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Evaluating a Distributed Temperature Sensing System for Anchor-Ice Studies

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Anchor ice is ubiquitous in ice-impacted rivers. Its formation and release can result in a variety of problems including flooding during freezeup and impacts to fluvial ecology. Although anchor ice formation and its subsequent release are poorly understood, it is clear that temperature variations of a few hundredths of a degree around the freezing point control these processes. This feature suggests the need to measure water temperatures at high spatial and temporal resolutions to gain an understanding of anchor ice processes. Over the past 15 years, hydrologists have deployed distributed temperature sensing (DTS) systems to gather high-resolution temperature data in a variety of environments. DTS systems use fiber-optic cable illuminated with a laser source as a thermometer. Temperature differences are determined by changes in backscattered light intensity along the length of the cable. Commercial DTS systems can measure temperatures along multi-kilometer-long lengths of cable with resolutions of <0.1°C. Here we report on the results of a field program using a DTS system to measure water temperatures during anchor ice formation events. Approximately 240 m of fiber optic cable were placed along the bed of the Laramie River downstream of a warm spring creek confluence for a two-week period in December 2016. The temperature of water near the bed was measured at 1m increments along the cable every 10 minutes during the experiment. As deployed, the DTS system recorded relatively large temperature variations associated with mixing of warm spring water and cold river water and diurnal warming of the water column, but could not distinguish small temperature variations associated with anchor ice formation and release events. Lessons learned from this experiment will be used to design further experiments.

1. Introduction

Fluvial anchor ice formation depends on a number of factors working in combination (Kempema & Ettema 2011, Stickler & Alfredsen 2009, Turcotte & Morse 2011). These factors determine when and where anchor ice will form along a river reach, and can be grouped into three broad categories: heat flux from the water to the atmosphere; characteristics influencing flow mixing (channel morphology, gradient, bed material, water depth, and current velocity); and the availability of seed ice particles. The authors' experience shows that these factors can vary from location to location along a reach.

There is a consensus in the literature, extending back to Barnes (1906), that supercooling of the water column is necessary for the formation of "sticky" frazil ice and subsequent anchor ice formation. There is also a broad, though vague, consensus on the stream characteristics where anchor ice forms. Anchor ice usually forms on gravel or coarser substrates (Arden & Wigle 1972, Gilfilian et al 1972, Tsang 1982, Wigle 1970) in "highly turbulent" riffle regions (Tsang, 1982). This consensus does not adequately delineate the flow details associated with observed anchor ice. Reported limiting minimum water velocities for anchor ice formation in rivers range from 0.1 ms^{-1} (Stickler and Alfredsen, 2009) to 0.7 ms^{-1} (Hirayama et al 2002). Stickler and Alfredsen (2009) discuss the range of values of stream characteristics associated with anchor ice formation. They conclude that anchor ice has a wider spatial distribution (in terms of stream characteristics) than previously recognized. Bisaillon and Bergeron (2009) modeled the formation of anchor ice along three gravel-bed rivers in Quebec. They found that water had to be supercooled for anchor ice production, and that fast and shallow conditions (as expressed using Froude numbers) favor anchor ice production. In summary, the various observations about flow velocity, water depth, and bed conditions actually express information about mixing within the flow. Accordingly, conditions leading to anchor ice formation are best expressed in terms of parameters characterizing flow mixing. The availability of seed ice crystals, as noted earlier, is another parameter that has been overlooked, with the result that its effect is not understood. Of central importance is the variation of water temperature along a river, both the water surface and the riverbed.

Anchor ice formation and release events can have critical impacts on many aspects of a fluvial system, including fish habitat (Brown et al 2011), increased water level and riparian flooding associated with freeze-up ice jams (Kempema et al 2017), sediment transport by ice rafting (Kempema & Ettema 2011), and hyporheic exchange (Weber et al 2013). All available evidence suggests that temperature changes of a few hundredths of a degree at the river bed drive anchor ice formation and release events. In order to gain new insights into anchor-ice processes, it is necessary to measure temperature at high spatial and temporal resolutions. High-resolution measurements in time and space offer the potential of determining how small temperature variations affect dynamic ice formation, for example, determining sites of preferential anchor-ice growth (Figure 1) or differential anchor ice release (Figure 2). Our paper discusses results from our first successful deployment of a distributed temperature sensing system (DTS) in an anchor-ice impacted stream. DTS systems collect high spatial- and temporal-frequency temperature records. We present examples of DTS data along with examples of the pros, cons, and pitfalls of using DTS systems in a freezing river.

2. **Distributed Temperature Sensing systems**

Water temperature is a useful tracer of heat fluxes in streams and rivers (e.g.Stonestrom & Constantz 2003). Small changes in the heat content of a stream, in both time and space, drive ice formation and melting events as freeze-up progresses. For example, the diel cycle of nighttime anchor-ice formation and morning release are driven by changes in the heat flux, and resulting water column temperature structure. Turcotte et al. (2014a) point out the advantage of having multiple hydrometric stations, measuring both water temperature and level along a river. The ideal field instrumentation would measure both of these parameters at almost continuous positions along the water surface and bed of a river. Such a dataset would greatly elucidate the intricacies of frazil and anchor ice formation.

Fiber-optic DTS systems were developed over 20 years ago, and were first used for industrial applications including pipeline monitoring, cable monitoring, and fire detection. Scientists and engineers began using DTS to monitor environmental systems in 2006 (Selker et al 2014). Today DTS systems are regularly used in hydrology, glaciology, oceanography, and atmospheric science studies. DTS systems are able to measure temperature at ~1 m increments over hundreds to thousands of meters of fiber-optic cable at time intervals of a few minutes. In the laboratory, temperature variations along the cable of as little as 0.01^{o}C are obtainable. In field deployments, precision is more likely to be ~0.1^{o}C. These values are temperature variations, absolute temperatures are harder to determine, and require comparison to multiple reference temperature sources.

DTS systems determine the temperature in a fiber-optic cable by measuring the ratio of backscattered, frequency-shifted photons. The DTS instrument pulses a laser signal along a fiber optic cable. A portion of the laser light is absorbed by the glass fiber and reemitted at a slightly different frequencies. This frequency-shifted light is known as Raman scattering. Light emitted at lower frequencies than the source is known as Stokes scattering, while light emitted at higher frequencies is referred to as anti-Stokes scattering. Stokes scattering is a linear function of the illumination intensity, while anti-Stokes scattering is a linear function of intensity while varying exponentially with local cable temperature. The ratio of Stokes to anti-Stokes backscattering provides a measure of cable temperature. Timing the arrival of photons at the instrument sensor allows measuring temperatures at spatial steps of ~1 m along the cable. The precision of the temperature measurement depends on the number of backscattered photons. Increasing the measurement time and the measurement step-length increases the precision of the temperature measurement. Selker et al. (2006) and Tyler et al. (2009) comprehensively review DTS applications in hydrology and offer detailed descriptions of operational theory, practice, and potential pitfalls.

3. Methods

For this study, we deployed a Sensornet Oryx SR DTS system. This system (Oryx) has a spatial resolution of 1 m and is ruggedized to operate in harsh environments. It is designed to operate at 12 to 26 volts with an active power consumption of 18 watts; power was supplied by two 12 volt deep-cycle batteries connected in parallel and recharged with a 240 watt solar panel. The operating temperature range for this instrument is -40 to 65^{o}C, making it suitable for deployment outdoors during winter months. The Oryx was mounted in a NEMA enclosure, along with an industrial computer and LCD monitor. Temperature data were collected for three minutes on two separate channels at ten minute intervals. After each sampling period, raw backscattering and reference-temperature data were downloaded to a solid-state drive and flash drive on the computer. Although this DTS is capable of measuring up to 4 km of cable on each of 4 individual channels, for the present study it was configured to measure 2 channels along a 353 m length of cable (OFS AT-LF28T7X-002 multimode cable). Although 343 m of cable was used, only 240 m were deployed on the river bed. The remaining cable was used to create four reference temperature sections and to connect to the DTS control box. A simplex calibration technique, utilizing two reference temperature baths equipped with PRT's and two reference cable sections in the stream equipped with RBR solo temperature loggers was used to calibrate the instrument/cable array. The DTS cable was anchored with a combination of T-stakes driven into the bed, attachment to logs attached to the stream bank, and rocks placed on top of the cable. In addition to the DTS system, Onset Hobo water level loggers were placed at each end of the fiber optic cable to record changes in the local stage.

The DTS system was deployed on the Laramie River just below Spring Creek in Laramie, Wyoming (Figure 3), an area where we have often observed anchor ice (Kempema & Ettema 2011). The Laramie River is a meandering, riffle-and-pool stream that flows through a large, semiarid intermountain basin straddling the Wyoming/Colorado border. The drainage basin area upstream of the study area is 2400 km^2. The elevation at the study area is 2200 m. Pools, which make up 85% of the river, have coarse sand beds and slopes of 10^{-4}. Riffle beds are composed of gravel and cobbles (median diameter of 15–20 mm), and have slopes of 10^{-3}. The average winter-time flow of the Laramie River is about 2 m^{3}s^{-1}, while average Spring Creek flows are around 0.06 m^{3}s^{-1}. Depending on ambient weather conditions, the temperature of Spring Creek water discharging into the Laramie River varies from near freezing to about 4^{o}C during winter months.

The 240 m of DTS cable were placed in the river from December 2 to December 15, 2016, starting at a site approximately 200 m below Spring Creek, and extending upstream into the Spring Creek channel (Figure 3). Weather conditions were retrieved from the Laramie Regional Airport (station KLAR), located 6 km west of the study reach, and having the same elevation and terrain.

4. Results

The DTS system was deployed from December 2 to 15, 2016. Cold fronts through the area (Figure 4) drove anchor ice formation on several nights (Figures 5, 6 and 7). Anchor-ice formation and release events drove stage changes, particularly at the upstream end of the cable (Figure 4). Although we have observed anchor ice at many locations along the cable reach over the years, over the study period relatively little anchor ice was evident along most of the cable length. Anchor ice was observed on December 3, 6, 7, 8 and 14. We attribute the relatively sparse anchor ice to changes in river flow driven by emplacement of a beaver dam about 750 m downstream of the downstream end of the DTS cable. Most anchor ice was observed along the upper portion of the cable array, where the two water masses had not yet fully mixed (Figures 3 and 6).

The seven temperature traces (temperature versus cable position) shown in Figure 8 indicate the cooling trend observed during the early hours of December 3. From 305 to 330 m, the cable was in the Spring Creek channel; the traces show the warm water input from the creek. Between locations 277 and 305 m, the cable looped into the main Laramie River channel, and then went back into the Spring-Creek-influenced flow between the 250 and 305 m locations. Mixing of the two water masses is clearly visible along this latter length of cable. The temperature downstream of 250 m (Figure 3) was spatially relatively uniform, while decreasing by about 0.7ºC over the two-hour measurement period (Figure 8).

Figure 9 shows 709 temperature traces recorded at 10-minute intervals between December 3 and 7. In this figure, distance is plotted vertically, time is plotted horizontally, and temperature at each pixel is represented by a color. This image shows the complex mixing that occurs in both time and space, as weather conditions and water temperatures change. The obvious, sharp temperature drop from green to blue on December 6 resulted from instrument shut-down caused by insufficient battery power at 04:06 AM and lasting for 4.5 hours.

Figure 9 also shows the potential utility of DTS use during freeze-up studies, but it was beyond the scope of the present study to further analyze these data. However, we are able to point out the following negatives, pitfalls and positives associated with DTS use for river freeze-up studies.

Negatives

- Substantial system costs. DTS systems require a significant initial investment of both resources and time. Ruggedized DTS control modules are (expensive) off-the-shelf items available from several different manufacturers. These control modules must be integrated into a complete data acquisition package. In addition, it requires a relatively large crew of five or more people to deploy the fiber-optic cable.
- Field-deployable DTS systems are not capable of accurately distinguishing the small temperature variations associated with supercooling events that drive frazil and anchor ice formation.
- DTS systems do not directly measure environmental temperatures. Instead, Raman backscattering is measured and converted to temperature based on independent measurements made along reference cable sections. In this study, we used a combination of reference temperature baths (cold and warm water baths encased in ice chests) and reference stream temperatures at two points in the stream, with stream references measured independently using RBR solo temperature loggers. Reference temperature baths are somewhat difficult to maintain during cold periods.
- Although the fiber-optic cable used in this experiment incorporated fiberglass strength members embedded in a plastic sheath, the fiber-optic elements themselves are relatively fragile, and are particularly sensitive to bending. Care must be taken to avoid straining the cable.

Pitfalls

- As anyone who has worked in frazil-infested waters knows, all cables can become unwanted substrates for anchor-ice formation. One of our major concerns at the start of the study was that either a halo of anchor ice or an anchor ice run (Figure 7) would create enough drag to rip the cable free of the instrument package. Although this did not happen during this study, portions of the cable were encased in anchor ice halos and buoyed up into the water column. Also, on several nights, portions of the cable shifted on the bed, although we saw no evidence that any of our anchors dragged. Fiber-optic cables deployed for ice studies should always have a weak link near the DTS control box that is intended to fail if the cable does drag.

- Do not underestimate power requirements in winter. The battery and solar cell array we used adequately powered the DTS system during a summer deployment. However, the shorter winter days and colder air temperatures resulted in several power failures during the present study. These power failures always occurred on cold nights when frazil and anchor ice were forming.

Positives

- DTS systems record temperatures at high spatial and temporal frequencies. The Sensornet Oryx SR used in this study has 4 channels which can each sample a 4 km cable length, so this system can potentially sample 16 km of stream at five- to ten-minute intervals.
- The data collected by the DTS system are recorded in a bank-side instrument. This alleviates the need to enter the river to download data loggers. Because the data are stored on a computer in the DTS housing, it is easy to incorporate a cell modem into the system to download data to an off-site location. This attribute makes it possible to monitor river-temperature conditions in near-real time.
- Although the initial investment is high, the fiber-optic cable is relatively cheap, at about US$1/meter for the cable used in this study. Moderate cable runs on the order of 1 km are relatively inexpensive, and the cable can be considered an expendable.

5. Concluding thoughts

The use of distributed temperature sensing (DTS) to monitor temperature changes in a variety of different environments has been well established over the last 10 to 15 years. Because of its proven success in other hydrologic studies, we are excited to incorporate this methodology into our studies of fluvial freezeup processes. Although DTS is not capable of distinguishing the very small temperature changes associated with supercooling and frazil formation, we believe it is still a useful tool in this field. We think the high spatial/temporal resolution DTS achieves will prove useful for filling in the gaps between high-precision and high–accuracy point source measurements. This DTS attribute will be especially useful for identifying warm-water inputs and hyporheic flow paths in small, low-order streams fed mainly by groundwater during winter months (Kempema et al 2017, Turcotte et al 2014a, Turcotte et al 2014b).

We look forward to continuing our use of DTS for diagnostic measuring of water temperatures along rivers, such as the Laramie River, during freezeup. The resulting information is essential to determining how frazil and anchor ice form along rivers.

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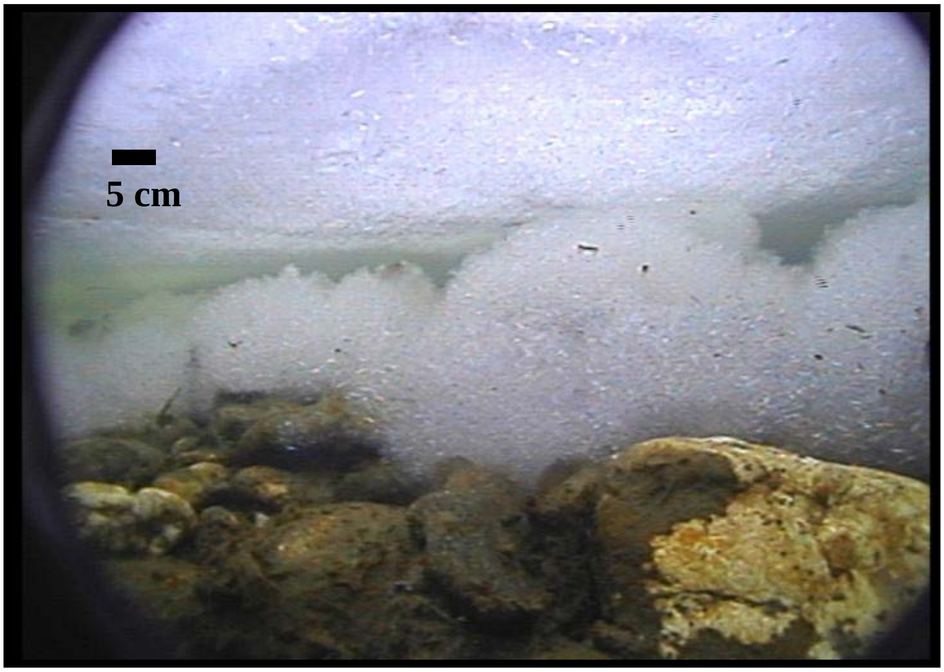

Figure 1. Anchor-ice accumulation on the bed of the Cache la Poudre River, Colorado. Small changes in water temperature may control the distribution of anchor ice on the bed.

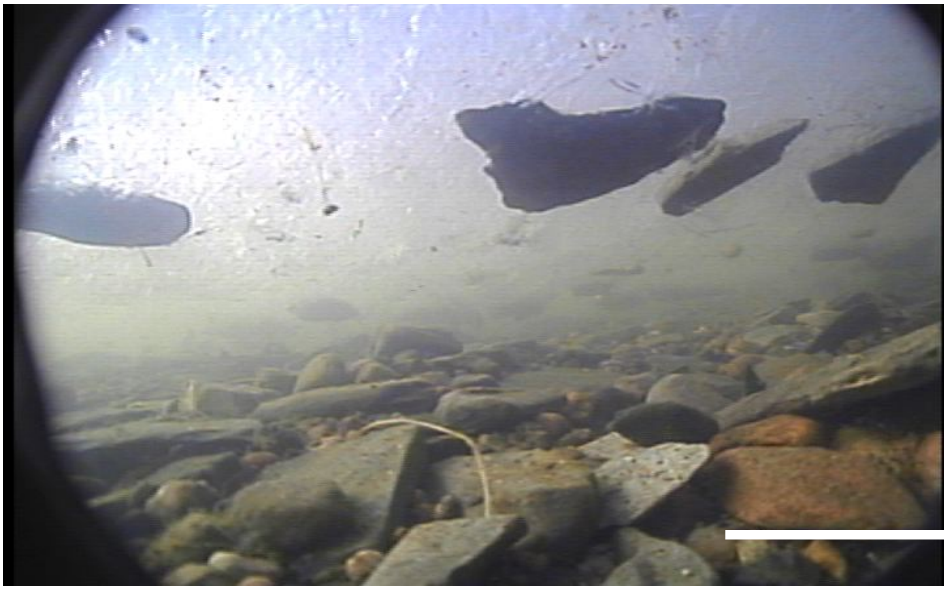

Figure 2. Early stage of anchor-ice release on the Laramie River, WY. As with anchor-ice formation, differential release is driven by small changes at the bed-anchor ice interface. Scale bar is 10 cm long.

Figure 3. Google Earth image showing the location of the DTS cable in the Laramie River. The DTS unit (LRDTS) was located at the downstream (north) end of the cable. The red line represents the 240 m length of the DTS fiber-optic cable on the riverbed. The white numbers indicate the distance from the DTS box in meters, and mark the positions of T-stakes and logs used as cable anchor points and reference locations. Reference temperature coils, RBR solo temperature loggers, and Onset Hobo pressure transducers were located at both ends of the cable. The Laramie River enters from the lower left, Spring Creek from the lower right.

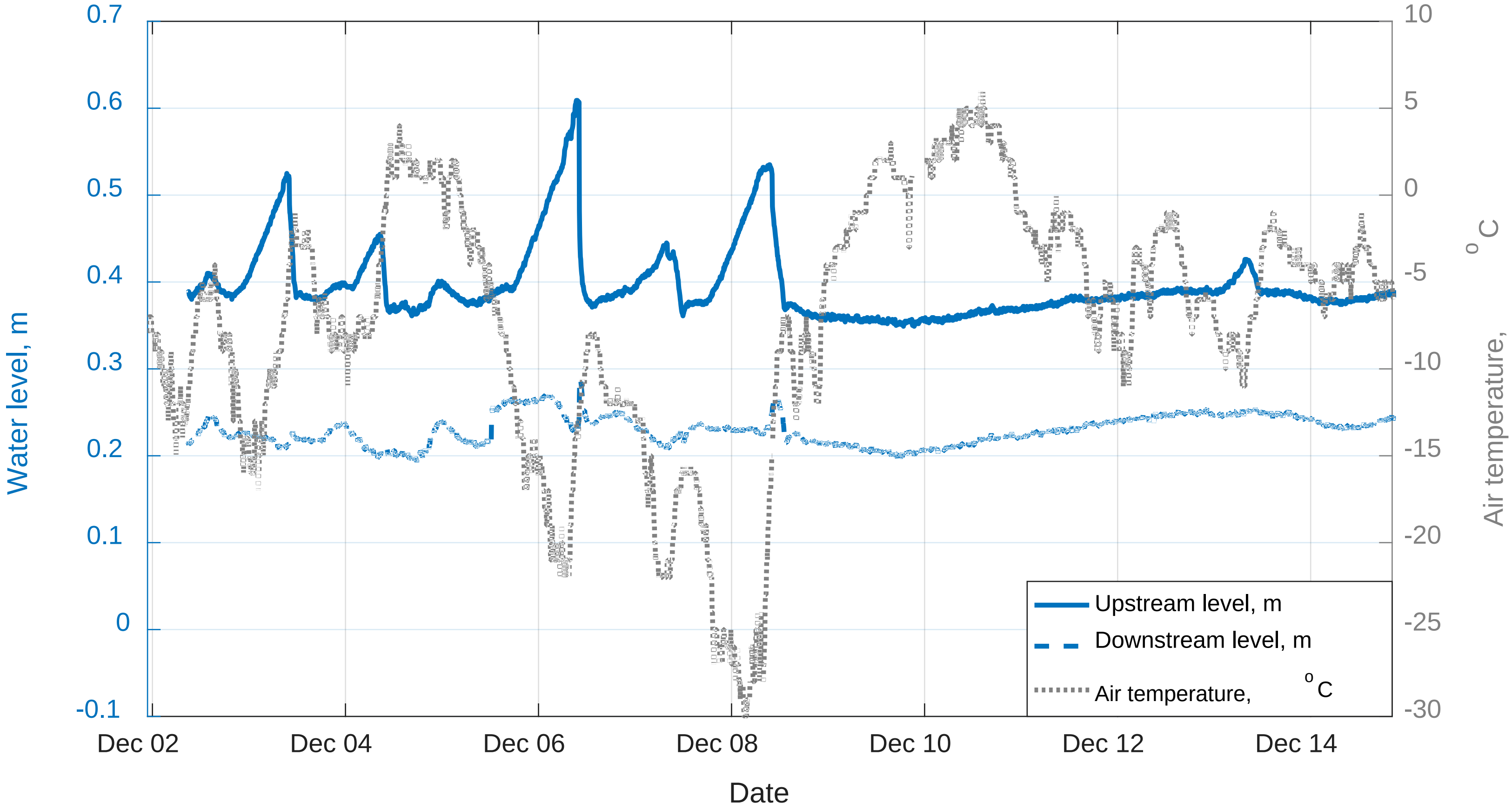

Figure 4. Water levels at the upstream and downstream end of the DTS string. The water level records were separated by 245 m along the river. The upstream level was affected by ice formation.

Figure 5. Image of DTS cable going under an anchor-ice mass.

Figure 6. An anchor ice weir on the Laramie River left just below the confluence of Spring Creek. Flow is from left to right. The photographer is standing on the fiber optic cable. Image taken by E. Kempema, December 12, 2017.

Figure 7. Downstream image of the study reach, looking toward T-stake T6, during an anchor-ice run on the morning of December 6, 2016. Essentially all of this released anchor ice came from upstream of the Spring Creek confluence; i.e., upstream of the measurement area.

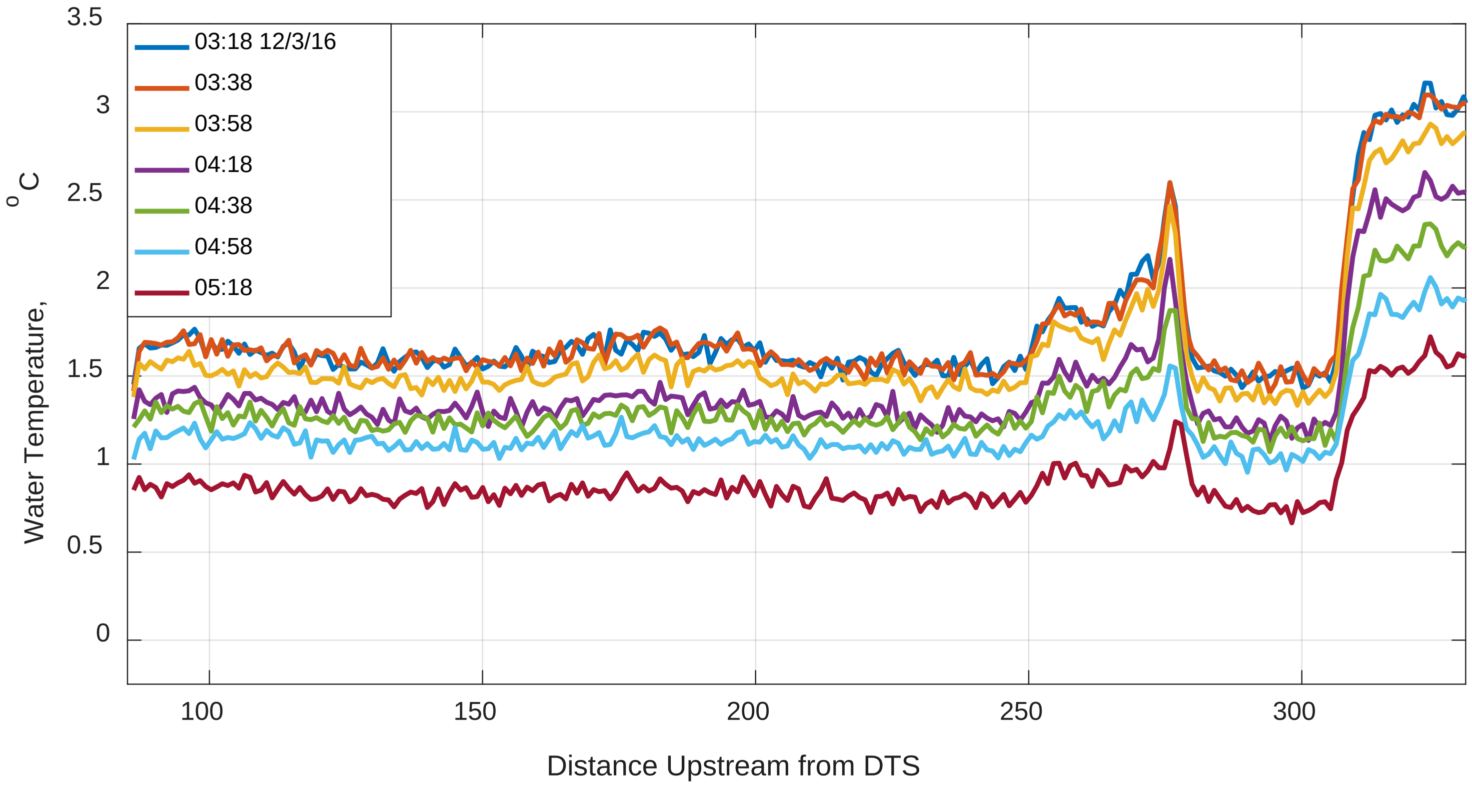

Figure 8. Seven traces showing the December 3, 2016 cooling trend in the Laramie River. The elevated temperatures at 177 m and 250 m to 277 m are shallow river bars. The high temperatures from 305 to 335 m are in the Flat Creek channel above the Laramie River confluence (Figure 3).

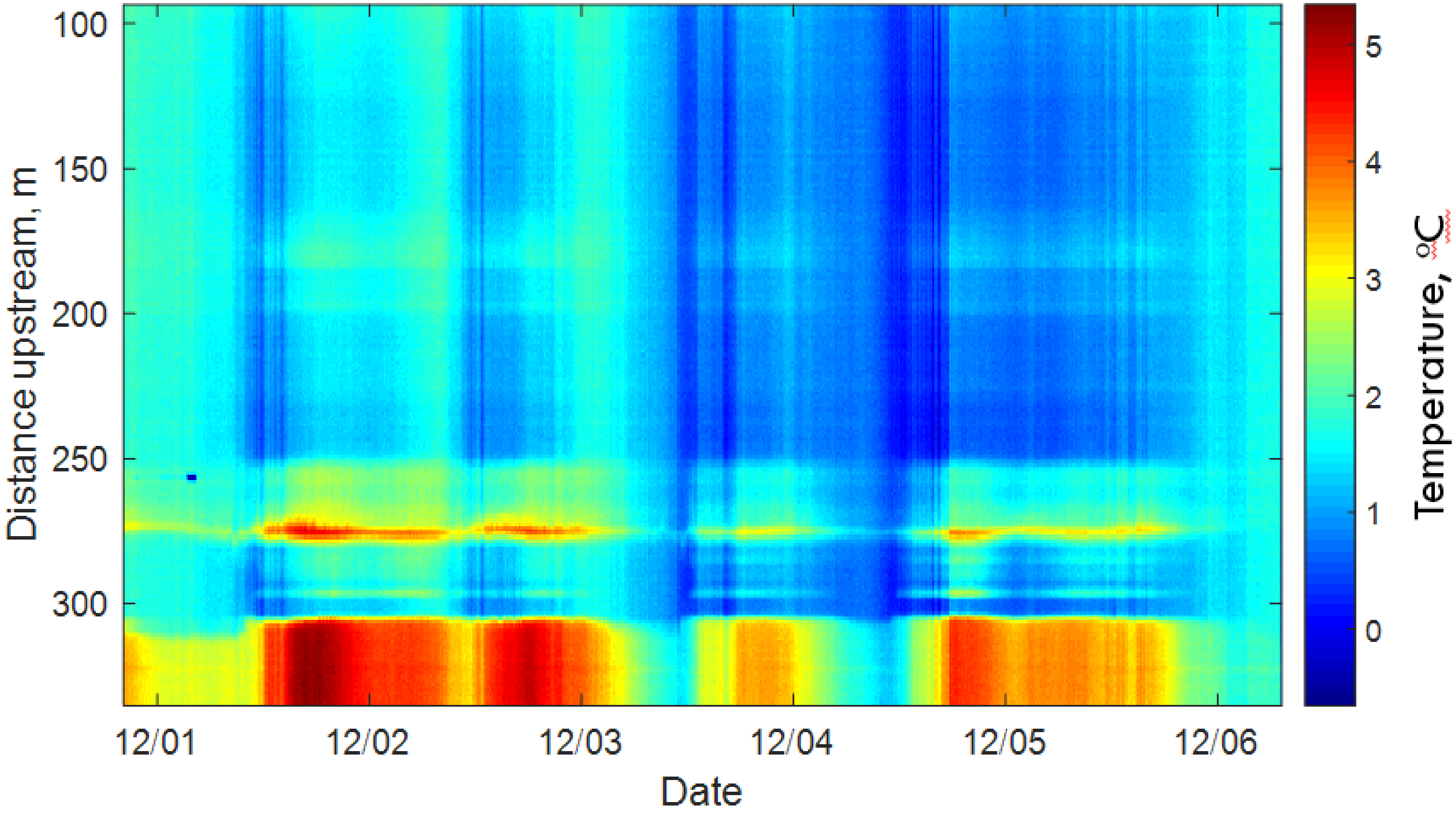

Figure 9. An example of over 700 temperature traces (Figure 8) plotted over time (horizontally) and space (vertically) illustrating spatial and temporal temperature variations in the Laramie River during freezeup. The consistently warm temperatures from 250 to 330 m show the influence of warm, Spring Creek water flowing into the Laramie River.