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Steep channels freezeup processes

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In addition to generating significant anchor ice, steep channels exposed to cold air temperatures actually develop an ice cover during the winter season. The dynamic ice production at freezeup creates unique ice features that significantly differ from the most documented floating ice covers associated to large low-gradient channels. The cover is often held in a suspended state and the water temperature is often above freezing even during the coldest months of winter. This work describes the freezeup process of steep channels, from small creeks to large rivers, and presents various ice forms and features that can develop under a wide range of atmospheric conditions.

1. Introduction

River ice literature mostly includes information regarding floating ice covers development along low-gradient, wide river channels. The freezeup patterns of high-gradient channels have received less attention over the past decades. The formation and release of anchor ice has been described (e.g., Ashton, 1986; Kempema, 1993) and different shapes of anchor ice accumulations have been studied (Kerr et al., 2002). However, a limited number of publications have contributed to answer this question: How can a steep channel be ice covered? “Dynamic ice production” principles have been pointed out by Norwegian scientists (Tesaker, 1994; 1996; Stickler et al., 2010) who explained how steep channels form anchor ice weirs (AIW) or ice dams (ID), which can eventually contribute to the development of a surface ice cover. More recently, Turcotte and Morse (2011) proposed that surface ice covers along steep channels are most often only partial, and are necessarily suspended above the water surface as a consequence of anchor ice melt and hydraulic storage release during the cold period. Such ice covers therefore behave differently from the most commonly studied floating ice covers.

A number of field observations and measurements were performed during winter 2010-2011 to verify the hypotheses presented by Turcotte and Morse (2011) and to push our understanding of steep channel freezeup processes to a further extent. The authors believe that steep channel freezeup processes can now be better explained along channels presenting distinct geometries and affected by different meteorological conditions. This work presents steep channels freezeup processes and ice features that have not been reported before.

2. Study reaches and instruments

The study sites are located in the Montmorency River watershed, a gravel bed river draining a hilly, forested basin located in the Canadian Shield, meeting with the St. Lawrence River at Quebec City, Qc, Canada (Fig .1).

Three channels (Table 1) were monitored throughout the 2010-2011 winter. The (Lepine) Creek study reach is located more than 1 km downstream of any tributaries that might influence ice processes. This channel mixes its water with the (De l’Ile) Stream, a flat gravel bed channel presenting numerous protruding rocks and a lack in regular control sections such as steps. The study reach of the Stream extends over 3 km. Most research efforts on the (Montmorency) River were directed to (1) the confluence reach with the Stream where the River separates into three flat-bed channels (length of 0.5 km), and (2) to a reach located immediately downstream of the confluence (length of 1.25 km), which consists of almost continuous rapids (flat-bed).

Tree-mounted cameras were installed along the research reaches taking photos every hour (only day-time photos could be used [7:00 to 17:00]) and three pairs of aquatic sensors recorded the water temperature of each channel (refer to Fig. 1 for instrument location). The freezeup progress and ice features were documented throughout regular field trips and with a portable camera.

3. Freezeup processes and ice features in steep channels

This section reports ice processes specifically occurring along the monitored reaches during the freezeup period of 2010-2011. The broad variety of weather conditions and the diversity of monitored channel sizes and morphologies allow a possible transposition of the reported processes to comparable cold region watersheds.

3.1 *Creek*

Both snow falls and cold spells affected the Creek at freezeup (Fig. 2). Low-intensity snowfall events were seen to generate a very limited amount of floating snow slush accumulations and to generate some anchor snow slush at the channel bed (Turcotte et al., 2011, submitted). As a result, their effect on the initial development of an ice cover appeared insignificant. On such steep, fast flowing channels, even intense snowfall events only result in the development of a limited amount of surface ice. This is due to the channel capacity to evacuate snow slush, which appears greater than the capacity of intense snow precipitation to clog it. As a result, the initial development of an ice cover along step-pool creeks mostly depends on cold air temperatures.

A first cold spell from December 8 to 10 (Fig .2) led to the development of ID. Anchor ice was seen to grow in pools while solid ice was covering steps (Fig 3a). Late on December 10, the ID backwater reached a maximum of 0.3 m locally (Fig 3b). On December 13, a rain-on-snow event (40 to 50 mm based on three Environment Canada weather stations) destroyed most of the Creek's ice features. The ice resisted the runoff event during at least 12 hours and it is not until the ice was completely submerged for several hours under fast flowing water (Fig 3c) that it was washed out (Fig. 3d). The characteristics of the ice contained in the Creek channel (three-dimensional ice matrix occupying a significant portion of the channel cross-section) and the channel geometry itself (narrow and incised) can explain such behavior. Therefore, newly formed ID in steep incised channels can resist a significant amount of hydraulic forces. This behavior is strikingly different from that of a floating ice cover as described for wide, low-gradient channels (e.g., Beltaos, 2008).

3.1.1 Initial freezeup processes

From December 15 to 17, the air temperature at the Creek was below -12 ^{o}C (Fig. 2) and a new freezeup cycle began. The ID buildup processes lasted for 60 consecutive hours. Figure 4 presents a scheme of the initial Creek freezeup process. The following paragraphs present a number of statements about this process.

AIW soon form along the channel at hydraulic control sections (i.e., steps; Fig. 4b) under air temperatures below -10 ^{o}C, which represents a gross threshold for water supercooling and anchor ice development (Beltaos et al., 1993; Hirayama et al., 1997; Parkinson, 1984; Terada et al.,1998). This process elevates the water level and reduces the water velocity (Tesaker, 1994; Turcotte and Morse, 2011). AIW are initially mostly made of porous, submerged anchor ice (immediately upstream of control sections) but also include emerging solid ice (shallow rocks at control sections). As anchor ice accumulations buildup and reach the water surface, icing (i.e., the freezing of thin layers of water on top of each other [Carey; 1973]) becomes the dominant ice development process and AIW become ID. As ID grow in size, the channel blockage and backwater level increase, further flooding the dams with shallow water layers that freeze.

While ID grow upward and downstream, border ice forms along slow flowing water areas. This border ice thickens by progressive flooding at the same rate as ID (Fig. 4c). With time (and significant heat lost) border icing extends towards the middle of the channel and fuses with ID and emerging anchor ice masses. As a result, the water remains flowing in an inverse trapezoidal channel clogged with anchor ice accumulations. The water flows on an anchor ice bed between fairly vertical icing banks (Fig. 5). This can be defined as the *ice canal* freezeup stage.

Initially, the growth rate of ID only depends on atmospheric parameters and on the shape of its crest. This rate reaches its maximum in the early morning, which often corresponds to the coldest air temperatures, and is reduced in the afternoon. In December 2010, average-size ID in the Creek reached a vertical buildup rate of 2 cm/h under an air temperature of -18 ^{o}C. However, the largest ID, which were not in a fixed camera range, can probably develop at a rate of 5 cm/h.

Most ID were longer (in the streamwise direction) than higher by a factor of two or more. Also, three ID higher than 1 m (Fig. 6) formed in a 120 m-long Creek reach while the average dam was 0.6 m-high. The shape and size of ID are believed to mainly depend on the channel slope and air temperatures: the higher the slope and lower the air temperature, the higher and shorter the ID.

The buildup cycle of ID can be stopped by three means:

- Dam breaking due to increased hydraulic head: Although this was not observed along the Creek in 2010-2011, this phenomenon has been reported by Tesaker (1994, 1996) and is believed to potentially lead to ID breakup from upstream to downstream with the surprisingly potential of producing flash floods at low air temperatures.
- Bankfull water level reached: Once the channel is completely filled with ice and water, the Creek starts flowing out of the channel. This results in reducing or simply stopping the ID buildup. On December 20, a 1.5 m-high ID was seen to flood the snow-covered forest next to the Creek. In addition to flash floods, ID can therefore produce floodplain icing, road icing, and can compromise winter access to properties.
- Reversed heat transfer budget: Under warming air temperatures, icing dams go from an *active* buildup state to a transitional *passive* state during which the backwater level does not show any variation (often observed during the last hours of daylight). This seems to correspond to a water supercooling interruption and to an equilibrium heat budget. In instances where the air temperature soon cools down (at sunset for example) most ID are reactivated. Otherwise, under a positive heat budget, ID can be *breached* (from the top down) or *perforated* (partial ice melt under the dam), which results in hydraulic storage release. This water released can last anywhere from many minutes to many hours. An air temperature above 0^{o}C necessarily means a positive heat budget and a release of hydraulic storage at the reach scale. However, a reach scale release can occur at temperatures well below 0 ^{o}C. This occurs when a partial ice cover develops over slow-flowing pools (Fig. 4d), which supports the heat transfer budget inversion. In turn the positive heat budget leads to dams breaching or perforating. Because the water level drops afterward, the partial surface ice cover and border ice is left suspended. If the cover does not support his own weight, or if a snowfall increases the constraints within the cover, ice slabs break and collapse into the water (Fig. 4e). This leads to the development of insulating air chambers above the water surface (Turcotte and Morse, 2011).

It was observed that the matrix of perforated ID is formed of multiple tunnels and galleries surrounded by different ice structures including petrified anchor ice balls (Fig. 7) and transparent ice layers. These voids carry the water from upstream to downstream through the active ID core. Breached or perforated ID can be reactivated by two processes: thermal or mechanical. Both processes can only occur if the channel remains fairly open and exposed to atmospheric conditions. The thermal process is associated to cold air temperatures leading to supercooling and to anchor ice production. The mechanical process is related to snow slush flocs (from a snowfall event) or to drifting ice pieces (from upstream cover or dam breaking) patching up the galleries within the perforated ID core. This second process was not observed in 2010-2011 but is probable because snow slush has been reported to accumulate on the substrate of the Creek bed (Turcotte et al., 2011, submitted) and because drifting ice pieces are known to create or promote ice jamming (Beltaos, 1995).

3.1.2 Secondary freezeup processes

Once all dams are breached or perforated, the Creek enters a secondary freezeup phase. It takes time for a lower-level ice cover to develop above open fast flowing water zones that are not insulated by suspended ice slabs. This ice cover progressively develops by splashing or spray ice and by turbulent bursts (or waves) progressively flooding the low-level ice cover. This ice cover does not float at the water surface; it is rigidly attached to other ice features or emerging rocks and it is only sporadically in contact with the turbulent water flowing underneath. Therefore, this lower-level ice cover is better described by the terminology *ice shell*.

Considering the heat produced by the steep Creek channel, Turcotte and Morse (2011) proposed that the combination of a partial suspended ice cover and ice shells cannot cover the entire Creek channel. This hypothesis was respected throughout the winter of 2010-2011. Once the Creek ice coverage reached its maximum in January 2011, the water temperature was consistently above 0 ^{o}C for air temperatures above -15 ^{o}C. The air temperature was -28 ^{o}C on the morning of January 24. In a partially open air chamber made of collapsed suspended ice slabs, the air temperature was only -2.8 ^{o}C. The water temperature even reached 1.3 ^{o}C on February 8 while the air temperature had been below -7 ^{o}C for more than 24 hours. This confirms that the combination of a partial suspended ice cover and a partial lower lever ice shell efficiently insulates the Creek throughout winter and that no ice is in contact with the flowing water.

3.2 Stream

The Stream freezeup dynamics described in Turcotte and Morse (2011) included a number of hypotheses which were yet to be confirmed. This section complements this work and compares the Stream freezeup process with that of the Creek.

The weather conditions presented in Figure 2 also affected the monitored Stream reach in 2010-2011. Snowfall events did not affect the development of an ice cover and even intense snow precipitation falling in an ice-free Stream channel has been seen to be carried downstream as floating slush with only minor effects on hydraulic conditions. A very limited amount of frozen border snow slush remained afterward. As for the Creek, the Stream requires cold air to freeze.

The cold spell of December 8 to 10 did result in the development of 0.1 m-high AIW every 20 to 50 m along flat bed sections. These weirs extended almost over the entire Stream width, connecting protruding boulders transversally and diagonally. Additionally to AIW, ID also developed at hydraulic control sections reaching a maximum height of 0.3 m. Before the rain event of December 13, the channel was partially roofed by snow-covered suspended *ice islands*. In the Stream, ice features do not form a rigid matrix that can resist significant hydraulic forces. Also, at a number of locations, no ice forms along the banks. These factors facilitated ice mobilization and breakup as it occurred on the morning of December 13.

3.2.1 Initial freezeup processes

From December 15 to 20, a new freezeup cycle started. While ID along step-pool channels form at the same cross-section from one freezeup cycle to another, AIW along flat-bed reaches develop at comparable locations but their alignment varies (i.e. emerging rocks included in the weir alignment change). This supports the possibility that the development of AIW along flat-bed reaches presents a random variable. Actually, ice weirs form by both anchor ice growth (depends on local hydraulic conditions) and when released ice floes settle in their alignment (modifying local hydraulic conditions). The resulting ice-forced step-pool pattern of the Stream compares with the ice-promoted step-pool morphology of the Creek except that one cannot predict where ice steps will form in the flat bed Stream.

At many sites along the Stream, a limited amount of anchor ice and icing forms along the banks (Fig. 8). This is explained by two reasons. First, warm groundwater springs exist along the banks. Second, the Creek channel (and other effluents) can be partly insulated by the time AIW develop in the Stream. As a result, water flowing from effluents into the Stream channel is not supercooled and can even be slightly warmer than 0 ^{o}C. Downstream of groundwater springs and effluents, water continues to flow freely along the banks over hundreds of meters. This greatly reduces the potential height of AIW developing in the middle of the channel. Also, the Stream gradient being lesser than the Creek gradient, average water velocities (and turbulence intensity) are reduced to a point where surface ice develop forming islands at emerging boulders or emerging anchor ice accumulations while AIW and ID are still small. This ice cover partly insulates the Stream water and promotes ID breaching or perforating.

Based on observations made in 2009-2010, Turcotte and Morse (2011) proposed that the height and areal coverage of a suspended ice cover could depend on average air temperatures and duration of the cold spell. In January 2010, under open water conditions, a 9-day cold spell (average air temperatures of -17 ^{o}C) led to the development of a partial ice cover extending over 60% of the channel and suspended on average at 0.5 m above the winter water level. In December 2010 (following winter), a 6-day cold spell (average air temperatures of -13 ^{o}C) led to the development of a partial ice cover extending over 30% of the channel and suspended on average at 0.3 m above the flowing water. These results support the initial hypothesis and therefore propose that colder and longer freezeup cold spells (1) contribute to increase the ratio of suspended ice coverage and (2) create higher AIW and ID along steep, flat bed channels.

After the 2010-2011 initial freezeup cycle in the Stream, the suspended ice coverage (30%) was low enough to allow significant heat transfers between the water and the atmosphere. A lower ice shell was seen to form in cold mornings but cold spells mostly led to ice weirs redevelopment (in this case, most AIW had completely melted and one cannot consider this to be a *reactivation* but a *reformation)*. This occurred on December 26 (average air temperature of -12 ^{o}C) and a new suspended ice cover progressively developed at the same level as before, covering 60% of the channel by December 29. A mild rain-on-snow event subsequently reduced this coverage down to 50%. Ice weirs reformed in the mornings of January 5 (minimum air temperature of -15 ^{o}C), 6 (-14 ^{o}C), and 7 (-14 ^{o}C). The water level increased and reached the suspended cover surface each time. This allowed the suspended coverage to increase back to 60%. This further supports the possibility that comparable air temperatures during the initial freezeup stage lead to the development of AIW of similar height. The year before (January 2010), a suspended cover also extended over 60% of the channel before a lower ice cover started to develop. Therefore, it is proposed that, under average freezeup air temperatures, when the Stream's suspended ice cover extends over 60% of the channel, a heat balance is achieved and water supercooling stops.

3.2.2 Secondary freezeup processes

In the following weeks, anchor ice was not seen to form anywhere in the channel and a lower level ice shell progressively developed. The Stream ice coverage reached a maximum of 98% (60% during the initial freezeup stage and 38% during the second, lower level, freezeup stage) on January 26. At the end of January the water temperature in the Stream reached a 0.15 ^{o}C plateau that lasted 4 days while air temperatures varied from -4 ^{o}C to -23 ^{o}C. Although this channel produces less headloss heat than the Creek, this data nonetheless confirms that a partial ice cover (total average of 90% during the period) in a flat bed channel also insulates the water from cold atmospheric conditions.

3.3 River

The River freezeup occurred later than the Creek and Stream freezeup, most ice coverage progress occurring in mid-January. This period corresponds to dry weeks including the coldest days of winter (Fig. 2). The most relevant freezeup stages are described in the following paragraphs and Figure 9 presents a scheme of the freezeup chronology.

Border ice started forming along the 1.75 km River reach after the rain-on-snow event of December 13, on the decreasing limb of the River hydrograph. However, the water temperature remained above 0 ^{o}C until January 14. This unusually high water temperature for an open channel exposed to sub-zero air temperatures is due to three factors. First, most contributing channels were insulated by a suspended ice cover since mid-December and were therefore releasing relatively warm water in the River. Second, the higher-than-average groundwater level associated with important pre-freezeup rainfalls supplied the River channel with water which temperature can be as high as 4 ^{o}C. Finally, the average air temperature was only -7 ^{o}C during 25 days. As a result, the ice coverage progress was slow and only consisted of thick accumulations of spray ice and icing along the banks and around protruding boulders (spray ice squirts or rim ice; Fig. 9b). By January 14, the River channel was only 30% ice-covered.

Once the water temperature drops to 0 ^{o}C while a large portion of a steep channel is exposed to the coldest air temperatures in winter, only one scenario can occur: substantial anchor ice growth (Fig. 9c). The River then develops a series of AIW and ID that change the initially flat-bed morphology into an ice-forced step-pool channel. Also, as it was described earlier for the narrow Creek, as icing consistently thickens along the channel banks and as the backwater level progressively rises, an ice canal freezeup phase is soon achieved (Fig. 9d). However, in the case of the wide River, a surprising process can occur: A thin layer of water flooding the border ice accumulation freezes before it reaches the channel bank. Subsequently, each additional water layer freezes faster than the previous one, possibly as a result of decreasing air temperatures at sunset. In the morning of January 15, this process had formed 0.1 m-high pyramid shaped icing accumulations made of 0.5 to 1.0 cm-thick ice layers. Since these ice features control the water level and extended longitudinally along the channel, they were termed *icing dikes* (Fig. 10). Icing dikes can contribute to form an ice canal that protrudes from the average ice level (Fig. 9e).

During the next week the River freezeup process continued with alternating active and passive ID stages. The dynamic freezeup process culminated on January 24. A number of field trips led to multiple observations on which the following statements are based:

- ID can grow as high as 2 m in steep river reaches and extend over 60 m-wide channels (Note that Tesaker (1996) reported an instance where a 4 m-high ID formed in Norway). ID can also extend longitudinally (i.e., in the flow direction) over 50 m and form various steps and pools.
- Icing dikes can grow as high as ID and extend over hundreds of meters, controlling the flowing water and diverting its path. Border icing can also be as thick as icing dams.
- Snowfalls can result in additional ice thickening by flooding and freezing. Therefore snowfalls do not affect the process if cold air temperatures remain.
- ID can suddenly divert most of the water out of icing canals resulting in massive heat loss (and fog). This can create large icing fields extending over hundreds of square meters. It can also lead to the development of a complex network of secondary ice canals. Finally, it can generate wide icing galleries into which water remains flowing for many days before finding (or melting) a path down to the channel bed.
- Wide rivers can also flow at bankfull level because of dynamic ice processes. The icing buildup of the River in 2011 achieved a level corresponding to an open water discharge of 400 m^3/s while the actual discharge was only 8 m^3/s. Since icing canals can be made of one icing dike and one channel bank, it is possible that one channel bank is overflooded while the ice level on the other side of the channel does not approach the upper bank level.
- Anchor ice can develop into one-meter-thick blankets extending over large areas, laterally surrounded by border icing and icing dikes and longitudinally intercepted by ID. This thick anchor ice does not necessarily release during day time, even when exposed to sunshine and air temperatures of -5 ^oC.
- As for the Creek and Stream, the massive amount of heat loss in wide, steep channels eventually leads to the development of a partial surface ice cover extending over ice-made slow-flowing pools. However, once the ice cover has formed, the transition between passive to perforated ID can last for many days. For instance, three days with an average temperature of -8 ^oC did not result in significant water level drop (i.e., no ID melting). This means that the passive ID stage does not always represent a precarious heat exchange equilibrium.

On January 26, ID were still building up in the River channel upstream of the Stream confluence while secondary freezeup processes (spray ice and ice shell development) were already taking place downstream. This early ID breaching was caused by the relatively warm water flowing from the Stream. On February 11, all ID in the River had been perforated and the water was flowing back along the channel bed leaving a complex ice topology made of emerging anchor ice surmounted by an air layer and a thin suspended ice cover (Fig. 9f). The total suspended ice coverage reached 70% and the ice surface was 1 to 2 m higher than the water level.

Insulating snowfalls affect the ice dynamics in two ways: they increase the weight on suspended ice sections and further insulate the channel. This results in a progressive melt and collapse of suspended ice slabs as winter progresses. However, ID and border icing break and melt at a much slower rate. This is due to (1) the ice being supported by protruding rocks and not being in contact with the water, and (2) to the significant thickness of these ice features compared to the thin suspended ice slabs.

4. Discussion

The freezeup dynamics of three steep channels have been explained and unique ice features have been described. The development of ice canals and icing dikes along flat bed reaches has been reported. Active, passive and breached or perforated ID represent the three initial stages of steep channels freezeup and occur during cold spells. This, however, only results in the development of a partial, suspended ice cover. Afterward, a second freezeup process begins, which consists in the development of a lower level ice shell in open water zones. This shell forms progressively under subzero air temperatures by splashing or by turbulent waves flooding and freezing. A water temperature above 0 ^{o}C does not stop the lower ice cover development because this ice cover is only sporadically in contact with the flowing water. The total ice coverage of a steep channel does not reach 100%, even under the coldest air temperatures, because the ground water and headloss heat need to be released at a rate that cannot be sustained by a complete ice cover.

The colder the air temperature and the longer the cold spell, the greater is the amount of ice produced. The greater the amount of ice produced, the greater the channel area is occupied by a suspended ice cover, and the higher this ice cover is suspended above the channel bed. One could be tempted to suggest that under very cold air temperatures, an ice cover soon forms along slow flowing channel sections, therefore limiting ID buildup (and ice cover elevation) by insulating the flow. However, under cold atmospheric conditions, it was seen that ID develop faster than a surface ice cover. The result is that an open lead surrounded by thick border ice often remains open (Fig. 4c; Fig. 9d), even under decreasing air temperatures. This is the ice canal, an intriguing cryologic state and heat balance equilibrium unique to steep channels. As long as the ice canal remains ice cover-free and full of water (Fig. 5), ID can buildup and floodplain icing and inundation can occur.

Considering the complexity of the ice processes described in this work, it appears difficult to associate given ice features or ID heights to (1) a minimum water velocity, (2) a Froude number or (3) a Reynolds number range, (4) a maximum air temperature, or (5) a maximum channel gradient. While the development of anchor ice has tentatively been associated to such thresholds (Bisaillon and Bergeron, 2009; Hirayama et al., 1997; Kerr et al., 2002; Parkinson, 1984; Stickler and Alfredsen, 2009; Terada et al., 1998; Tesaker, 1994; Yamazaki et al., 1996), this only applies to the very initial steep channel freezeup phase. The global freezeup process in steep channels depends on additional parameters such as the amount of heat produced by headloss (channel gradient and water discharge) and the ground water contribution to the heat balance. The constantly evolving ice features in steep channels at freezeup continually modify the hydraulic and heat exchange conditions. As a result, more research needs to be done on the topic before the steep channel freezeup dynamics can be expressed into an equation form.

In mid-winter, once steep channels are snow-covered, thick ID and border icing cannot be easily differentiated from fragile suspended ice sections. Animals such as deers identify and use the safest ice features for travelling along and across steep channels throughout winter. Since, humans do not have the same skills and instinct, it is not recommended to travel on foot in steep channels during the winter period. Breaking through a suspended ice cover can cause injuries (shallow creeks and streams) and even lead to drowning (rivers). For the same reasons, snowmobile circulation should also be avoided.

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Table 1. Research channels.

	Creek	Stream	River
Watershed area	7 km^2	70 km^2	1100 km^2
Channel morphology	Step-pool / single channel	Rapids with protruding boulders	Rapids / multiple channels / confluence
Channel width	1.5 – 3.0 m	15 – 20 m	60 to 120 m
Average Slope	5%	1%	1%

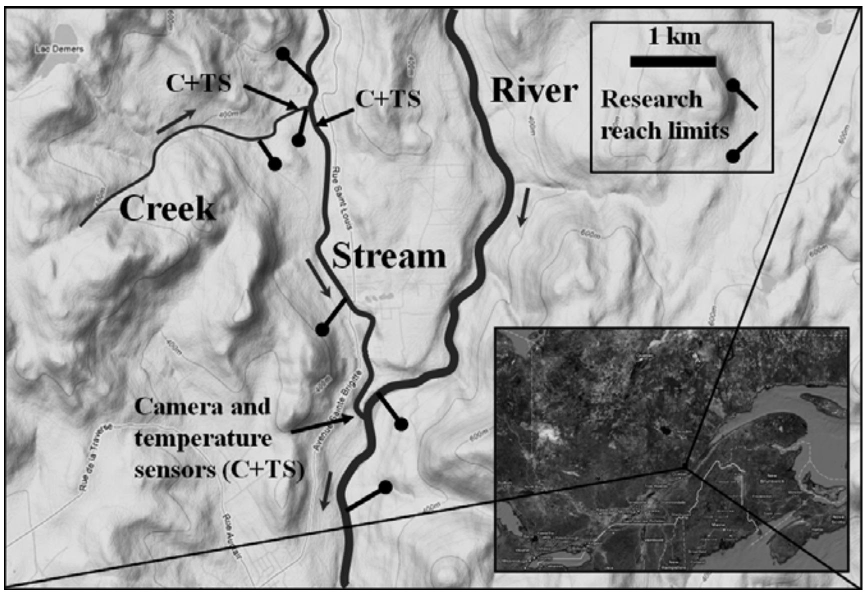

Figure 1. Research sites located in the Montmorency River basin, 30 km north of Quebec City, QC, Canada.

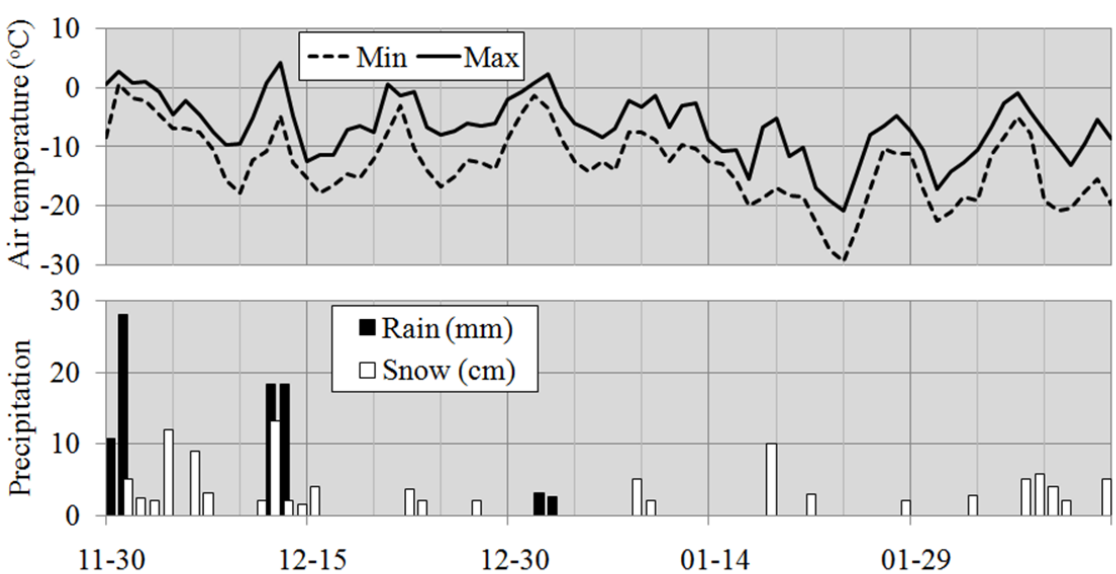

Figure 2. Maximum and minimum daily air temperatures, and snowfall (cm) and rainfall (mm) events in the research area from November 30, 2010, to February 13, 2011.

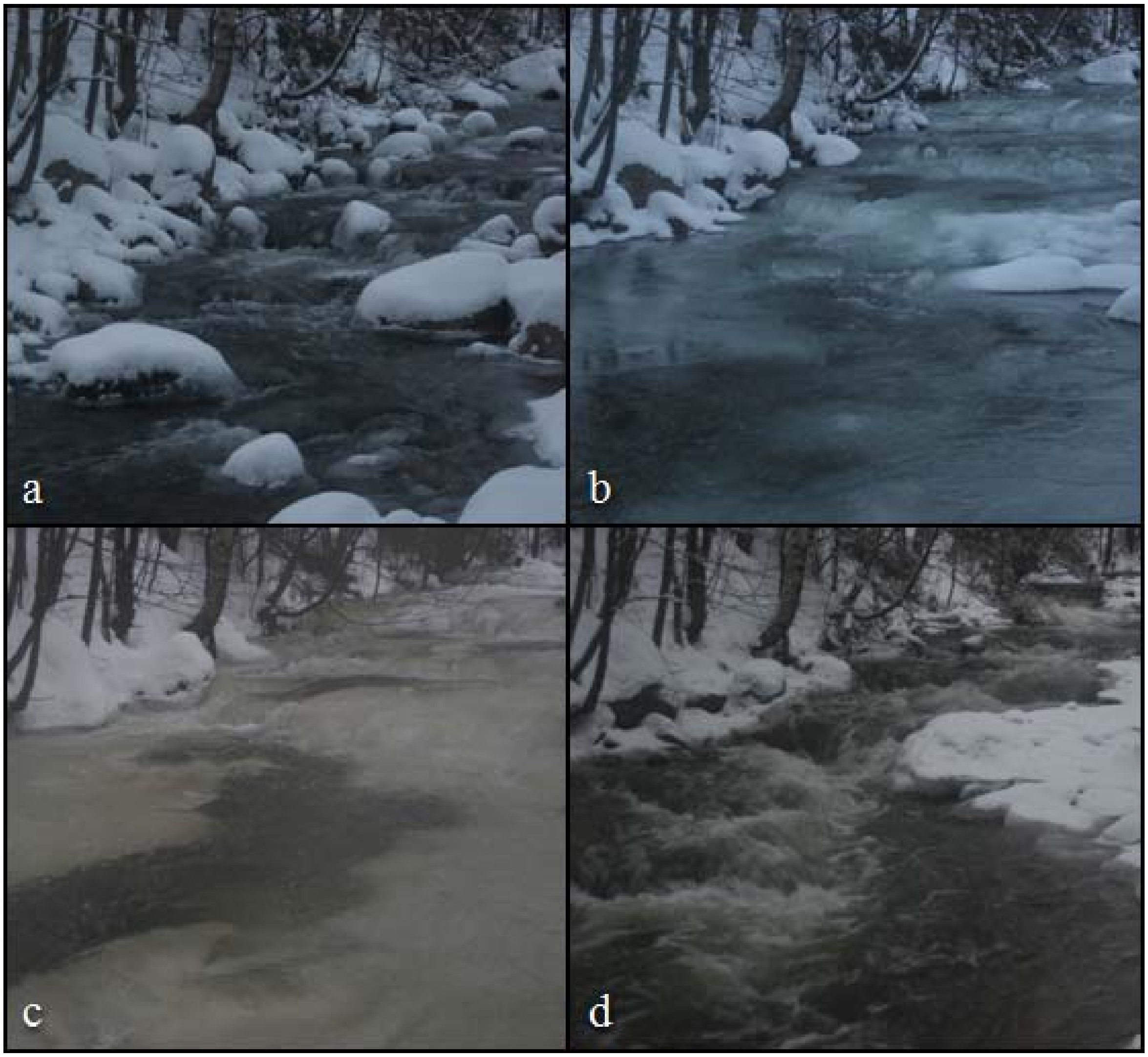

Figure 3. Freezeup and mechanical breakup in the Lepine Creek (looking upstream) (a) Spray ice forming on emerging rocks and anchor ice forming in pools on December 8; (b) Maximum ID level achieved on December 10; (c) Ice cover flooded after a rain event on December 13; (d) Almost ice-free channel on December 14.

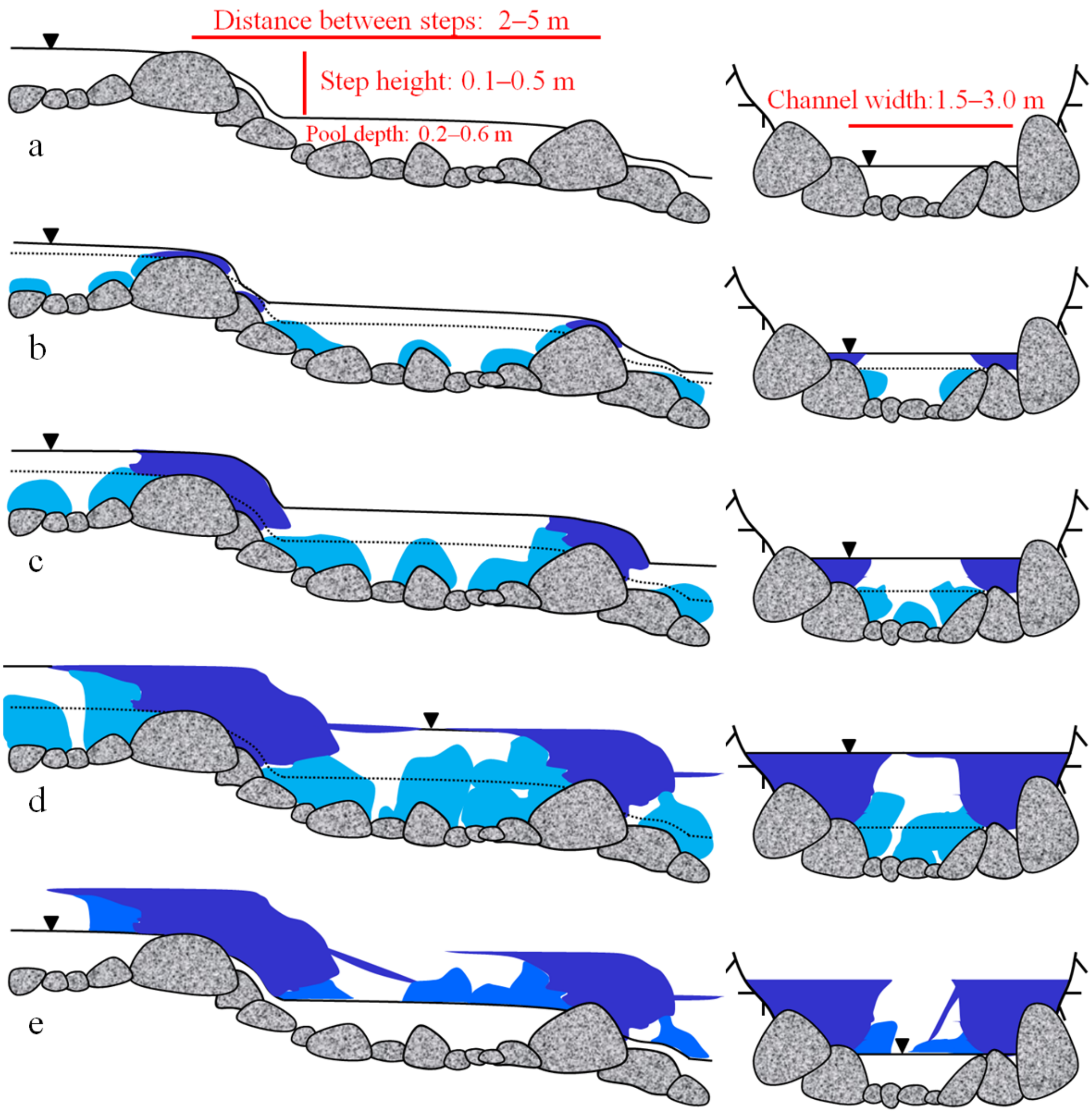

Figure 4. Scheme of the initial freezeup phases in a step-pool creek. The dark blue represents low porosity icing and the light blue represents porous anchor ice. The side view of the channel is on the left and cross-sections on the right. (a) Initial conditions; (b) Anchor ice forming in pools and icing forming on steps (dashed line is the water level reference from initial conditions); (c) ID building up and icing thickening along the banks (ice canal); (d) Maximum ID height and surface ice cover developing; (e) perforated ID, emerged anchor ice accumulations (lower porosity), partial collapse of suspended ice cover sections, and water level back to initial conditions.

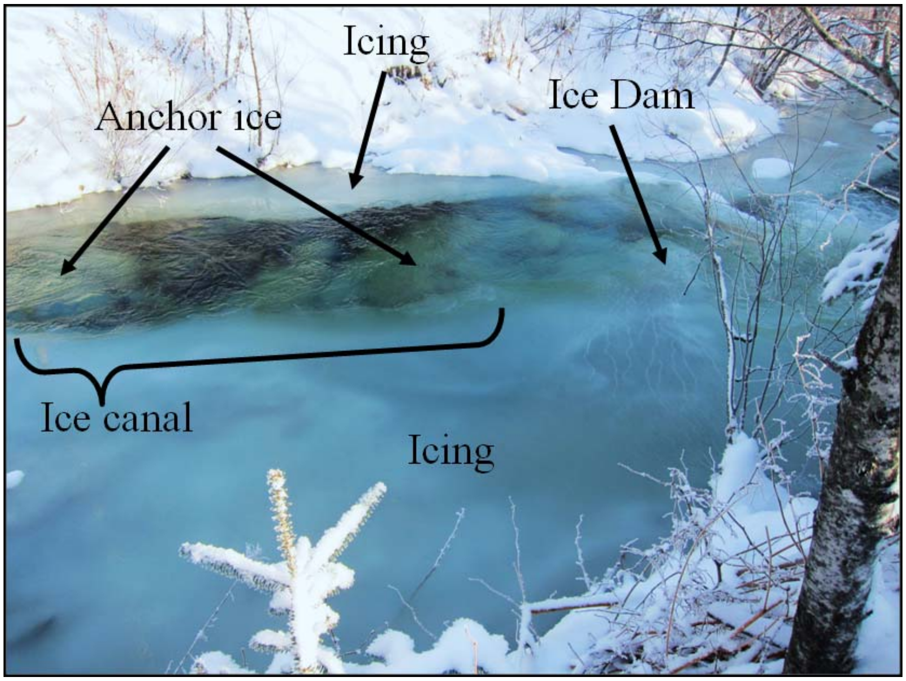

Figure 5. Ice canal in the Creek on December 16, 2010 (flow is from left to right; channel width is 4 m ; water depth is roughly 0.8 m in the ice canal).

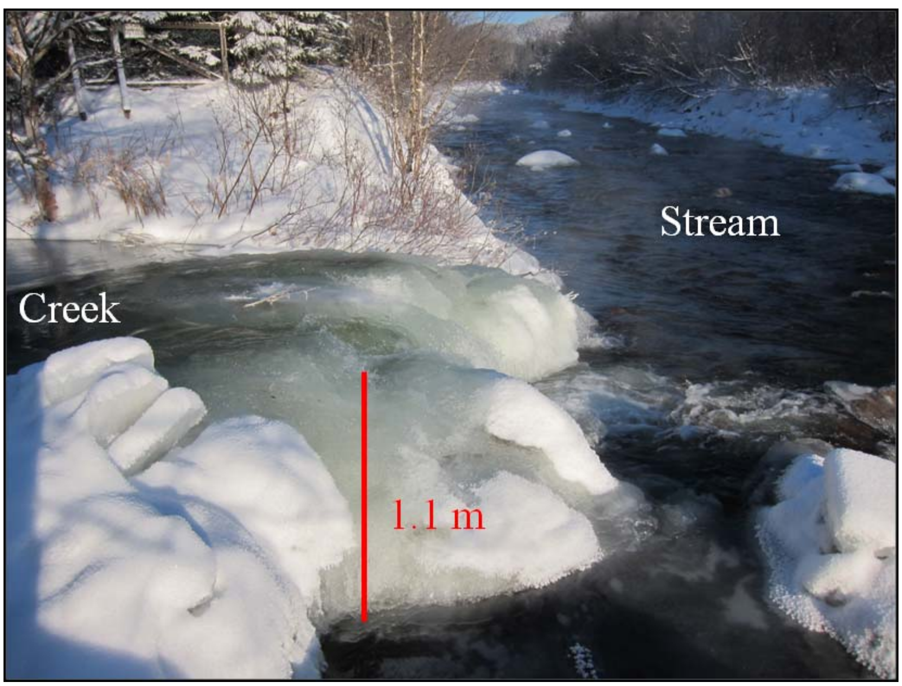

Figure 6. ID at the exit of the Creek (Stream flowing toward the camera) on December 16, 2010.

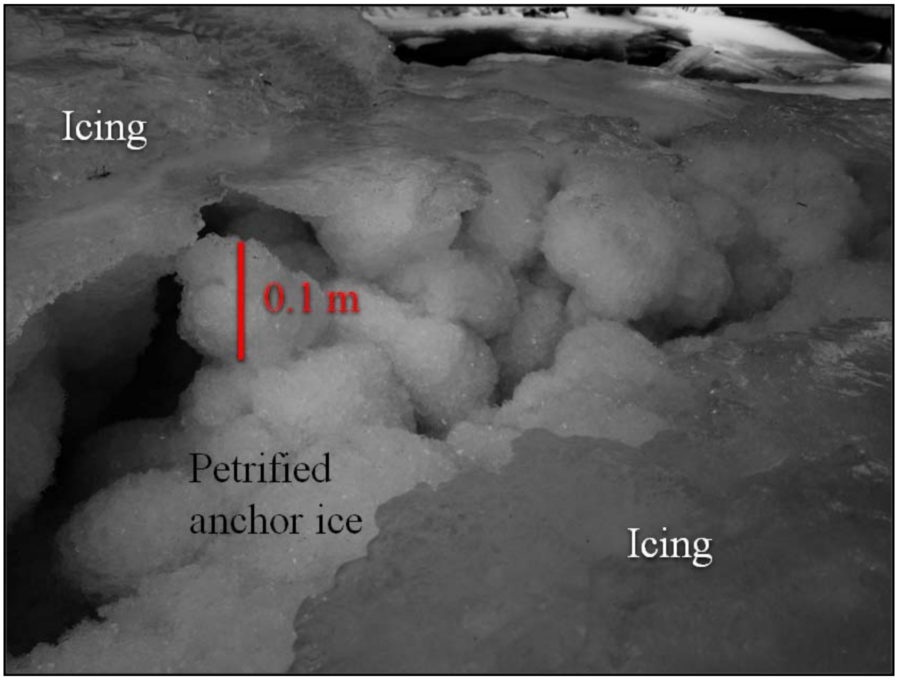

Figure 7. Photo taken at the upstream face of a perforated ID in the Creek on December 20, 2010. One can appreciate the petrified anchor ice balls and the water-free galleries within the dam.

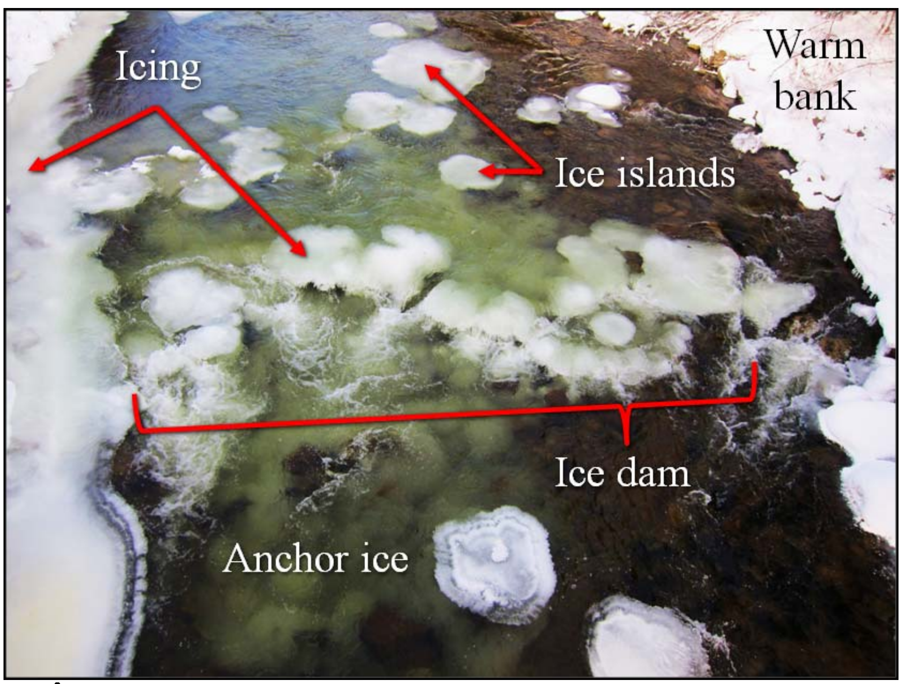

Figure 8. De l'Île Stream (channel is 20 m-wide) looking upstream from a bridge on December 20, 2010. There are warm water springs along the left bank (right of the photo) while the active ID extends from the right bank (left of the photo).

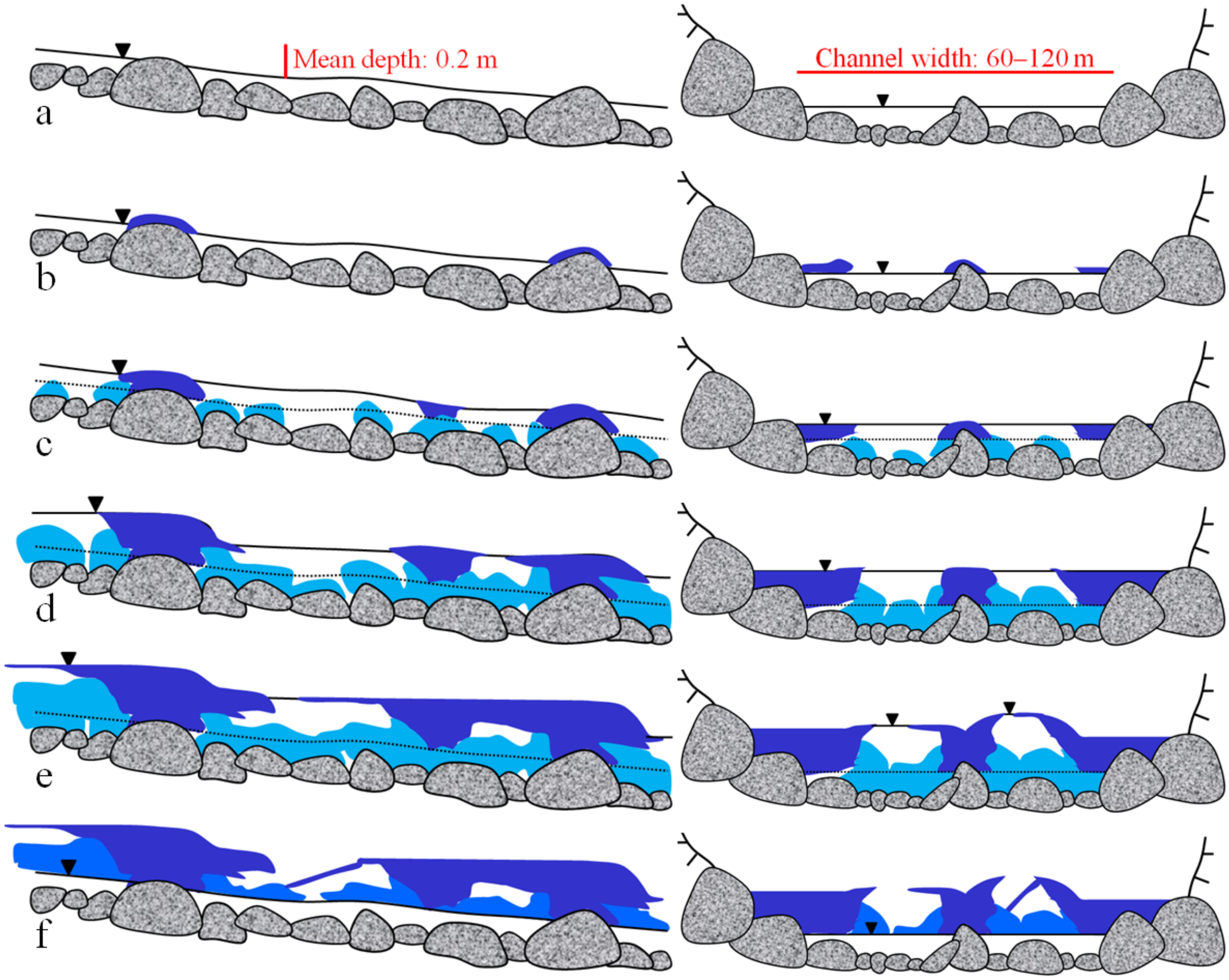

Figure 9. Scheme of the initial freezeup phase in a flat bed river. The dark blue represents low porosity icing and the light blue represents porous anchor ice. The side view of the channel is on the left and cross-sections on the right. (a) Initial conditions; (b) Spray ice development while the water temperature is still above 0 ^{o}C; (c) Icing and anchor ice growth (dashed line is the water level reference from initial conditions); (d) ID forming, side icing thickening, and ice canal developing; (e) Maximum ID level achieved and icing dikes formed; (f) ID perforated, emerged anchor ice accumulations (lower porosity), partial collapse of suspended ice cover sections, and water level back to initial conditions.

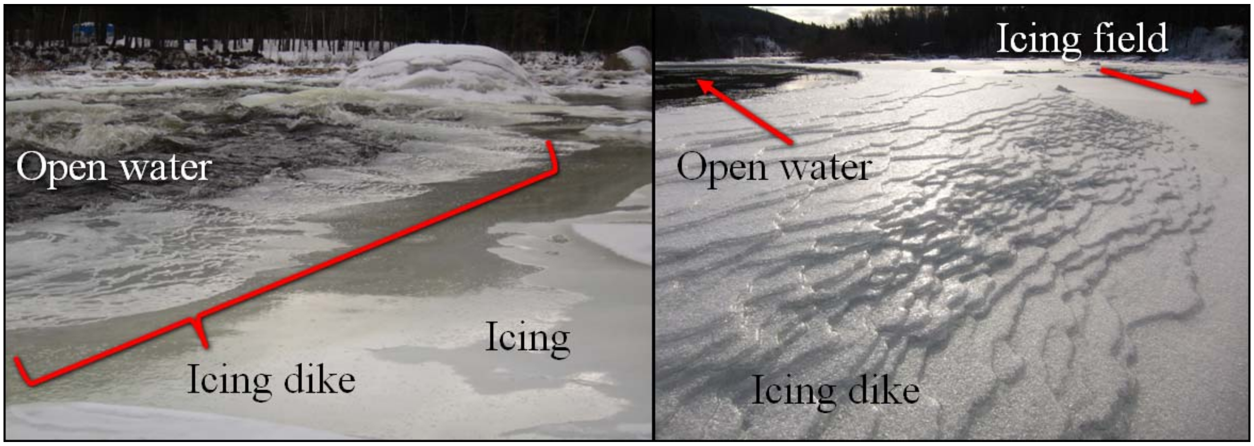

Figure 10. Left: 0.1 m-high icing dike along the Montmorency River (looking downstream) on January 15, 2011. Right: 0.3 m-high icing dike at the head of an ice canal on January 28, 2011.