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Monitoring river ice processes: Sharing experience to improve successful research programs

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Understanding and quantifying river ice processes often represents an important phase of scientific and engineering projects along cold region rivers. Indeed, gradual and dynamic river ice processes can affect aquatic and riparian habitats, significantly disturb hydraulic conditions, alter sediment transport modes and rates, influence channel morphology, and damage or destroy river and floodplain structures that are not appropriately designed or located. Monitoring river ice processes using expensive and high-tech instrumentation deployed in the field is increasingly common. However, retrieving accurate data from ice-affected rivers is often a frustrating task with frequent unsuccessful attempts or recovery of only partial results. This may be for several reasons including the difficulty of working in a very cold environment or simply not finding remote instruments after the cold season. The objective of this paper is to share the experience and knowledge of river ice experts who have worked along rivers of different sizes and morphologies over with the aim of sharing information in order to prevent others repeating the same errors they have made. It presents a list of factors to consider and situations to avoid in order to maximize the chances of retrieving the desired data from a harsh environment affected by surprisingly complex and dynamic phenomena. Determining the best instrumentation for river ice monitoring purposes, installing instruments at appropriate locations underwater or along the banks, and organizing successful winter field trips may save a significant amount of time and resources to those who endeavour to understand and quantify river ice processes during winters to come.

1. Introduction

The presence of different forms of ice on watercourses greatly adds to the complexity the river environment. Ice has historically generated technical and engineering problems, environmental disasters, and fatalities, a reality that still applies nowadays. The tremendous research effort on the topic of river ice and cold regions hydrology in the past decades and the emergence of productive river ice experts have significantly contributed to improving our understanding of the winter dynamics of watercourses. Tools and models have also been developed to support scientists and engineers in their respective professional tasks. However, the answers to basic questions often remain partially available, even for an ice expert that is unfamiliar with the site. Some examples:

- How high could the water level be and at what frequency?
- Is the design of this hydraulic structure adequate?
- Can I leave this vehicle (machinery or boat) here for a few hours or days?
- How much water is really available for different purposes?
- Does specific ice processes destabilize river channels from a morphology point of view?
- How far has the contaminant front travelled and how did it evolve?

Despite the fact that general knowledge applies to a broad range of channel conditions, it is understandable that the hydrological and morphological behaviours of each watercourse is unique. This especially applies to cold region channels that are temporarily affected by ice processes. Moreover, every winter is different, in terms of meteorological and hydrological conditions, which adds to the apparent chaotic character of cold region channels.

Therefore any sustainable project, and the research results that support it, should be based on reliable, site-specific data obtained from the monitoring of watercourse including during the ice period. River ice and winter hydrological data is needed to document watercourses during the cold season, to identify specific processes that may affect operational decisions, to calibrate models that intend to simulate different ice and flow conditions, and to adapt the design of engineering structures.

Monitoring campaigns need to be as efficient and effective as possible because the time window for observing many river ice processes is small and field conditions can be harsh. Postponing a project by a year because representative data was not obtained is rarely acceptable. The authors of this paper have made errors in the past that have led to a loss of data or instruments and all of them have been standing on the shore, frustrated and disappointed, in the cold and snow or in the rain and surrounded by clouds of blood sucking insects. The intention of the authors is to contribute in improving the success of future river ice and winter processes monitoring campaigns, to reduce the cost of research as well as to minimize the ecological impact of lost instruments in a natural environment by sharing tips, tricks, and experiences that may not be immediately obvious when planning and implementing a field program.

2. Monitoring watercourses during winter

2.1 Ice processes to expect and monitor

The type of river ice cover as well as the nature and intensity of freeze-up, mid-winter and breakup ice processes are diverse and they can significantly vary from one winter to another, between neighboring watersheds, as well as from one river segment to the next. It is important to anticipate or to understand the potential range of ice processes that can affect the study or project site(s) because this will influence the monitoring strategy and field trip planning. Direct observations, statistics, historical photos and local peoples' testimony all represent important information to gather. These should not be restricted to the ice period and should include open water conditions where the channel and bank characteristics can be documented.

Winter information, if available, can be compared with an ice cover type and ice processes classification model presented by Turcotte and Morse (2013) and in the absence of any information, this model can be used as a first step. Depending on the channel size, channel gradient, and channel morphology from downstream to several kilometers upstream, as well as on climate indicators, the following ice cover types and ice processes can be expected:

- Open water (downstream of natural or anthropic heat sources, including lakes and reservoirs), even during very cold conditions
- Floating ice cover (along most low-gradient channels; e.g., Ashton, 2013)
- Suspended or free-spanning ice cover (along high gradient channels; e.g., Turcotte et al., 2012)
- Frazil (mostly, but not exclusively forming along high gradient channels; e.g., Daly, 2013a)
- Anchor ice (along any channel with enough flow turbulence; e.g., Malenchak and Clark, 2013; Nafziger et al., 2017a)
- Ice dams (mostly along high gradient channels, e.g., Turcotte et al., 2011a)
- Thickened freeze-up ice jams (mostly downstream of high gradient segments or in regulated channels; e.g., Beltaos, 2013; Clark and Wall, 2016)
- Hanging dams (mostly downstream of long stretches of high gradient channels that remain open during many days to weeks during winter; e.g., Beltaos, 2013)
- Aufeis (mostly, but not exclusively along sub-arctic and arctic braided channels; e.g., Daly, 2013b)
- Breakup ice jams (mostly, but not exclusively, against obstacles and at locations where the flow velocity decreases, e.g., Beltaos, 2008)
- Ice runs and javes (mostly downstream of ice jam sites, e.g., Jasek and Beltaos, 2008; Nafziger et al., 2016)

Beyond the ice cover type and possible ice processes, hydrological processes such as severe freeze-up discharge recessions, mid-winter runoff events, low late-winter flows and potentially sudden rises in discharge during the spring should also be anticipated and documented. The instrumentation strategy, including instrument types, installation and retrieval dates, anchoring systems and locations, data acquisition rates, security issues, and maintenance frequency will all significantly depend on the nature and intensity of expected ice and hydrological processes. For example, underwater optic and sonar instruments may not deliver the expected data in the presence of entrained bubbles or anchor ice, Also, water depth sensors will not provide usable data if they either emerge or become frozen in thermal ice during critical periods.

2.2 Parameters of interest

For engineering purposes, the most common parameters of interest to be estimated or quantified along streams and rivers during the winter period include:

- Water discharge,
- Water depth and velocity (including two-dimensional velocity distribution)
- Water temperature
- Surface ice concentration and drifting ice discharge
- Channel ice coverage
- Streamwise ice front location and progression rate
- Ice cover thickness and composition as well as ice cover carrying capacity
- Ice accumulation thickness and extent
- Ice temperature gradient
- Ice-water interface elevation
- Frazil concentration in the water column
- Ice forces on structures such as dams (e.g., Kharik et al., 2015)

In addition, engineers and scientists may be interested in documenting other winter processes:

- Erosion and sedimentation rates as well as channel mobility
- Sediment transport rates (bedload, suspended load and ice rafting load, e.g., Turcotte et al., 2011b)
- Flood zones and flood envelopes in the presence of ice (e.g., Burrell et al., 2015; Turcotte et al., 2017)
- Various environmental parameters including dissolved oxygen, pH, and contaminant concentrations (e.g., Turcotte and Morse, 2017)

Important complementary meteorological data is often required to understand and simulate observed or expected ice processes. At a minimum the air temperature should be measured. If a more accurate estimation of the heat and hydrological budgets (that largely dictate ice processes) is required, other key parameters may include:

- Atmospheric pressure
- Net radiation (shortwave and longwave)
- Wind speed and direction
- Humidity
- Precipitation (solid and liquid, which also affects ice processes and types)
- Snow depth or snow water equivalent

Important complementary information to simulate a heat budget include latitude, channel gradient, channel shading by riparian vegetation and topography, groundwater temperature and fluxes as well as bed heat. More information on the topic is available in Ashton (2013) for large channels and in Dubé et al. (2015) for small channels. Additional information about river ice-related parameters is presented by Hicks (2016).

For numerical simulations of river and ice processes using hydrodynamic models, a more or less detailed floodplain, river bank, and in-channel topography will be needed. Water surface elevations at various locations, discharge estimations and ice thickness measurements or estimations will enable an adequate calibration of the model.

3. Experience from various rivers

This section presents an overview of the methodology and success rates associated with various river ice survey projects in very small to very large channels in temperate to sub-arctic regions. More information about each research project can be found in the cited literature.

3.1 Small rivers in Quebec, Canada

Channels of different sizes and morphologies in the Montmorency River and Etchemin River watersheds (Appendix A) were instrumented with the purpose of documenting hydrological, environmental, and river ice processes at the watershed scale (Dubé et al., 2015, Turcotte et al., 2012, 2013, 2014; Turcotte and Morse, 2017). The success of this study depended on the reliability of various instruments including water pressure sensors (Onset HOBO U20), water depth and velocity sensors (Teledyne ISCO 2150), multi-parameter sensors (YSI 6600 V2), light and water temperature sensors (Onset HOBO UA-002-64) as well as cameras (Canon 20D with automatic shutter) and air temperature sensors (Onset HOBO Pro V2). Onset sensors were autonomous for the entire winter whereas the batteries or internal memory of other instruments had to be changed every 15 to 60 days. This limitation imposed the planning of regular field visits (about twice a week) that turned out essential to understand and adequately document ice and channel conditions.

Quantifying, predicting and mitigating ice-induced floods has been the purpose of current studies conducted along tens of kilometers of the Montmorency and St. Anne Rivers (Appendix A), including their respective tributaries (Turcotte et al., 2016; Vergeynst et al., 2017). In addition to regular observation field trips and estimated discharge data provided by the provincial government, automated instruments have been deployed under water (Onset HOBO U20, YSI 6600 V2, RBR Solo T) and along the banks (Canon 20D and Onset HOBO Pro V2) for many consecutive winters (November to May).

Aquatic instruments were systematically placed in perforated PVC tubes, mounted on steel plates, and anchored in sediment using rebar pins, or steel cables or chains (Figure 1) at sheltered locations. These were manually installed in the fall and retrieved after the snowmelt period, most often in less than one meter of water. In turn, air temperature sensors and cameras (placed in modified Pelican cases; Figure 2) were fixed to trees and retrieved at the end of the ice period. Over the years, the success of finding intact instruments and retrieving the anticipated data ranged from 60% to 95%. The lowest success rates were caused by (1) batteries failing (instruments exposed to cold atmospheric conditions), (2) by humidity or water intrusion, (3) by teared out anchoring systems (under unexpectedly dynamic ice processes and erosion), and (4) stolen instruments by presumable badly intended or ignorant individuals.

3.2 Small rivers in New Brunswick, Newfoundland and Alberta, Canada

Three small rivers in northern New Brunswick, and four in central Newfoundland as well as the Kananaskis River in Alberta (Appendix A) were studied with the purpose of documenting the meteorological and flow conditions that lead to various ice conditions and to determine how regulation for hydropower production impacts ice conditions, and depending on the study, salmonid embryo survival, and hyporheic processes. These studies extended for the entire ice-affected season and captured both freeze-up and breakup (Nafziger et al. 2011, 2013, 2017a, and 2017b).

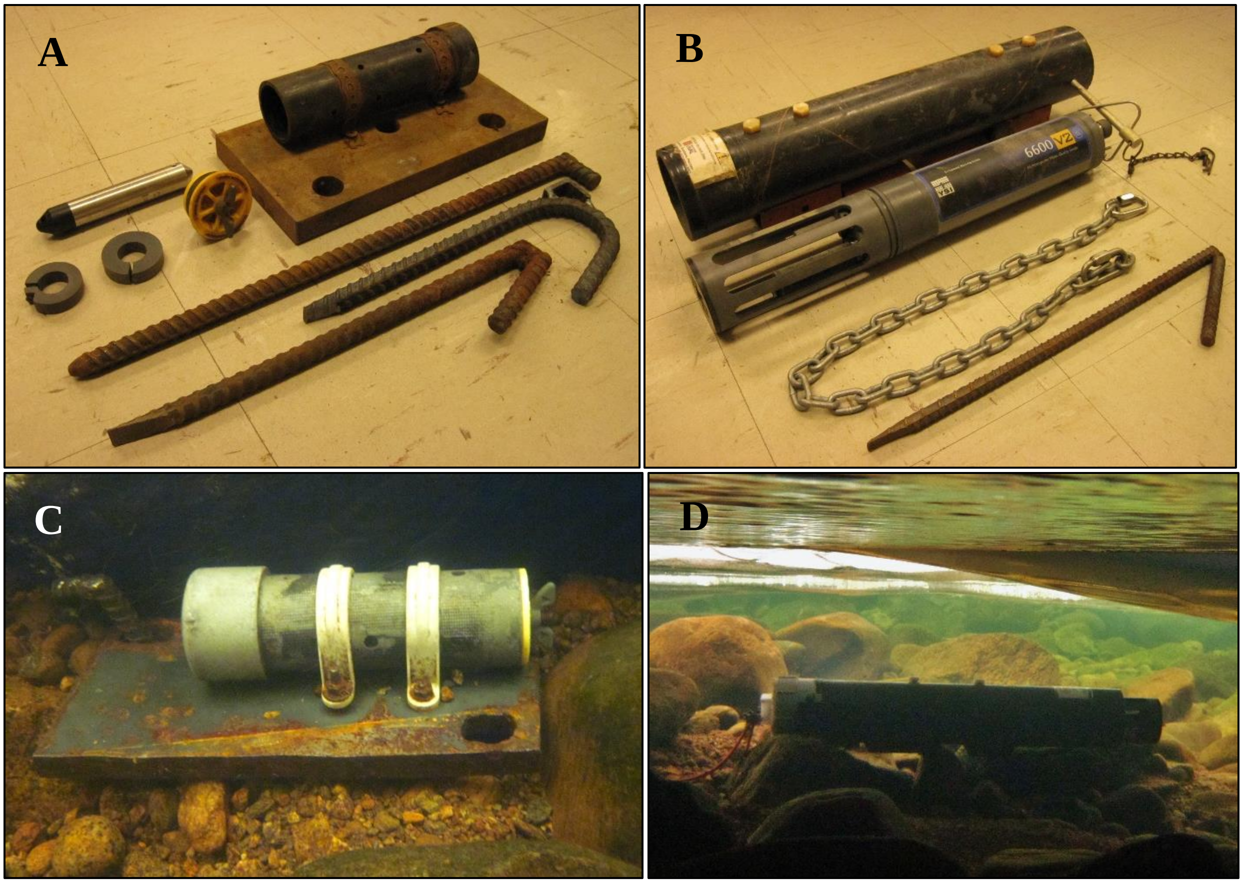

Figure 1. (A) HOBO U20 sensor with plastic rings, PVC tube attached to a steel plate and different shapes and lengths of 0.5 inch rebar anchors, (B) YSI 6600 V2 with PVC tube mounted on steel plates, with a chain and a rebar, (C) HOBO U20 installed underwater and (D) YSI 6600V2 installed underwater.

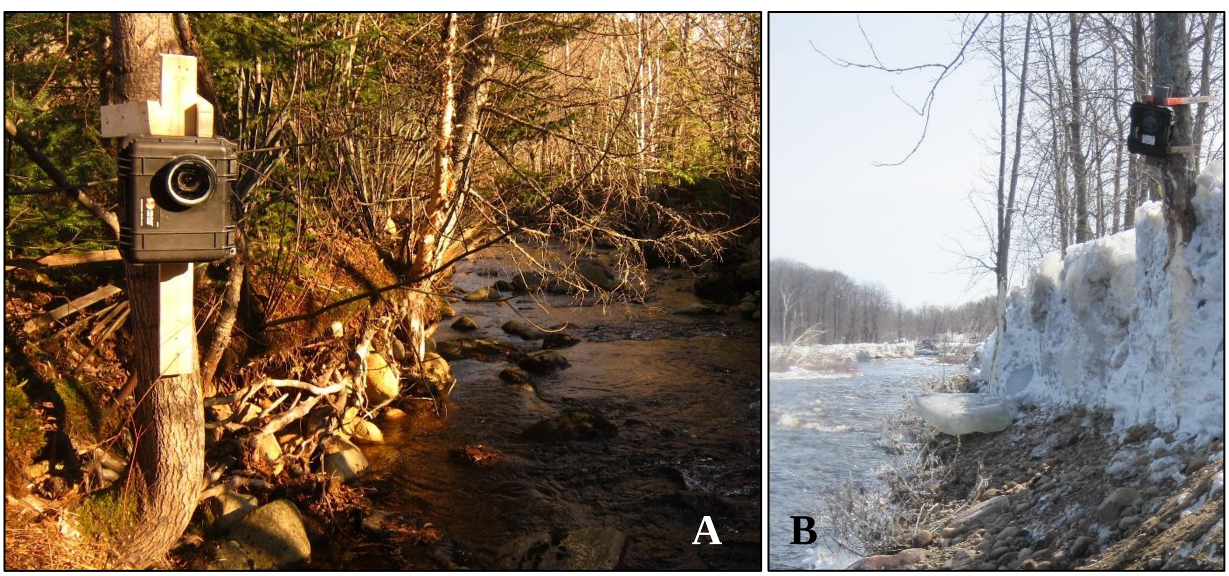

Figure 2. (A) Canon 20D camera installed on a tree on the side of a small stream in the fall and (B) Camera almost damaged by a major spring breakup event on the side of a large stream.

Ice conditions were observed using time-lapse cameras (Reconyx and Moultrie) mounted on trees or posts. Camera failures were common, especially during cold or damp conditions and the most expensive cameras (by Reconyx) failed the least often. However, in warmer and dryer conditions during breakup, even relatively inexpensive cameras (i.e. 1/10 the cost of Reconyx) performed well.

Water levels were measured using Diver pressure transducers/temperature loggers (Schlumberger Water Services, now Van Essen Instruments) or with similar instruments manufactured by Onset HOBO. At sites where dynamic breakup conditions were expected, these instruments were attached to the inside of perforated heavy steel cases which attached flush with the bed using heavy rebar pins and, over 5 years, recovery of these instruments was about 90%. In the smaller streams, the instruments were attached to cinderblocks (Figure 3) which were tethered to the bank using steel cable and, over 2 years, the recovery rate was also 90%. The use of custom-sewn geotextile "socks" prevented silt intrusion; without which, irreparable damage and data loss occurred in several cases in one silty stream.

Figure 3. Cinder block anchor and cable tether for autonomous water level and temperature sensor on a small stream where dynamic ice processes were not expected.

Finally, water temperatures were measured using instruments of various accuracies (Onset HOBO TidbiTv2, Vemco Minilog-II-T, RBRSoloT, and the Schlumberger Diver instruments), as explored in Nafziger et al. (2013). These instruments were installed in the same manner as the water level instruments when measuring surface water temperature, and in either dug or driven holes in the riverbed when measuring hyporheic temperature (see Nafziger et al., 2017b).

3.3 Dauphin River, MB, Canada

The Dauphin River (Appendix A) has been heavily instrumented in recent years in an attempt to better understand the processes involved in the formation of a consolidated ice cover during freeze-up (Clark and Wall, 2016). During the 2016 freeze-up period 16 Solinst water level and temperature logger (Model 3001) and six high accuracy Sea-Bird water temperature loggers (SBE 56) were installed at various locations along the riverbed. All loggers were covered with a silt sock and secured to heavy-gauge sections of angle iron, and most of these instruments were then secured to the river bed with 0.5 inch rebar. In several locations the angle iron was instead tethered with steel cable to a mature tree or anchor point bolted to bedrock. The instrument locations were immediately logged with a hand held GPS. A Solinst barologger was also deployed to measure barometric pressure to facilitate water level measurement compensations.

The study also involved deploying a weather station that consisted of: 3 m high tripod (UT10, Campbell Scientific) with an air temperature and relative humidity sensor (HC2-S3-L, Rotronic), wind monitor (05103-10, RM Young), barometric pressure sensor (CS106, Vaisala), net radiometer sensor (NRLITE2, Kipp & Zonen), and data logger (CR1000-XT). A second tripod was equipped with an outdoor camera (CC5MPX, Campbell Scientific) and a high accuracy water temperature probe (RBR Virtuoso T) linked to a satellite modem (9552B Iridium, Campbell Scientific). The camera sent daily images to a website which facilitated the timing of observation field trips. Time-lapse images were also acquired along the length of the river with Moultrie M-1100i trail cameras mounted to mature trees in order to document the timing of certain freeze-up events and facilitate estimates of surface ice concentration. During field visits an unmanned aerial vehicle (Phantom 2 Vision+) was used to provide a top-down view of incoming ice pans and ice shoving events. Over the course of the project thus far equipment has been lost due to river bank failure, ice scour, ice encompassing trail cameras, and fallen trees. A couple of instruments have failed due to battery issues and unknown manufacturing defects.

3.4 Saint John (NB), Mackenzie (NWT), and Athabasca Rivers (AB), Canada

Recent studies by Environment and Climate Change Canada of ice breakup processes in upper Saint John River (NB). Mackenzie River and Delta (NWT), and Athabasca River near Fort McMurray (AB; Appendix A) have focused on the spatiotemporal variation of the water level. This information can be used to calibrate numerical models and quantify key hydrodynamic variables (velocity, discharge, shear stress). Accordingly, the field components of these studies were designed around the central requirement of obtaining detailed water level-time variations at numerous locations along the study reaches during the ice breakup event.

All three study reaches contain permanent (federal government) water level gauges but these are too far apart to supply the necessary information and frequently malfunction during breakup, as the orifice lines are dislodged or torn by ice. Moreover, they record water level at 5 to 15-minute intervals, which may be far too coarse for analysis of severe ice jam released waves (javes). Portable pressure loggers (some of them also measuring the water temperature), of the kind depicted in Figure 4, have proven to be effective and robust means of obtaining practically continuous water level recordings during the breakup period (Beltaos et al. 2011; Beltaos 2014). These instruments contain a logger-and-transducer combination manufactured by RBR Ltd. They are designed with single and dual channel capabilities; the pressure (DR-1050 series) and pressure/temperature (TDR-2050) options were used in this study.

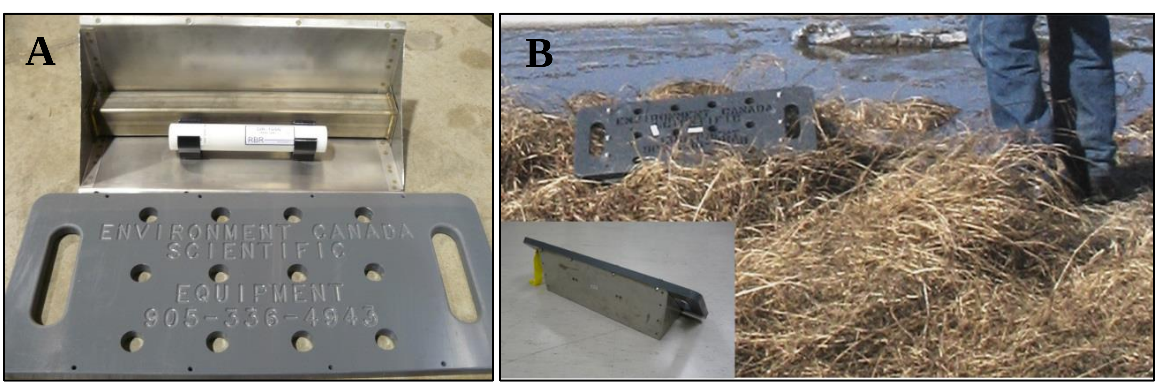

Figure 4. Logger deployment. A: transducer, metal casing, and 0.6 m long PVC lid. B: field deployment and rear view (inset). Logger assembly weighs ~45 lbs, including a lead weight inserted for stability.

The loggers were placed at relatively sheltered sites on the river banks shortly before the commencement of breakup (April on the Saint-John River, May on the Mackenzie River and Delta channels) and their elevations were tied to nearby TBMs (Temporary Benchmarks); they recorded total pressure at pre-programmed time intervals (5 seconds in the present study); the difference from the (separately recorded) prevailing atmospheric pressure was then converted to depth of water above the sensor. In late summer or early fall, the loggers were retrieved and the geodetic elevations of the corresponding TBMs was determined using GPS technology and gravimetric geoid data.

Loggers can be damaged or lost due to theft or, more commonly, due to ice and water action. Out of a combined total of 28 loggers that were deployed on the Saint John and Mackenzie Rivers, only one logger was lost as a result of massive bank erosion. For deployments along the Athabasca River, 6 loggers out of 41 were lost because of massive bank erosion and ice gouging attributable to the extremely dynamic ice jams and javes. The triangular casing of a few loggers was damaged or moved by ice action. In the latter case, the logger readings had to be adjusted by comparing the water level signal to that of nearby loggers.

Visual recordings of the breakup process at various logger sites can provide valuable material that can assist data interpretation and analysis. Time-lapse cameras were installed at key locations along the Athabasca River in April of 2013 and programmed to last for at least a month, taking one image per minute. Despite manufacturer specifications, the set of cameras only recorded a few images, possibly due to weak batteries. A new set of cameras were purchased for the 2014 breakup and, together with the old ones, were equipped with lithium batteries; the enhanced set performed satisfactorily. Periodic aerial and/or ground-based reconnaissance of ice conditions along the entire study reach, with GPS-referenced video and photography supplied important ancillary information.

3.5 Peace River, AB, Canada

Significant ice issues can occur along the regulated Peace River (Appendix A) and its very long length (1240 km) makes meaningful monitoring a challenging and expensive. A large quantity and diversity of data have been collected over the decades to support ice jam flood mitigation, to optimize hydropower production and to assess new hydroelectric projects (Jasek, 2006, Jasek and Pryse-Phillips, 2014, 2015, Jasek et al., 2015). These have consisted of permanent, real-time water level gauges, temporary gauges consisting of submersible water level/temperature loggers, Shallow Water Ice Profiling Sonar (SWIPS) and remote cameras.

Typically, approximately 20 Solinst water level/temperature loggers and RBR Solo T water temperatures loggers are deployed in October and retrieved in May or early June, and the loss rate per ice season, which is about 1%, have been attributed to ice action. Leaving retrieval to late June or later increases the risk of debris collecting on the sensors and cables from summer rain induced high flows increasing the probability of sensor loss up to 15%. To minimize movement by anchor ice, freeze-up consolidation ice jams and dynamic break-up, anchors made of steel are used (often used grader blades readily available from local municipal or provincial road/highway maintenance departments, or from snow removal contractors). Instruments are inserted in an electrical PVC tubing and attached to the steel anchor using U-bolts (Figure 5).

Figure 5. Anchoring system for autonomous water level and temperature loggers (PVC tube tied to a grader blade using U-bolts)

Loggers are normally deployed about 50 m from shore in the deepest water possible using a boat (a depth sonar can identify deep locations), but also from the banks. In the latter case, steel rebar (with a 90 degree bend at the top) is used to secure the grader blade to the river bed. For the deeper installations, loggers are retrieved by boat by following the cable from shore and pulling upwards. A barometric pressure reference is normally deployed in a nearby community, ideally in a heated municipal building such as a water intake.

Real time water level gauges consist of a standard steel shelter housing located on the river bank with a data logger and HDR GOES transmitter, a Constant Flow Bubbler and a Pressure Transducer (all instruments supplied by Sutron). A secondary water level gauge (KPSI 355 Small Bore SDI-12) is often deployed at the same site. The bubbler line and secondary pressure transducer cable are both armored with steel cables and their ending (bubble orifice and transducer) is tied to a grader blade. One of these real-time installations uses a downward looking Sommer acoustic sensor for discharge estimation, based on a water level detection signal and a stage discharge relationship. Because the speed of sound depends on air temperature -a parameter that can vary significantly between the sensor and the river surface- this instrument has only been used to obtain discharge trends. Sommer does now make a radar version of this instrument which is not susceptible to air temperature errors.

The SWIPS was originally mounted to a concrete base that proved to not be dense enough as anchor ice build-up would tend to uplift, change the angle or even flip the platform upside down causing data loss (Jasek and Marko, 2007). A subsequent metal pyramid attached to both river banks with steel cables was lost because of anchor ice built up on the cables that generated floatation (this produced enough drag and ice floes pressure to snap both cables). The new, successful, SWIPS platform now consists of a large pyramid made of heavy steel and covered with Teflon (Figure 6) to minimize anchor ice adherence. This platform is then heavily attached to a single river bank using a steel cable. Surprisingly, anchor ice can still develop on the platform if the 500 W internal heater malfunctions, which can cause acoustic beam blockage (Marko et al., 2017). Deployment is performed with a boat mounted crane (Figure 6) and tilt sensors are activated during the operation in order to reposition until it is determined that the instrument is pointing near vertical. The instrument is retrieved in the summer by dragging it onto shore with a vehicle.

Figure 6. Instrument platform housing Multi-frequency SWIPS and Teledyne ADCP.

3.6 St. Lawrence River, QC, Canada

Ice on the St. Lawrence River (Appendix A) forms within three distinct environmental regimes. Ice west of Quebec City develops initially as frazil pans which subsequently coalesce within quieter stretches of the river. East of Quebec City, the river becomes brackish, with tongues of salty water intruding during high tides. Finally, estuaries abound along the coast east of Quebec, where fresh water and salt compete for space at the ice-water interface. The ice regime of this complex environment has been the topic of many studies and surveys, mostly because the St. Lawrence is open to commercial navigation down to Montreal throughout winter. Overviews of ice motion and development on the St. Lawrence have been made using digital time-lapse cameras from high points along the banks, as well as flyovers using Infra-red cameras (Richard and Morse, 2008; Emond et al., 2011). On a larger scale, the Canadian Ice Service, an operational unit of the Meteorological Service of Canada, provides information and warnings regarding ice conditions in Canadian waters on a daily basis. Water levels are available real-time from the Canadian Hydrographic service.

Fast ice sheets under both fresh water and brackish conditions have been studied extensively along the St. Lawrence (e.g., Morse, 2011). The effect of ship transport on the integrity of shorefast ice has been studied by attaching long wire displacement transducers (RVDTs) to the ice cover, and lowering the attached wire to the bottom of the river (Stander et al., 2005). Ice growth under brackish water tidal conditions has been studied by profiling the underlying waters using YSI SCT meters, and subsequently thin sectioning cores were collected from the estuary (Morse et al., 2002). Ice thickness has been measured by using a shore-based laser rangefinder oriented 45 degrees to the ice surface, which gave the sail height of the ice with respect to the underlying waters and provided the added benefit of surviving spring breakup. Lasers have also been used to profile ice accretion on structures, while real-time ice concentration, thickness, and the kinetics of jamming events have been measured via ADCP.

Recently, an attempt was made to measure frazil concentration parameters across the length of the St. Lawrence using multiple instruments welded to the bottom of a container ship including a RBR Solo T, a YSI 6600V2 (with an optic turbidity sensor), a Seatech transmissometer (used to collect frazil data; Pegau et al., 1996) and a small scale polarimeter (set of crossed polarizer sheets photographed over time using a Brinno time-lapse camera used to discriminate between ice and other organic and non-organic matter). An attempt was also made to measure the adhesion of frazil using underwater cameras and a MTI Microcap capacitance sensor (based on the dielectric difference between water and ice). Unfortunately, the field reliability of these devices could not be tested due to loss of the instrumentation package at some point during the season, though all showed promise in the laboratory.

3.7 Rivers of Norway

Ice has been recently monitored on several rivers in Norway. On the regulated Orkla River (Appendix A) ice formation (Reconyx Hyperfire, Moultrie I65), water temperature (Seabirds SBE39 and SBE56 as well as Vemco Minilog II) and local meteorological conditions (Campbell Scientific temperature sensor, humidity sensor and data logger, Young wind sensor and Kipp and Zonen net longwave and shortwave sensor) have been monitored with the purpose of testing and using the MIKE-ICE model to investigate the impacts of regulation and climate variations on ice processes (Timalsina et al., 2013). Underwater cameras (a custom-built system using a cabled underwater camera and a Sony videorecorder) have been tested to capture the details of anchor ice buildup but no quantitative data has been extracted from the pictures, in part because of anchor ice accumulation on the camera and because of a limited operational period. The formation of ice dams and icing along the Sokna River (Appendix A) has been monitored over several years using automated bank side cameras (Reconyx Hyperfire and Sony videocameras with time-lapse or a custom built triggering device) and temperature sensors (Seabird SBE56) (Stickler et al., 2010; Timalsina, 2014). In addition, locations of anchor ice dams have been manually measured using a GPS system (Leica and Topcon). Ice thickness (using a Kovacs ice thickness kit) has also been measured in both the Sokna River and the Ingdalselva River (Appendix A) as a foundation for determining triggering factors for ice breakup (Heggen and Alfredsen, 2013).

One intake of the Dyrkorn hydropower plant on the Dyrkorn River (Appendix A) has also been recently instrumented with:

- A Shallow Water Ice Profiler (SWIPS by ASL, to evaluate the depth of frazil in front of the intake and to estimate the total frazil production),
- Pressure transducers (Onset HOBO U20, Schlumberger Diver),
- Water temperature sensors (Seabirds SBE39 and SBE56, located at the surface and at the bottom to study the distribution of supercooled water)
- A wild life time-lapse camera (Reconyx Hyperfire)

The purpose of this setting is to further document the winter operation procedure of a second intake and to study the efficiency of a suction intake to mitigate the impact of frazil transport. Moreover, the combination of SWIPS and meteorological data is used to define critical frazil conditions at the intake (Kovanen Sæten, 2016).

The experience with the Moultrie and Reconyx cameras are in general very good. The Moultrie has been powered by an external battery and have lasted over the winter in all cases as long as the air temperature remained above -15^{o}C while the Reconyx Hyperfire has performed adequately with standard Lithium AA batteries and has never failed in any of the deployments. Cameras have been installed in protective housing for safety and to provide an additional protection against snow.

Most of the Seabird, HOBO and Diver sensors deployed over the years have been mounted in metal or heavy plastic pipes on the river bed, anchored to concrete blocks or rocks. Pressure sensor were georeferenced and an atmospheric sensor was deployed nearby to evaluate the absolute water pressure. In turn, the less expensive but robust and reliable Vemco Minilog II sensors were usually fastened to heavy objects on the bottom and anchored to the bank with wire or nylon rope, or placed into the bed substrate. The SWIPS was mounted on a custom designed iron platform with moveable supports to keep the instrument level.

The deployment of bottom mounted instruments has generally worked well, but both a Minilog and a Diver have been lost most likely due to the anchoring wire getting frozen into the surface ice and then cut and transported away during ice breakup. The Minilog temperature sensors performed well, but needed to be checked for small measurement deviations. Some problems with the accuracy of Seabird was solved by returning it to the manufacturer for calibration.

3.8 Small rivers in Northern Sweden

River ice processes in several small streams of the Ume and Vindel River watersheds (Appendix A) were monitored during 2011-2013 with the objective of improving our knowledge of ice formation in small streams (Lind et al., 2016). Both rivers originate from the Scandes mountain range and merge 40 km upstream of the Gulf of Bothnia in the Baltic Sea. A total 25 sites along 19 tributaries (draining 9.5 to 225 km^2) of width smaller than 25 m were surveyed and instrumented. Ice formation processes were documented by frequent observational surveys and using automated cameras (Model WSCA04, Wingscapes). Water temperature, air temperature and water pressure were recorded using Stevens Diver sensors. IButtons temperature data loggers (DS1921G, Thermochron, Maxim Integrated Products) within silicone waterproof enclosures (Signatrol) were used as a backup to determine the occurrence of overbank flooding. Hydraulic conditions and discharges were measured punctually over time using a hand-held velocity recorder (Valeport, Model 801).

Side cameras, set in time-lapse mode, were tied to trees close the river bank with elastic straps. They stopped working when experiencing (1) very cold temperatures (below -15°C) or (2) humid (with air temperatures above 0ºC) conditions, but they could be manually restarted afterward. Diver sensors were installed and anchored using perforated plastic tubes that where attached in the bed substrate or river bank with rebar, zip-ties and nylon rope. In most cases the tubes were placed at sheltered locations. The sensors were installed during summer and retrieved after three years. They were still working after each winter, and only two of them had been affected by transient freezing of the stream bed. Finally, IButtons were placed into nylon mesh bags that were attached to the floodplain ground using tent pegs. About 95% of the IButtons were still working after one winter season (as long as their enclosure remained intact), but their data handling process was time consuming.

4. General considerations about instrumentation

An increasing diversity of instrument types exist on the market to provide direct and indirect aquatic and environmental parameter measurements. User needs, technological development, and competition among the scientific instrument developers contribute in constantly improving sensors accuracy, battery and memory capacity, communication means, as well as global reliability under harsh conditions while adapting their dimensions and weight to specific requirements.

There are different options to obtain river ice and winter environmental data:

- Remote autonomous instrumentation
- Real-time autonomous instrumentation
- Punctual field monitoring
- Remote sensing

Choosing one or a combination of options will influence the monitoring strategy and the type of instruments that will be used or purchased. Before choosing the best instrument that addresses the study needs, it is important to determine:

- The specific event or process to document and the associated parameters to monitor
- The suitable data acquisition rate (dynamic river ice breakup processes need a higher acquisition rate than gradual freeze-up processes)
- The coldest expected temperatures (aquatic instruments that are adequately located are only exposed to a temperature of 0°C whereas instruments installed [in or more likely] above the ice cover will be exposed to much colder temperatures)
- The maximum expected parameter range and the desired accuracy (some sensors offer a trade-off between precision and range)
- The battery duration (considering the temperature, winter duration and acquisition rate)
- If cabled or non-cabled data is preferable (cables enable the download of aquatic sensors and are used to confirm their status, but they significantly increases the probability of damage by water, ice, erosion, and animals)
- If real-time data is required (this can complicate the installation and it is associated with additional costs, but instrument malfunctions can be identified immediately and data availability contributes in planning effective study site visits)
- The available budget (which should be reasonable, considering the risk associated with unreliable or unrepresentative measurements; i.e., The conception of an expensive infrastructure such as a bridge or a dam may justify a comprehensive river monitoring campaign and project managers should contemplate the risk associated with ice and winter)

Sales representatives are often helpful for specific requests regarding complex field surveys and research projects, and will propose what they believe to be the appropriate instruments, if the needs are clearly expressed. Some retailers may even have enough experience to recommend what parameters should be monitored to adequately quantify specific ice and hydrological processes. Therefore, they should definitely be consulted while defining the monitoring strategy. It is important to mention that suppliers can rarely guarantee that their instruments will perform adequately under harsh ice and hydrological conditions and they cannot be held responsible of instruments loss due to natural or anthropogenic reasons.

5. Planning a successful river ice monitoring program

Before going in the field, it is important to recall what parameters will be monitored, if the instrument protection and anchoring system allows these parameters to be adequately measured, and if the planned deployment period is acceptable. The following subsections present a list of answers to questions that should be considered prior to the final approval of a river ice monitoring campaign and strategy.

5.1 Underwater autonomous installation

Before leaving expensive instruments in the field, under or in the ice, for a prolonged period of time, the following points should be considered:

What?

- The water pressure (depth, stage, or georeferenced water elevation) and temperature are among the most commonly quantified parameters in river ice studies. They represent direct indicators of most ice and hydrological processes taking place along any channel and they can be monitored relatively accurately and inexpensively. When the interpretation of other parameters becomes uncertain (e.g. images, signals, flow velocities, etc.) a reliable water level or temperature data set can be used as a complement.

How?

- Most sensors sold on the market need to be protected and anchored to resist hydraulic, sediment and ice forces, and they cannot simply be deposited on the river bed, even at apparently low velocity locations. The most reliable installation normally consist of: (1) a perforated enclosure (that allows water to reach the sensor) made of plastic (to help prevent ice accretion) into which the sensor is placed; (2) a perforated heavy plate (that stabilizes the installation and lowers the center of gravity) on which the enclosure is mounted; and (3) an anchoring system to attach the unit to the bed below the ice using steel bars with an inverted “J” or “L” shape (that allows easier retrieval using a pick axe or a comparable tool).
- Instruments should be held in place inside the protective casing using strong fasteners. Plastic ties should be avoided, especially where dynamic hydrological events are expected.
- The research team should make sure that the instrument and its protective casing do not affect the parameter to be monitored (e.g., velocity, turbulence, ice accumulation, etc.). This is particularly critical when measuring structural ice parameters because the instrument itself can affect the force field and temperature gradient.
- If the sensor head, often the most vulnerable part of the instrument, needs to be exposed to the flowing water, it should be oriented downstream, unless a frontal measurement is needed (e.g., flow velocity). This reduces the probability of damage by drifting debris, gravel and ice.
- The gap between the sensor and the protective tube (or casing) could become filled by fine to large sediment particles. In gravel-bed channels, the largest particle that fits into this gap could lead to the instrument jamming in the tube. Using a flexible tube or flexible foam lining inside a rigid tube could mitigate this problem.
- Anchoring an instrument to the banks using a cable should be avoided, because ice may grow on it and it may snag woody debris and ice floes. In smaller rivers, the anchoring cable could be installed in the plume of a warm effluent (anthropic heat or phreatic heat from headwater channels) that will prevent ice formation. In larger river systems, the anchor cables should be

heavy, especially where anchor ice formation is expected. In any case, burying or covering the cable should be considered.

- Redundancy by installing two (identical or similar) instruments not far apart can prove valuable, especially in exposed areas or if obtaining the data at specific sites is more crucial than retrieving all instruments.
- If the instrument uses desiccant, it should be as dry as possible, as should the inside of the sensor's protective casing prior to deployment. Leaving the instrument open in a heated and dry room for 24 hours prior to deployment may maximize desiccant lifespan. O-rings and other barriers should be inspected and maintained prior to deployment.
- If cable-free sensors are not an option (e.g., real-time communication, to measure absolute water depth) the communication / external battery cable should be appropriately protected, anchored and buried, especially on the emerging part of the banks. Care should be taken not to crush the cable under the anchors, especially in the case of bubblers or vented instruments. Note that plastic or rubber cables are often chewed on by rodents such as beavers, porcupines and squirrels, and may need additional protection.
- Taking notes and photos of the instrument setting and the anchoring system (how long are the anchor pins, how heavy is the ballasting plate) could save some valuable time and minimize frustration when retrieving the instrument.

Where?

- Most of the time, there is a macro site selection process (within several channel widths) and a micro site selection process (within several meters).
  - Macro site selection must consider (1) access and private properties, (2) exposure to specific ice processes (pools and low flow areas may be associated with frazil accumulation, outer bends may be associated with ice push and abrasion at breakup, and inner bends may be associated with shallow water that freezes down to the bed), (3) major tributary (plumes of distinct physicochemical characteristics), (4) the presence of multi-channel or island sections, (5) substrate characteristics, (6) channel depth, and (7) riverbank topography (including unstable banks).
  - Micro site selection will involve finding the optimal spot along the identified area. It is important to understand (1) that any sediment, from fine grains to large boulders, can be moved by water or ice, (2) that significant sedimentation (low flow) and erosion (high flows) may occur around and downstream of the largest boulders, and (3) that thermal ice may migrate down to the bed at low flows and may develop around large emerging boulders and bridge piers to significant depths. Therefore anchoring the instruments downstream of a bar or of a large, flat rock that remains submerged during winter seems more appropriate.
- The formation of thermal ice may encapsulate aquatic sensors and cause data loss and irreparable instrument damage (especially for pressure transducers with relatively fragile membranes). The instrument supplier could provide some information about the potential resulting damage.
- Protecting temperature sensors from ice abrasion and erosion by placing them under the surface layer of the substrate should be avoided because the presence of heat from the bed and groundwater influxes can affect the results. Recent studies in the Ste. Anne River (Appendix A) have measured supercooling conditions in the main flow (-0.001^{o}C) and 0.75^{o}C

under a 0.2 m substrate layer at the same location. In contrast, pressure transducers can generally be anchored under a thin layer of sediment.

- The installation site often looks completely different at the time of retrieval. The growth of riparian vegetation, different water levels and morphological activity (or simply a few snowstorms for a winter retrieval or maintenance; Figure 7) may completely change the landscape and any reference point. Finding the instruments may be facilitated by:
  - Geo-referencing the instrument (as precisely as possible)
  - Using markers or survey tape (bright colors contrasting with the landscape at remote sites, and dark, subtle colors where people may transit)
  - Taking pictures from different angles
  - Measuring the instrument location from two or three distinct points (such as mature trees or large boulders located upstream or downstream of the location)
  - Writing a description of the site and location and making a detailed drawing
  - Installing a device that will deploy a buoy after the ice period (in the case of a deep deployment)
  - Using a metal detector during the instrument retrieval campaign. This may be tested at the time of installation because some river beds are filled with anthropogenic or natural magnetic material. Survey-grade pin finders have been found to work more reliably than consumer-grade brands.
  - Attaching passive inductance transmitter (PIT) tags to instruments, and using a PIT antenna to find them; however, any metal enclosures may shield the PIT tags
- If the area shows signs of recent beaver activity, changing location or installing cable-free sensors should be considered. Beavers have also been associated with thinner ice.

Figure 7. Ice and snow making mid-winter instrument retrieval challenging on a small stream. (Photo courtesy Paula Thoms)

When?

- It is preferable, if possible, to wait until the water level has receded as much as possible before installing underwater instruments. This will facilitate the installation at desired locations and elevation. In some cases and situations, however, the installation can occur weeks in advance of the ice season, which would allow the monitoring of a few pre-winter runoff events that can provide valuable data sequences, which can be used as a comparison against winter sequences.
- Loggers can be started before submersion, which, in the case of pressure sensors, will provide a first, reliable initial water depth measurement (if the acquisition rate is smaller than any expected water level variation). This is useful if only one reference atmospheric logger is used as a reference, especially if it is located far (many kilometers or at tens of meters in difference of altitude) from a number of instrumented sites. Atmospheric pressure loggers should be installed *before* water level loggers.
- Water level loggers should be surveyed once deployed if the measured depths are to be later converted to elevation above a datum. Surveyed at both installation and retrieval will also help assess whether the loggers have moved during the ice season.
- If possible, instruments that have been deployed in the field should be inspected prior to the most important part of the monitoring period. Investing time and resources to make sure that instruments are still in place and intact can save a seasonal data set. During such field trips, repair and maintenance kits, replacement instruments and extra batteries should be brought.
- Field trips should always be carefully planned in terms of expected weather and hydrological conditions and enough time should be allowed for adequate installation to be performed. Unexpected delays should always be expected and budgeted for.
- Involving experienced field personnel will make the field trip more successful and efficient. Including people that are familiar with the channel reach to be monitored may also contribute in saving time in the field. Although their testimony is important, it should not be assumed that local residents and workers provide accurate and comprehensive information (they could express their past observations using expressions and a terminology that is different from what is scientifically accepted). Therefore, it is suitable to perform an initial expert assessment, and then to objectively compare this interpretation to local, non-scientific sources.
- Instruments should be retrieved as soon as possible once the target processes have ended. This reduces the potential instrument damage or loss due to natural hazards or human activity.
- Time changes between daylight savings time and standard time can pose a problem for instrument data collected during a winter research program because time changes may occur during the time the instrument was deployed. For example, instruments may have been programmed and installed during daylight savings time, but may be downloaded during a mid-winter trip, causing the instrument's time stamp to synchronize with the standard time on a field laptop. This would cause a time shift in the recorded data. One solution is to set up all instruments to have time stamps in standard (winter) time. The manner in which time changes are handled by the instrument firmware and by data analysis programs should be understood and notes should be taken during instrument setup and downloading that includes the exact time, time zone, and whether the instrument time stamp was set in daylight saving time or standard time.

5.2 River bank installation

Before leaving autonomous instruments in the field, it is preferable to test them in a cold environment (e.g., a cold room, industrial freezer). Many authors reported problems with cameras and batteries, either because of cold temperatures or humidity. This advice may apply to other types of instruments.

What?

- There is an infinite number of ways to miss the observations of an important ice event or phenomena, dynamic breakup probably being the most common because it is important for design purposes and because it can occur in a matter of minutes. Most authors of this paper have reported on the importance of using riverbank cameras to document, either quantitatively or qualitatively, relevant ice processes. While the presence of experienced observers in the field is valuable and allows any site to be documented from different perspectives and angles, it is not often affordable for financial (or personal) reasons. This is why autonomous cameras should be installed along watercourses at critical locations. Using an objective aperture priority (AV mode) is normally recommended, if this option exists, because it maximizes the chance of successful night time photographs.
- If the air temperature and barometric pressure is not measured by another agency in the area, these should definitely be included in the list of parameters to monitor.

How?

- Using rigid collars to fix an instrument on a tree may affect sap circulation in the spring. This effect can be minimized using multiple wood pieces between the collar and the trunk, or simply using a slightly elastic strap. Using screws directly into the tree trunk remains a defendable option in specific circumstances, if this does not affect its health. The death of a tree is not only a loss of riparian habitat, but can eventually destabilize the channel bank.
- Using extra desiccant may be necessary in temperate or maritime areas with frequent mid-winter rain events. Desiccant can be manipulated cleanly and easily using cheap, empty paper-salt shakers or used (but intact and clean) socks.
- Using solar panels to extend battery life is recommended if the capacity of the internal battery is limited. However, solar panels are hard to hide and they may attract curious people to the monitoring sites.
- Sticking warning signs on visible instruments, including radioactive or any other hazard symbol may repeal delinquents. Leaving a phone number could also be appropriate if local people find the instrument. On the other hand, leaving the name of the company or institution on the instrument may encourage vandalism where it is locally unpopular.
- Inexpensive plastic tie straps may be damaged or broken during the cold season. A more robust attach system is recommended. However, some researchers have had success with cold-temperature-rated plastic tie straps purchased from electrician supply outlets.
- Accessible instruments and plastic or wooden instrument setups may be damaged by different wild animals such as beavers, squirrels, porcupines, bears (including polar bears), and even wolves. Additional protection may include metal plates or spikes.

Where?

- Weather stations can be installed relatively far from the monitored channel. If the station needs to be installed close to the channel, the dominant (and storm) wind direction should be kept in mind because the channel itself (open water conditions during cold fall days and melting ice during warm spring days) may influence the temperature and humidity measured by the instruments.
- The best photographs obtained from river-side cameras are normally obtained when looking along the stream, as opposed to across the stream or zoomed in on a small section of the river surface. This allows for a more complete picture of the ice processes, and aids in georeferencing the photos, if desired.
- The sunlight angle should be considered when placing cameras. For example, if morning observations are more important (i.e. for anchor ice), cameras facing away from the bright early morning sun will take better pictures.
- Selecting a large tree will avoid potentially undesired oscillations during wind storms and will maximize the probability of a stable photograph frame during the entire season.
- The impact of potential freezing rain and snowfall events should be considered because the resulting ice may remain in place for several days. Some researchers have had success using plastic "hats" over the cameras to prevent heavy snow accumulation (Figure 8).

Figure 8. Camera installation including screwed-in mount, snow protection "hat", and security cable with lock.

- Conifer branches may become loaded with snow and may occasionally bend into the photograph frame. Removing branches above the cameras before winter may be considered.
- Care should be taken regarding the erosion potential along the river banks. Installing a camera near a high, vertical, and unstable bank may provide a great vision angle to monitor the desired channel conditions, but there is a chance of never finding the camera and the photographs it contains.
- If the instrument is mounted on a tree, it is important to tie it above the highest ice scars in the area. If the objective of the monitoring program is to investigate the consequences of a river modification (e.g., dam construction) on ice processes, ice scars from past events may not represent a safe elevation indicator and a higher elevation may be recommended.

- Before installing an instrument (or a solar panel) on a tree, the research team should look for recent beaver activity. Beavers can cut down large or small trees that a camera is installed in, or a tree can fall on an instrument.
- In specific regions, instruments installed along the bank may become partially or completely buried by snow. If unfamiliar with the research area, the research team should seek snowpack depth statistics. Windblown snow accumulation should also be considered. This is usually not a problem on the ridge of a high bank where the snow gets blown down into the channel.
- Installing instruments along the banks, especially if largely visible from far away, may represent a problem. If vandalism or theft is anticipated, and if there is a limit to how instruments (or anchoring systems) can be hidden from malicious individuals, encouraging the active participation of local residents in the winter survey may contribute to reducing the risk of instrument and data loss. Obtaining the agreement for an installation on a private property is generally beneficial if the land owner understands the project and what this implies (e.g. regular field visits or potential intruders that could be attracted to the land owner's property).
- In all cases, the position of instruments should be documented (see section 5.1)

When?

- A research team should take advantage of any mid-winter opportunity to change the batteries and to inspect the instruments, even if the instrument specifications are fully respected under the past and potential environmental conditions.
- Mid-winter field trips, even if only observational, may reveal conditions that will facilitate remote data interpretation and analysis. Organizing a field trip, even if this is associated with some cost, is never a waste of time if the participants are well prepared. Photos and notes should be taken, even if there is apparently nothing relevant to see. Once analyzing the data, this anecdotal information may end up being useful.
- Mid-winter field trips may also confirm whether the snowpack is affecting the quality of the monitored data. Removing the snow surrounding instruments may not be effective because windblown snow from the next snow storm may fill in the area. Raising the instrument may prove to be more effective.
- If the research team is leaving visible tracks in the snow (snowmobiles, snowshoes, skis, boots), it may attract people to the instrumented sites and may stress landowners. In this case, planning a field trip on the days before a forecasted snowfall may represent a fair trade-off.

5.3 Mid-winter field trips

The use of autonomous instruments and in-person field visits are complementary methods for observing winter river processes, and both should be employed in a field program if possible. During field visits, apart from observations and instrument maintenance, a diversity of complex processes can be quantified (e.g., discharge estimations, ice cover roughness) and short term, but spatially extensive parameters can be measured (e.g., ice thickness distribution, ice coverage). If the field trip involves the presence of people and possibly vehicles on the ice cover, a strict security protocol most be applied. Information on this can be found in Andrishak and Hicks (2015).

Field trips represent an opportunity to perform observations downstream, between and upstream of permanently and temporarily instrumented sites. Aircrafts and helicopters have been used to perform observational ice surveys along long stretches of rivers and some flights have been planned with enough knowledge (and luck) to document dynamic ice processes such as ice jam release events and ice runs. In recent years, unmanned aerial vehicles (UAV) equipped with high-resolution cameras have become more affordable and accessible to research teams and those can be useful, cheaper and available on short notice to perform surveys on smaller rivers and on short distances (usually less than 10 km). UAV are especially useful to document the spatial ice coverage as well as the position of ice jams that are not easily accessible from the ground. They can be equipped with GPS systems and the new generation of software can automatically map the ice cover in two dimensions (surface ice cover in low gradient reaches) or in three dimensions (ice jams, ice dams, etc.). Using a UAV may require a permit and time should be budgeted so that the proper regulatory and safety requirements can be satisfied. The battery life of UAVs are also negatively affected by cold temperatures, and this fact should be incorporated into winter flight plans.

In all cases of mid-winter field trips:

- Bringing basic tools, ropes, a printed map and protocol, and extra batteries that have been fully charged may save the day and therefore avoid extra expenses and frustration.
- Keeping as dry and warm as possible at all times is essential.
- Bringing appropriate clothing including boots, waders and arm-long gloves is recommended.
- Drying any wet equipment or tools immediately after the return from the field is suitable.

5.4 Remote sensing

Radar and optical imagery from satellites have been used to investigate the extent of the ice cover as well as the type of ice cover on large rivers (e.g., Gauthier et al., 2015, Lindenschmidt et al., 2016) over hundreds of kilometers. This approach provides very useful spatial river ice processes data, but has currently three limitations that may prevent its applicability to a wide range of projects and contexts:

- The requested image, depending on the satellite orbit and use by other agencies, is not always available when needed and this is why this approach has mostly been applied to document gradual freeze-up processes and not dynamic, sudden breakup processes that occur with short notice. Governments that have invested in those satellites have identified priorities for their use and research projects are rarely on the top of the list, especially when they do not involve public security matters. The new generation of satellites may be able to provide more regular images under shorter notice.
- Low image spatial resolution has enabled ice cover surveys to be performed only on large rivers, but the new generation of satellites may allow river ice cover monitoring on medium size watercourses.
- The accuracy (or even the applicability) of the algorithm used to automatically interpret radar imagery to discriminate ice cover types has suffered from the presence of wet snow or water on the ice cover (interpreted as open water) as well as from the presence of rapids and waves (interpreted as an ice jams or a rough ice cover). Further calibration of algorithms developed by various agencies and research groups should contribute to increasing the accuracy of ice cover types’ interpretation in the near future.

6. Conclusions

Monitoring watercourses during the ice period and obtaining accurate, site-specific data is often necessary:

- For the development of river ice and cold regions engineering, hydrological, morphological and biological knowledge,
- To facilitate smart operational and public security decisions,
- To develop new (or to calibrate existing) models and equations, that will affect the design of a sustainable infrastructure or construction project in the channel or on the flood-plain.

This paper has provided basic information on what parameters can be measured or monitored along watercourses during the cold season. It has presented a list of field studies that have emphasized how to gather field data, how to protect scientific instruments and what errors should be avoided. The most important contribution of this paper was to mention a list of questions and answers that should be referred to before:

- Planning a river ice research project that involves the description and quantification of complex ice and hydrological processes,
- Purchasing expensive instruments,
- Designing and instrumentation strategy,
- Going in the field to install and retrieve the instruments,
- Organizing a mid-winter field trip.

Essentially, a river ice research project can follow these steps:

1) Identify the type and range of ice processes that can be anticipated in the field. If a limited amount of accurate information exists, the morphology of the studied channel can be classified and a conceptual model (Turcotte and Morse, 2013) can be used to identify ice cover types and potential ice processes to be expected. Observations during the open water season can be interpreted by knowledgeable people to identify probable ice processes that can affect specific channel reaches.
2) Identify the parameters that need to be measured in order to adequately document the processes that are relevant to the project (see the list of tips and advices under the question "*What*?" in Sections 5.1 and 5.2).
3) Iterate between possible instrument types and technologies and the available budget until a preliminary instrumentation strategy obtains a consensus (under the question "*How*?").
4) Define the survey period (under the question "*When*?") and the available resources.
5) Select macro sites using maps and complementary information (question "*Where*?").
6) Perform the installation in the field at optimal micro-sites (question "*Where*?").
7) Dedicate enough resources for winter observation trips or other means to directly or indirectly observe what is happening along the river during the cold season (Sections 5.3 and 5.4).
8) Retrieve the instruments as soon as possible and restore the site to its natural state.
9) Analyse the data successfully obtained.

Even the most experienced river ice expert or field technician may want to read this paper prior to going in the field, even if it only serves as a refresher. The authors have lost time, data and instruments in the past and they sincerely hope that, although they have learned the hard way, readers can benefit from their experience. Good luck, have fun and stay safe!

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Appendix A

	Watercourse	Prov. / Country	Median Winter Q (m^3/s)	Gradient range (%)	Flow regulation	Dominant ice process - cover type	Related publications
3.1	Montmorency River and tributaries	QC, Canada	0.01 to 10	0.2 to 12	None	Ice dams, frazil jams, suspended ice cover, surface ice cover	Dubé et al. (2015), Turcotte et al. (2012, 2013, 2014), Turcotte et al. (2017), Turcotte and Morse (2017)
	Etchemin River and tributaries	QC, Canada	0.05 to 10	0.1 to 0.4	None	Anchor ice and surface ice cover	Turcotte and Morse (2017)
	Ste. Anne River	QC, Canada	15	0.0 to 0.7	None	Frazil, anchor ice, hanging dam, suspended ice cover	Turcotte and Morse (2016), Turcotte et al. (2017), Vergeynst et al. (2017)
3.2	River Dee	NB, Canada	0.6 to 13.5	0.6	Regulated	Anchor ice and surface ice cover	Nafziger et al. (2013) Nafziger et al. (2017a)
	Serpentine River	NB, Canada	0.3 to 6.0	0.35	Regulated	Anchor ice and surface ice cover	Nafziger et al. (2013) Nafziger et al. (2017a)
	Gulquac River	NB, Canada	NA	1.1	None	Anchor ice and surface ice cover	Nafziger et al. (2013) Nafziger et al. (2017a)
	Twillick Brook	NFL, Canada	NA	0.6	None	Surface ice cover	Nafziger et al. (2011)
	Compensation Creek	NFL, Canada	NA	NA	Regulated	Surface ice cover	Nafziger et al. (2011)
	West Salmon River	NFL, Canada	NA	0.8	Regulated	Anchor ice and surface ice cover	Nafziger et al. (2011)
	Unnamed Creek	NFL, Canada	NA	NA	None	Anchor ice and surface ice cover	Nafziger et al. (2011)
	Kananaskis River	AB, Canada	0.3 to 24	0.5	Daily hydropeaking	Anchor ice, surface ice cover, anchor-ice derived icing	Nafziger et al. (2017b) Emmer et al. (2013)
3.3	Dauphin River	MB, Canada	60	0.03 to 0.15	Moderate	Consolidated freeze-up jams, hanging dam, surface ice cover	Clark and Wall (2016)
3.4	Saint John River	NB, Canada	110	0.02 to 0.08	Limited	Floating surface ice, dynamic breakup	Beltaos et al (2011)
	Mackenzie River	NWT, Canada	3800	< 0.002	Minimal	Floating surface ice, dynamic breakup	Beltaos (2014)
	Athabasca River	AB, Canada	150	0.02 to 0.09	Minimal	Floating surface ice, dynamic breakup	2 papers submitted -under review
3.5	Peace River	AB, Canada	1 600	0.03	Regulated	Frazil consolidated ice cover, anchor ice, occasional dynamic breakup triggered by unregulated tributaries	Andres et al (2005), Jasek et al. (2005, 2006, 2007) Jasek and Pryse-Phillips (2015)
3.6	St. Lawrence River	QC, Canada	10 000	Tide-influenced	Moderate		
3.7	Orkla River	Norway	50	0.1 to 0.5	Regulated	Anchor ice, frazil, surface ice cover in bypassed reaches	Stickler and Alfredsen (2009), Timalsina et al. (2013)
	Sokna River	Norway	2.5	0.2 to 1.8	None	Anchor ice dams and surfce ice	Stickler et al. (2010), Heggen and Alfredsen (2013)
	Ingdalselva River	Norway	2.6	1.7	None	Anchor ice, frazil, surface ice cover. Winter ice runs and ice jams	Heggen and Alfredsen (2013)
3.8	Ume River tributaries	Sweden	0.1 to 2.2	0.5 to 7.4	Regulated	Anchor ice and surface ice cover	Lind et al. (2016)
	Vindel River tributaries	Sweden			Free flowing but channelized	Anchor ice and surface ice cover	