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Freeze-up, breakup, and winter ice observations on four small regulated and unregulated streams in Newfoundland, Canada

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Although winter ice processes are well documented in large, low-gradient rivers, only a few studies on smaller, steeper streams have been published, and none compare regulated environments to unregulated ones. This paper documents the ice conditions observed on two regulated and two unregulated, wadeable streams in south-central Newfoundland from October 2010 to May 2011. Ice conditions were observed using 16 remote camera stations at eight salmonid spawning sites along West Salmon River, Twillick Brook, Compensation Creek, and another unnamed creek. The West Salmon River and Compensation Creek are both regulated streams, while Twillick Brook and the unnamed creek were chosen as potential (unregulated) reference sites.

The thermal effects of regulation on water temperature and duration of ice cover were observed at some sites. However, no definitive conclusions could be drawn regarding the impacts of regulation on winter ice regime, as differences in stream morphology at comparison sites were potentially sufficient to explain the differences in observed ice processes. It is recommended that future studies of this type should include more detailed morphological characterization of the streams and employ a more reach-based study method.

1 Introduction

Winter conditions can have significant impacts on fish (Prowse, 2001) and streamflow regulation for hydropower production may serve to mitigate or amplify these effects through changes to the thermal regime and fluctuations in water levels. Although many river ice investigations have been carried out in large, regulated rivers, and under conditions of variable ice formation, few have been carried out in biologically complex small (wadeable) rivers and almost no data exist on the relevance of physical habitat characterization in winter in terms of implications for biota, even for salmonid fishes (Huusko et al., 2007). A few studies of ice processes on steep or small streams exist in the English literature (e.g. Tesaker, 1994; Stickler et al., 2010); the most recent detailed study is that of Turcotte and Morse (2011). These studies noted the importance of anchor ice "weir" and "dam" accumulations which can effectively change the stream geometry by forcing ice-induced step-pool morphology, controlling further ice cover development. Turcotte and Morse (2011) also described unique ice features such as ice "dresses" and documented the transient nature of these features with respect to varying water level and meteorological conditions.

The Natural Sciences and Engineering Research Council of Canada's HydroNet research network aims to investigate the effects of streamflow regulation on the productive capacity of small streams and includes a project component to explore the effects of winter stressors. The principal aim of this project component is to broadly characterize the winter regime of selected small streams so as to identify those environmental stressors that directly influence fish habitats and productive capacity and to distinguish how those stressors may vary in regulated versus unregulated systems. As part of those investigations freeze-up, breakup, and winter ice processes were monitored on four small streams (two regulated and two unregulated) in south-central Newfoundland over the winter of 2010/11 using automated time-lapse cameras. A key objective in this first field season was to assess the potential of proposed project sites in terms of their suitability for more long term study and, in particular, to assess the suitability of the natural streams as reasonable analogs to the pre-regulation characteristics of the regulated streams under study. This paper presents the preliminary results for this investigation.

2 Study Areas

This study focuses on two areas of south-central Newfoundland: the Upper Salmon area and the Granite Canal area (Figure 1). At each area one regulated and one natural flow stream were chosen to compare their ice regimes. In the Upper Salmon area, the West Salmon River (regulated) and Twillick Brook (unregulated natural flow) were studied. At Granite Canal, Compensation Creek (regulated) and an unnamed creek (unregulated natural flow) were studied. All streams support salmonid spawning activities and Atlantic salmon (*Salmo salar)* and brook trout (*Salvelinus fontinalis*) are the species of interest in this area. On each stream, two study sites were chosen where it was observed that Atlantic salmon spawning had occurred.

The study areas are remote, which affects site access and the amount of publically-available data for the area. There is no winter road access to the sites; therefore, all ice data was collected remotely by camera. Though only 50 km apart, there is no direct road connecting the two areas - a 6 hour drive was required to access one study area from the other. Also, there are no nearby

Water Survey of Canada streamflow gauges or Environment Canada (EC) meteorological stations. The nearest EC meteorological station is located at Badger, NL (~100 km from study areas), while the closest EC meteorological station with consistent snowfall data is Gander, NL (~125 to ~180 km from study areas). Based on the data from these stations, in 2010-2011 central Newfoundland experienced a relatively warm winter (seasonal maximum accumulated degree days of freezing below the 10 year average) and received an average amount of snow (Figures 2 and 3). In this study, accumulated degree days of freezing were calculated from the first instance of mean daily temperatures ≤ 0°C, as multi-day periods of freezing were not observed until after ice had begun to form on the streams. Likewise, accumulated degree days of thaw were calculated from the first mean daily temperature >0°C, as spring temperatures fluctuated frequently at Badger.

3 Methods and Equipment

Ice conditions were observed on each stream using automated time-lapse cameras. Sixteen cameras were installed in October 2010 and took a combined total of ~56,500 hourly photos of the study sites. Fifteen of these cameras were equipped with an infrared flash for night photography. These night time photos were not sufficiently well lit to fully characterize the ice cover; however, in many cases the presence or absence of ice, water level fluctuations and snowfall events could be detected.

This first year of the study provided the opportunity to field test different camera types and configurations. Three different camera models were tested (Moultrie Game Spy I-65, Reconyx HyperFire, and Reconyx PC85) with different battery types (alkaline and lithium). In addition, five of the eight Moultrie cameras were outfitted with small (12V) solar panels. Some difficulties were encountered with this equipment. One camera was improperly programmed, leaving only 15 cameras to provide ice data for the season. In addition, all of the Moultrie cameras stopped collecting images before the memory cards were full. Finally, cameras that were powered by alkaline batteries occasionally did not take photos when the air temperature was very cold (i.e. at temperatures below ~ -15°C).

In addition to ice observations, air and water temperature data were recorded. Each camera recorded air temperature and stamped the value onto each photograph. The accuracy of these measurements has not yet been fully confirmed, particularly with respect to wind and sun exposure. However, a preliminary comparison against EC air temperature data at Badger, NL in over a two-week period in December 2010 showed good correlation ($r^2 = 0.96$) and demonstrated the same heating and cooling trends over a range of air temperatures from 8 to -15 °C. Water temperatures were also measured on each stream in the Upper Salmon study area. These data were collected at one minute intervals with a Vemco Minilog II temperature probe placed at the surface of the bed material. Water temperatures 30 cm beneath the substrate and dissolved oxygen values were also monitored at the water temperature sites, but are not analyzed in this paper.

4 Ice Characterization

The ice cover at each site was characterized using the hourly photographs taken by two time-lapse cameras. Each hourly photo was analyzed and the proportion of ice cover was extracted on a daily basis. In general, the photograph taken at 2:00 pm was taken as representative of the entire day. However, if the ice conditions changed throughout the day, the maximum coverage of a newly formed ice condition was recorded as the ice condition on that day. For example, if 20% skim ice cover was present at 10:00 but had melted by 14:00, the ice condition for that day was recorded as 20% skim ice cover. Frazil ice may be underrepresented in the observations because floating pans and slush were often difficult to identify in the photographs, particularly when they were floating just below the water surface or were floating at the surface but had not yet formed a frozen surface crust. Table 1 presents a summary of the ice-affected dates of each site, including: first day with permanent ice; first day ice free; and the number of days the reach was at least 90% ice covered. For each site, a summary of the ice conditions in relation to the air temperature (measured at Badger, NL), the water temperature measured on site (where available), and the snowfall events observed with the ice observation cameras are presented along with ice photographs from the season. These data is found in Figures 6 to 23.

4.1 Upper Salmon Area

Two streams were studied in the Upper Salmon area. The West Salmon River (Figure 4) is the regulated stream in the study area. Flow to the stream is released from Cold Spring Pond via a control gate which releases a constant outflow of 2.6 m^3/s from 1-Jun to 30-Nov and 1.3 m^3/s from 1-Dec to 31-May (Scruton and LeDrew, 1997). The river's habitat has been classified as predominantly riffle, run, and flat with a cobble-boulder substrate (Hiscock et al., 2002). Twillick Brook (Figure 5) was chosen to serve as an unregulated comparison to the West Salmon River. It is a tributary of the Conne River, one of the most productive salmon rivers in Newfoundland (Beacham and Dempson, 1997). Ice conditions were observed at two sites on each stream (termed upstream and downstream) and water temperatures were measured at the upstream sites only.

The upstream study site on the West Salmon River was a wide (~30 to 60 m), shallow reach with many emergent boulders. As Figure 6 illustrates, freeze-up was initiated overnight on 17/18-Jan when mean daily air temperatures dropped to -7°C and water temperatures reached ~0°C. Anchor ice formed adjacent to emergent boulders and on the stream bed (Figure 7a) and was accompanied by a rise in water level. As the air temperature rose to -1.8°C on 20-Jan the water level dropped and the anchor ice diminished. Anchor ice formed again overnight on 23/24-Jan. After this date, most of the ice cover was obscured by snow. The ice cover slowly melted starting 20-Feb when the mean daily water temperature was above freezing at 0.16°C. On 27-Feb and 5-Mar the water level rose again, inundating the ice cover (Figure 7b). With the exception of skim ice forming adjacent to emergent boulders on cold nights, the site was intermittently clear of ice starting on 6-Apr and totally clear of ice from 17-Apr onwards.

Grassed bars were present in the channel at the West Salmon downstream site, which was wider (~60 to 75 m), shallower, and had fewer boulders than the upstream site. Ice conditions observed at this site are summarized in Figure 8 and were similar to those observed at the upstream site. However, skim ice and small amounts of anchor ice were observed downstream before they were observed upstream. Two anchor ice formation events occurred on 17/18-Jan and 23/24-Jan (Figure 9a), the same dates as those observed at the upstream site. After this time, the stream remained almost entirely ice-covered until ice melt began in early March. Broken pieces of ice were observed at the site on 15-Mar and 24-Mar (Figure 9b). These pieces moved through the site over the course of the day. The site was permanently ice free on 14-Apr.

The upstream study site on Twillick Brook was a 40 to 50 m wide, wadeable stream. The observed reach consisted of a pool and a riffle, with a small, frequently submerged grassed bar adjacent to the riffle. One camera at this site was the one that was improperly programmed (and thus did not take any ice photos), while the other was one of the Moultrie cameras that stopped before the memory card was full (and thus took photos only until 12-Mar), prior to breakup. Ice conditions observed at this site are summarized in Figure 10. Freeze-up processes were dominated by the growth of thermal/border ice from the stream margins and from the edges of the bar. This occurred first on 21-Nov when mean daily air temperatures dropped to -3.9°C, before melting and re-forming on 11-Dec (minimum daily air temperature: -9.1°C) and then re-melted. During each of these ice-forming events the measured water temperature dropped to ~0°C. Permanent ice first formed when both border ice growth and frazil slush were observed on 6-Jan. Ice first covered the entire reach on 2-Feb when a freeze-up front passed by the observation camera and mean daily air temperatures reached -15.3°C (Figure 11a). The water level rose in the stream, partially inundating the ice cover on 23 to 27-Jan, 1 to 3-Feb, and 27-Feb to 2-Mar (Figure 11b). Water temperatures remained at ~0°C from 17-Jan to 16-Mar.

The downstream study site on Twillick Brook was a 30 to 40 m wide, wadeable stream. The observed reach consisted of a pool and a riffle, with a few emergent boulders on the riffle and a very large bedrock remnant near the left bank. The bedrock banks at this site were high and steep. As Figure 12 illustrates, freeze-up processes were similar to those observed at the upstream site; however, anchor ice was observed in the fast portion of the riffle, while no anchor ice was observed at the upstream site. Similar to the upstream site, freeze-up processes began with thermal ice growth and frazil activity on two separate occasions: 21-Nov and 11-Dec (Figure 13a) before the ice retreated and completely melted. Permanent ice growth also began on 6-Jan and was dominated by thermal ice growth, some frazil activity and anchor ice on the riffle. This reach did not entirely freeze over, as an open lead was present all winter. Breakup began 25-Feb when the rapids upstream of the site appeared to open up and mean daily air temperatures reached -2.6°C. Broken ice moved into the reach and over the top of the intact ice at the study site. The permanent ice at the study reach began to breakup 8-Mar, while mean daily air temperature first reached above ~0°C the day before on 7-Mar. This culminated in a small ice jam (Figure 13b) which was most pronounced on 13-Mar and then slowly cleared downstream over the next several days. Following the clearing of the winter ice from the reach, border ice formed at the channel margins and floating frazil slush formed a floating cover over the small open central portion. Anchor ice was again observed at the riffle at this time. The channel was first completely ice free on 31-Mar and permanently ice free 6-Apr.

4.2 Granite Canal Area

Two streams were studied in the Granite Canal area. Compensation Creek is a man-made, regulated stream designed as habitat for both landlocked Atlantic salmon and brook trout (Figure 14). Flow into the creek is regulated by a control gate, which releases water stored in RR Pond to an arm of Meelpaeg Lake (Gabriel et al., 2009). The stream consists of a 1600 m long, low-gradient channel with two side channels and is dominated by riffle-pool morphology (Enders et al., 2007). An unnamed creek (Figure 15), located approximately 11 km north of the Granite Canal camp, was chosen to serve as a natural flow comparison stream to Compensation Creek

(Figure 15). This creek drains an area west of the Granite Canal Road through a series of ponds before running under a Bailey bridge. The stream then flows for another 500 m before emptying into an unnamed pond east of the road. Two sites were studied on each stream (herein termed upstream and downstream).

The upstream study reach on Compensation Creek was a ~15 m wide pool section at the apex of a bend. As Figure 16 illustrates, the freeze-up processes at this site were dominated by thermal border ice growth. The first ice growth occurred as skim ice at the channel margins on 21-Nov when mean daily air temperatures dropped to -3.1°C. This skim ice formed, melted and reformed repeatedly until 5-Jan, when the first permanent ice formed. This ice gradually advanced and retreated over the course of the season, with a maximum of 90% border ice coverage (Figure 17a) on 17/18-Feb when mean daily air temperatures dropped to -8.6°C. The ice slowly melted until the first ice-free day 13-Apr. There were two events on the mornings of 1-Jan and 2-Jan where the water level dropped so significantly that much of the channel bed was exposed (Figure 17b).

The downstream study reach on Compensation Creek (regulated) was a ~15 m wide reach at the downstream end of a bend with emergent boulders. As Figure 18 illustrates, the freeze-up processes at this site were similar to those at the upstream reach in that they were dominated by thermal ice growth. However, unlike the upstream reach, a complete ice cover formed here. The ice cover first began to form at the channel margins as well as at the boundaries of the emergent boulders 22-Nov when mean daily temperatures dropped to -3°C. This ice cover melted before reforming briefly on 12-Dec when mean daily temperatures dropped to -6.7°C. There were two events on the mornings of 1-Jan and 2-Jan where the water level dropped so significantly that much of the channel bed was exposed. The first permanent ice began to form 4-Jan, though no data exist for 5-Jan because of fog or frost on the camera lenses. This ice cover gradually advanced from the stream borders and the emergent boulders (Figure 19a). Broken ice was observed on 31-Jan when the water level dropped, exposing ice shelves attached to the boulders (e.g. Figure 19b), which cracked and collapsed. The thermal ice gradually retreated, with the first ice free day occurring 7-Mar and the channel permanently open from 29-Mar onward.

The upstream study reach on the unregulated unnamed creek was an ~8 m wide wadeable reach with step-pool morphology. Two pools and two steps were included in the observed area. As Figure 20 illustrates, freeze-up processes at this site were dominated by thermal ice growth on the pools and anchor ice growth on the exposed boulders at the steps. The first ice growth observed was on 15-Nov when skim ice formed at the margins of the pools. Thermal ice formed and melted periodically starting 22-Nov, 11-Dec, 27-Dec, 30-Dec, and 6-Jan, which are all periods when the mean daily temperature dropped to below 0°C. The first permanent ice 12-Jan (Figure 21a). In all instances, ice formed as thermal ice on the surface of the pools and anchor ice adjacent to the boulders in the stream. Floating frazil slush ice was observed 2-Feb and 3-Feb on the surface of the pools, stranded behind the frozen boulder steps (Figure 21b). The channel was 100% covered by ice for only 3 days from 12-Feb to 14-Feb, while much of the time, an open lead existed at the base of one of the steps. Breakup began when rising water levels inundated the ice cover on 26-Feb and 28-Feb, followed by ice cracking on 28-Feb. The reach then re-froze before being inundated again by rising water levels 8-Mar to 14-Mar, when the ice broke up and was cleared from the reach. Thermal ice began to reform 18-Mar when the mean daily air temperature dropped to 1.4°C and the minimum daily temperature was -2.4°C, reaching only 15% of the channel area. The channel was clear of ice from 18-Apr onward, when high water levels cleared the channel of ice.

The downstream study reach on the unnamed creek was much wider than the upstream reach, consisting of a large pool upstream of an area with many large emergent boulders and an island with willows growing on it. As Figure 22 illustrates, freeze-up at this site involved many different ice processes. Skim ice first formed between the boulders and growing from pool margins on 16-Nov (mean daily air temperature: 2.5°C, daily minimum: -3.2°C). This ice melted and then skim ice and thermal ice formed 21-Nov, which melted by 3-Dec. Overnight 11/12-Dec (the coldest period in that month: mean daily air temperature -9.1°C) the channel was covered with thermal and floating frazil ice. During that night a frazil ice stopping front was observed passing by the view of the camera. This ice had melted by 16-Dec. Overnight on 26/27-Dec, anchor ice formed at the emergent boulders and the borders of the pool, forming a possible ice blockage on the camera side of the island (Figure 23a). The space upstream of the anchor ice then filled with floating frazil slush. The ice then melted out over the course of 28-Dec. Thermal border ice re-formed on 29-Dec and frazil ice filled the space between the border ice. The channel was completely covered by 8-Jan (Figure 23b). This ice cover stayed largely intact from 17-Jan to 5-Apr. On 6-Apr, water levels rose enough to inundate a portion of the ice cover. The ice then began to crack and broken ice was visible in the open sections of the stream starting 8-Apr. Most of the winter ice cleared out of the observed reach on 13-Apr. On 16-Apr, new border ice and frazil slush were observed, but melted within 1 day. The channel was permanently ice free on 18-Apr, after which mean daily temperatures below 0°C were observed only once more (22-Apr at -0.6°C).

4.3 Discussion

A comparison of the water temperature data from the West Salmon River and Twillick Brook (Figure 24) suggests that the regulated stream is likely influenced by releases of warm water from the reservoir. For example, the water temperature at Twillick Brook responded more dramatically to cold air temperatures (i.e. 11- to 13-Dec and 5- to 7-Jan) than did water temperatures in the West Salmon River. Also, the water temperature at Twillick Brook reduced to ~0°C, 38 days before the water temperature at the West Salmon River reduced to ~0°C. Moreover, during breakup, the Twillick Brook water temperature displayed much larger daily fluctuations and rose more quickly than that at West Salmon River. No water temperature data was available for the Granite Canal sites. Figure 25, which shows the accumulated degree days of freezing at the time each site first formed a permanent ice cover, also supports this assertion. Specifically, the West Salmon River (regulated) required more degree days of freezing to form a permanent ice cover in than did Twillick Brook (unregulated), implying a thermal influence from Cold Spring Pond. The number of accumulated degree days of freezing required to form a permanent ice cover on Compensation Creek (regulated) was between those required for the two unnamed creek sites. This suggests that differences in channel morphology may have a greater effect than flow regulation on ice conditions.

The thermal effects of regulation on these streams can also be seen by comparing the accumulated degree days of thaw at which the stream was entirely ice free (Figure 26) and the number of days each site was ≥ 90% ice covered (Figure 27). On the West Salmon River (regulated), the upstream site was ice free before the downstream site and it also was ice covered for a shorter period of time. On Compensation Creek (regulated), the upstream site formed a permanent ice cover before the downstream site, but the upstream site did not completely freeze over and had a 90% ice cover for only 2 days. This suggests that the upstream sites were more affected by the thermal effects of the reservoirs than were the downstream sites (i.e. that the thermal effects were attenuated along regulated streams). These longitudinal differences were more pronounced at breakup than they were at freeze-up. Here also, no clear trend emerges when comparing the accumulated degree days of thaw between Compensation Creek (regulated) and the unnamed creek (unregulated). However, Compensation Creek (regulated) was ice covered for fewer days (14.5 average) than was the unregulated unnamed creek (74 days average), suggesting thermal effects on the regulated stream.

5 Conclusion

There is evidence of thermal effects of regulation at the study sites; however, these effects may be masked by differences in channel morphologies at each site. In general, the regulated sites had more consistent water temperatures and exhibited a shorter duration of ice cover. However, when comparing the number of accumulated degree days of freezing and thaw that contributed to freeze-up and breakup, no clear trends emerge. This may be because of the influence channel morphology is stronger than the influence of thermal regulation.

The unregulated comparison sites studied may not have been satisfactory analogues to the regulated streams, in terms of channel morphology and ice processes. In particular, the stream pair at the Granite Canal study area have very different widths, slopes, and bed material. Also, the morphologies of the upstream site and the downstream site on the unnamed creek are quite different, making this site difficult to use as a comparison. Future studies should include a more complete geomorphic characterization (including surveyed slope, cross-sections, substrate sizes) of possible study sites so that the effects of regulation are more clear than they were in this study. Finally, more reach-based (as opposed to site-based) observations should be included in future studies, so that the longitudinal effects of regulation can also be observed. This may include longitudinal surveys of ice condition and geometry as well as water temperature.

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Table 1. Summary of dates of first ice and first ice free, and extent of ice-covered season for winter 2010-2011.

Stream	Site	Range of Observations	Day of First Permanent Ice	First Ice Free Day	Number of days ≥ 90% Ice Coverage
West Salmon River *(unregulated)*	Upstream	27-Oct to 18-May	18-Jan	6-Apr	33
	Downstream	27-Oct to 23-May	17-Jan	14-Apr	50
Twillick Brook *(unregulated)*	Upstream	27-Oct to 12-Mar	6-Jan	not observed	not observed
	Downstream	27-Oct to 23-May	6-Jan	31-Mar	46
Compensation Creek *(regulated)*	Upstream	28-Oct to 16-May	5-Jan	13-Apr	2
	Downstream	28-Oct to 17-May	4-Jan	7-Mar	27
Unnamed Creek *(unregulated)*	Upstream	29-Oct to 17-May	12-Jan	15-Mar	41
	Downstream	29-Oct to 18-May	27-Dec	18-Apr	107

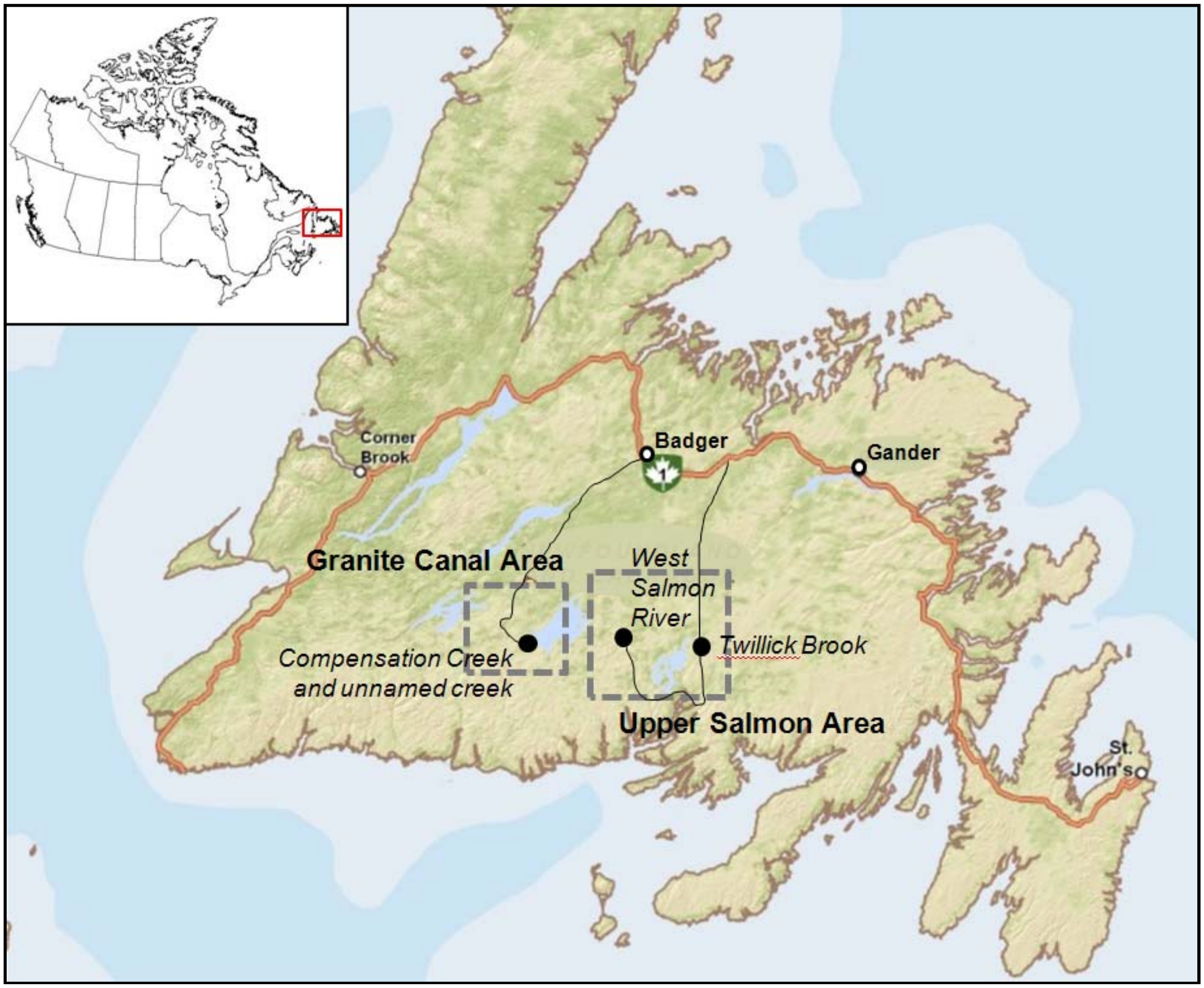

Figure 1. Location of study sites within Newfoundland, Canada (Base image source: Esri basemaps).

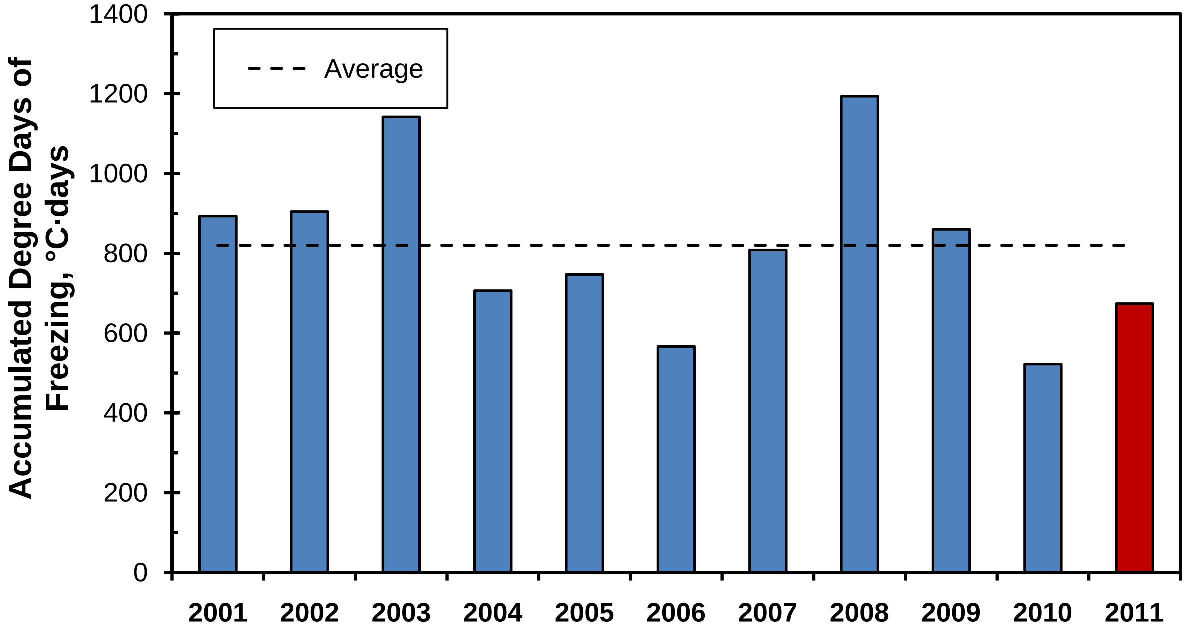

Figure 2. Maximum accumulated degree days of freezing at Badger, NL.

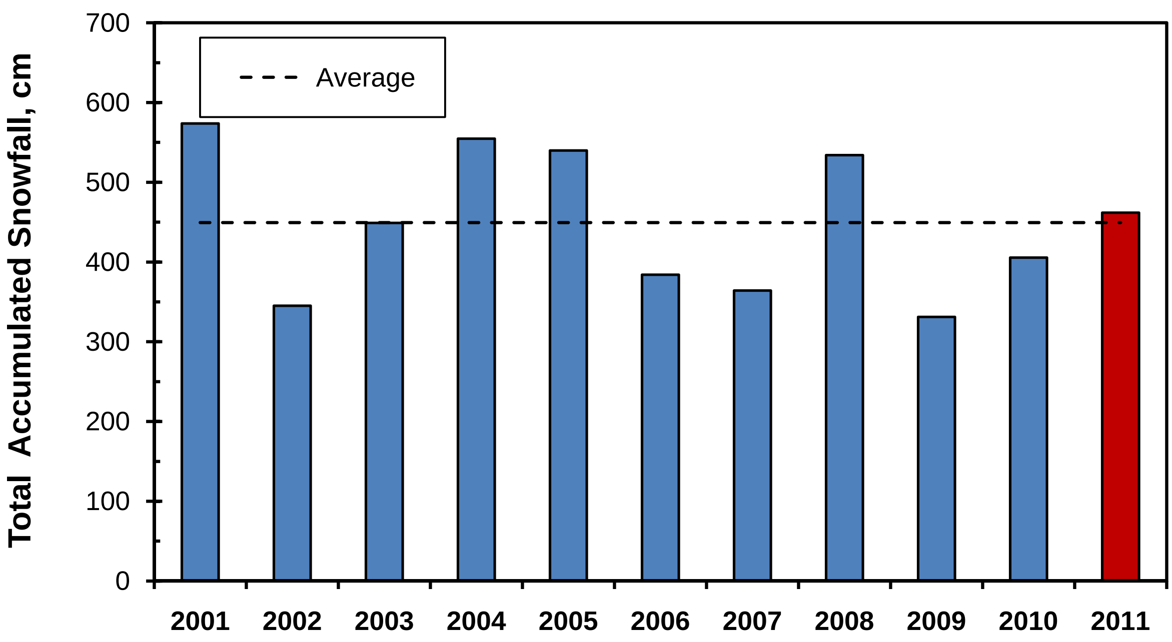

Figure 3. Total accumulated snowfall at Gander, NL.

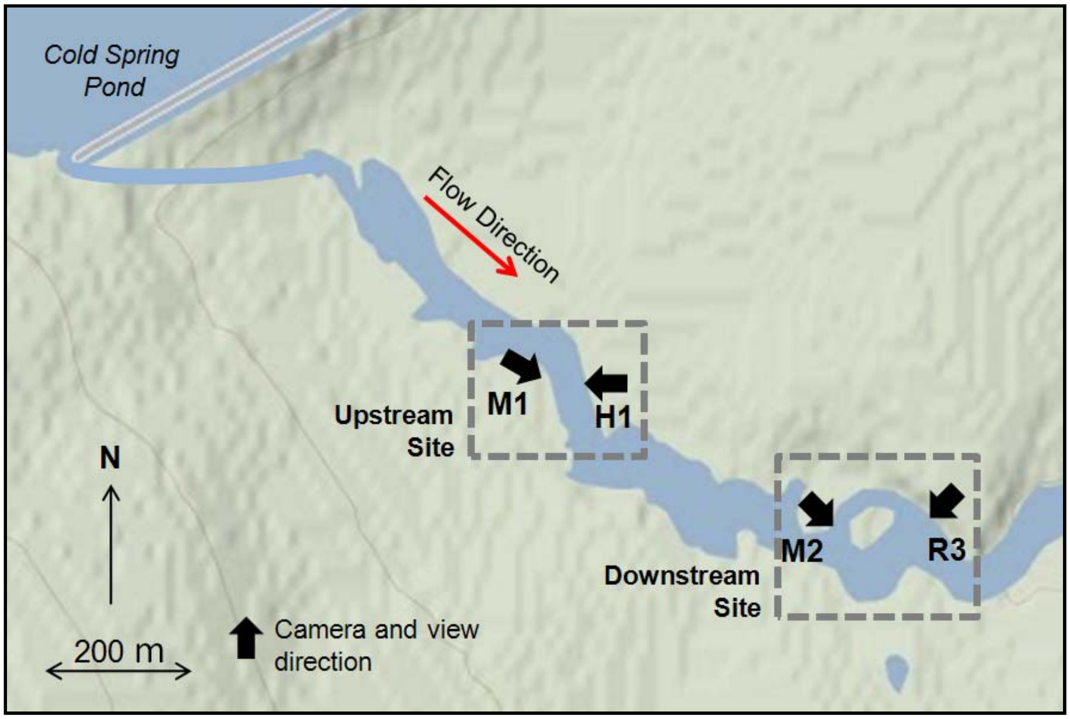

Figure 4. Location of the study sites on the West Salmon River, including camera deployment locations (base image source: 2011 Google Terrain map).

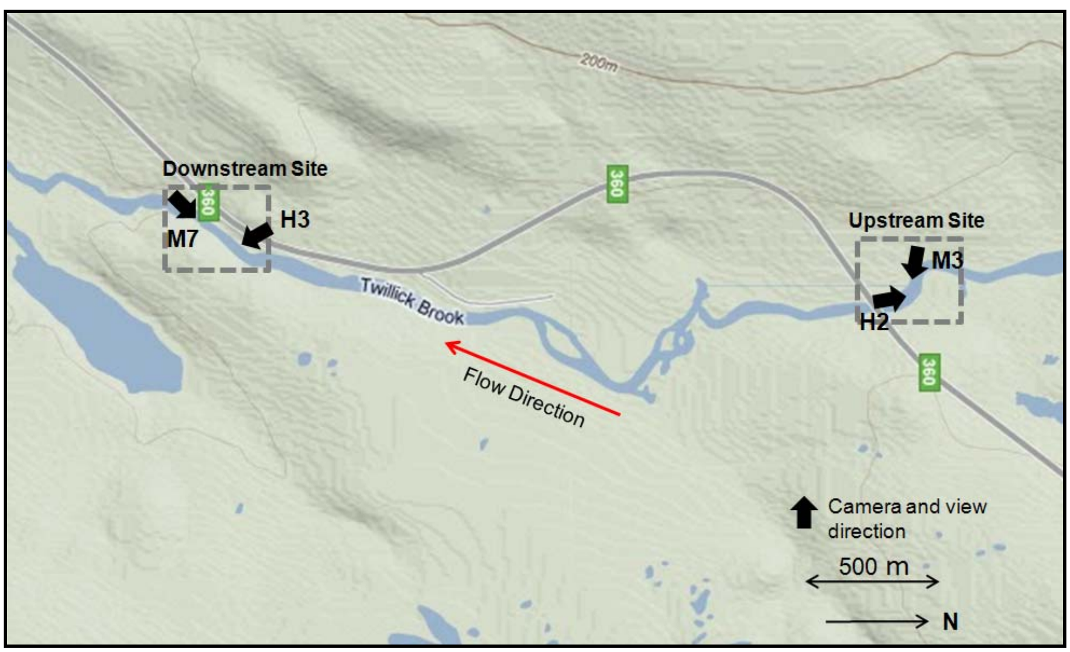

Figure 5. Location of study sites on Twillick Brook, including camera deployment locations (base image source: 2011 Goolge Terrain map).

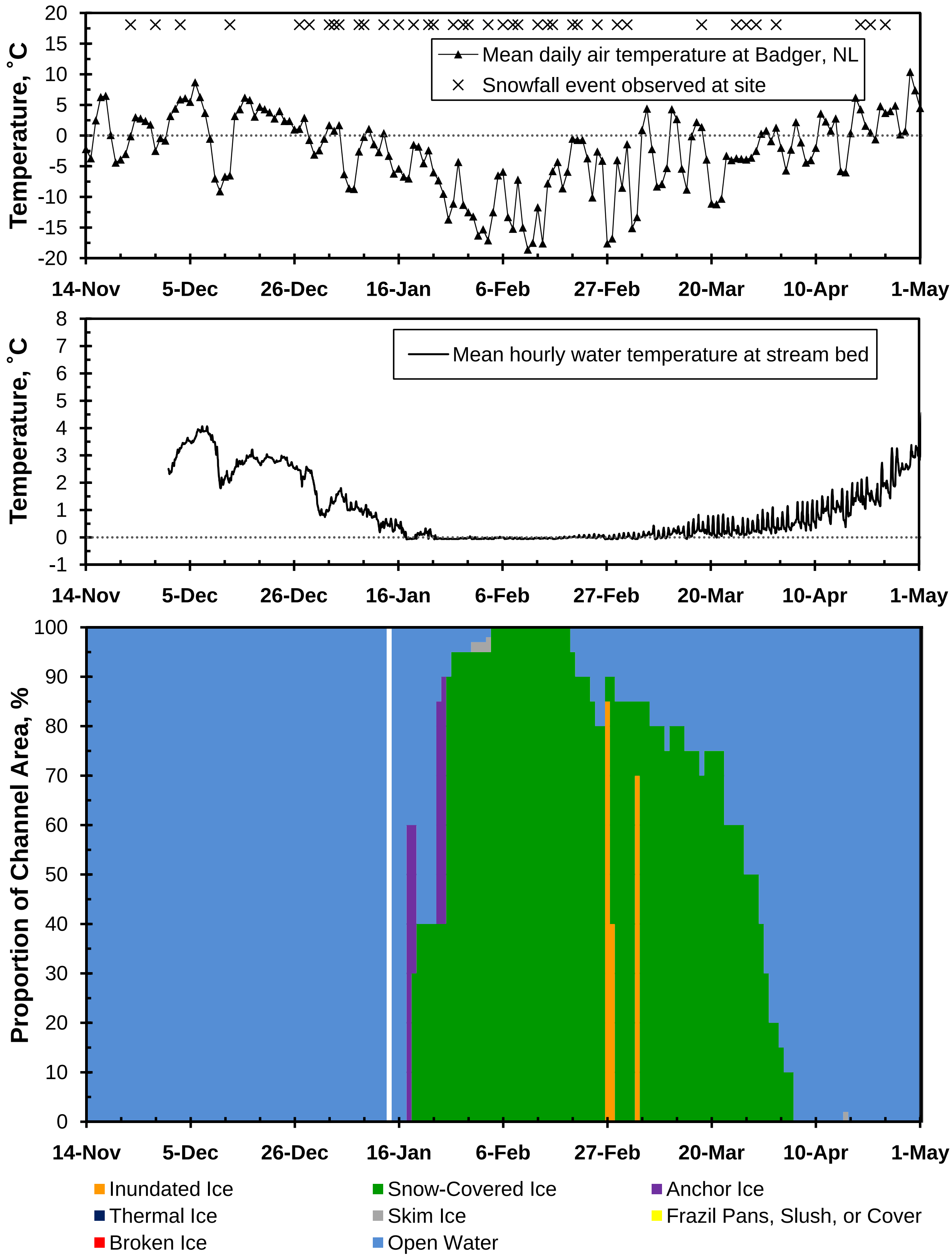

Figure 6. Ice conditions at West Salmon River (regulated) upstream site for winter 2010-2011 (cameras H1 and M1). Data gaps are denoted by white spaces.

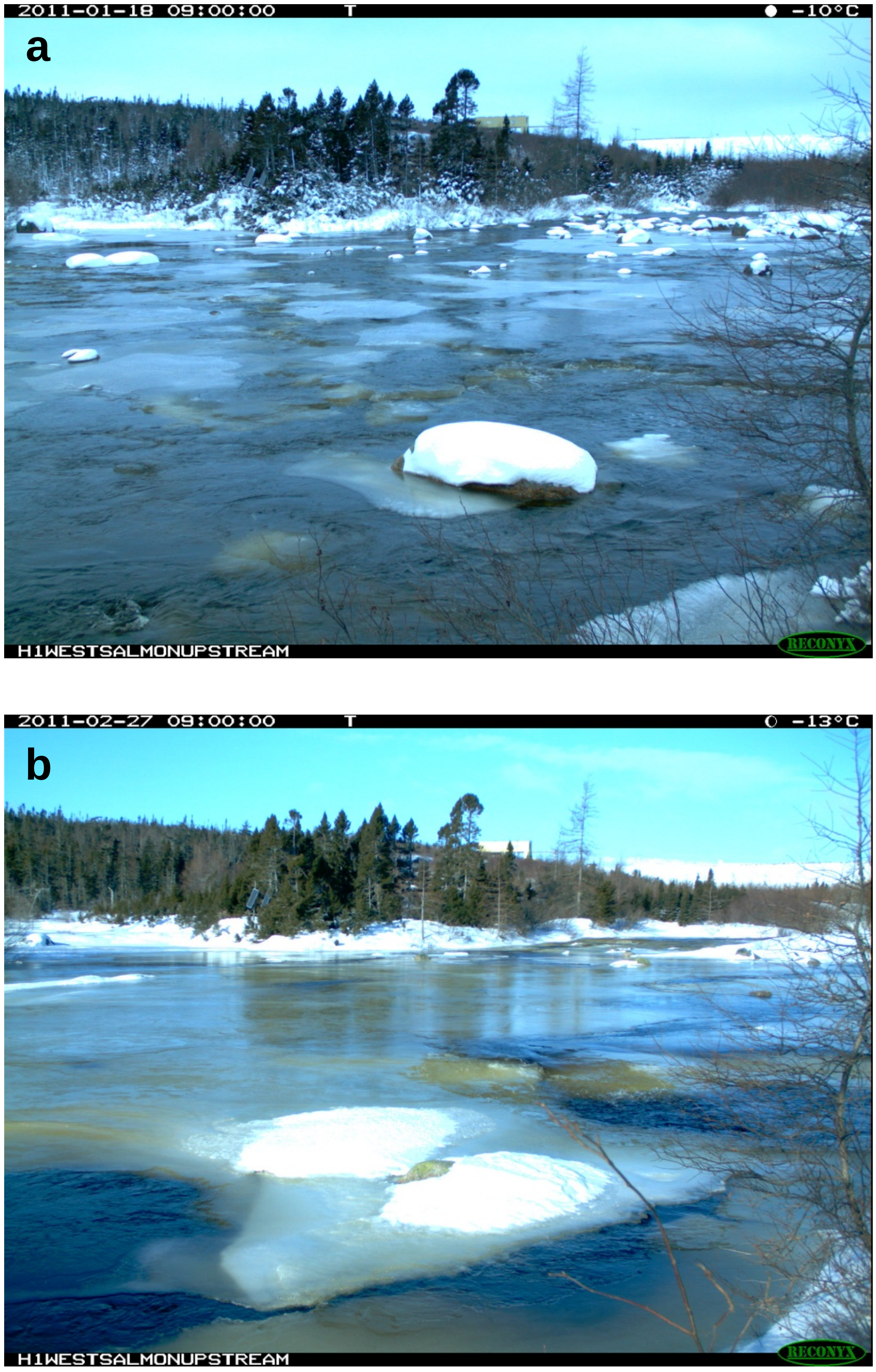

Figure 7. Ice observation photographs from the West Salmon River (regulated) upstream site taken by camera H1 showing: a) anchor ice formation on 18-Jan-11; and b) ice inundated by high water levels on 27-Feb-11.

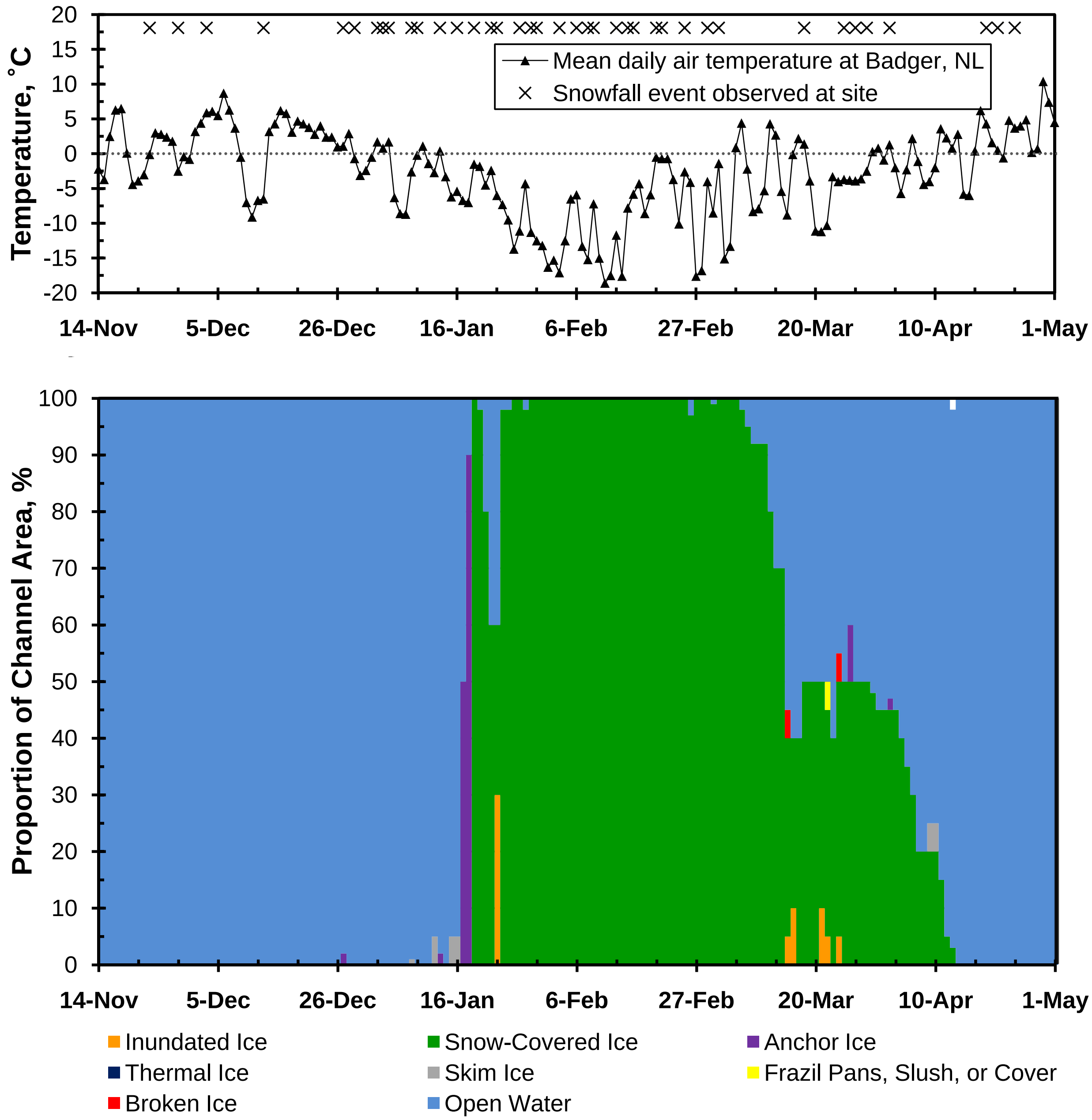

Figure 8. Ice conditions at West Salmon River (regulated) downstream site for winter 2010-2011 (cameras R3 and M2).

Figure 9. Ice observation photographs from the West Salmon River (regulated) downstream site taken by camera R3 showing: a) anchor ice on 23-Jan-11; and b) broken ice in the channel on 24-Mar-11.

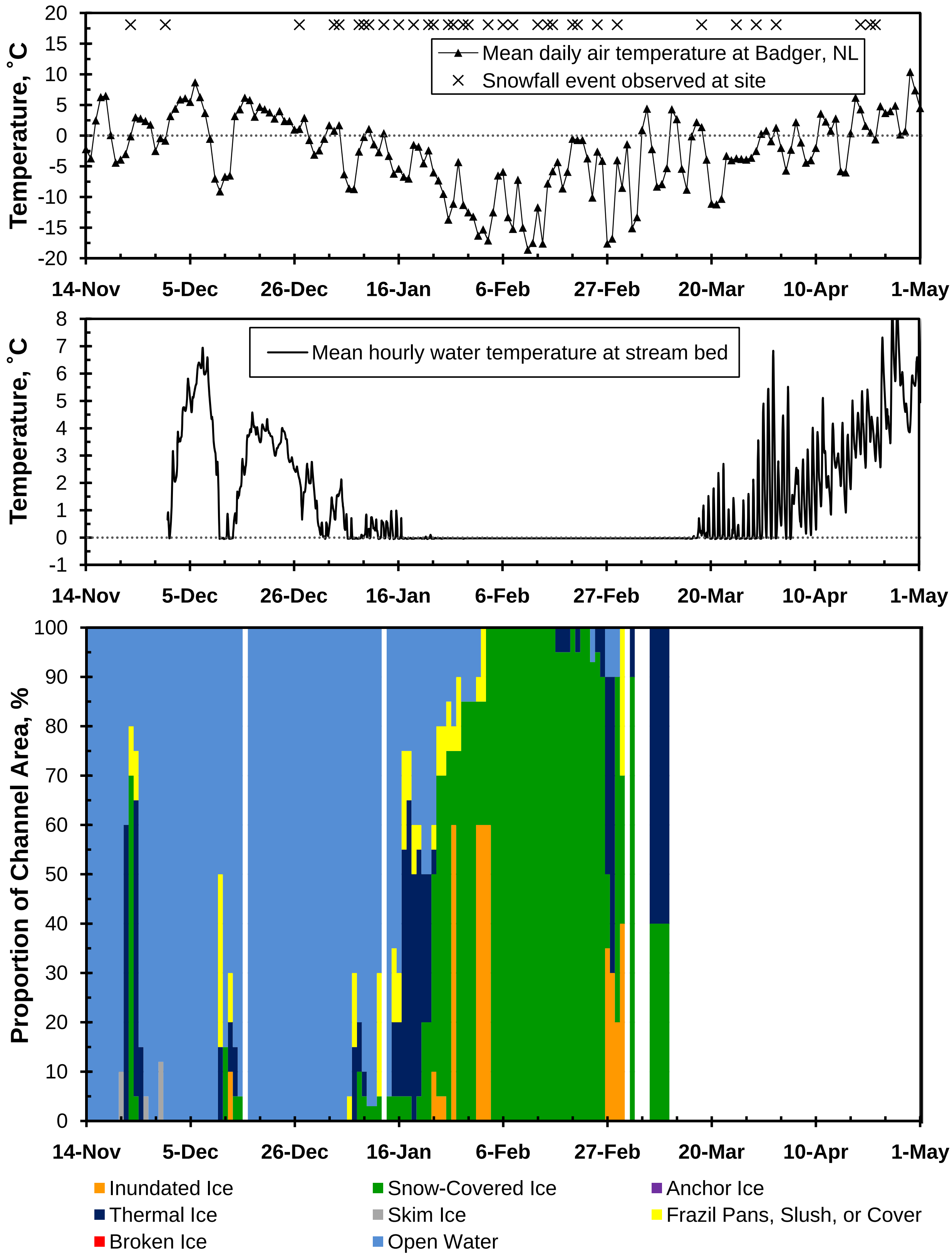

Figure 10. Ice conditions at Twillick Brook (unregulated) upstream site for winter 2010-2011 (cameras H2 and M3). Data gaps are denoted by white spaces.

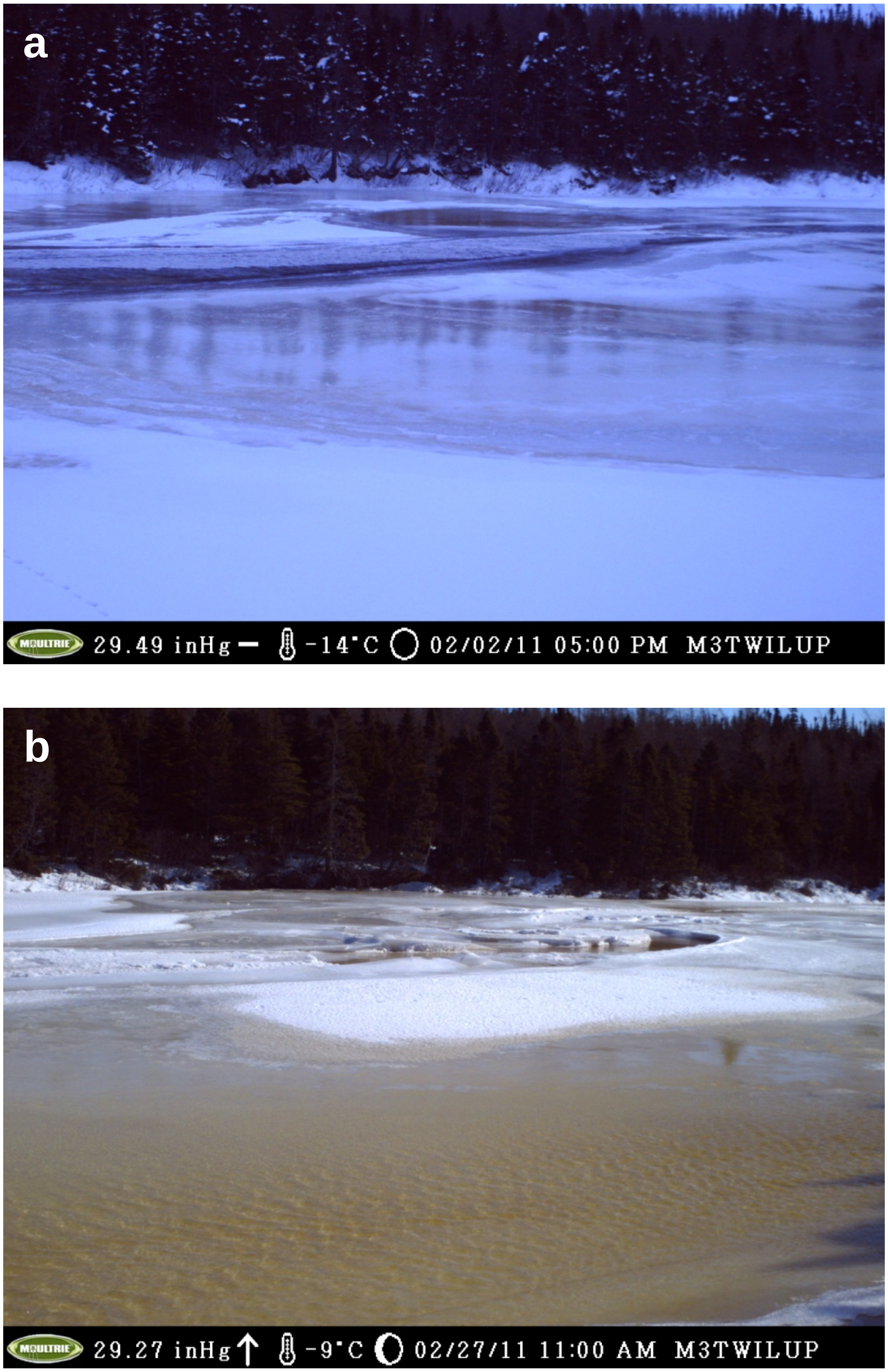

Figure 11. Ice observation photographs from Twillick Brook (unregulated) upstream site taken by camera M3 showing: a) frazil ice filling in an ice cover on 2-Feb-11 and; b) ice inundated by high water levels on 27-Feb-11.

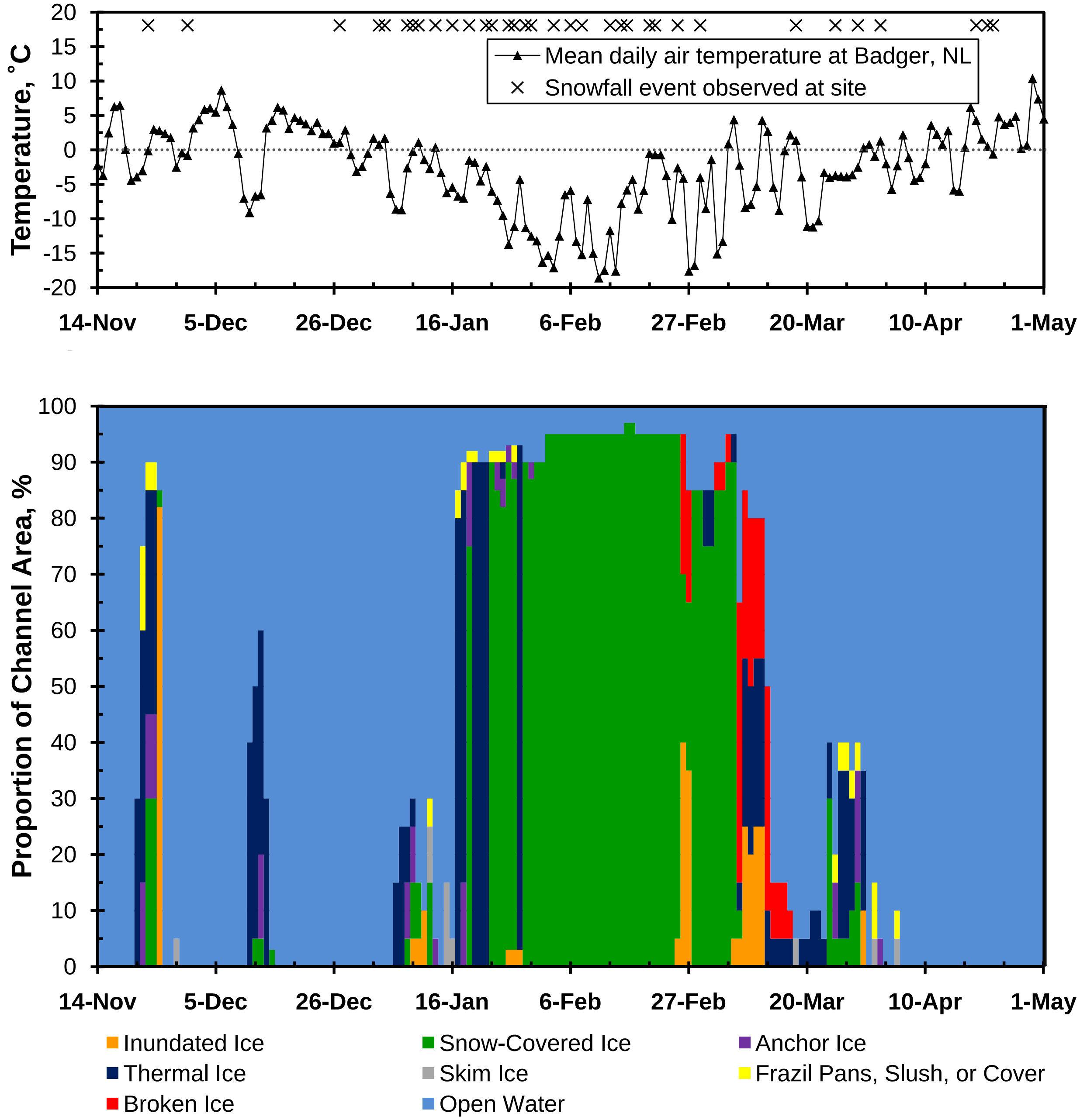

Figure 12. Ice conditions at Twillick Brook (unregulated) downstream site for winter 2010-2011 (cameras H3 and M7).

Figure 13. Ice observation photographs from Twillick Brook (unregulated) downstream site taken by camera H3 showing: a) partial ice cover on 11-Dec-10; and b) small ice jam on 12-Mar-11.

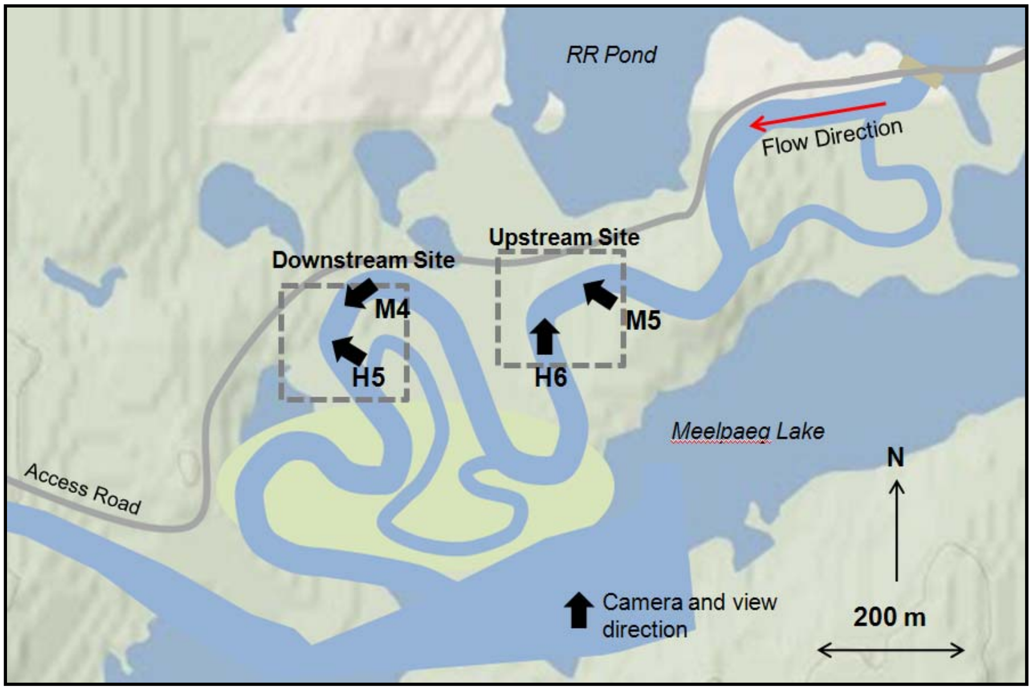

Figure 14. Location of the study sites on Compensation Creek, including camera deployment locations (base image source: 2011 Google Terrain map).

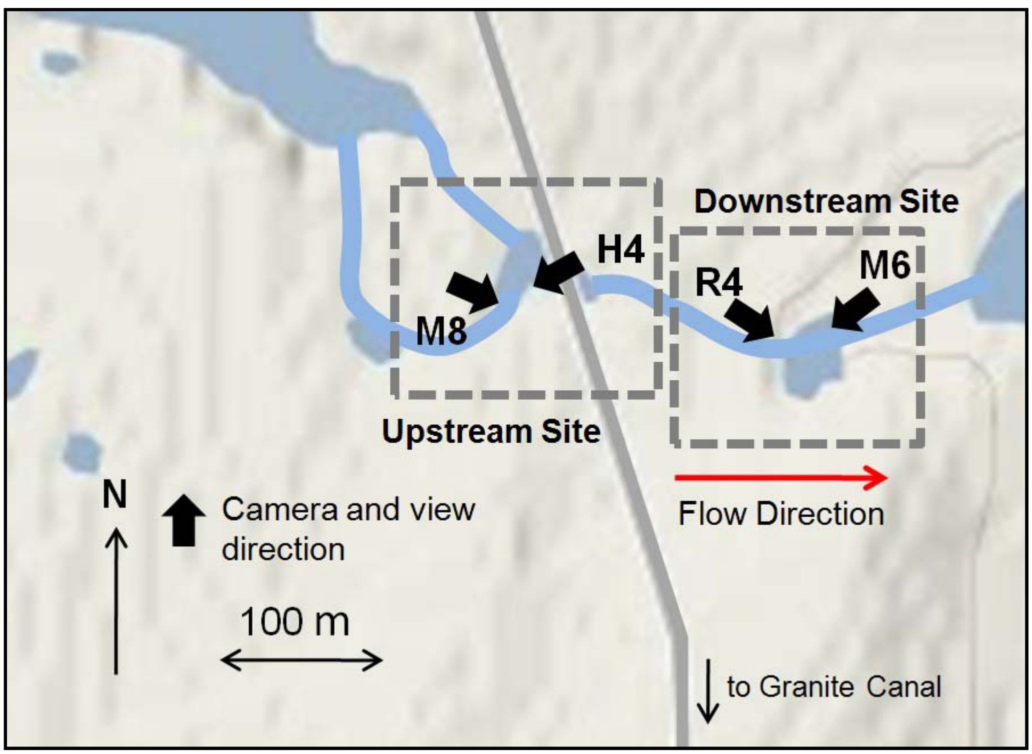

Figure 15. Location of the study sites on the unnamed creek, including camera deployment locations (base image source: 2011 Google Terrain map).

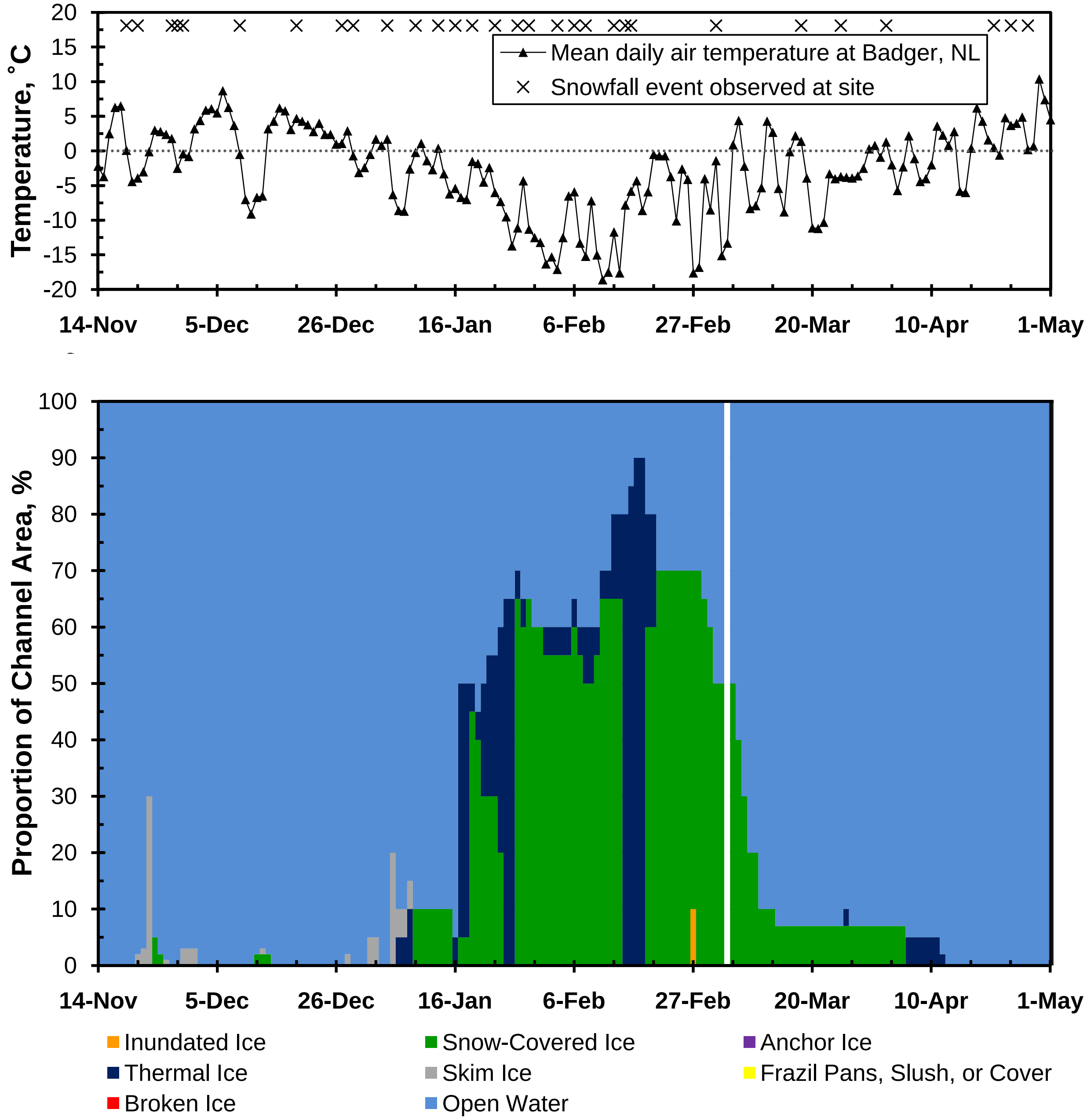

Figure 16. Ice conditions at Compensation Creek (regulated) upstream site for winter 2010-2011 (cameras H6 and M5). Data gaps are denoted by white spaces.

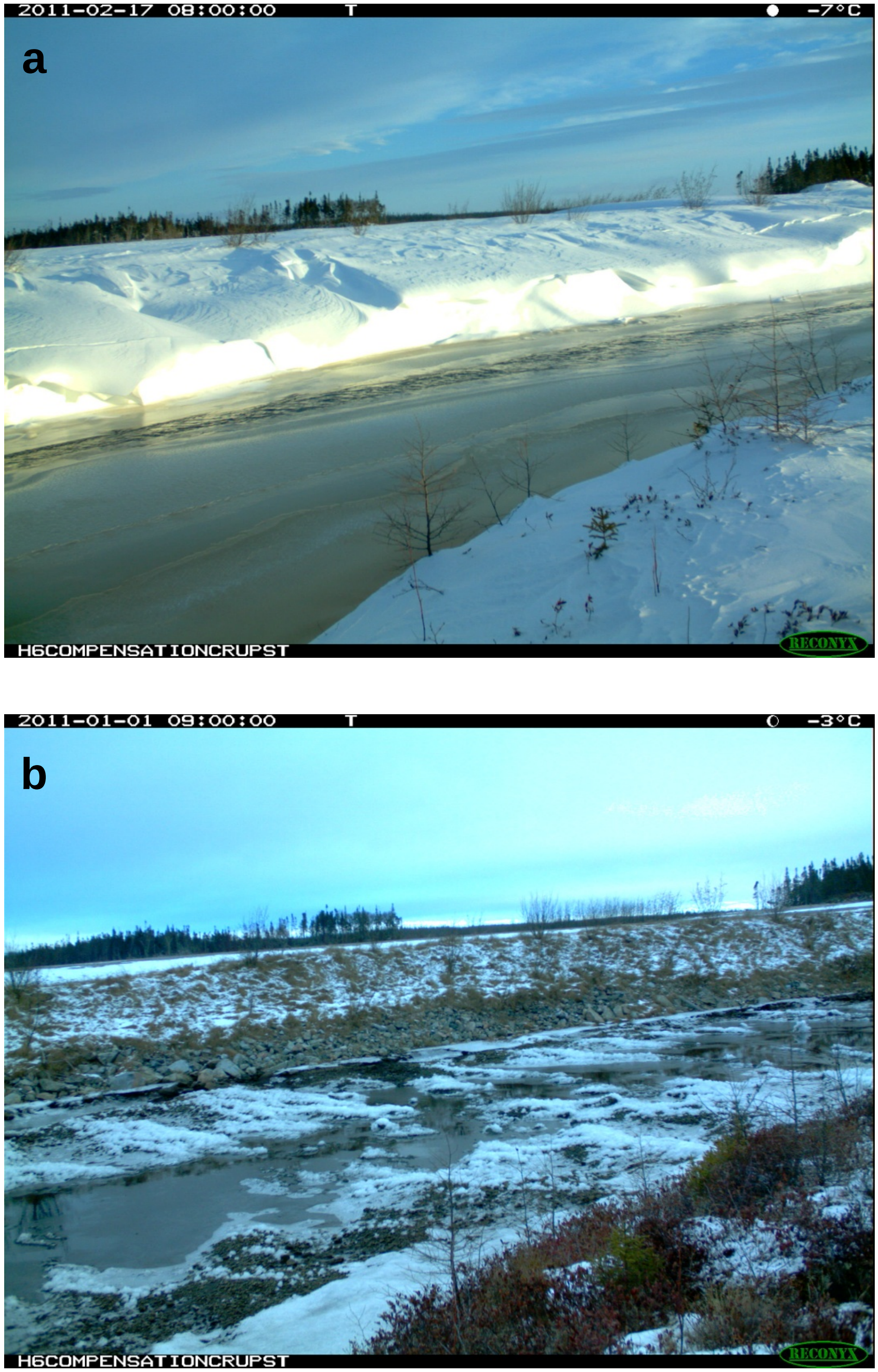

Figure 17. Ice observation photographs from Compensation Creek (regulated) upstream site taken by camera H6 showing: a) ice cover on 17-Feb-11 and;
b) low water condition on 1-Jan-11.

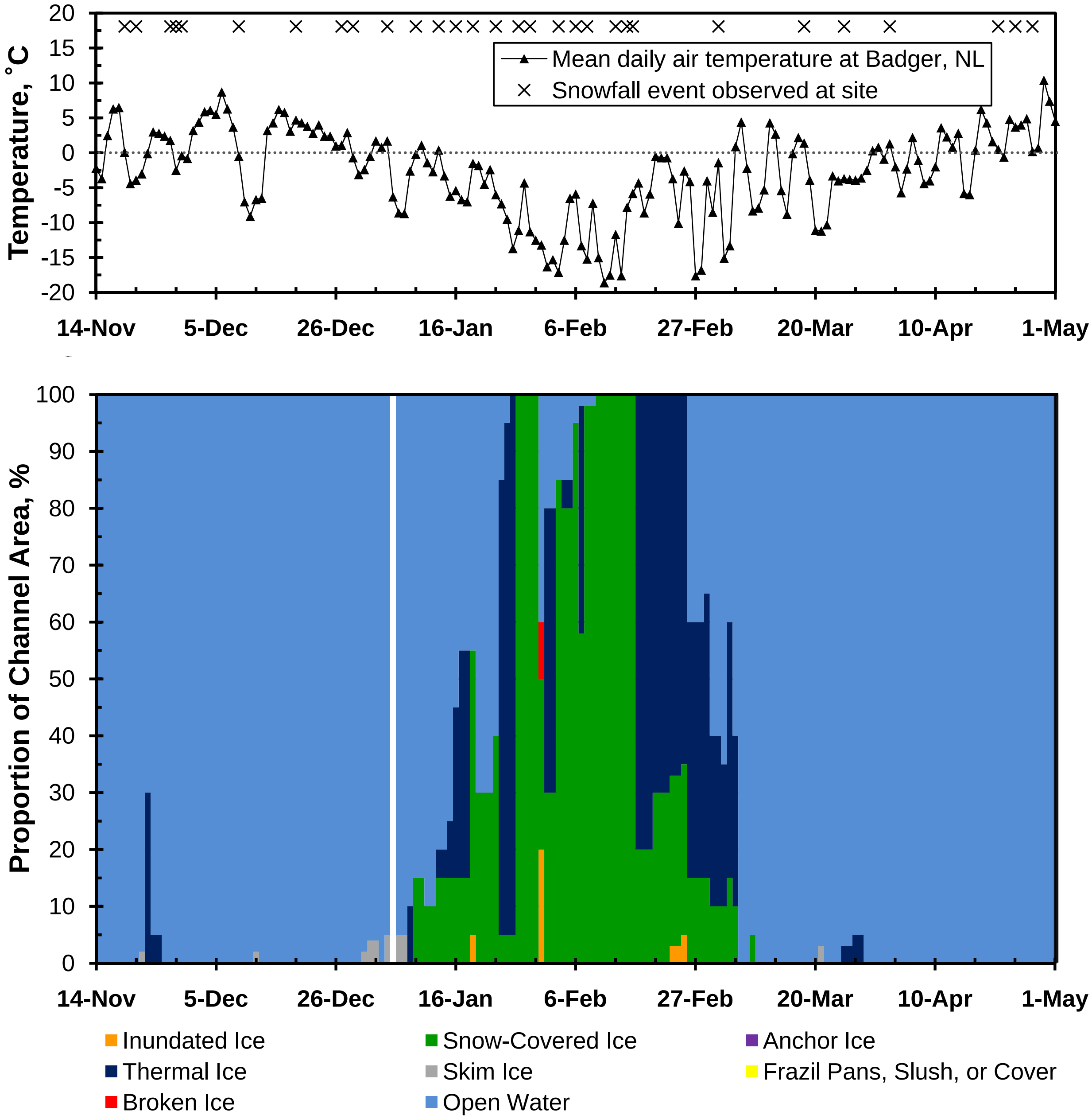

Figure 18. Ice conditions at Compensation Creek (regulated) downstream site for winter 2010-2011 (cameras H5 and M4). Data gaps are denoted by white spaces.

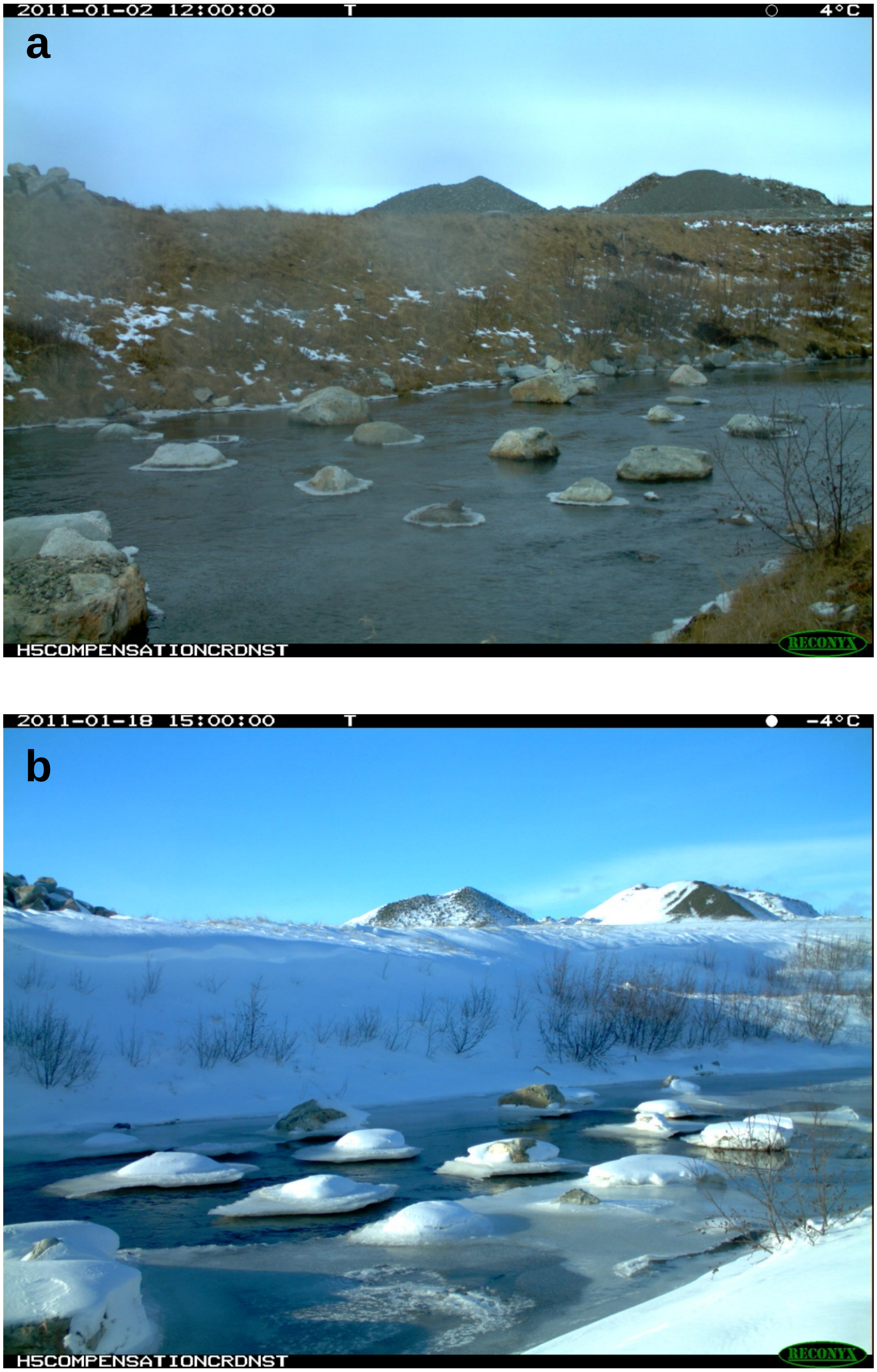

Figure 19. Ice observation photographs from Compensation Creek (regulated) downstream site taken by camera H5 showing: a) ice cover advancing from boulders and stream margins on 2-Jan-11; and b) ice shelves on 18-Jan-11.

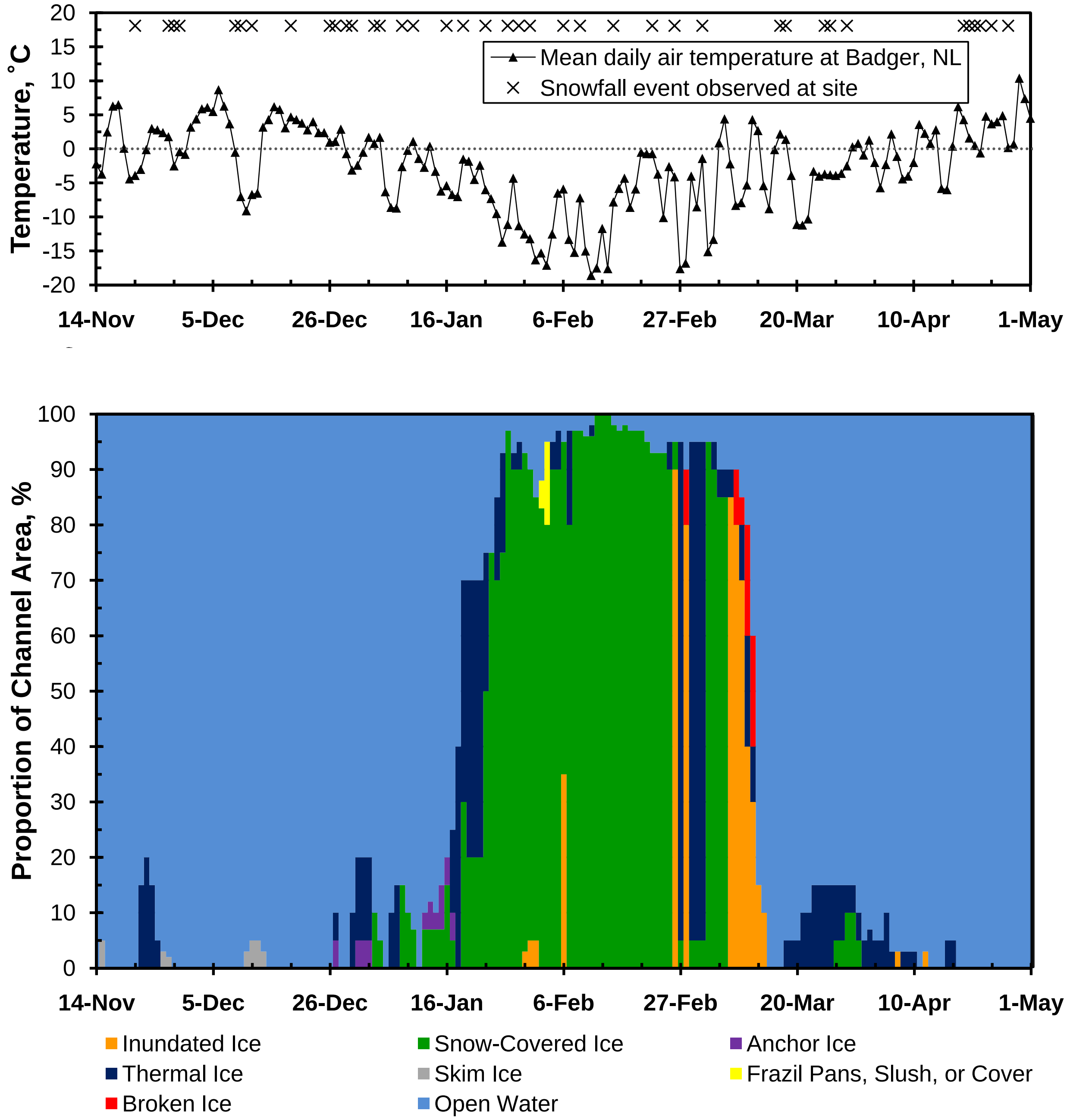

Figure 20. Ice conditions at No Name Creek (unregulated) upstream site for winter 2010-2011 (cameras H4 and M8).

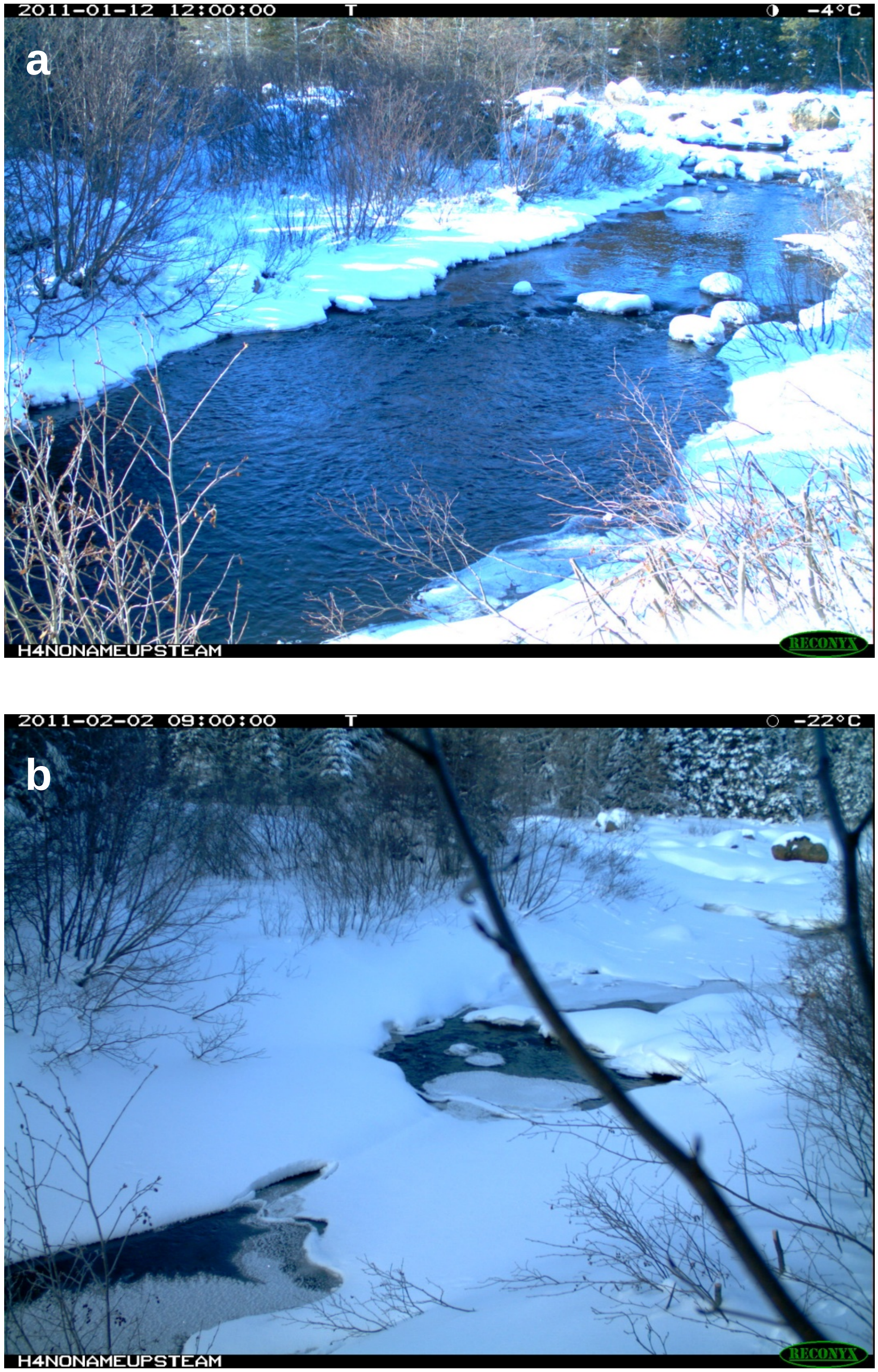

Figure 21. Ice observation photographs from the upstream site on the unnamed creek (unregulated) taken by camera H4 showing: a) first permanent ice on 12-Jan-11; and b) floating frazil on 2-Feb-11.

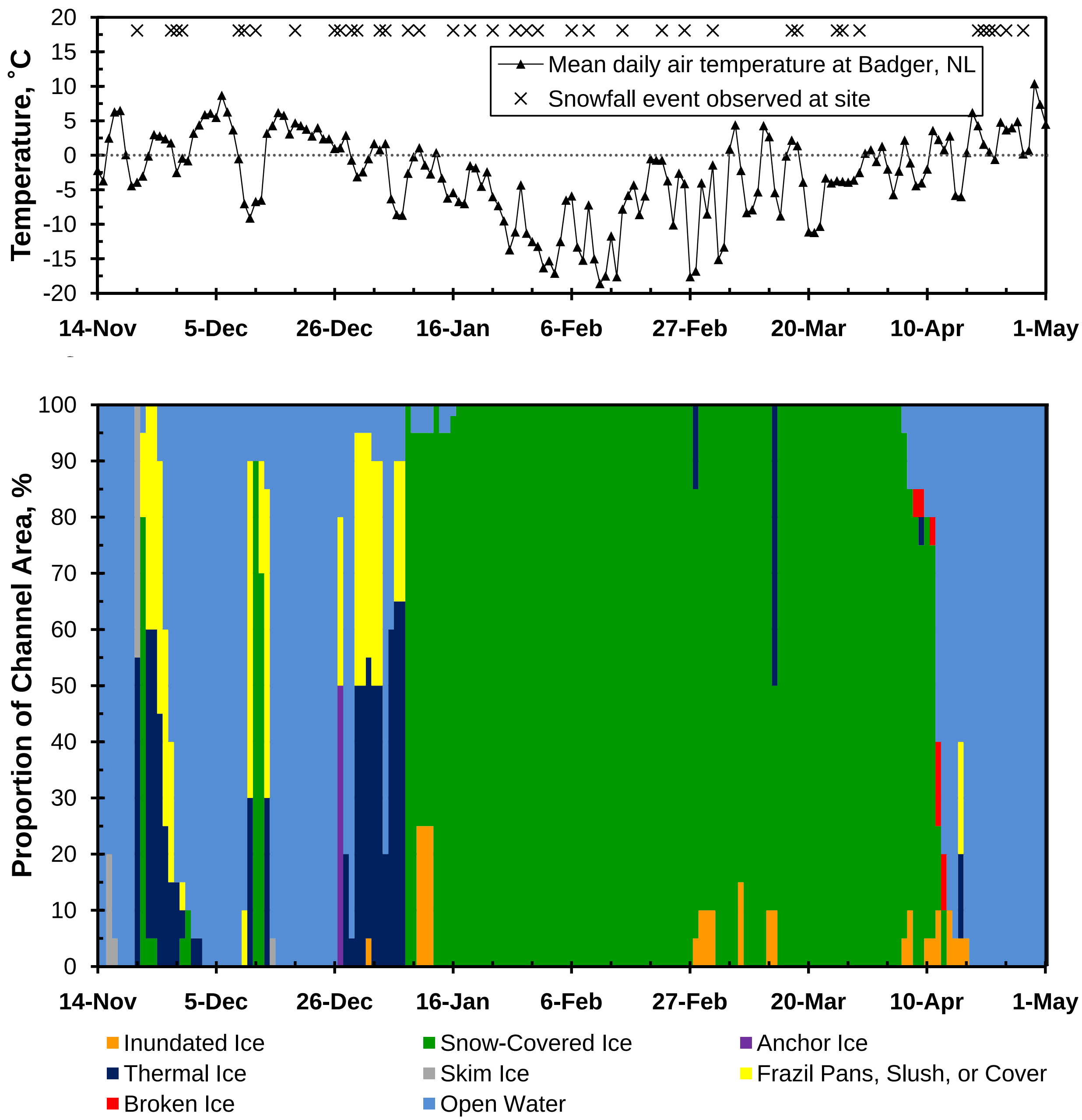

Figure 22. Ice conditions at No Name Creek (unregulated) downstream site for winter 2010-2011 (cameras R4 and M6).

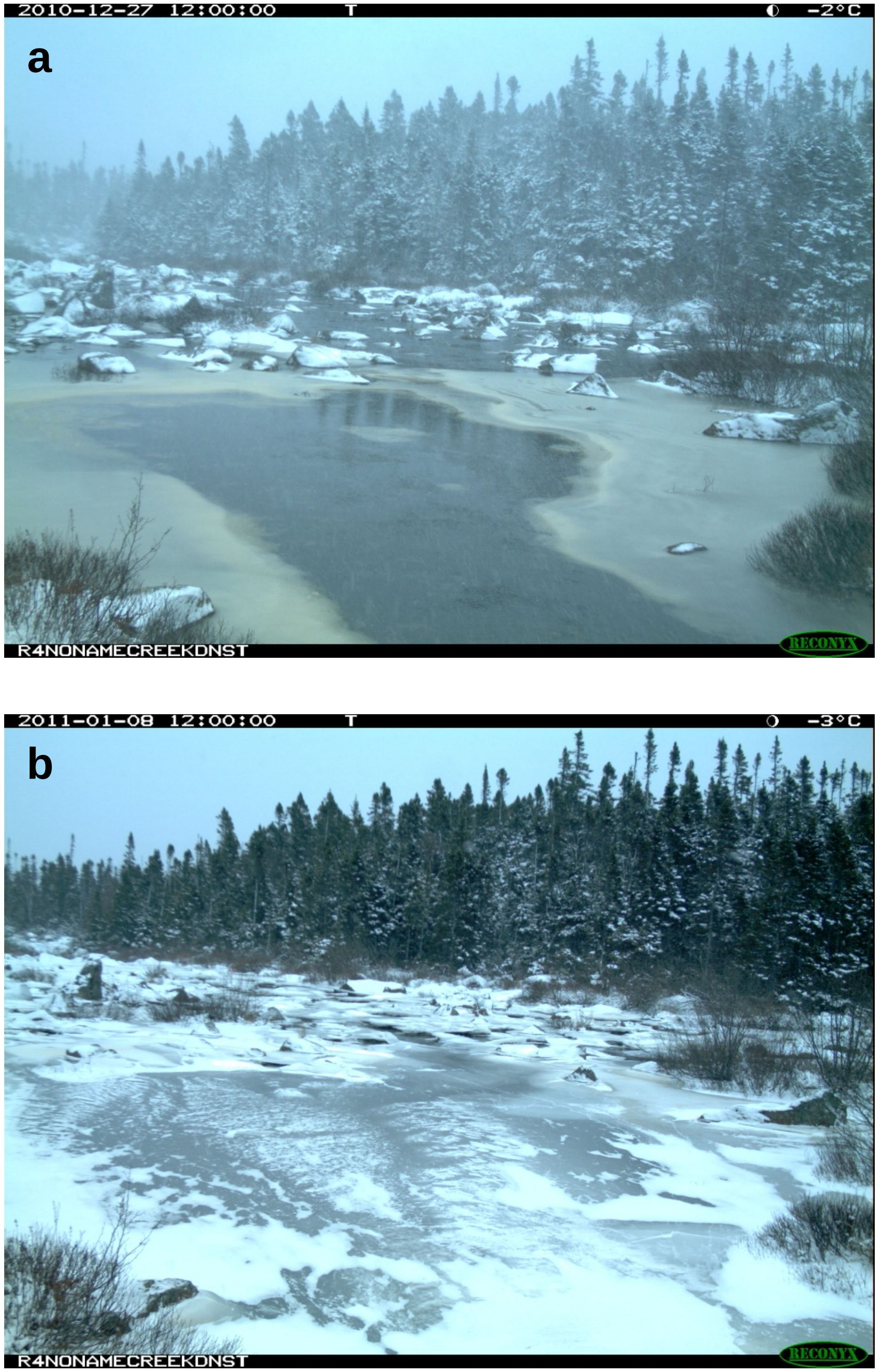

Figure 23. Ice observation photographs from the downstream site on the unnamed creek (unregulated) taken by camera R4 showing: a) anchor ice on 27-Dec-11; and b) ice cover on 8-Jan-11.

a)

b)

c)

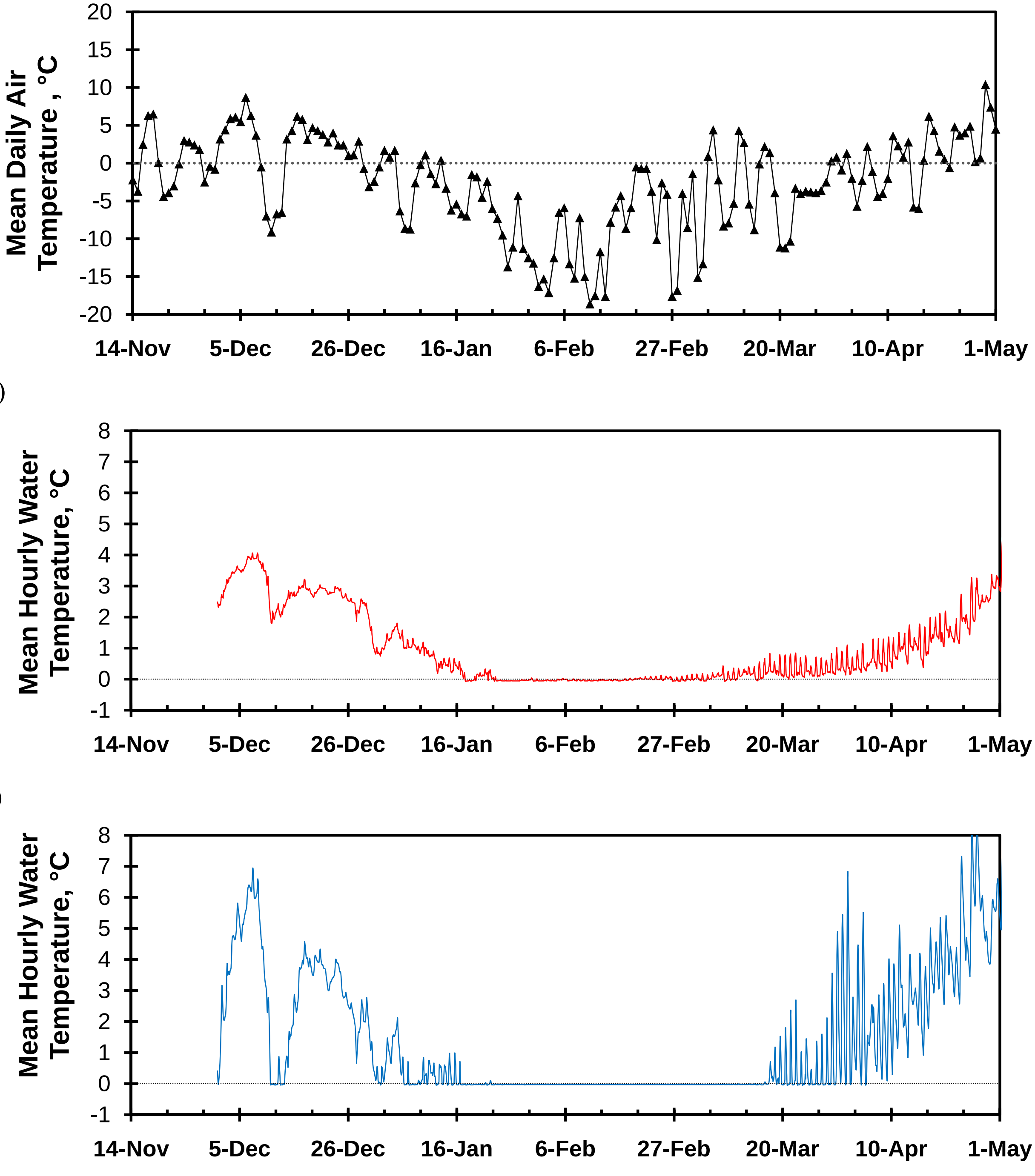

Figure 24. Comparison of: a) air temperature measured at Badger, NL and water temperatures measured at: b) West Salmon River, a regulated stream and c) Twillick Brook, a natural flow stream, for winter 2010-2011.

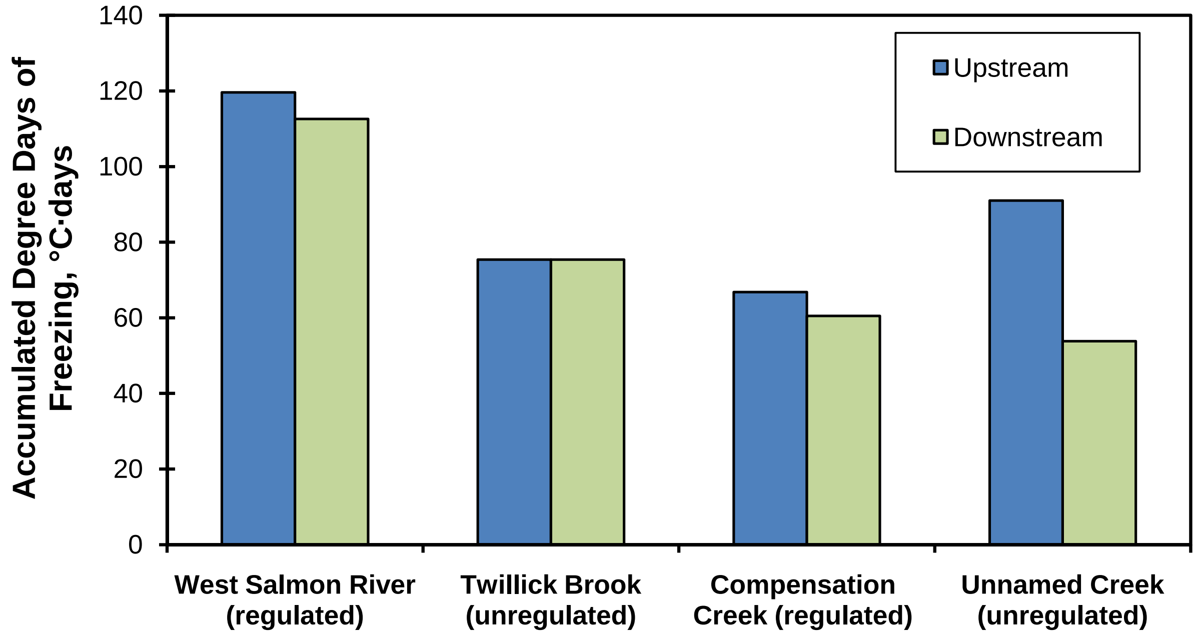

Figure 25. Accumulated degree days of freezing at Badger, NL when first permanent ice forms at each stream.

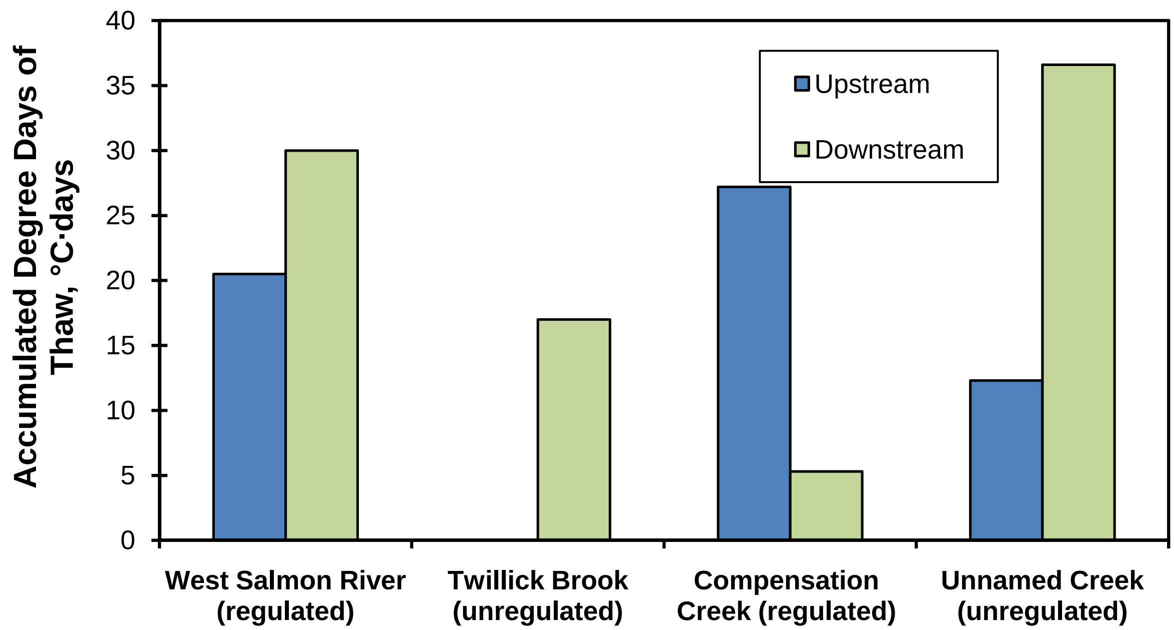

Figure 26. Accumulated degree days of thaw at Badger, NL when streams are first ice free.

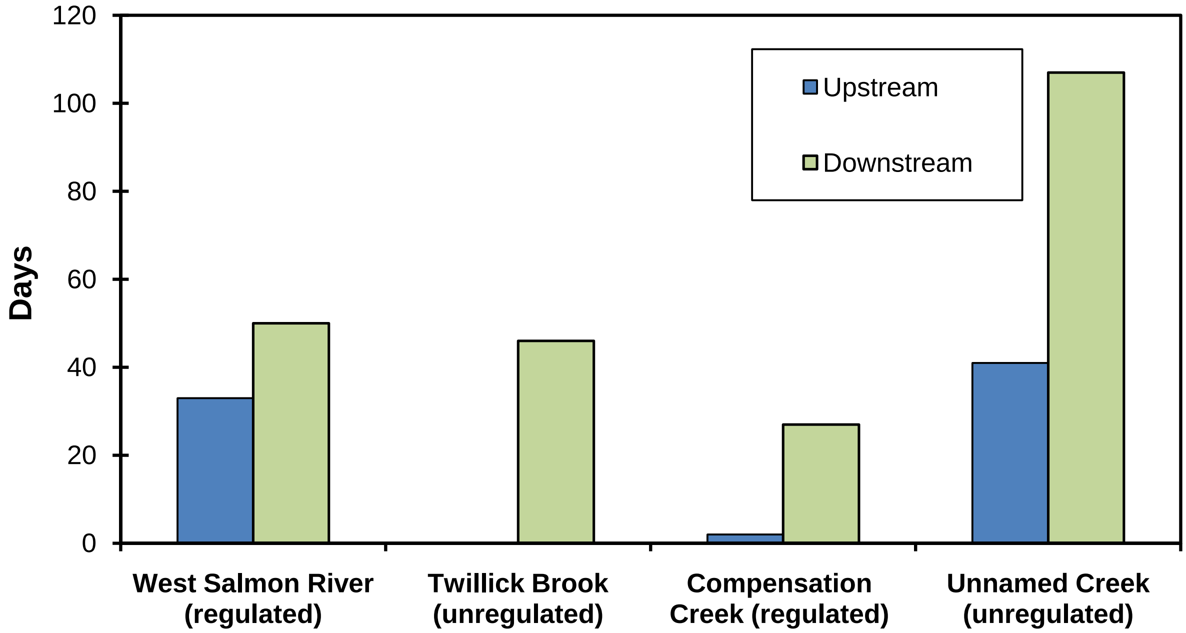

Figure 27. Number of days of $\geq 90\%$ ice coverage at each site.