CGU HS Committee on River Ice Processes and the Environment
21st Workshop on the Hydraulics of Ice Covered Rivers
Saskatoon, Saskatchewan, Canada, August 29-September 1, 2021

The influence of tributaries on breakup dynamics: Insights from the Chaudière River, Québec

Catherine Blouin[1], Tadros Ghobrial[1], Brian Morse[1], Gabriel Pelchat[1] and Benoit Turcotte[1&2]

[1]Department of Civil & Water Engineering, Université Laval, 1045 avenue de la Médecine, Québec, QC, G1V 0A6
catherine.blouin.7@ulaval.ca
tadros.ghobrial@gci.ulaval.ca
brian.morse@gci.ulaval.ca
gabriel.pelchat.1@ulaval.ca
benoit.turcotte@gci.ulaval.ca

[2]YukonU Research Center, Yukon University, 500 University Drive, Whitehorse, YT, Y1A 5K4
bturcotte@yukonu.ca

Ice-jams in recent years have caused significant damages in the province of Québec. This includes the ice-jam flood in the spring of 2019 on the Chaudière River. Following these events, a research project supported by Québec's Ministère de la Sécurité publique (MSP) was initiated to study the effect of tributaries on breakup ice-jams. Tributaries often play an important role during the breakup season, leading to complex spatial ice processes and occasional flooding. The behavior of tributaries during breakup as well as their impact on the initiation of ice-jams is very site specific and depends on ice, morphological and hydrometeorological conditions. The research project involves the Chaudière's main tributaries (Du Loup, Famine and Bras St. Victor rivers) and the objective of this paper is specifically to document how theses tributaries affect breakup dynamics at, and downstream of, major confluences of the Chaudière River. This paper briefly analyzes the factors controlling the breakup sequence at each confluence during the 2021 season. For the Du Loup confluence, breakup was governed by the ice control structure located downstream in the Chaudière River as it intercepted the ice at the confluence as well as at the entrance of the tributary and only released it at the end of the breakup sequence. Small islands and a bridge at the mouth of the Famine River prevented the ice from exiting that tributary and a discharge of 30 m^3/s had to be attained for the ice to be able to mobilize towards and downstream of the confluence. Ice runs in the Bras St. Victor River created multiple jams, both in the tributary and in the main river, and the tributary therefore controlled the evacuation of the ice in this section of the Chaudière River.

1. Introduction

Floods have become more frequent all over the world in recent years and they now represent the most common of all natural disasters (Jha et al., 2012). Ice-jams continue to be responsible for a large ratio all flood events and flood damages in eastern Canada and these floods are known to be more destructive than their open-water counterpart (Beltaos & al., 2001). Water levels from an ice-jam flood can rise very quickly, that is within minutes, as opposed to open-water flooding, posing a greater challenge in planning evacuation and alleviation measures (Beltaos et al., 2001). In a context where some watersheds in Québec could be affected by more dynamic breakup events in the future (Turcotte et al., 2020), predicting ice-jam flooding and implementing mitigation measures remains very important.

One of the main factors for estimating ice-jam flooding potential is predicting the location of ice pieces build-ups. Several studies have reported the river geomorphological factors leading to ice-jam formation (e.g., Beltaos, 2008; Lindenschmidt and Das, 2015; De Munk et al., 2017). These factors include reduction in channel slope (slope break), reduction in channel width, either naturally (due to sharp meanders, sand bars or islands) or man-made (e.g., bridges, groins), as well as the presence of confluences and deltas. Typically, breakup on small streams or tributaries begins before initial ice movements in the main river because of their more rapid response to runoff and their often steeper gradient. Depending on the sequence and speed of breakup, the risk of ice-jam flooding may be high at the vicinity of confluences. However, our knowledge of tributary behavior during breakup and their role on downstream ice-jam formation is still limited. Confluences have been studied in the laboratory through small-scale hydraulic models (e.g., Ettema and Muste, 2001). Two-D models have also been used to investigate ice at confluences or deltas as well as in the presence of islands (e.g., Brayall, 2012; Kolersky, 2015). Finally, some field studies have reported observations on the dynamics of river ice in deltas (e.g., McDonald et al., 2002; Blackburn et al., 2015; Beltaos et al., 2012; Nafziger et al., 2019). These studies have focused on the dynamic characteristics of jam formation and, to the best of the authors knowledge, there has not been a comprehensive study on the hydrometeorological, morphological, and river ice conditions affecting breakup processes at confluences.

Therefore, the objectives of this study are to understand the interaction between tributary ice and downstream river ice during breakup, and to quantify the environmental factors affecting the sequence of breakup and jam formation near confluences. To achieve these objectives, the Chaudière (CH) River in Québec has been studied at the vicinity of three of its main tributaries (Du Loup (DL) River, Famine (FA) River and Bras St. Victor (BSV) River) during winter 2020-2021. Multiple sites were instrumented in the CH River and in the tributaries themselves. The data collected includes air temperature and pressure, water temperature, depth and near-bed turbulence, time lapse images, drone flights videos and GPS data. River discharge data were also available for the CH and the FA rivers from stations operated by the Government of Québec. This paper presents the methodology used in this study as well as some preliminary results and conclusions.

2. Study area

The CH River was selected for this study because of the presence of several relatively large tributaries as well as for its history of frequent ice-jam floods. The river originates from Mégantic Lake and flows north for 185 km, reaching the south shore of the St. Lawrence River, south of Québec City. Its watershed drains 6694 km^2. Figure 1 presents the CH River watershed including the subcatchment areas of its main tributaries which are, from south to north, DL River, FA River, BSV River and Beaurivage (BE) River. BE joins the CH River only 7 km upstream of its mouth in a steep reach of the main river and therefore does not pose a flooding threat, and thus the BE-CH confluence was excluded from the present study.

The DL River joins the CH at km 103.4 from the Innergex Dam, located at approximately 4 km from the mouth, and has a watershed area of 893 km^2 which represents 29% of the upstream watershed. The FA and BSV rivers join the CH at km 97.5 and 75.3, and have catchment areas covering 714 km^2 and 735 km^2, which represent around 19% and 15% of the catchment area upstream of each confluence, respectively. All together, these three tributaries account for 35% of the total catchment area of the CH River.

As shown in Figure 2, the CH River is mainly divided into three reaches with distinct bed slopes, namely the upper (from km 185 to km 99), intermediate (from km 99 to km 39), and lower (from km 39 to km 0) reaches with average slopes of 0.262%, 0.039% and 0.205%, respectively. The average slope in the downstream section of each tributary is 0.516%, 0.847% and 0.694%, for the DL, FA and BSV rivers, respectively. This results in the DL River being twice as steep as the CH in the upper reach and this ratio is 22 and 18 times for the FA and the BSV rivers in the intermediate reach.

It is important to note that there is an ice control structure (ICS) called Barrage Sartigan located at km 102.6, approximately 0.8 km downstream of the confluence with the DL River.

The typical spring breakup timing of the CH River and its tributaries is between early March and mid-April. It is usually very dynamic and is characterized by the formation of several ice-jams and subsequent flooding within the intermediate reach. Beyond spring breakup events, there are often partial but substantial winter breakup events on all of the tributaries as well as on the CH River (e.g., Turcotte et al., 2020).

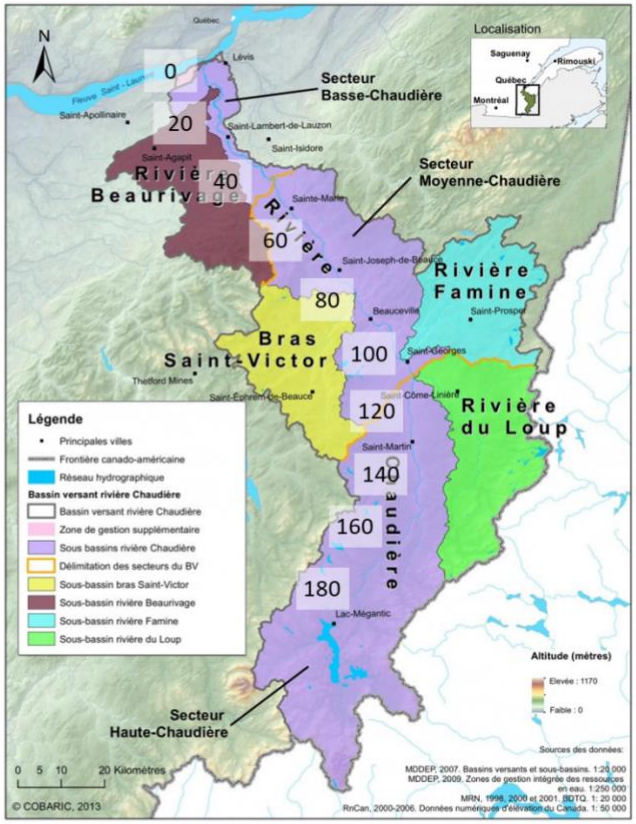

Figure 1. Watershed areas of the CH River and its main tributaries (source: Cobaric) with stationing from the Innergex Dam located at approximately 4 km from the mouth.

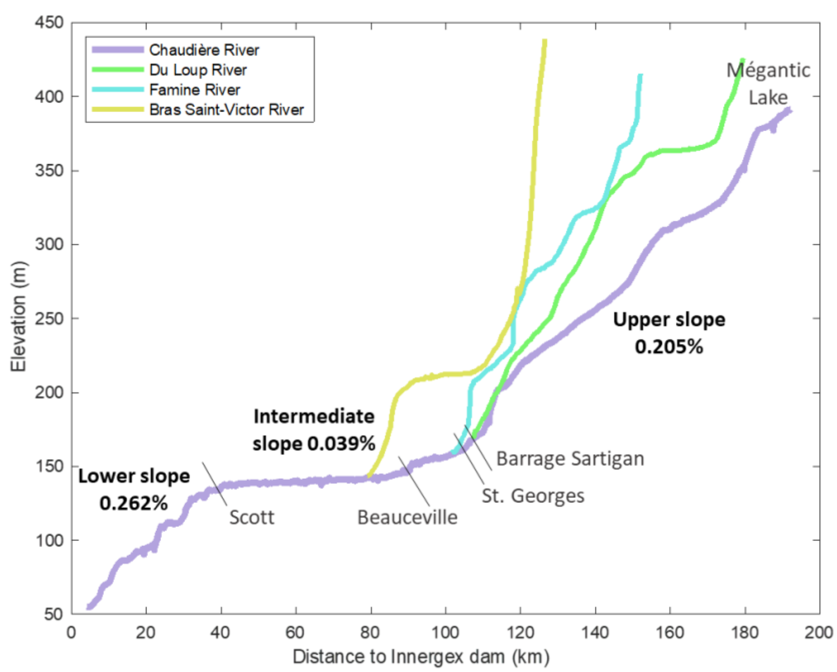

Figure 2. Elevation profiles of the CH, DL, FA and BSV rivers.

3. Instrumentation and methods

Meteorological data was acquired from the St. Georges (ID 7027283) and the Beauceville (ID 7028754) meteorological stations operated by Environment Canada. They are approximately 15 km from each other and near the three studied tributaries. The data from these two stations includes hourly air temperature, total precipitation, atmospheric pressure, daily rainfall and total snow on ground. Laval University also installed atmospheric pressure sensors (HOBO U20-001-01®) in St. Georges and Beauceville as well as air temperature sensors (HOBO UA-002-64 ®) near each studied tributary to complement public weather data.

The Centre d'expertise hydrique du Québec (CEHQ) operates 2 relevant stations collecting flow data on the CH River, namely St. Martin station (km 120.5, ID 023448) and St. Georges station (km 102.5, ID 023429) downstream of the Barrage Sartigan. In addition, the CEHQ has a hydrometric station on the FA River (km 6.6, ID 023422) with discharge estimates year-round, but there are no hydrometric station on the two other tributaries. The St. Martin station was used to provide hydrometric data upstream of the DL confluence, while the St. Georges and FA stations were used to provide hydrometric data on the CH River upstream of the FA confluence and on the FA River itself, respectively. Finally, a virtual station called 'Beauceville' was created by summing the discharge data from the St. Georges and the FA stations to provide discharge data on the CH River upstream of the BSV confluence.

To complement the available hydrometric data, Laval University installed submersible instrumentation platforms, trail cameras and GPS trackers at multiple observation sites in the vicinity of each confluence. Submersible platforms and trail cameras setups are presented in Figure 3. Each platform included the same set of three instruments: a water temperature logger (RBRsolo^{3}T ®) recording data every minute, a pressure logger (HOBO U20L-01 ®) acquiring data every 10 minutes and an acceleration pendant (HOBO UA-004-64 ®) monitoring near-bed turbulence at 15-minute intervals (Figure 3a). Loggers were installed inside pipes made out of PVC, tightened with fitted plastic rings and closed with a bolt allowing water to go through while keeping the sensors in place (Figure 3b). The pipes were fixed to a 11 kg metal plate and the platform was fixed to the riverbed using rebar spikes. A chain was also welded to each plate to hold the device in place using metal stakes in case it was pushed from its location by ice (Figure 3a and b). Acceleration sensors were clamped with a rubber tube and bolt inside a hole in the plate handle (Figure 3b). Platforms were painted bright orange to facilitate retrieval and were installed carefully downstream of rocks, to protect them against from being shoved by ice.

Cameras gathering time-lapse images (Brinno BCC100 ®) were installed on trees and underneath bridges, when possible (Figures. 3c, d and e). Pictures were taken every 30 to 60 minutes depending on the location of the camera and the time of the year. Images were generally taken more frequently during the spring breakup. All submersible platforms and their adjacent trail cameras were deployed in late October 2020 and were successfully retrieved in April 2021 once rivers were clear of ice. Drone flights were conducted over the confluences on multiple occasions to further observe the extent of ice-jams during the winter and spring breakups. Lastly, GPS trackers (Tracki 2021 Mini Real time ®) were fixed on the ice cover during the third week of March 2021, before the breakup started, and were used to create a spatio-temporal map of ice movements during that period.

The main challenges regarding the field work were finding adequate locations to deploy the instruments and locating the equipment for retrieval at the end of the season. In case no direct access to the river was present near the deployment site, the collaboration of citizens was necessary to access the river through private properties. Submersible platforms had to be protected by rocks to avoid their displacement and cameras required trees that were high and close enough to the river to yield exploitable images. Modifications were made to the submersible platform after the 2019-2020 winter season to increase their retrieval rate. These include the use of a bolt rather than a plug to close the PVC pipes, an additional anchor to fix the platform through a metal chain, and a bright orange paint on the platforms to increase their visibility.

Figure 4 presents the location of relevant CEHQ hydrometric stations, observation sites as well as the location of the GPS trackers deployed by Laval University at each confluence prior to the 2021 spring breakup. For each confluence, there were two observation sites on the tributary (one upstream and another near the mouth) and generally three sites on the CH River (one upstream, one downstream and another at the confluence itself). The information for each observation site is summarized in Table 1.

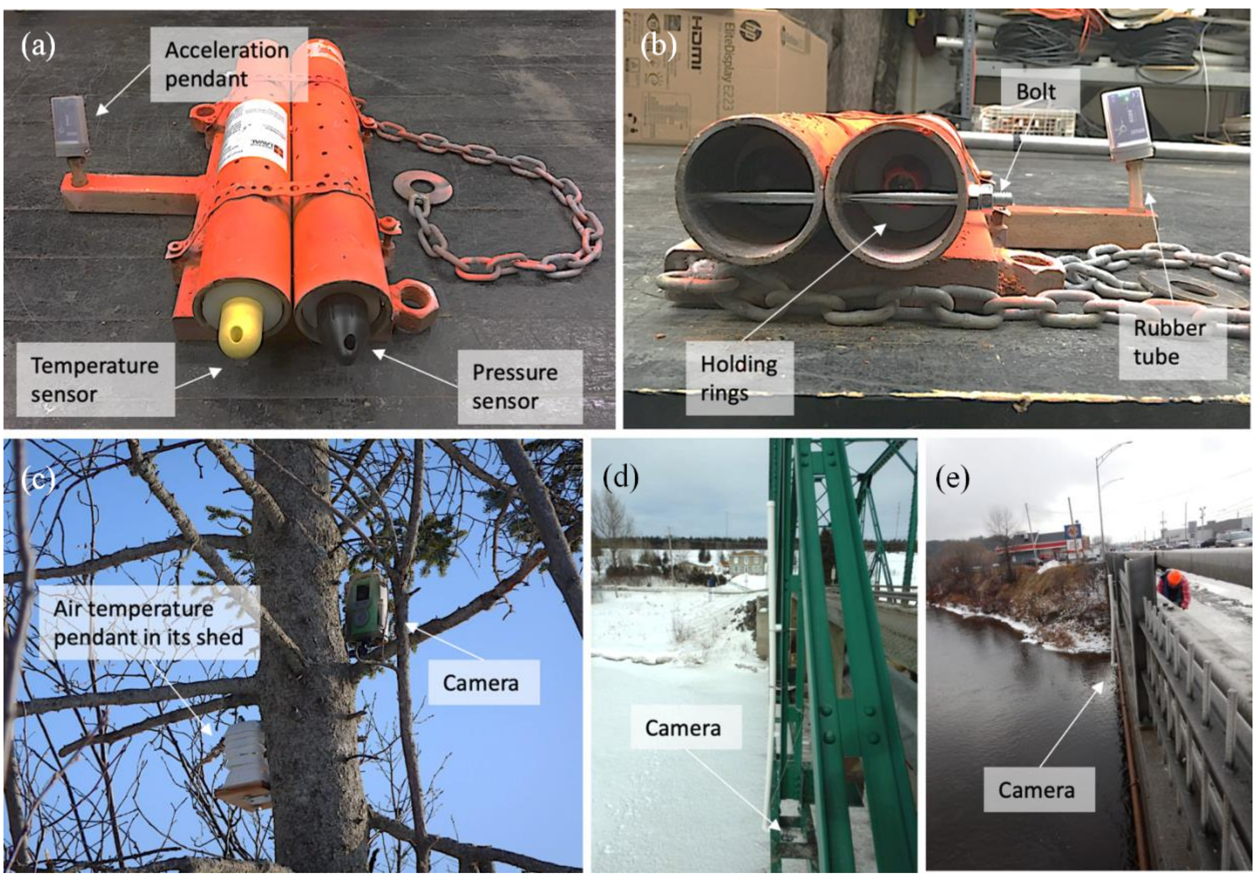

Figure 3. Observation setups showing a) the instruments and b) the holding apparatus used in the submersible platforms; installed cameras c) on a tree with a temperature pendant in its protective case and on bridges in d) the BSV River and e) the DL River.

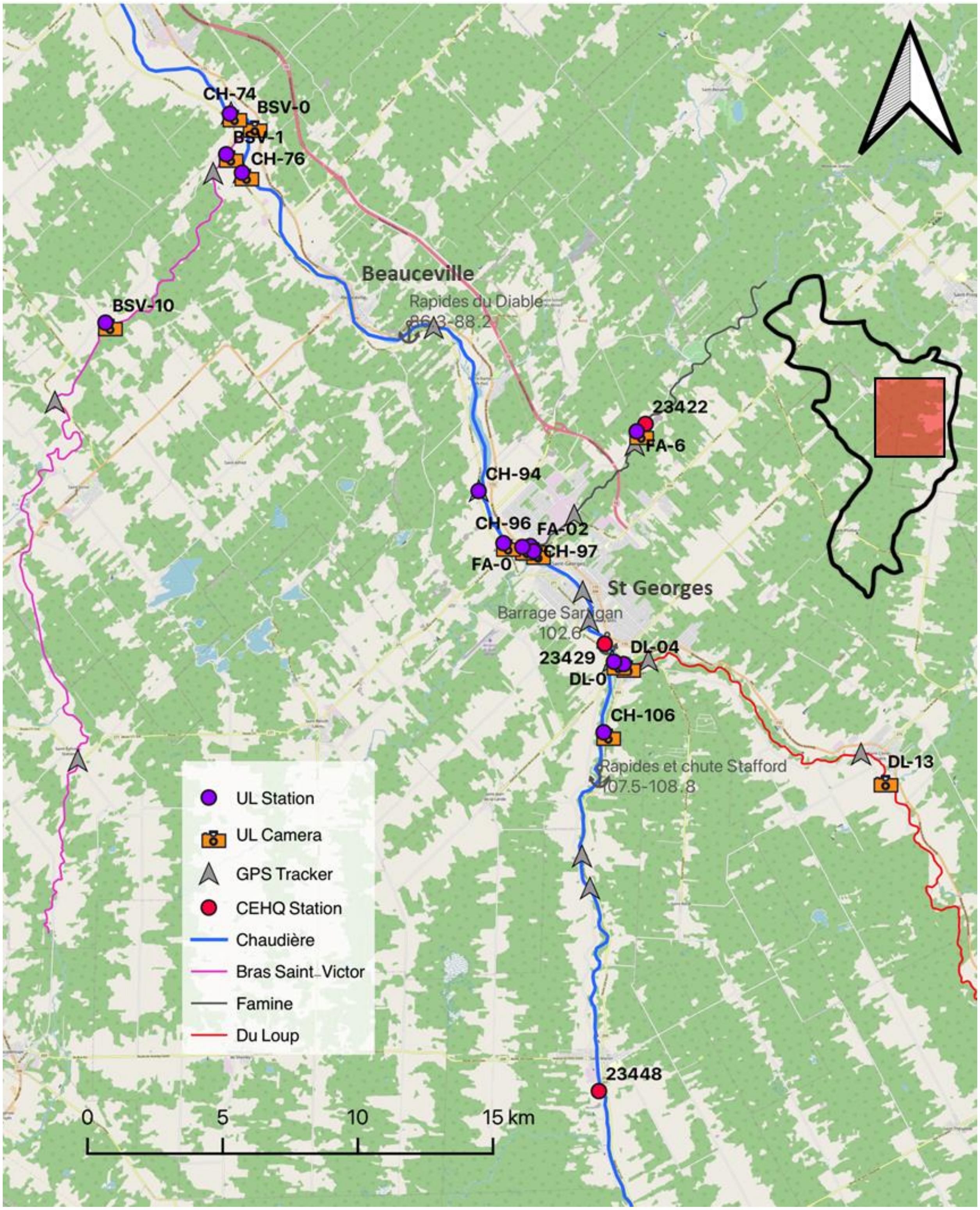

Figure 4. Locations of submersible stations, trail cameras and GPS trackers installed during the 2020-2021 winter season. The relevant CEHQ stations are also shown.

Table 1. Summary of observation sites and monitoring stations within the study reaches.

Confluence	Site Number	Observation Location	River	Stationing (km from the mouth*)	Instrument
DL	CH-106	Upstream of confluence	CH	106.0	Submersible platform Trail camera
	DL-0	At the confluence	CH	103.4	Submersible platform Trail camera
	DL-13	Upstream in the tributary	DL	13.5	Trail camera
	DL-04	Downstream in the tributary	DL	0.4	Submersible platform Trail camera
FA	CH-97	Upstream of confluence	CH	97.9	Submersible platform Trail camera
	FA-0	At the confluence	CH	97.5	Submersible platform Trail camera
	CH-96	Downstream of confluence	CH	96.7	Submersible platform Trail camera
	FA-6	Upstream in the tributary	FA	6.6	Submersible platform Trail camera
	FA-02	Downstream in the tributary	FA	0.2	Submersible platform Trail camera
BSV	CH-76	Upstream of confluence	CH	76.9	Submersible platform Trail camera
	BSV-0	At the confluence	CH	75.1	Trail camera
	CH-74	Downstream of confluence	CH	74.2	Submersible platform Trail camera
	BSV-10	Upstream in the tributary	BSV	10.6	Submersible platform Trail camera
	BSV-1	Downstream in the tributary	BSV	1.2	Submersible platform Trail camera

*Stationing is from the Innergex Dam in the CH and from the confluence in the tributaries.

4. Results and discussion

4.1 Meteorological conditions

Meteorological conditions during breakup are presented in Figure 5. Since air temperatures measured in each tributary were very similar (within ± 1˚C), only air temperatures from the FA River are presented (Figure 5a). Air temperatures generally remained below -5˚C until March 10th, at which time the cumulative degree-days of thawing above -5˚C (CDDT-5) started to be greater than 0˚C.D (Figure 5b). The local snowpack started to melt that same day and had completely disappeared by March 20th (Figure 5d), which is fairly early for the region. Finally, an extended rain event totaling 48 mm fell on the study area between March 24th and 31st (Figure 5c).

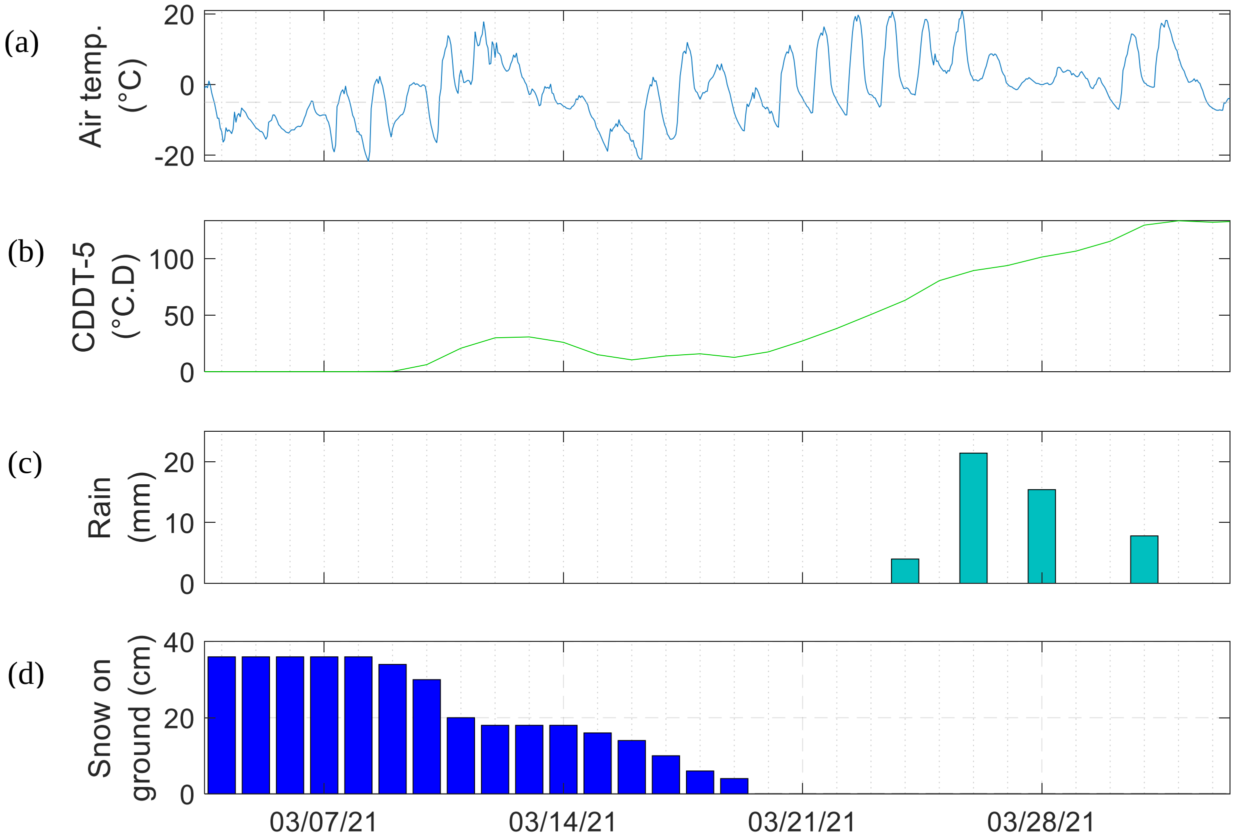

Figure 5. Meteorological conditions covering the breakup period (between March 4th and April 2nd, 2021) showing a) air temperature, b) cumulative degree-days of thawing above -5˚C (CDDT-5), c) daily rainfall and d) daily snow depth on the ground.

4.2 DL confluence

Figure 6 presents the results at the DL confluence. In response to snowmelt and rain events shown in Figure 5c, the water levels and discharge started to rise from March 23rd until it reached its peak on March 27th with a value of 302 m^3/s on the CH River (CH-106). This input combined with air temperatures consistently above -5˚C contributed to the weakening of the ice cover. The first section to lose its cover was in the tributary at DL-13 on March 23rd. The site upstream from the confluence on the CH (CH-106) then started to lose its cover gradually starting from March 25th and was free of ice by March 27th. During this period, the water temperature began to rise rapidly, partially in response to the absence of ice cover. From March 26th, water levels started to decrease gradually as the effect of the rain event faded and because of the reduced friction to flow associated with the evacuation of the ice.

The last section to lose it cover was at station DL-0 and downstream of the confluence. Figure 7 presents images from a drone flight conducted over the confluence on March 23rd that confirmed the presence of an ice-jam with its toe at the confluence and its head approximately 1.5 km upstream in the tributary. Also, a bridge is located less than 400 m from the confluence in the DL River at the ice-jam location, as seen in Figure 7. The ice cover was retained in place by the ICS located 0.8 km downstream of the confluence. The cover melted thermally between March 30th and April 1st in response to the rainfall event of 7.8 mm on March 31st and warmer air temperatures reaching 18.2˚C as well as a CDDT-5 of 133.3˚C.D by April 1st. During the entire breakup period, the water temperature remained very close to 0˚C at DL-0 compared to values measured at other nearby sites, varying from 0.037˚C to 0.147˚C. The rapid disappearance of the ice cover shows that it was flushed out through the ICS, and thus the water level during the event did not vary significantly as it was controlled by the gates of the Barrage Sartigan.

Results confirm that the Barrage Sartigan ICS has maintained a stationary ice cover on the CH River that extended upstream to the confluence with the DL River during breakup. This stationary ice cover forced an ice-jam to form in the tributary, where a bridge also causes additional constrain, and impeded the evacuation of the ice from the DL River and from upstream sections of the CH itself. This shows that the ICS performed as designed, sparing St. Georges (and downstream municipalities) from ice runs and ice-jam flooding.

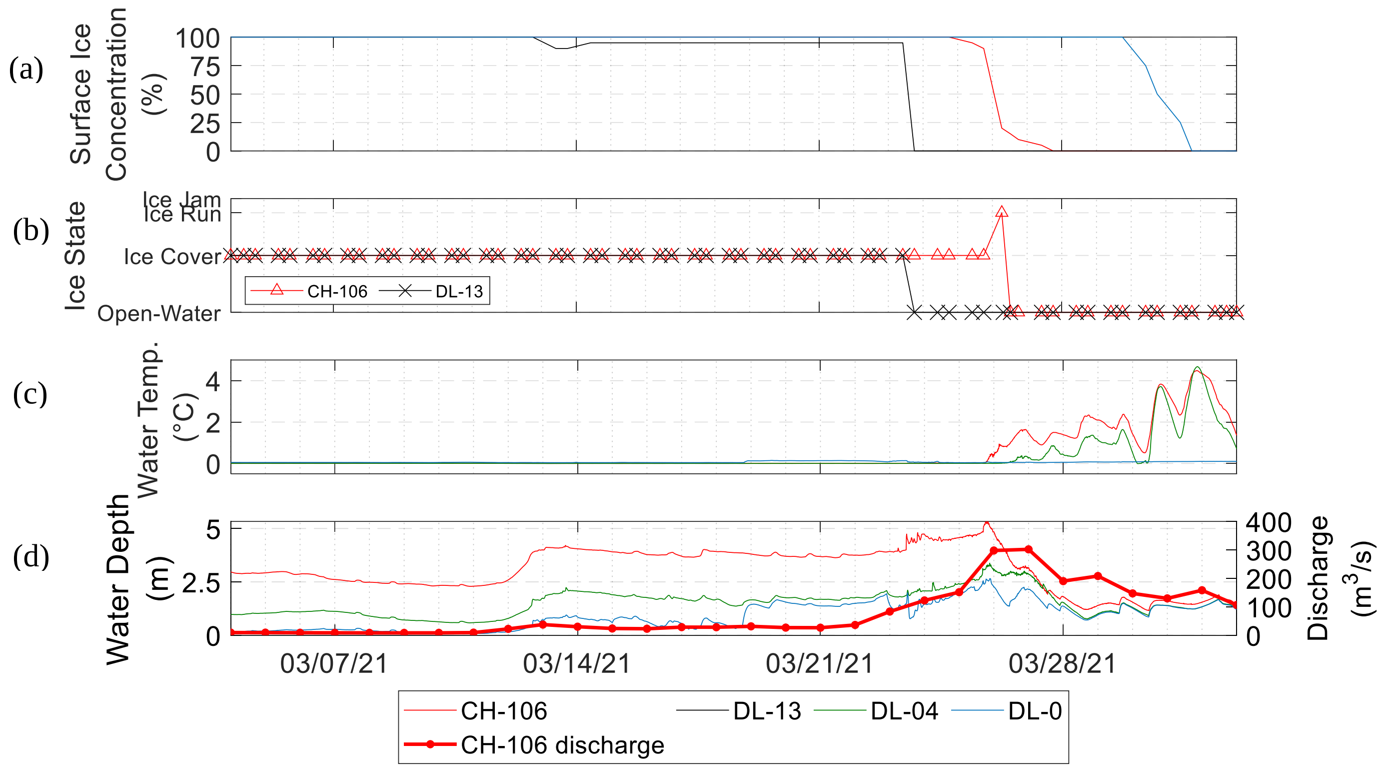

Figure 6. Data for the DL confluence: a) surface ice concentration, b) ice condition, c) water temperature and d) water depth and discharge. For reference, the elevation under the pressure sensors at the water depth sites were 172.74 m at CH-106, 172.86 m at DL-04 and 172.77 m at DL-0.

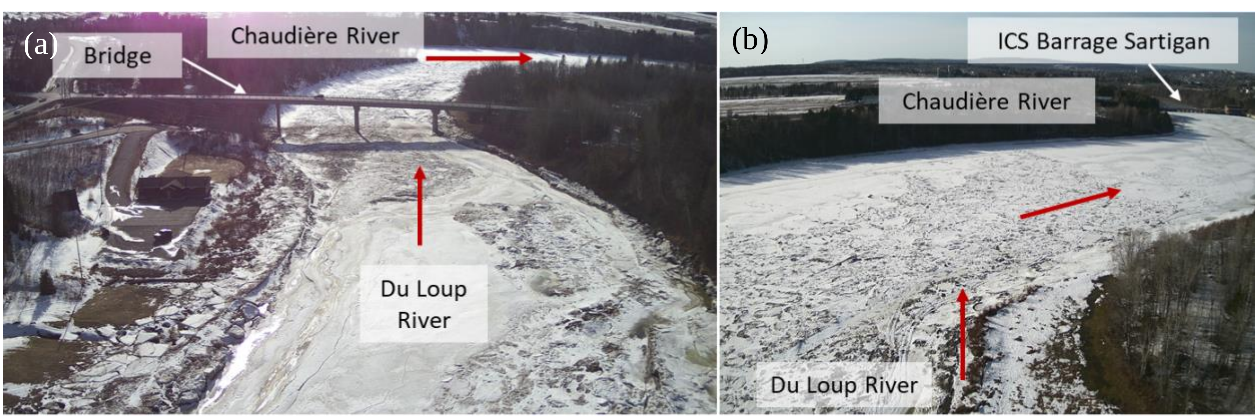

Figure 7. Drone flight images taken on March 23rd showing a) an ice-jam with its head in the DL River around the bridge present in the tributary and b) its toe at the confluence. Red arrows are showing the direction of the flow.

4.3 FA confluence

Results of the FA confluence are shown in Figure 8. First, the sections at the confluence (FA-0) and immediately downstream of the confluence (CH-96) lost their cover between March 11th and 13th. This occurred in response to the warmer air temperatures resulting in the CDDT-5 rising from 6.2˚C.D on March 10th to 30.7˚C.D on the 13th. It should be noted that the ice cover at site CH-96 was affected by the warm water discharges from the St. Georges water treatment plant located at 0.8 km upstream (see Figure 9). As a result, an open lead corresponding to about 20% of the channel width persisted over the entire winter at that site (Figure 8a). The effect of the water treatment plant is also visible in the warmer spikes of the water temperature data at site CH-96 (Figure 8b). On March 23rd, that is 10 days after the downstream sections lost their cover, the site upstream of the confluence (CH-97) lost its cover as well. That day, the water temperature started to rise at all three sites in the CH.

Finally, the FA River lost its ice during the night of March 24th to 25th because of an increase in discharge reaching a value of 30 m^3/s on March 24th (see Figure 8d). It is important to note that although the section downstream of the confluence lost its cover 10 days earlier, the discharge in the FA was not high enough to lift and dislodge the cover past the deposition bars and small islands located at the mouth of the river. A bridge less 400 m from the confluence also contributed to the retention of the ice (see Figure 9). FA-02 was cleared of ice entirely within a night while some of the cover remained at FA-6 due to a pronounced bend in the river (see Figure 10). Following the evacuation and melt of the ice cover in the tributary, the water temperature started to increase at both stations on March 25th. The peak discharge was reached on March 27th both in the FA and in the CH rivers, with values of 145 m^3/s and 442 m^3/s, respectively.

The breakup process at the FA confluence occurred from downstream to upstream in the CH River and finally into the tributary itself. This implies that the ice in the main river did not control the evacuation of the ice in the tributary. In turn, it seems that there is a morphological control associated with the presence of bars and a bridge at the mouth of the tributary. A threshold discharge of 30 m^3/s in the FA River had to be reached to evacuate its ice.

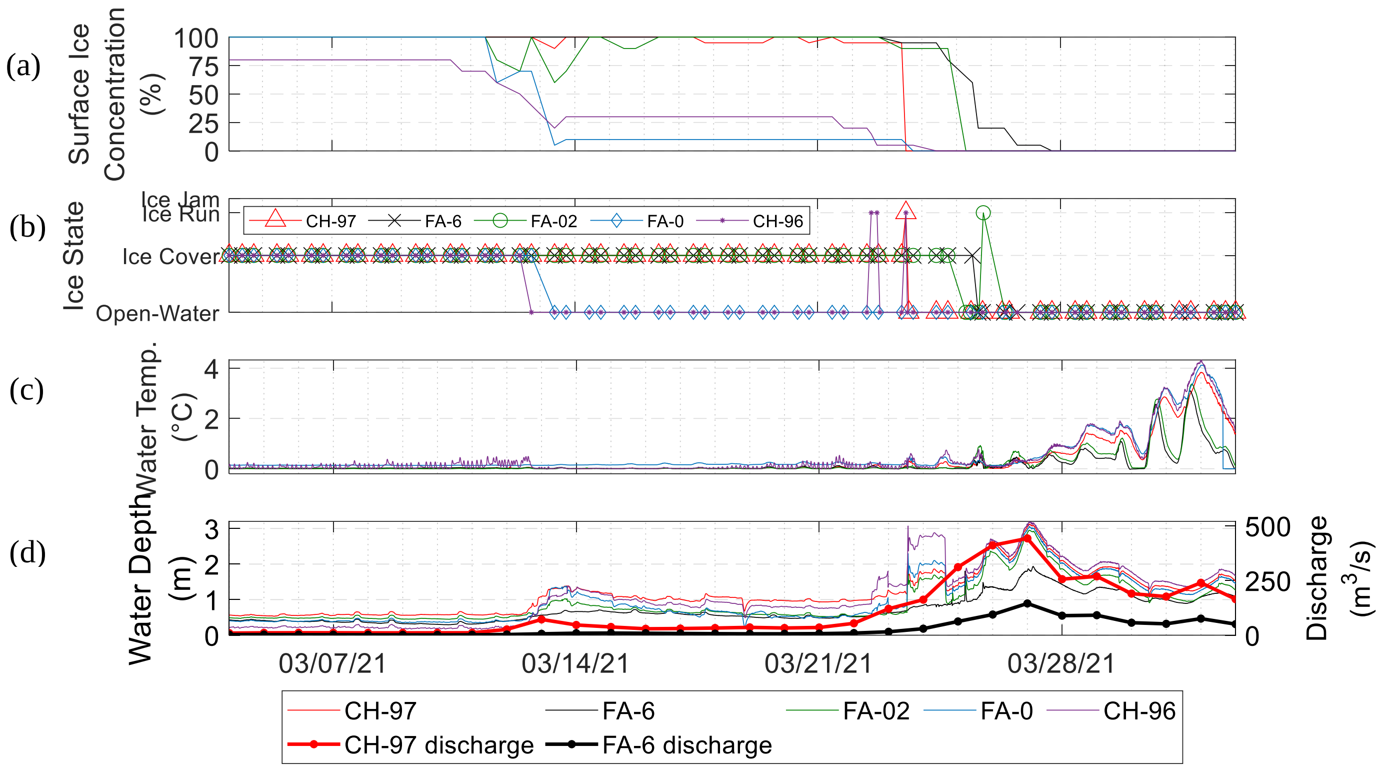

Figure 8. Data for the FA confluence: a) surface ice concentration, b) ice condition, c) water temperature and d) water depth and discharge. For reference, the elevation under the pressure sensors at the water depth sites were 158.71 m at CH-97, 158.67 m at FA-02, 207.53 m at FA-6, 158.22 m at FA-0 and 157.38 m at CH-96.

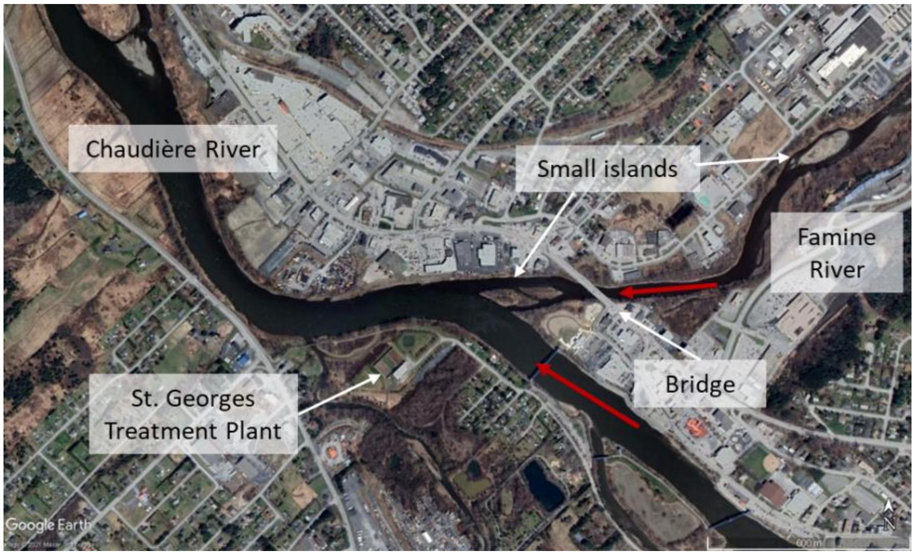

Figure 9. FA confluence showing small islands as well as the bridge present in the tributary and the water treatment plant adding its water to the CH River. Red arrows are showing the direction of the flow.

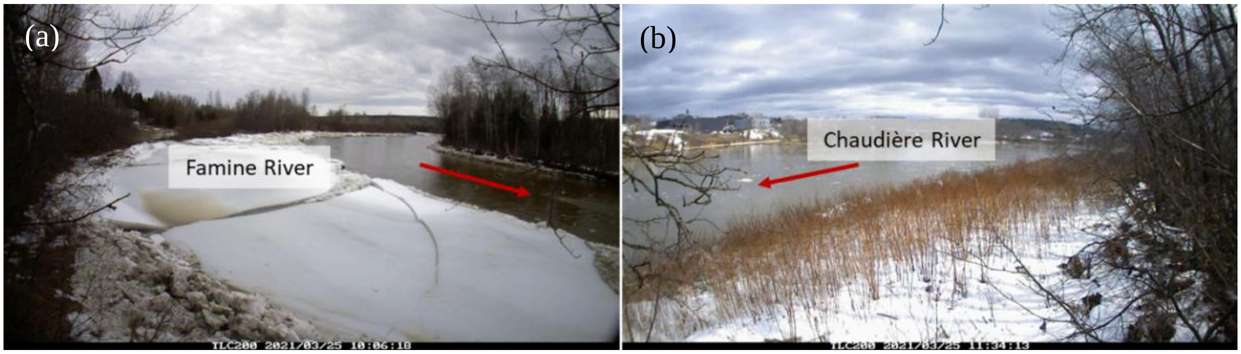

Figure 10. Images taken on March 25th showing a) the ice cover stuck in the bend in the FA River (FA-6) and b) the pieces of its breakup passing through at the confluence in the CH River (FA-0). Red arrows are showing the direction of the flow.

4.4 BSV confluence

The results from the BSV confluence are presented in Figure 11. The ice persisted at all observation sites until breakup occurred simultaneously on March 24th when the discharge increased to 192 m^3/s on the CH River.

An ice-jam first formed at the upstream site on the BSV River (BSV-10) on March 23rd. The jam then got released and an ice run moved downstream at 9:55 AM on March 24th to form a new jam at the mouth (BSV-1) at 11:46 AM. The ice run traveled just over 9 km in the span of two hours and BSV-10 was free of ice from this point on. The ice-jam then moved downstream to reach BSV-0 at 2:36 PM on March 24th, traveling the remaining 1.2 km to the confluence in approximately three hours (see Figure 12). Downstream of the confluence on the CH River (CH-74), an ice-jam formed on March 25th when the discharge increased to 374 m^3/s (Figure 11d). This however did not seem to clear the ice upstream of the confluence (CH-76) which was probably obstructed by the jam from the tributary. Ice-jams were present at BSV-1, BSV-0, and CH-74 until March 25th (see Figure 13) when the jams were mobilized from BSV-0 and CH-74 during the night. The last obstruction finally gave way at BSV-1 on March 26th and the ice-jam probably stayed longer at this site because the channel is restricted by a bridge located 1.1 km into the tributary (see Figures 13 and 14). No subsequent ice runs were observed at the two downstream sites indicating that the ice-jam melted in place after a rainfall of 21.4 mm combined with minimum air temperatures of 1.0˚C on that day. Water temperatures began to rise on March 27th at all sites of this confluence as the CH discharge (CH-76) reached its seasonal peak of 588 m^3/s.

In summary, the ice runs from the BSV River affected the ice evacuation in the CH, causing multiple jams in the tributary near a bridge as well as downstream of the confluence in the CH.

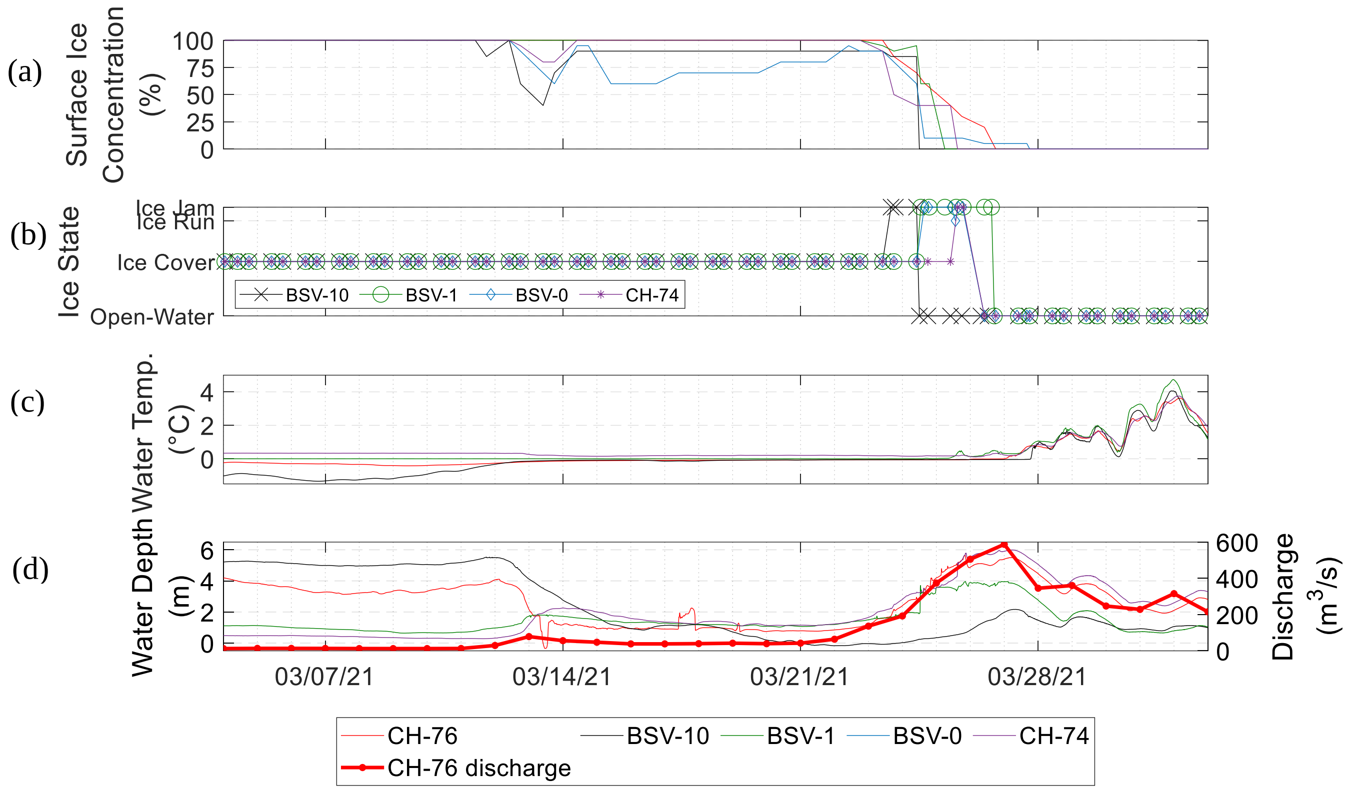

Figure 11. Data for the BSV confluence: a) surface ice concentration, b) ice condition, c) water temperature and d) water depth and discharge. For reference, the elevation under the pressure sensors at the water depth sites were 143.48 m at CH-76, 201.63 m at BSV-10, 145,02 m at BSV-1 and 141.21 m at CH-74.

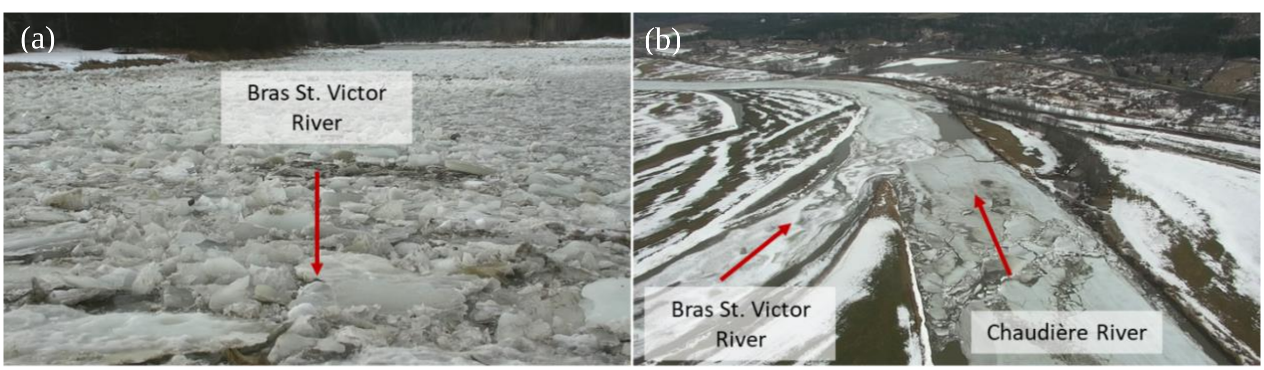

Figure 12. Drone flight images taken on March 24th showing a) an ice-jam starting the in BSV River and b) extending to the CH River at the confluence. Red arrows are showing the direction of the flow.

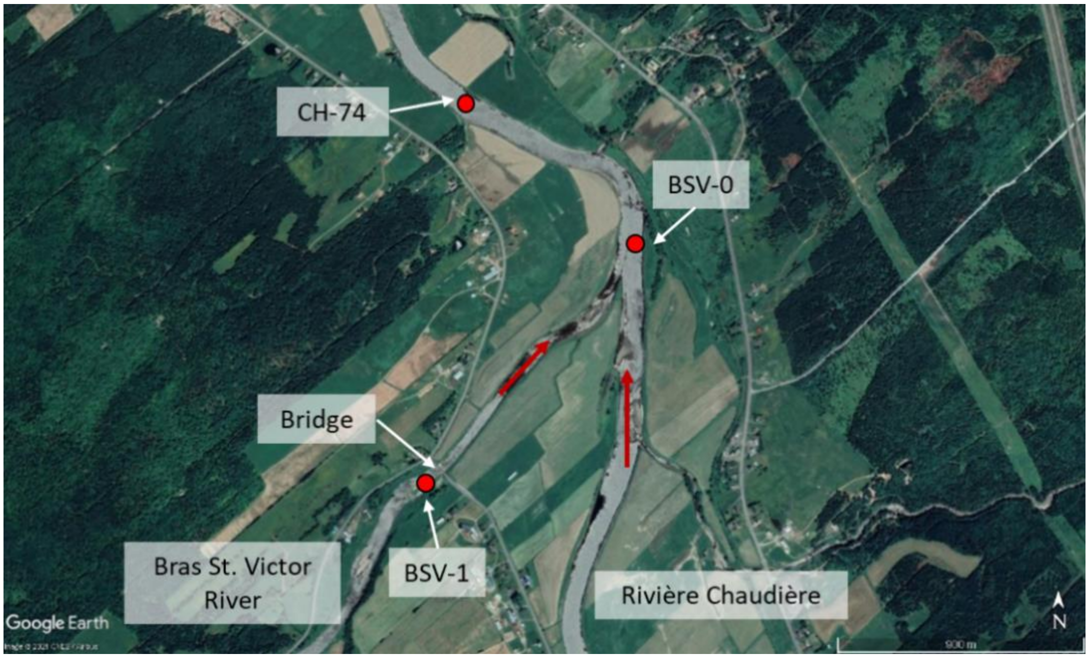

Figure 13. BSV confluence showing the bridge that restricted the ice-jam until March 27th and the three sites at which ice-jams were present between during the breakup. Red arrows are showing the direction of the flow.

Figure 14. Photo taken on March 26th, 12:40 PM, at BSV-1 showing the ice-jam upstream of the bridge. The red arrow is showing the direction of the flow.

5. Conclusions

The dynamic nature of ice-jams directly affects their flooding potential, which also means these events are hard to predict and to plan for. A better understanding of the driving environmental forces behind these occurrences is essential to better predict their timing as well as their location and here lies the motivation for this study. Confluences are particularly prone to ice-jam formation due to the convoluted nature of the junction’s geometry and to the slope difference, or break, between the two rivers. The CH River in southern Québec has a long record of repeated ice-jam floods during breakup, in part because of its multiple tributaries. The three largest upstream tributaries represent 35% of the CH watershed area and their slopes are 2 to 22 times steeper than the main river’s gradient in their respective sections. Those streams have consequently been the focus of the field work during the 2020-2021 winter season.

This study aimed to better comprehend the interaction between tributary ice and the downstream river ice at breakup. To achieve these objectives, instruments were placed near three confluences of the CH River, belonging to the DL, FA and BSV rivers. For each confluence, two sites were instrumented in the tributary and generally three in the CH River (upstream, downstream and at the confluence itself), hence a total of 14 sites were monitored. Submersible platforms as well as time-lapse cameras, GPS trackers, and drone flights were used to study the factors affecting ice-jam formation. Data from all these instruments was presented in this paper except for the GPS data which will be used for future analysis.

Although the breakup event of spring 2021 was generally thermal and occurred very early, some preliminary conclusions can be drawn from the 2020-2021 winter data as to which factors control the breakup at each confluence. For the DL confluence, the ICS downstream of the junction effectively impeded the ice evacuation by retaining a stationary ice cover that formed an ice-jam extending upstream into the tributary past a bridge, letting the ice being evacuated through its gate at the end of the season. The FA confluence did not produce any obstruction since breakup was initiated downstream of the confluence, moving upstream and ending in the tributary, allowing the ice in each section to move freely, section by section. Small islands and a bridge located near the mouth of the FA River controlled the ice clearing process in the tributary rather than the main river and a discharge of 30 m^3/s had to be reached for the ice to be broken and flushed down. Because the ice cover broke-up simultaneously at every site of the BSV confluence, large ice runs from the tributary caused multiple jams, notably near the mouth of the tributary and in the CH River at the confluence, and the BSV River therefore dictated the breakup sequence for this area of the CH.

The data presented in this paper describes the second winter during which Laval University monitored the CH watershed. Combining the data from both years will allow trends in ice-jam behavior to be identified, considering a constant morphological influence but a different hydrometeorological sequence. Future work will compare the results from both years, which will support the development of an ice-jam formation predictive tool able to forecast the release of tributary ice as a function of geomorphological characteristics of the river and meteorological conditions. The tool will be built for the monitored confluences with a possibility of generalizing its use to other locations.

6. Acknowledgments

This research project was supported by Québec's Ministère de la Sécurité publique (MSP) under the FLUTEIS project (project number CPS 18-19-26). We would like to thank Pascal Marceau, Catherine Guertin and Jean-Philippe Baril Boyer from the MPS. Also, Amandine Pierre and Éric Boucher (Université Laval) for their contribution to the field work. Lastly, we thank Professor Mark Loewen (University of Alberta) for his advice and Ana Radmanovic (University of Alberta) for her contribution to the figures presented in this paper.

References

Beltaos, S. 2008. River Ice Breakup. Water Resource Publications, LLC., Highlands Ranch, Colorado, USA, 480 pp.

Beltaos, S., Carter, T., Rowsell, R., 2012. Measurements and analysis of ice breakup and jamming characteristics in the Mackenzie Delta, Canada. Cold Reg. Sci. Technol. 82, 110–123.

Beltaos, S., & Prowse, T. D. 2001. Climate impacts on extreme ice-jam events in Canadian rivers. Hydrological Sciences Journal, 46(1), 157-181.

Blackburn, J., She, Y., Hicks, F., Nafziger, J., 2015. Ice effects on flow distributions in the Mackenzie Delta. In: CGU HS Committee on River Ice Processes and the Environment 18th Workshop on the Hydraulics of Ice Covered Rivers, (Québec City, Canada. August 18-20).

Brayall, M., Hicks, F.E., 2012. Applicability of 2-D modeling for forecasting ice jam flood levels in the Hay River Delta, Canada. Can. J. Civ. Eng. 39 (6), 701–712.

Comité de bassin de la rivière Chaudière (Cobaric). 2014. Plan directeur de l'eau du bassin versant de la rivière Chaudière : Mise à jour 2014 - Portrait. Comité de bassin de la rivière Chaudière, 2014, 256 p.

Ettema, R., Muste, M., 2001. Laboratory observations of ice jams in channel confluences. J. Cold Reg. Eng. 15 (1), 34–58.

Jha, A.K.; Bloch, R.; Lamond, J. Cities and Flooding, A Guide to Integrated Urban Flood Risk Management for the 21st Century; The World Bank: Washington, DC, USA, 2012; ISBN 978-0-8213-8866-2.

Kolerski, T., Shen, H.T., 2015. Possible effects of the 1984 St. Clair River ice jam on bed changes. Can. J. Civ. Eng. 42 (9), 696–703.

Lindenschmidt, K. E., & Das, A. 2015. A geospatial model to determine patterns of ice cover breakup along the Slave River. *Canadian Journal of Civil Engineering*, *42*(9), 675-685.

McDonald, R., White, K. D., Daly, S., & Massie, D. D. 2002. Implementation of an ice jam predictor with user interface. In Proceedings of the 16th. IAHR International Symposium on Ice, Dunedin, New Zealand (Vol. 1, pp. 220-227).

Munck, S. D., Gauthier, Y., Bernier, M., Chokmani, K., & Légaré, S. 2017. River predisposition to ice jams: a simplified geospatial model. Natural Hazards and Earth System Sciences, 17(7), 1033-1045.

Nafziger, J., She, Y., & Hicks, F. 2019. Dynamic river ice processes in a river delta network. Cold Regions Science and Technology, 158, 275-287.

Turcotte, B., Morse, B., & Pelchat, G. 2020. Impact of Climate Change on the Frequency of Dynamic Breakup Events and on the Risk of Ice-Jam Floods in Québec, Canada. Water, 12(10), 2891.