundred and forty-eight images were acquired through five surveys, but only 856 were used to create the orthomosaic.

Short-range photogrammetry, or the Structure from Motion (SfM) technique (Ullman 1979), was used to construct an RGB orthomosaic representing the ice jam with Pix4D. The use of the GPS drone during the overflight made it possible to locate a portion of the ice jam without control points. The ice jam was pictured using SfM, which uses a sequence of spatially overlapping two-dimensional images. The process is based on the automatic recognition of common features between images that establish the orientation of the photographs (Micheletti et al. 2015). It differs from traditional photogrammetry in that it automatically resolves camera positions and orientations without using control points with known three-dimensional positions (Westoby et al. 2012).

Optical images were collected from different sources, such as Sentinel-2 (Copernicus Sentinel Data 2022), Planet (Planet Team 2022), and Landsat images (courtesy of the U.S. Geological Survey) (Figure 3). The images were selected because they had close to zero cloud cover over the river (<10% cloud coverage). Ice type maps were also gathered from MSPQ's Données ouvertes portal (Gouvernement du Québec 2022) (Figure 3). The maps using RADARSAT-2 images were created by MSPQ with an unsupervised classification algorithm that is denoted IceMAP-R, which was developed by Gauthier et al. (2016).

Optical images are overlaid in a geographic information system (ArcGIS) and the river was divided into 250-metre-long reaches to match the Ice jam Predisposition Index reaches that were used by De Munck et al. (2017) and which are operational at MSPQ. Each reach is then visually qualified into three categories, based on the presence of ice: "Water"; "Partially Iced"; or "Ice Covered" (Figure 4).

Although it is possible to visually distinguish the presence of ice cover directly from radar imagery (Figure 5), ice type maps that are released by the MSPQ were used since they are more widely available. Radar imagery permits the study of ice type because the radar penetrates the snow cover during the winter period and, thus, directly reflects the characteristics of the ice (Unterschultz et al. 2009). The radar signal is sensitive to ice roughness and texture. Therefore, it can distinguish several ice types, such as smooth ice, ice floes, open water, and consolidated frazil rafts. During melt time, the presence of humidity in the snow modifies the signal. The legend of IceMAP-R then needs to be switched manually from freeze-up to thaw. The maps from the radar images were also layered within a geographic information system in ArcGIS to classify the presence of ice according to the same categories for each 250-m section.

The different ice maps served as a baseline to create freeze-up and melting sequences of the river. Summary maps illustrate these processes of ice development and withdrawal. These changes are detected by merging the sections to establish homogeneous zones. Each expansion or reduction of the ice cover is illustrated and dated. River segmentation characterizes the areas of ice production, transport, and accumulation along the river (Figure 6). The characterization is inspired by studies on the hydro-sedimentary dynamics of rivers that had been theorized by Kondolf (1994) and taken up in Quebec by Demers et al. (2014). Our method considers ice as sediment, analogous to the river segmentation work in log-jam studies that were conducted by Boivin et al. (2015, 2019).

Reaches where breakup occurs or that remain icy throughout the duration that our data cover will be

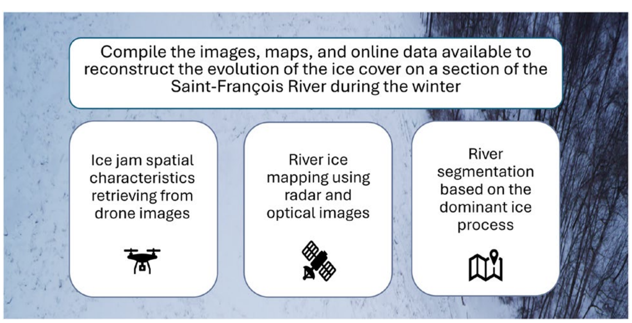

Figure 2. Methodological overview of the proposed approach.

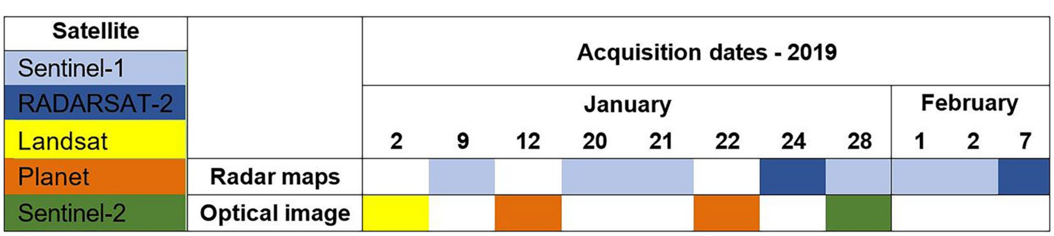

Figure 3. Satellite images used for ice monitoring on the St-François River, winter 2019.

Figure 4. Visual qualification of the ice reaches from optical images from Planet satellite on January 12th and 22nd, 2019 (Planet Team 2022).

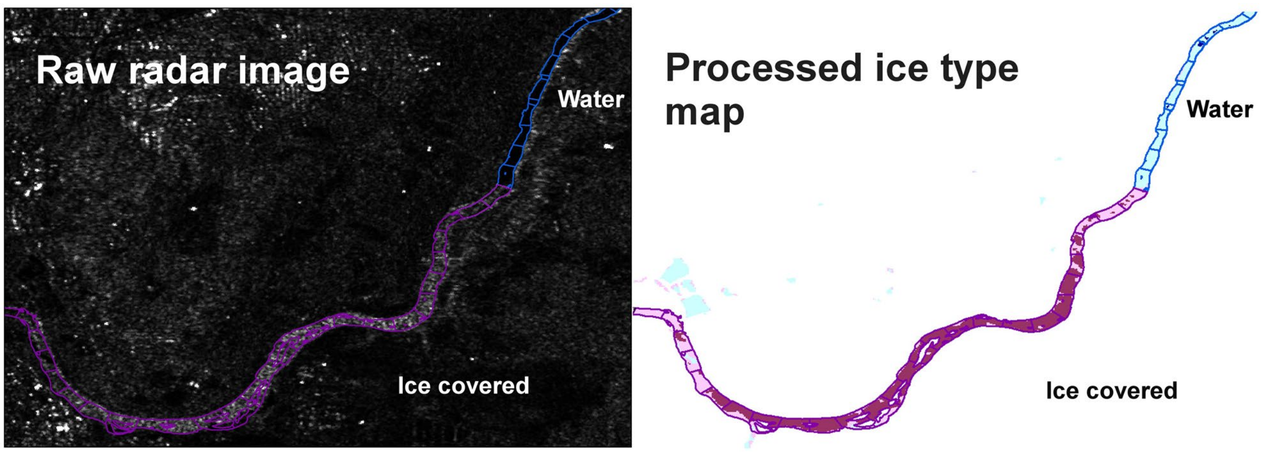

Figure 5. Visual qualification of the ice reaches from Sentinel-1 radar images on January 28th, 2019 (Copernicus Sentinel Data 2022).

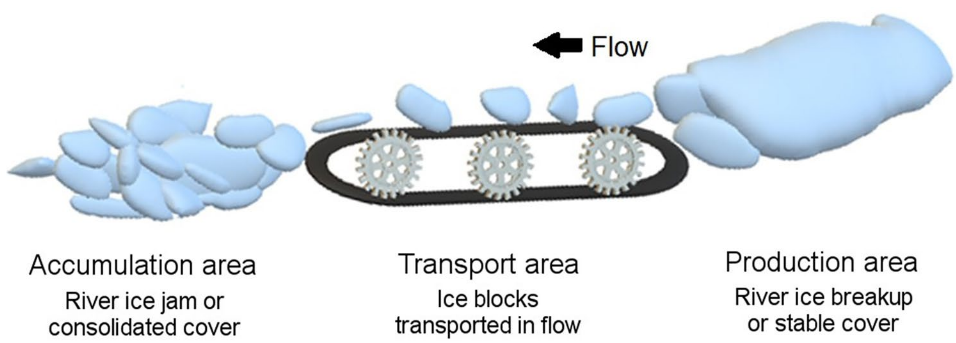

Figure 6. Adaptation of the Kondolf Convey (1994) that is applied to river ice showing production, transport and accumulation areas.

considered ice production areas. Transport areas will be assigned to reaches where ice is inconsistent or non-existent. The various reaches where ice jams occur will be referred to as accumulation areas. The type of ice on the radar ice maps allows us to differentiate between growth and accumulation areas, given that the presence of blocks in the ice jams should induce greater roughness in the maps.

Results

RGB imagery acquisition by drone

The drone survey allowed us to obtain RGB data on a portion of the ice jam (Figure 7). An attempt to deploy the drone was made on January 26th, 2019, but the weather conditions were considered too hazardous to take pictures. However, the survey February 7th revealed that the ice jam had consolidated and was covered with snow. The comparison with the other maps allows us to see that the area that had been over-flown does not cover the entire ice jam. This area was selected because it was close to the shoreline, accessible, safe, and respected all regulations.

The IceMAP-R legend (thermal ice, agglomerated frazil, and consolidated ice) does not appear to match the ice formation process closely. By assuming that textural roughness is increasing with each category, we can interpret the maps in a manner that meets our needs. The roughness that is visible on the map excerpt appears to match those patches that were observed on the RGB orthomosaic. The spatial resolution of 2.25 cm provides a clear indication of the texture of the ice cover. Particularly smooth areas next to the islands can be seen both on the orthomosaic and on the map. Furthermore, the absence of black edges provides a good indicator of the softness of the ice. Therefore, even in the absence of elevation or surface models, the orthomosaic can still be used to interpret ice texture.

Ice cover evolution with satellite images

The following timeline of winter 2019 shows the development of ice cover on the river, according to satellite images (Figure 8). The freeze-up began near the end of January and was almost complete by the beginning of February when the ice jam occurred.

As stated, by January 2nd, small portions of ice cover were visible upstream of our sector of interest (Figure 9). The images for January 12th show slight growth of this cover upstream. Yet, it was not until January 20th that the Lennoxville sector of the river began to freeze. From January 20th to 22nd, the ice cover extended considerably and even covered the portion where the ice jam had occurred a few days later. On January 24th, this portion was again clear of ice (Figure 10). On January 20th, a few days after the formation of the ice jam, it was visible on the map. A new section of cover also had formed upstream. A whole portion of the ice cover disappeared between the two image acquisitions immediately upstream of the ice jam. It is very likely that the ice broke off and piled on top of the existing ice cover to create the ice jam.

It is also possible that a portion of the input of ice comes from the Massawippi River, which flows immediately upstream of the foot of the ice jam. Like the St-François, this river is known for its ice-jam regime, as are its tributaries, i.e., the Salmon and Coaticook Rivers. This ice could be the initial cause of the ice jam at the confluence. Yet, it does not appear to be the sole input, given that the maps had shown that the ice jam was located several kilometers upstream.

Monitoring of hydro-meteorological conditions during the winter is complementary to remotely sensed monitoring of ice-jam risks. The ice jam of January 25th occurred during a mild period that was followed by a colder period. The average temperature during the breakup of January 24th was slightly above freezing (i.e., 0.3 °C; Figure 11). The temperature reached a maximum of 5.2 °C at the Lennoxville station and 31.3 mm of rain were recorded that day. The ice jam formation also corresponds to the time when the cumulated freezing degree-days (CFDD) reached 600 CFDD, which accounts for about half of the total freezing degree-days that are cumulated for the entire season. Yet, thawing degree-days (TDD) were just beginning to accumulate for the season. Simply stated, TDDs are cumulative daily temperatures that are ≥0 °C, in contrast to GDD (growing degree-days) that require some physiological threshold (for plants or animals) to be met, i.e., base temperatures of 5 or 10 °C.

The data at Saint-François hydrological measuring station (030208), which is downstream of the study sector, was unavailable for most of the winter. Unfortunately, there are no other nearby stations with which a comparison could be made. A dam regulating the flow is located 0.6 km downstream, while the nearest station upstream is situated on the Eaton River, the watershed area of which is much smaller (646 *vs.* 7930 km^2), thereby making subsequent comparisons challenging. Nevertheless, at the time of the ice jam, daily mean flow increased significantly. It was around 40 m^3/s at Eaton and daily mean water level had reached values around 26.5 m (Figure 11).

The ice jam is clearly visible on the ice type maps that were derived from the IceMAP-R algorithm (Figure 12). On January 28th, a few days after the event, the ice cover resembled rubble, probably because it had not yet consolidated and the edges were still sharp. Although the IceMAP-R-generated map indicates agglomerated frazil ice, it is more likely that the ice jam had become consolidated on January 2nd and that the difference between the blocks of ice and their interstices was less important than when open water was present. Cold temperatures were pointing in that direction as well. The consolidated ice returned to the ice jam section on February 7th. This could be caused by a rise in water level, leading to an elevation of ice blocks with sharper edges and thus a rougher-looking texture.

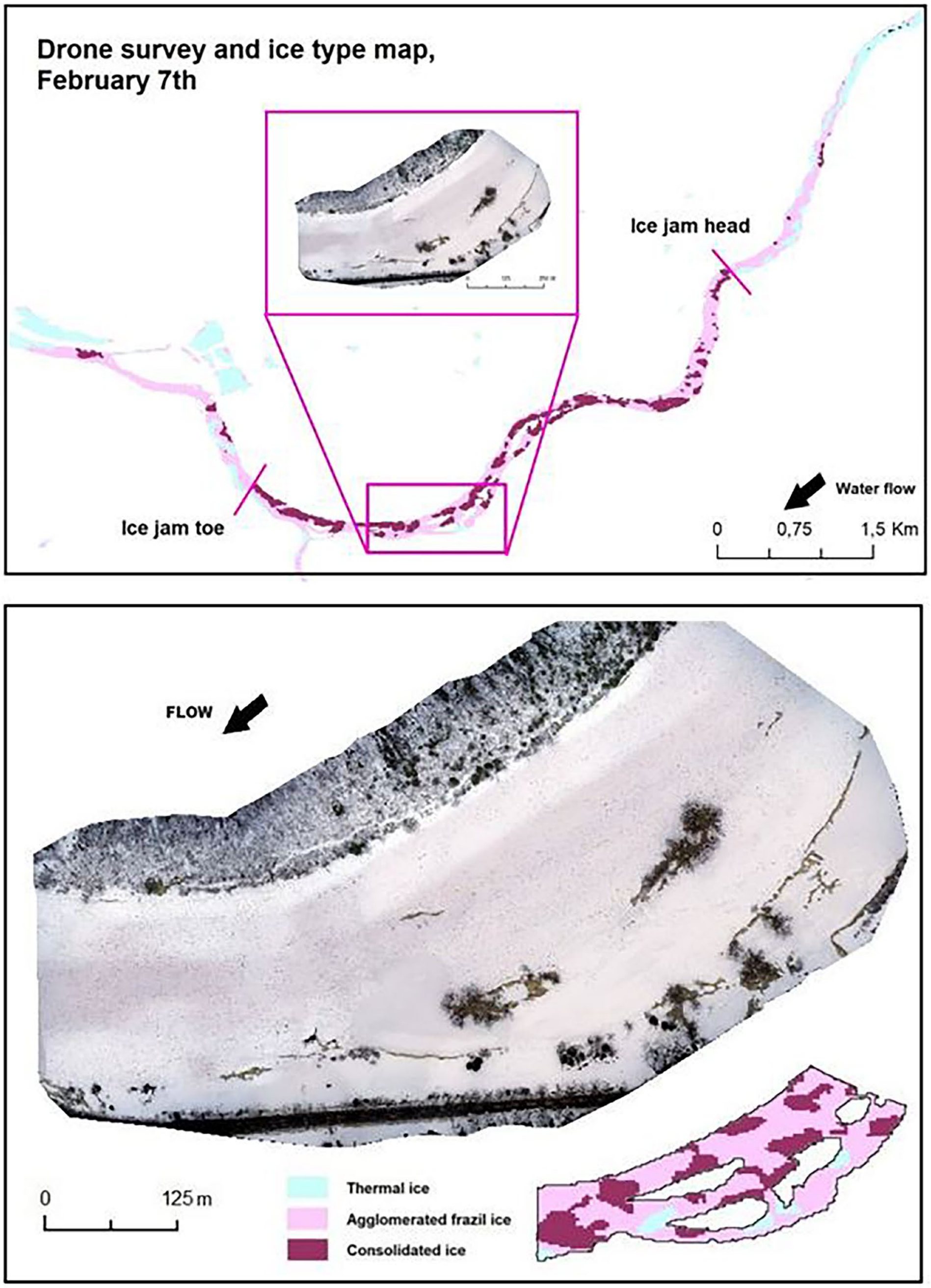

Figure 7. RGB data acquired by drone over the Saint-François River ice jam and ice type map made from RADARSAT-2 image by MSPQ with IceMAP-R freeze legend on February 7th, 2019.

Alternatively, all those changes could be attributed to different incidence angles and times of acquisition of the radar images. The incidence angle is crucial for classifying ice types in radar imaging as it alters the interaction of radar waves with the ice. At high angles, the waves penetrate the ice, promoting volume scattering and making impure ice appear brighter. At low angles, surface reflection is enhanced, making rubble ice more visible. Under freezing conditions, dry ice allows better wave penetration, while under thawing conditions, wet ice promotes surface scattering. Surface roughness also influences backscatter, which is essential for accurate classification (Weber et al. 2003; Unterschultz et al. 2009).

River segmentation by predominant ice process

River segmentation identifies the production, transport, and accumulation areas that were present on the map (Figure 13). Only one transport area is present in this section of the river. This section does not particularly meander, has no natural or anthropogenic

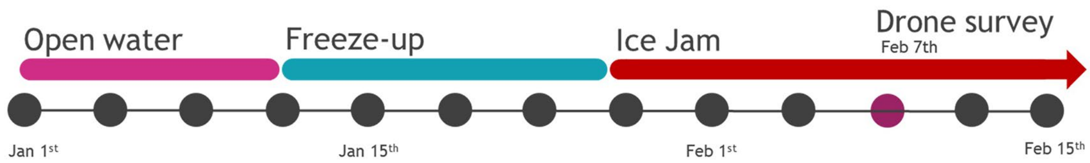

Figure 8. Timeline of ice cover development on the St-François River, winter 2019.

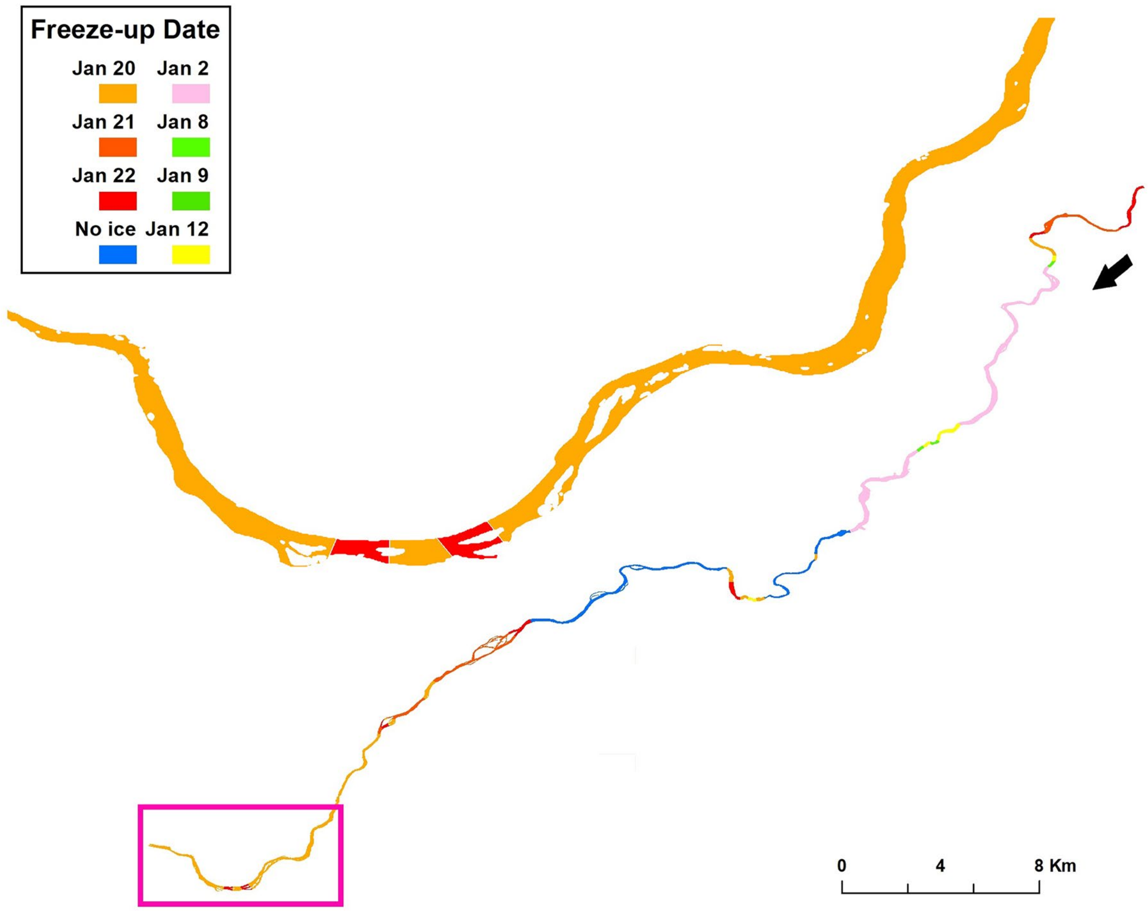

Figure 9. Development of ice cover prior ice jam occurrence on the St-Francois River between January 2nd and 22nd, 2019, from satellite ice type maps.

obstacles, and does not correspond to rapids. Nearly all satellite images that were acquired show pockets of open water in this area. Some sections appeared to contain more ice on the map for January 24th and February 7th, the two days when substantial increases in river flow occurred. The radar images, therefore, likely captured the transport of ice. As previously stated, it is also possible that inputs of ice originate from the Massawippi River.

The accumulation areas correspond to sites experiencing ice jams during the winter. Ice type maps from January 28th, February 2nd, and February 7th show that the ice cover resembled rubble at these locations following ice-jam consolidation (Figure 12). The farthest upstream ice-jam section is where the river splits into the most channels and where the most islands are present. The maps indicate that the two ice jams formed at the same time. The presence of this second accumulation area indicates the ice that formed the Lennoxville ice jam originated from production and transport just upstream of its location.

The two production areas are located on both sides of the accumulation area farthest upstream. They exhibited smooth and complete cover during most of our monitoring. The production and transport areas are interesting to follow since they are the source of ice jams. Maps from January 21st and 22nd show the maximum extent of the ice. The

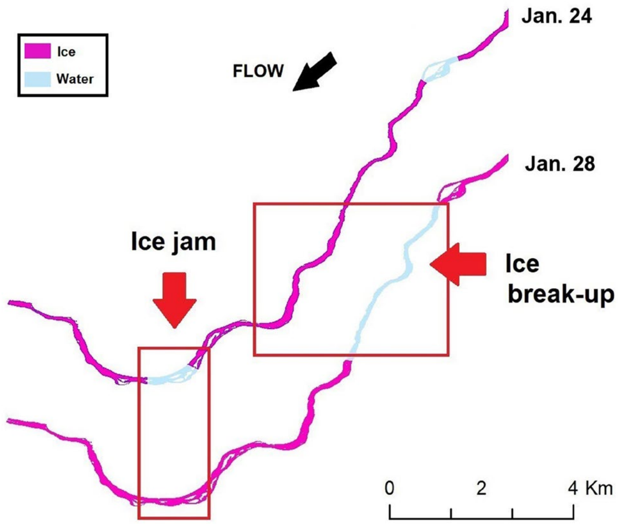

Figure 10. Ice movement leading to the ice jam on the St-Francois River between January 24th and 28th, 2019.

increase in the flow on subsequent days broke up the ice cover and transported it to the accumulation areas. The production and transport areas are visible when comparing maps from January 24th and 28th, as they change from water to ice (Figure 10). Like the transport areas, the production areas generally do not have specific geomorphological features that would restrict ice transport.

Discussion

Ice cover monitoring

According to the ice maps (Figure 9), very little ice cover was present on the Saint-François River during the greatest monitored discharge increase in early January. Of course, river ice breakup and ice jam risks would not occur, given the absence of ice. Hydro-meteorological monitoring alone would have raised a false alarm. The information that is acquired by remote sensing is a complement to currently measured flow and weather monitoring, i.e., temperature and cumulative freeze or thaw days, which provided proxy data for ice cover. Remote sensing tools can refine the use of cumulative freezing degree-days (CFDD) as a proxy for ice cover status. By studying

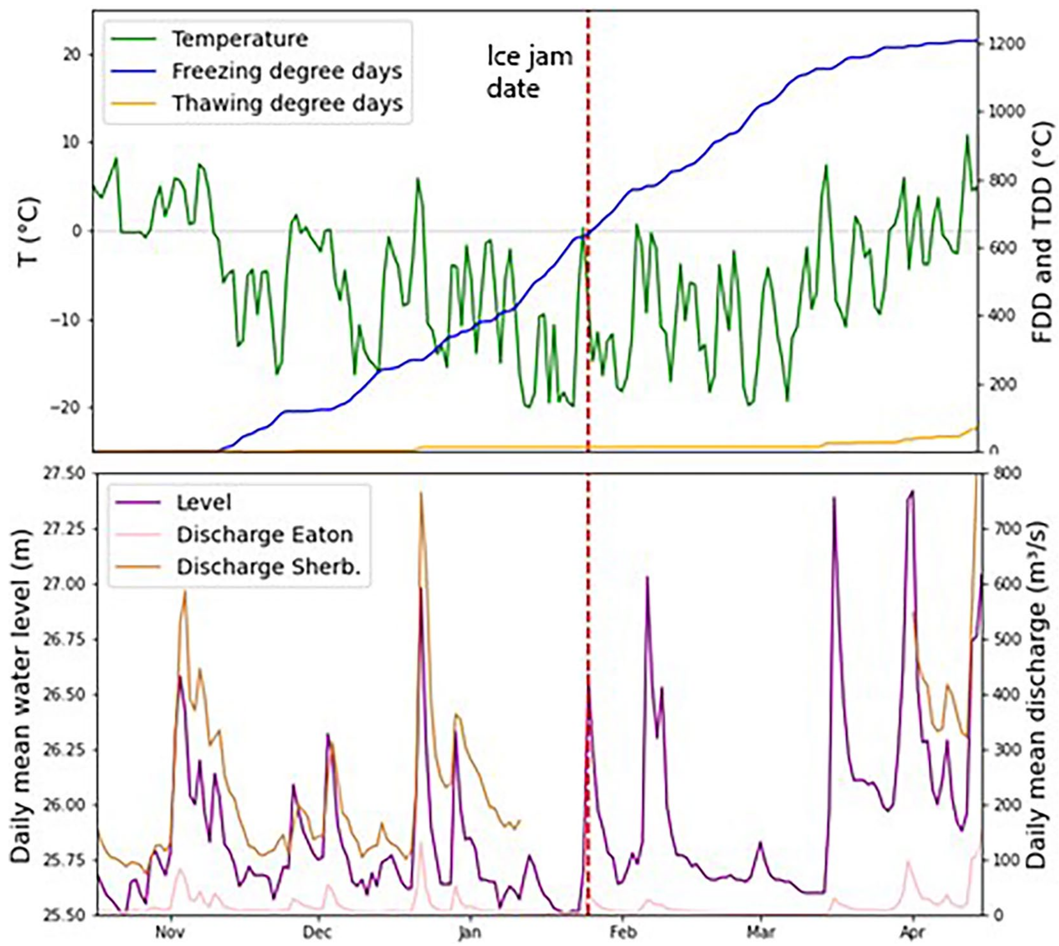

Figure 11. Hydro-meteorological indices for the Lennoxville sector, winter 2018–2019, meteorological data were taken at the Lennoxville station meteorological station (7024280) and hydrological data from the SaintFrançois station (030208). Eaton measuring station (030234) is shown for comparison.

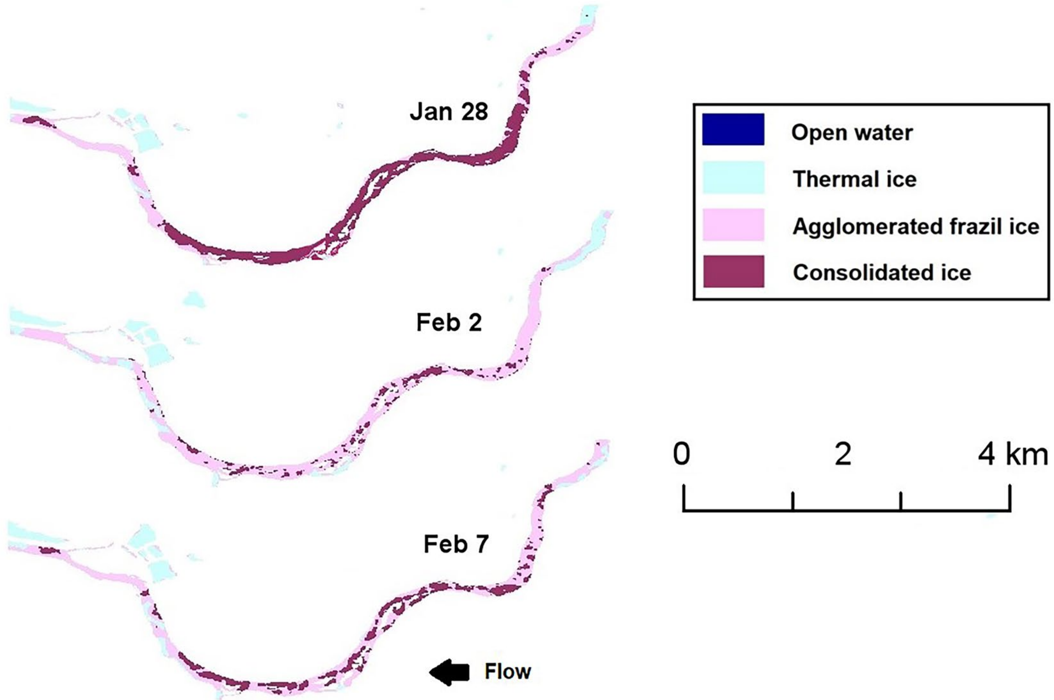

Figure 12. St-François River ice type evolution on post-ice jam maps between January 28th, February 2nd and February 7th, 2019, from Données Ouvertes (Gouvernement du Québec 2022).

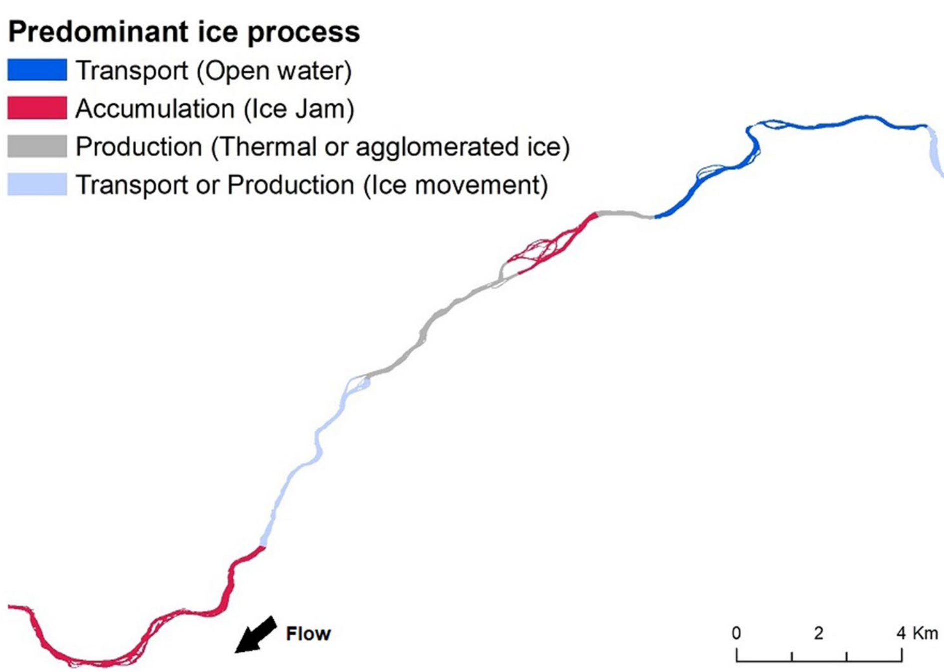

Figure 13. St-François River segmentation by predominant ice process between January 24th and 28th, 2019.

the occurrence of historical ice-jam events, Morse and Turcotte (2018) considered that a non-zero probability of ice-jam formation on the Saint-François River would emerge at 50 CFDD. The development of ice cover before the ice jam (Figure 9) indicates that it would not appear in this portion of the river until about 400 CFDD had been amassed.

It is impossible to know precisely when flow rates that caused the ice cover to break on January 24th had occurred, given the absence of data from the hydrometric station. These technical failure events are relatively frequent and can extend over most of the season, as was the case in our study. Monitoring with several different satellite sensors helps to overcome this problem by providing a more reliable technology and a synoptic view. The most conservative thresholds for ice mobilization that were estimated by Morse and Turcotte (2018) would place the required flow at 300 m^3/s. The exact value is unknown. Yet, based on the trend at the Eaton station, together with the early and late season data from Sherbrooke, this threshold was likely reached during the ice jam of January 24th. The most damaging ice jams would be created at a flow of 600 m^3/s, according to the same study. The ice jam that we monitored generated a minor degree of flooding but is not considered a major event.

Around February 6th, another temperature increase was observed (Figure 11). As shown on the maps (Figure 12), the consolidated ice jam at Lennoxville and the second upstream ice jam were still in place. The ice cover was likely thicker and more cohesive than on January 24th, when precipitation and temperature conditions caused the ice jam and, therefore, were harder to break up. Later that spring, runoff appeared to have brought about a substantial increase in flow (Figure 11). The weak ice cover in place and its absence over large sections of the river ensured that the ice was easily dispersed. Our study, however, had only targeted mechanical breakup of ice-jam events. Even without ice, there could still be a risk of a frazil-related ice jam.

Channel geomorphology and the presence of obstructions influence the location of ice jam accumulation areas (De Munck et al. 2017). Considering the results of river segmentation in relation to the dominant ice formation process, it would be useful to investigate the links between the geomorphology of the production areas and their predisposition toward breakup. The freeze-up sequences of the production, transport, and accumulation areas along the length of the river could also provide indicators of the risk of breakup and ice jams.

Complementarity of satellite and drone images

Satellite and drone images allow us to gather information on large portions of the river at the same time and to repeat this data collection at regular intervals throughout the winter. It also enables us to collect information on dangerous zones in a safe manner. Optical satellite imagery provides images that require very little processing to be interpretable. In the context of river ice monitoring, the high contrast colors of dark water and light ice facilitate their distinction. The use of optical images is ineffective when there are clouds or precipitation that obscures the zone being monitored.

In our case, it was impossible to acquire optical images with good visibility between January 12th and 22nd. This is a serious limitation, since ice jams that are caused by the dynamic breakup often occur following warm climatic conditions and precipitation events (Beltaos 2008). The quality of the satellite radar images is not dependent upon the presence of cloud cover. The maps that were generated by the IceMAP-R algorithm illustrate not only the distribution of ice but also the type of ice. These additional data allow us to identify ice jams. Our use of Sentinel-1 and RADARSAT-2 satellites increases the frequency of available radar images. The new satellites in the RADARSAT Constellation Mission will increase the temporal frequency of images, thereby maximizing the chances of acquiring quality images at short and regular intervals. On certain dates, such as January 28th, it was possible to obtain both Sentinel-1 (radar) and Sentinel-2 (optical images). This match made it possible to compare both methods and showed that the maps generated by MSPQ using Sentinel-1 were apparently accurate. This kind of validation throughout the winter is very useful in assuring the quality of the radar classification. However, smaller rivers are impossible to monitor using radar images because of the latter's coarse resolution. While the Massawippi River seems to have played a role in the formation of the ice jam, this watercourse could only be mapped for a few meters before becoming too narrow. In the coming years, the increase of commercial radar satellite accessibility, such as ICEYE (2023), could solve this problem by permitting finer monitoring resolution.

It is impossible to predict whether a radar or optical satellite pass would be synchronized with the presence of an ice jam or its breakup. Drone-mounted sensors overcome this uncertainty by allowing for rapid deployment (Garver et al. 2018; Rødtang et al. 2021). Drone observation of ice cover also allows access to hard-to-reach zones without risking the operator's safety (Alfredsen et al. 2018). In our case, the toe of the ice jam was located on the other side of a bridge that could not be reached by the drone, since current regulations proscribe road crossings. Furthermore, as a research team, it was impossible to enter private land without the owner's authorization to launch drones and make sure that they remained within our field-of-vision. The current regulation, therefore, are not entirely adapted to accommodate emergency measures. Floods that require drone surveys or interventions are generally occurring in populated areas where flight rules are very strict.

Unfortunately, there was almost a two-week gap between the ice jam formation and the drone flight.

Over this period, changes in weather conditions, such as temperature fluctuations, precipitation, and wind, can alter the ice's structure and surface characteristics. During this time, the ice could transition from a freshly jammed state to a more consolidated state, potentially smoothing out sharp edges and leading to changes in surface roughness.

Despite these constraints and delays, the survey allowed us to acquire precise and complementary information to accompany the radar and optical images, particularly in the presence of a snow cover and regarding the state of ice-jam consolidation. The potential uses are also very interesting. Depending upon the type of drone, its flight height, and the equipment it carries, it could acquire data on the thickness, volume, roughness, or spatial distribution of the ice cover. Drones also can be reliable tools for validating ice type maps. Especially during springtime or other occasions when ice melts, the presence of water over the ice cover can lead to classification errors (Gauthier et al. 2016). Only a few drone images are required to solve this problem and to aid in the interpretation of the ice type maps.

Importance of ice cover mapping

Monitoring ice maps over time can be used to locate or to detect the degradation of the ice cover on certain sections of a river. Signs of melt were detected by Gauthier et al. (2010) by coupling terrestrial photos with ice maps to highlight the presence of water, together with signs of melt in Nunavik (northern Quebec). They were also used in a study to extract indicators of type change and melting signs by sections of ice maps that were created by the IceMap-R algorithm. Chu et al. (2015) used a similar method. These authors attempted to detect changes in ice cover by examining differences between two ice classifying maps. By approaching the changes from the perspective of pixels rather than by section, they further illustrated the appearance of portions of open water within an existing cover. These observations are relevant to the current study. The breakup that led to the 2019 Lennoxville ice jam had occurred too suddenly to be visibly registered on the ice maps. Indeed, melting signs are more often seen on spring ice jams (i.e., thermal breakups) than on mid-winter breakups (i.e., dynamic breakups). If hydro-meteorological surveillance had been taking place, it would have been possible to spot ice cover upstream of accumulation areas and to monitor the breakup closely.

Remote sensing makes it possible to monitor the entire river and, thus, obtain data on the ice front. The location of the ice front and its development over time indicates where the breakup first occurs and where it will happen next. Monitoring can be indicated on ice maps (Gauthier et al. 2015) or on other figures synthesized with additional data. Our monitoring showed that the ice front started on January 2nd and expanded until January 22nd, mainly in the production areas (Figure 7). During the ice-jam event, the ice front extended upstream, starting from the intact ice cover and extending to the accumulation areas. Having information on the ice front location can be very useful for identifying sections that are prone to ice jams since these can act as barriers and stop the ice run.

As stated earlier, our research had focused on the Lennoxville ice jam because it occurred in a more densely populated area and, therefore, was reported rapidly by the MSPQ. However, our monitoring using satellite images revealed a second ice jam upstream of the first. This ice jam, which is located in a wooded and less accessible area, could have gone completely unnoticed by the civil security teams. If this ice jam had started to move and merged with the first one, more floods could have been expected.

Further research on the Saint-François River using remote sensing could focus on how the freeze-up processes can affect breakup in specific areas. Nafziger et al. (2021) showed that the breakup of both the Athabasca and Peace Rivers (northern Alberta) were influenced by ice cover formation. An analysis of the relationship between ice formation and breakup with maps could be useful. The early February temperature increase (Figure 11), which was comparable to the one in late January, did not lead to an ice jam. It was likely the consolidated cover was more cohesive than the first thermal breakup.

Conclusion

This paper highlights the integration of satellite, radar, and drone technologies to comprehensively monitor and segment river ice conditions, enhancing risk assessment and management by detecting ice jams in hard-to-reach areas and offering a safer, more detailed alternative to traditional monitoring methods. Remote sensing tools are reliable for ice monitoring, given that they can cover large territories. In utilizing optical imagery, ice maps that were made with radar imagery, and drone-acquired imagery, it was possible to track the formation of the ice jam on January 25th, 2019, and observe its subsequent consolidation. Our study demonstrated that the use of ice maps could discriminate between various hydro-meteorological events and their consequences. Some could have been considered at risk of causing ice jams by demonstrating the absence of ice on the river. By using a variety of data sources, we were able to compensate for sensor deficiencies or sensitivity to weather. By targeting certain areas according to the dominant ice process from year to year, we could better target ice production and accumulation areas that deserve closer monitoring.

Beyond predictive models, remote sensing remains an effective way to exercise vigilance and to monitor ice cover development over long periods. Optical images allow large-scale monitoring that is fairly accurate over time and which can be used to extract data on temporal or spatial patterns. Radar imagery also allows this type of monitoring, but with a constant coverage that is not influenced by weather. The level of detail that is captured by pixels—a few meters wide—also permits textural analysis and recognition of the types of ice in various locations. Possible automation of ice cover monitoring with free and easy-to-use tools could lead to the democratization of the method by facilitating its implementation. In the context of climate change, where the frequency and intensity of dangerous natural events may be amplified, it is relevant to have access to as much data as possible to make informed decisions.

Ice jams are poorly documented events and populations who are living along a watercourse are highly vulnerable to their effects. On one hand, citizens are not equipped to deal with this type of hazard, and on the other hand, society has long minimized the risks that are associated with ice processes. Many actors are working to reduce this vulnerability and to raise awareness of ice-induced flooding. The complex character and the difficulty in predicting ice events add to their danger and open the door to research that is trying to equip governments to improve prevention and preparation for these situations. No tool is yet able to make reliable predictions and to integrate well with the procedures that are already in place within a framework of interoperability. By using information that is easily available and coupling it with already existing monitoring measures, we could increase our knowledge regarding these phenomena and be better prepared to face them.

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