# Preliminary Analysis of Ice-Related Flooding on Flat Creek, Wyoming, Winter 2015-2016

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For:
Flat Creek Water Improvement District
Jackson, Wyoming

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# Table of Contents



# List of Figures

# List of Tables

# Executive Summary

We believe the FCWID is taking the correct approach to understand and mitigate ice-related winter flooding along Flat Creek. The monitoring information gathered by Alder Environmental shows that Flat Creek has complex, constantly changing temperature, hydrologic, and ice regimes throughout the winter. The most significant finding from the 2015-2016 data is that minimum water temperatures at the Cache Street/189 bridge are between 0.5 and 0.3°C through the middle of January. This warm water influx maintains a dynamic open-water reach that grows and shrinks with changing weather conditions. This open water reach allows supercooling of the water column and the formation of frazil ice and its derivative forms, including anchor ice, ice weirs, ice dams, and hanging ice dams. These ice forms, along with aufeis (icings formed by water freezing onto an existing ice surface) retard flow, thereby exerting a backwater effect that potentially causes local flooding and extensive overbank ice deposits. We note that the conditions along Flat Creek are not unique, as other small streams in cold climates experience similar winter temperature regimes and ice-related flooding. A short-term goal for the FCWID should be to collect more data during the approaching winter to correlate ice-related flooding events with air temperatures, in-stream structures, and thaw-well operations, with a long term goal being to develop operating procedures to minimize ice-related flooding along the creek.

We present a theoretical discussion of methods to control ice formation in the creek. There are two management strategies to control ice formation in the creek: (1) manage flow and thermal conditions to maintain an ice free channel through the FCWID boundaries; or, (2) manage flow and thermal conditions to promote the formation of a floating ice cover, which will inhibit the formation of frazil and other dynamic ice types that lead to flooding (this is the approach that has been attempted previously, with limited success). There are only two variables, or "knobs," that can be used to achieve either of these management strategies: adjusting the flow, or adjusting the temperature (amount of heat) in the water. Adjusting flow is difficult and may negatively impact the stream biome. Adjusting water temperatures (heat content) is somewhat easier, but it is difficult to determine exactly how a given temperature change will affect ice conditions. We believe that ice-related flooding in Flat Creek can be minimized, but never completely eliminated, through either of these two management practices. There will be times when the only flood mitigation strategy will be to have excavators remove ice from the channel. We recommend that FCWID works to develop an overall plan that minimizes flooding using the above management strategies, while acknowledging that sometimes the only solution will be bringing in heavy equipment.

For the upcoming winter, we recommend that the FCWID continue with a data collection and management plan similar to the one that was used last winter, but with the following changes:

1. Add six to eight pressure loggers to the stream to measure along-stream variations in stream heights through time. A possible logger type would be the Onset Hobo UL20-04 (http://www.onsetcomp.com/products/data-loggers/u20l-04). Placing six of these units in the creek would cost approximately $2750 (7 logger units, software, and a data shuttle, the 7th logger is required to make atmospheric pressure corrections). This brand is just a suggestion. The FCWID's local monitoring contractor may have other ideas based on their past experiences. Placing staff gages along the creek will still be necessary, so the pressure records can be corrected for absolute water level.
2. Place six to eight game cameras along the river to collect pictures at ¼ or ½ hour intervals throughout the day to monitor rapidly changing flow and ice conditions along the creek. Having

mounted cameras would allow a semi-quantitative analysis of the images. A suitable camera, that is an update to a camera we've used in the past, is the Moultrie Wingscapes Timelapse Cam (http://www.wingscapes.com/wingscapes-timelapsecam-camera). Six cameras, with batteries and SD cards, but not mounting hardware, will cost about $900.

3. Rely on the JKNW4 weather station data for air temperature and precipitation data. It is not necessary to place air temperature loggers near the creek.
4. The game cameras will take place of photo points collected in 2015-2016, but personnel should still walk the creek regularly to observe ice and flow conditions and take 'spot photos' of any unusual ice, flow, or morphologic features.
5. Positions of temperature loggers, pressure loggers, and cameras will be determined through conversations between Alder Environmental, FWCID, and us. Efforts should be made to determine water and ice cover conditions on the Elk Refuge (the major source of the warm input water), around the thaw wells, and possibly at the Kelly Tube outlet.
6. Equipment should be deployed by no later than mid-November to catch the earliest freezeup events.

In addition to the specific recommended monitoring changes, we recommend that Dr. Kempema visit the site at least once during the winter to view ice and flow conditions along the creek. We also recommend that historic data be examined, if it is available, to determine if there are places where flooding regularly occurs along the creek or if there is a pattern to the flooding (e.g., do ice dams regularly form on the same instream flow structures).

We suspect that it will be possible to minimize ice-related flooding by taking an active approach to managing the creek during the winter. This approach will likely consist of sometimes promoting ice cover formation and sometimes promoting melting of all of the ice in the channel through Jackson. At this point, the goal should be to determine what management practice to implement for every set of existing creek condition and predicted weather condition. The path to this goal is to collect and analyze more data to relate stream flow, ice, and weather conditions in order to make reliable predictions.

## Purpose of Report

Flat Creek through Jackson, Wyoming has a long history of ice-related winter flooding (e.g. Daly, 2002). In fall 2015, the Flat Creek Water Improvement District (FCWID) contracted with Alder Environmental (AE) to monitor water and ice conditions in Flat Creek through the Town of Jackson during winter 2015-2016. Of focal interest was the reach of Flat Creek within the FCWID boundaries. Our report analyzes the findings of AE's monitoring and recommends further considerations toward mitigating ice-related flooding.

AE's winter monitoring included measurements of water temperatures, air temperatures, water levels (stage), water volumes (discharge), thaw well operations, and ice conditions along the creek. In addition, a GIS database containing locations of the various measurement stations, along with ice conditions seen along the creek, was developed. The measurements and GIS database are described in the report "*Flat Creek Winter Characterization Study, Methods and Data Summary, Data Deliverables*" by Alder Environmental (2016, hereafter AE 2016).

In particular our report focuses on the following questions stemming from AE's monitoring and our knowledge of ice-related flooding:

1. What is the current knowledge regarding ice formation processes in small streams similar to Flat Creek?
2. What ice-formation processes do the observations and data collected from Flat Creek during winter 2015-2016 show?
3. Are there significant gaps in the observations and data, and, relatedly, what observations and data should be collected in future winters?
4. What are the possible options for mitigating winter flooding, and what level of data analysis is needed to identify possible options?
5. Is the FCWID presently taking the correct approach to understand and mitigate winter flooding along Flat Creek?

This report contains the following sections that address these questions:

- A short, illustrated review of frazil and related ice formation processes relevant to winter flooding experienced on Flat Creek. The aim here is to provide FCWID members with insight into the physical processes leading to winter flooding;
- Preliminary analysis of AE's observations and data. The analysis enables us to define significant processes and identify possible gaps in observations and data. Included here is a comparison of the observations and data from Flat Creek with the limited amount of observations and data from similar streams and small rivers;
- A discussion of approaches to mitigate ice-related flooding along Flat Creek, and preliminary assessment of the approaches;
- Recommendations for further acquisition and analysis of observations and data; and
- Interim conclusions.

We intend this report to be viewed as the first substantial component of possibly a longer-term project aimed at optimizing hydrologic, hydraulic, and thermal conditions in Flat Creek with the goal of reducing ice-induced winter flooding.

## Observation and Data Sources

The observations and data we analyze come directly from AE 2016 and streams similar to Flat Creek. Our report should be considered as adjunct to AE's report. AE 2016 provides detailed information on the observations and data presented in our report. Brian Remlinger of AE provided additional information about specific points mentioned in AE 2016.

Although AE 2016 describes the observations and data collected during winter 2015-2016, it contains no information on the geologic, meteorologic, or hydrologic characteristics of Flat Creek and its watershed. However, *Flat Creek Water Management Plan* (Remlinger, 2006) is a good source for this information. Most relevant for our report is the observation that there are significant losses from Flat Creek to groundwater where the creek enters the upstream section of the Elk Refuge. This 'lost' water is ". . . most likely returned to the Creek in the lower portion of the Elk Refuge." The report further states that from September through April, Flat Creek flows are almost entirely from groundwater and spring sources. Another intermittent, sometimes significant, winter-season input into the creek is the runoff from the Town of Jackson's snowmelt draining directly into the creek, even during the coldest winter months.

Daly (2002; 2005) studied anchor ice formation and thaw-well performance in Flat Creek. Daly (2002) reviews meteorological and hydrologic conditions affecting the creek. Both of his reports analyze thaw-wells performance in preventing ice-related flooding in Jackson. Daly (2002) reports that Flat Creek is comparatively steep, with a slope of 0.0055 through Jackson. This slope creates a relatively fast-flowing, shallow stream channel conductive to frazil and anchor ice formation.

## Review of Ice-Formation Processes

This section of the report is divided into two subsections. The first subsection focuses on turbulent water column cooling and the initial formation of ice. The second subsection deals specifically with the types of ice that are generated by evolving frazil and anchor ice in small rivers.

### Initial cooling of water and ice formation

Ice formed in turbulent, flowing water is often referred to as "dynamic ice." Before ice can form, water cools to its freezing temperature. Flowing water exposed to frigid air exhibits the characteristic cooling curve showed in Figure 1. Assuming a constant air temperature, the water temperature decreases linearly to some minimum temperature below the freezing point. All natural water contains some amount of dissolved solids, which depress the freezing point of the water to below 0$^{o}$C by a small, relatively hard to determine, amount. This is represented in Figure 1 as $T_e$, the equilibrium temperature for the water body. $T_e$ is the freezing point for a particular water body. The water is supercooled (the temperature of the water is below its freezing temperature) when its temperature falls below $T_e$, although no ice is yet present. At the nucleation time ($t_n$) frazil ice, ~1 mm disk-shaped crystals of ice, appears in the water column. These frazil crystals multiply and grow rapidly, releasing heat into the water and raising the water temperature to a residual, but still supercooled, temperature ($T_r$). As long as the temperature remains supercooled, the flowing water will continue to produce frazil. The length of time the water remains supercooled varies depending on prevailing atmospheric, flow, and ice cover conditions. In Wyoming it is common for water column supercooling and frazil production to occur on a nightly basis during late fall and early winter, with the water warming to the freezing temperature during the day (Kempema and Ettema, 2011). However, in some situations, supercooling can last for days at a time (Turcotte and Morse, 2011). This is commonly the case in Flat Creek (B. Remlinger, personal communication).

Frazil is the primary type of ice initially formed in moving water; all other ice types in flowing water can be considered as derivatives of frazil ice. Although frazil crystals are small and widely dispersed during the initial stages of cooling, they rapidly increase in both number and size in the supercooled water column. Frazil crystals in supercooled water are “sticky” (Daly, 2013), clinging to each other to form frazil flocs, and sticking to the bed to form anchor ice (Figure 2). At flow velocities less than about 70 cm/sec, frazil flocs and released anchor ice floating to the surface are incorporated into a growing, stable surface ice cover. At higher velocities, the unconsolidated floating “slush” ice can be transported under the ice cover to form thick slush ice deposits (Figure 2) often referred to as hanging ice dams; Beltaos (2016) contains a detailed discussion of hanging dam formation. Hicks (2016) notes “. . . freeze-up jams and hanging ice dams occur when copious amounts of frazil are generated, and they are particularly prevalent downstream of river reaches that remain open for all or most of the winter (e.g. rapids) where persistent frazil production occurs.” As discussed below in more detail, these are the conditions that prevail in Flat Creek during winter.

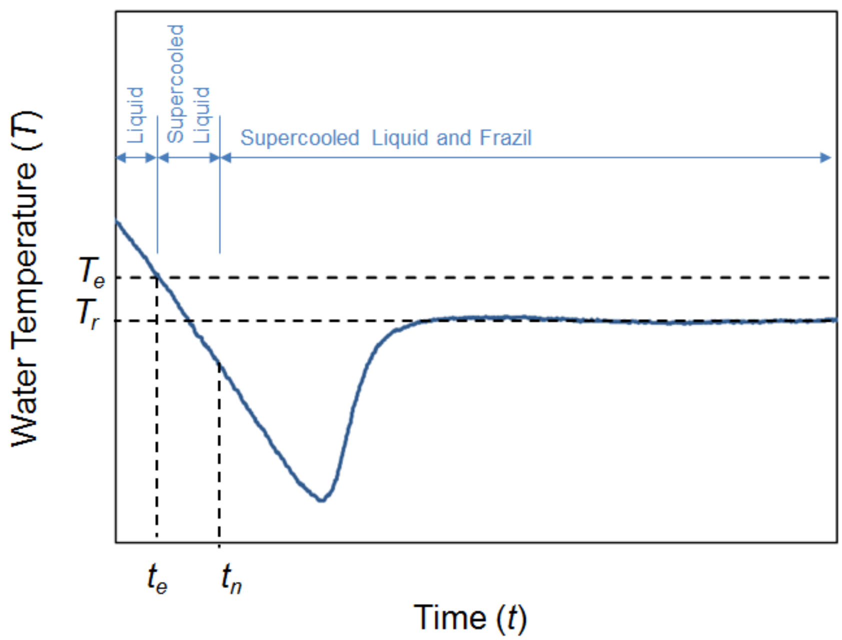


*Figure 1. Schematic of a supercooling event for a constant rate of heat loss, $T_e$ = equilibrium temperature, $t_e$ = time of phase equilibrium temperature, $t_n$ = time of nucleation, $T_r$ = residual super-cooling temperature. From Nafzinger et al. (2013).*

While there are no units indicated on the axes in Figure 2, the vertical axis has units of depth. Depending on perspective, the horizontal axis can represent two different measurement units. First, the horizontal-axis can represent time. In this interpretation, the figure represents what happens at a fixed point along the river as time increases. Assuming the length of time in the figure is about 12 hours, the figure represents what might happen on a typical fall night in Wyoming when air temperatures drop significantly below freezing. As the initially above-freezing water column cools through the freezing point, seed crystals initiate frazil ice production. Through time, this frazil is partitioned into flocs that rise to the surface or form anchor ice on the bed. Eventually, anchor ice is released and rises to the surface, contributing to the formation of a stable ice cover. In typical Wyoming streams, this process may occur nightly for two or three weeks before a continuous floating ice cover develops. Once developed, a floating ice cover impedes frazil and all other dynamic ice formation.

An alternative, equally valid, way to interpret Figure 2 is to view the horizontal axis as a measure of stream-wise distance. In this interpretation, the figure represents a cross section of the stream, with warm water entering at the upstream (left) side and cooling as it moves downstream. No ice forms in the stream at the upstream location; significant frazil, slush, and anchor ice form in the middle of the reach, and the frazil, along with its derivative ice forms, are transported downstream to form the surface ice cover, along with hanging ice dams composed of accumulated frazil slush, released anchor ice, and ice blocks. This view represents what happens along Flat Creek through the Town of Jackson.

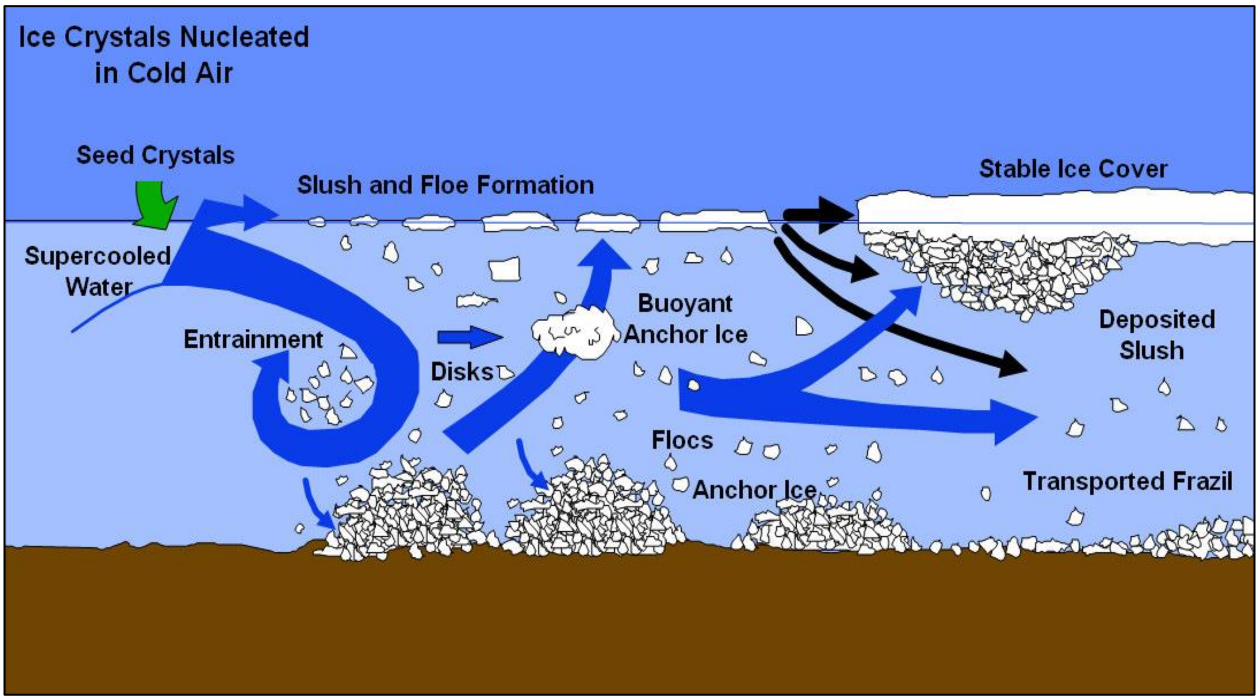


*Figure 2. Forms of dynamic ice in flowing water include frazil disks and flocs, attached and released anchor ice, floating slush ice and floe formation, and stable ice cover formation. Ice transported from upstream (frazil, released anchor ice, and floes) may accumulate on the underside of a stable ice cover as an ice jam or hanging ice dam (shown hear as "deposited slush". Other types of dynamic ice not shown in this figure include ice weirs, ice dams, and aufeis[1]. From Daly (2002).*

## Freeze-up processes in small rivers

Figure 2 illustrates our understanding of river ice formation based mainly on observations from medium and large rivers. Although Figure 2 is broadly applicable to small streams, in the last 10 years it has been recognized that freeze-up processes in small streams differ significantly from those in large rivers (Kempema et al., 2008; Lind et al., 2016; Stickler and Alfredsen, 2009; Turcotte and Morse, 2011, 2013;

[1] Aufeis (literally "on ice") forms when a thin layer of water flows over an existing ice cover or ice surface, and accretes on it.

Turcotte et al., 2014; Turcotte et al., 2013). Flat Creek, being less than 20m wide, shallow, relatively steep (slope=0.0055, Daly, 2002), and having coarse bed sediment, is a “small stream.” The main differences in freeze-up processes for small streams arises because the presence of channel boundaries and large rough elements (e.g., rock outcrops and boulders) can directly interact with ice formation processes and, thereby, with water flow.

Ice formation processes are controlled by heat fluxes, which are in turn governed by local weather conditions and by flow conditions in a stream or river. Typically, a heat (or energy) flux equation is used to define all of the energy sources and sinks in a stream. These sources and sinks include advective and conductive heat transfer, precipitation, short and long wave radiation, friction, and groundwater inputs into the stream (Ashton, 2013). It is usually impossible to identify the magnitudes of these sources and sinks, as they vary in time and location. Flow conditions include levels of flow turbulence as well as velocity. Flow turbulence and turbulence structures (e.g., eddies), especially in small streams, can be rather problematic to formulate, because they relate to flow passage around boundary roughness elements and protrusions. Thus, it is difficult to come up with a predictive model that accurately forecasts different modes of ice growth. At times, empirical relationships are developed for certain reaches of streams – as could be done for Flat Creek through Jackson. Such relationships are based on air temperature and the duration the air temperature is below freezing temperature for water, for a given initial water temperature.

Recent research and thinking (e.g., the Canadian researchers, Turcotte et al., 2013, 2014) suggests using the concept of dynamic ice formation, which is pertinent for small streams like Flat Creek. This concept rightly indicates that ice formation is initiated by the development of frazil and anchor ice in fast-flowing channel segments. Frazil quickly triggers anchor ice formation. Then, anchor ice accumulations form and create backwater effects, especially when they cover significant portions of the bed or create ice “weirs” at shallow points in the river. A second stage of dynamic ice formation occurs when ice weirs emerge into air and evolve into ice dams during prolonged cold periods. Whereas submerged ice weirs are relatively porous and fragile accumulations of ice, emergent ice dams are hard and strong accumulations of ice. Ice dams, as their name implies, may block flow in a channel. Growing, or active, ice dams form by freezing of successive, thin layers of water overtopping the dam. Such ice dams are evident along Flat Creek during winter flooding events.

Ice dams can reach heights of 1m (3 feet) or more, creating significant backwaters and flooding (Figure 3). Warming trends can cause ice dams to breach, releasing their stored water downstream. Alternating cold and warm spells during winter can generate alternating cycles of dam activation (growth) and beaching until a solid ice cover forms. The research of Turcotte et al. (2013, 2014), along with our own investigations, indicate that ice dams are the most threatening, flood-provoking features on small streams during frigid winter weather.

River and stream reaches that remain open throughout frigid winters experience persistent frazil ice formation. Such reaches are colloquially termed “frazil factories,” as they produce large volumes of frazil, anchor ice, and other related dynamic ice forms. The volume of frazil slush and anchor ice produced per unit area per hour can be calculated as

$$V_{ice} = \frac{-T_{air}C_h A}{\rho_{ice}\lambda p_{ice}} * \frac{3600\ seconds}{hour}$$

Here, $V_{ice}$ is the volume of ice produced per hour, $T_{air}$ = air temperature (°C), $C_h$ is a heat transfer coefficient from water to atmosphere, a commonly used value is 25 W/($m^2$ °C), A is open stream area ($m^2$), $\rho_i$ is the density of ice (920 kg/$m^3$), λ is the latent heat of fusion of ice (3.3 x $10^5$ W/kg), and $p_i$ is the slush/anchor ice porosity (0.5). Assuming a nighttime air temperature of -25°C (-13°F), in a 12 hour night a 100 m long by 10m wide reach of river open to the atmosphere can produce about 145 $m^3$ of slush ice (190 cubic yards). If all of this ice is deposited locally as anchor ice, it will raise the river bed surface by 14 cm (5.5 inches) of ice. However, to be kept in mind are that not all frazil forms anchor ice. Moreover, all anchor ice eventually releases from the bed. In steep streams, released anchor ice tends to float downstream until it comes to an obstruction or a low velocity reach (Figure 4). The ice that floats downstream accumulates as a hanging dam, which reduces the cross-sectional area of the channel. In extreme cases, the ice may completely block the channel, causing water to flow over and freeze on top of the existing ice cover, creating an aufeis. The main difference between ice dams and aufeis is along-steam scale. Ice dams in small streams tend to be relatively thin features (<5 m long). Aufies, in contrast, can form long, channel filling deposits up to 100's of meters long that rest on the river bed and cause significant flooding. Tuthill (2008b) studied an ice jam that formed on the Rio Blanco River in Colorado in 2005 that formed a combined aufeis and slush ice accumulation that was more than 5 miles long. This large jam/dam forced the entire river out of its channel, creating extensive flooding and thick ice accumulations in a rancher's alfalfa field. The jam began where frazil and released anchor ice collected on a rock weir that was placed to divert water into an irrigation canal.

All ice, including surface ice, increases water levels in streams by increasing drag. This effect is increased in small streams because the thickness of the ice cover can account for a significant portion of the stream depth. The effect is exacerbated by the formation of dynamic ice forms, including frazil, anchor ice, ice dams, ice weirs, hanging ice dams, and aufeis. This leads to the peculiar situation that overbank flooding may be most severe in the winter, when discharges are at a minimum.

## Observations and Data from Winter 2015/2016

In this section, we present results of our analysis of the winter 2015-2016 observations and data reported in AE 2016. Rather than represent all of the information and figures in that report, we will refer to it when necessary, using, for example, "AE 2016, Table 1" to reference their Table 1. Our analysis is not complete, as the goal at this point was to identify the quality of the data collected in 2015-2016, and to make recommendations for improved data collection for the upcoming winter. We consider air and water temperatures and water discharge magnitudes.

The foregoing review of frazil and anchor ice processes indicates that ice formation in Flat Creek is typical of small streams; the associated problem of winter flooding is also typical of such streams. The review also indicates that contemporary understanding of small-stream freeze-up has evolved since Daly's (2002) report was written. Daly's recommendation to modify stream morphology to enhance formation of a floating, surface ice cover makes sense, because a surface ice cover reduces the rate of heat loss to the atmosphere and the associated dynamic ice processes. However, the efficacy of this ice-management approach depends on the incoming water being marginally above the freezing temperature when it enters the reach of interest. AE's monitoring reveals that a difficulty with Flat Creek through Jackson is that water entering the reach is substantially above the freezing temperature.

## Temperature log records (air and water)

AE placed 13 RBR solo water temperature loggers in Flat Creek for the period of November 26, 2015 through February 10, 2016. The temperature logger locations, named T1 through T13, are shown in the appendix of AE 2016. These high-accuracy loggers were placed along 5.6 km of Flat Creek from the north Cache Street Bridge on the upstream side (T1) to the High School Road Bridge on the downstream side (T13).

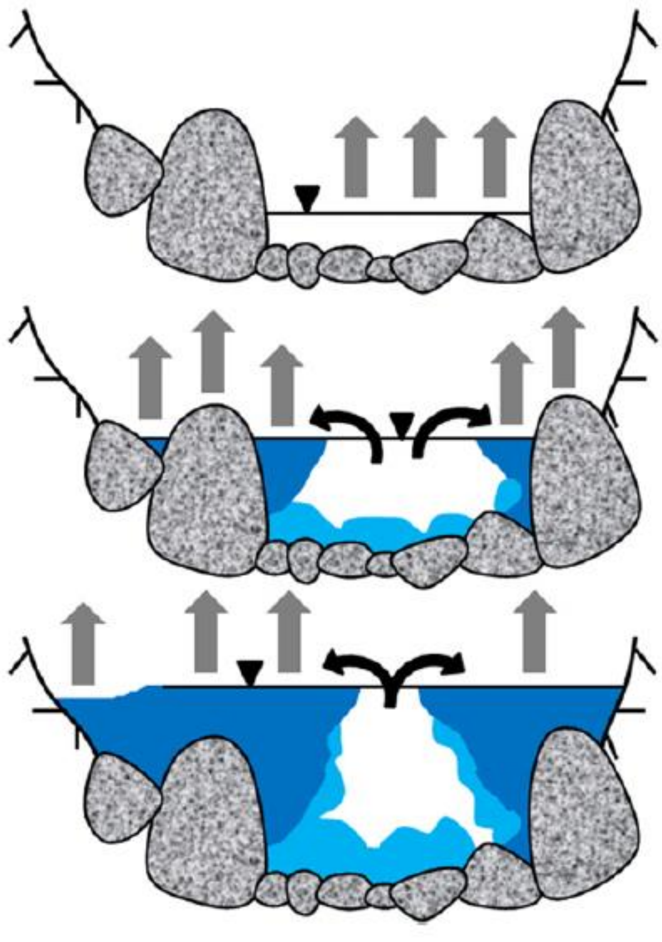

*Figure 3.Shown here (from top to bottom) is the accumulation of ice creating an ice dam where water is constantly flooding newly-frozen ice surfaces. The upward pointing gray arrows represent heat loss from the stream to the atmosphere and the inverted triangle represents the water surface. There is a significant loss of cross-section area as ice grows both upward and outward, light blue represents anchor ice attached to the bed. (Source: Turcotte et al. (2013).*

In addition, two air-temperature loggers were placed near the creek for the period of November 30, 2015 through February 25, 2016. Weather data were collected during December 1, 2015 through February 10, 2016 from the met station JKNW4, located at the Jackson headquarters of the U.S. Bureau of Reclamation. Comparison of the three sets of temperature records showed similar trends, with minor variations between stations at any given time. Based on this finding, we use the temperature data from station JKNW4.

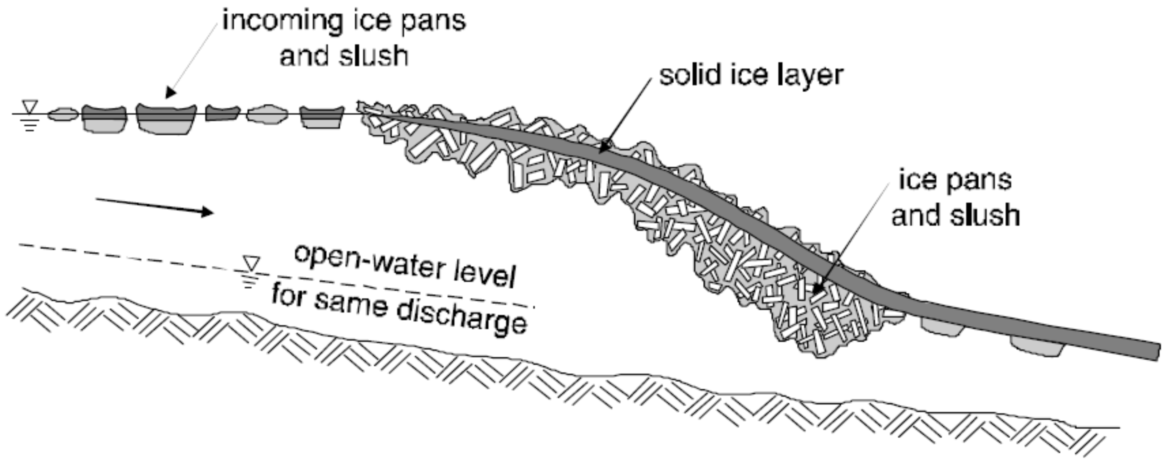


*Figure 4. The effect of a freeze-up ice jam or hanging dam on stream water level. A freeze-up jam can be composed of a mix of all the ice types shown in Figure 2. The ice jam decreases the cross sectional area of the stream, creating an increase in water level at and upstream of the jam.*

Figure 5 shows records of water and air temperatures during winter 2015-2016. These records are perhaps the most important data sets to result from AE 2016. Except for a few nights in February 2016, the water temperature at T1 was always at least 0.3$^o$C above the freezing point. In hindsight, this should not be surprising, considering Remlinger's (2006) observation that Flat Creek is fed predominately by spring water. Spring water usually discharges at the average annual air temperature, which is 4.1$^o$C (39.5$^o$F) in Jackson (http://www.usclimatedata.com/climate/jackson/wyoming/united-states/uswy0088), so it appears the creek water has already cooled considerably before reaching T1. In a telephone conversation, Brian Remlinger reported that an ice cover forms upstream of the north Cache Street Bridge (personal communication August 2016). This observation implies that the flow is tranquil enough to stratify, with denser warm water near the bed separated from the ice by colder, less dense water. In this situation, the ice cover acts to insulate the warmer water underneath. The T1 temperature record is important because it, combined with a basic understanding of how small-streams freeze, suggests that it may be very difficult to promote a continuous surface ice cover through the winter.

The difficulty in developing a floating ice cover is also indicated by water temperature changes along the entire creek when air temperatures rose above -5$^o$C (23$^o$F). When air temperatures were greater than -5$^o$C, water temperatures along the entire creek also rose; e.g., see Figure 5, 12/3-12/21. Consequently, ice in contact with the water weakened and melted, creating open water and setting the stage for eventual renewed frazil and anchor ice formation when air temperatures dropped. This process is illustrated by the temperature curves in Figure 6. The atmosphere reached a high of 2$^o$C (35.6$^o$F) on December 11, while the nighttime low was -12$^o$C (10$^o$F). Figure 6 shows a supercooling front advancing upstream from T13 to T2 as water temperatures dropped through the night. The characteristic temperature curves, similar to Figure 1, are an indication that frazil and derivative ice types formed along the entire Creek on this (and many other) nights. It seems counterintuitive, but it is probable that long cold spells, like the period from December 25 to January 4, are less likely to produce significant flooding than a warm spell followed by a very cold snap. We use "probable" here because this statement is based on our experience in other river systems; e.g., the Laramie River. Local residents near

Flat Creek may have better insights into dangers represented by long cold snaps, and should be interviewed for their observations.

The temperature records show that warming atmospheric trends had another effect on water temperature. When water temperatures rose above the freezing point, it was fairly common for water temperatures at stations T2 through T4 to reach higher temperatures than at T1 (Figure 7). This trend indicates other heat sources influence the creek between T1 and T2, T3, and T4. Because the higher downstream temperatures are always associated with warming trends, it seems probable that the heat source is warm melt-water runoff from town. This hypothesis is reinforced by the photo logs, which show open-water leads in ice-covered stream reaches directly below culverts discharging runoff water.

The temperature records show that there is a consistent warm water source entering at the upstream end of the measurement reach (Figure 5). Water at this source rarely, if ever, reached the freezing point during winter 2015-2016, and drives what we see as a complex, constantly changing, ice-and-water system in Flat Creek through Jackson during winter.

## Stream discharge and water levels

Discharge was measured on six different days during the ice season (Table 1). Considering the difficulty of determining discharge when ice is present, the flows appear to be remarkably consistent. Inspection of the photo logs for January 26, the day with the highest discharge, shows that there is essentially no surface ice in the channel. There is, however, evidence of attached anchor ice at the upper end of the reach, and released anchor ice floating downstream at the lower end of the reach. However, the water in the channel is below the highest suspended ice levels along the banks from earlier in the season; there is no sign of flooding.

Table 1. Water discharge measurements in Flat Creek during winter 2015-2016

| Date | Location | Discharge (cfs) |
|---|---|---|
| 12/9/15@14:00 | High School Road bridge on downstream edge of bridge | 68 |
| 12/31/15@15:00 | Crabtree Lane path bridge on downstream edge of bridge | 49 |
| 01/05/16@15:30 | Crabtree Lane path bridge on downstream edge of bridge | 55 |
| 01/15/16@08:30 | Crabtree Lane path bridge on downstream edge of bridge | 47 |
| 01/19/16@13:45 | Crabtree Lane path bridge on downstream edge of bridge | 60 |
| 01/26/16@14:30 | Crabtree Lane path bridge on downstream edge of bridge | 83 |
| | **AVERAGE** | **61** |

Water height (stage) was measured with staff gages at 10 locations along the creek, with between 15 and 18 stage measurements taken at each location (AE 2016). These readings show trends in water and/or ice levels at various times along the stream, but they are not frequent enough to record the dynamic nature of changing water levels, in both time and space, along the creek. We recommend that a number of submersible pressure gages be placed in the stream during the upcoming winter to record water levels at a higher temporal frequency. The staff gages should also be reinstalled near the pressure sensors, and should be read on a weekly interval to provide reference data for interpreting the pressure sensor records.

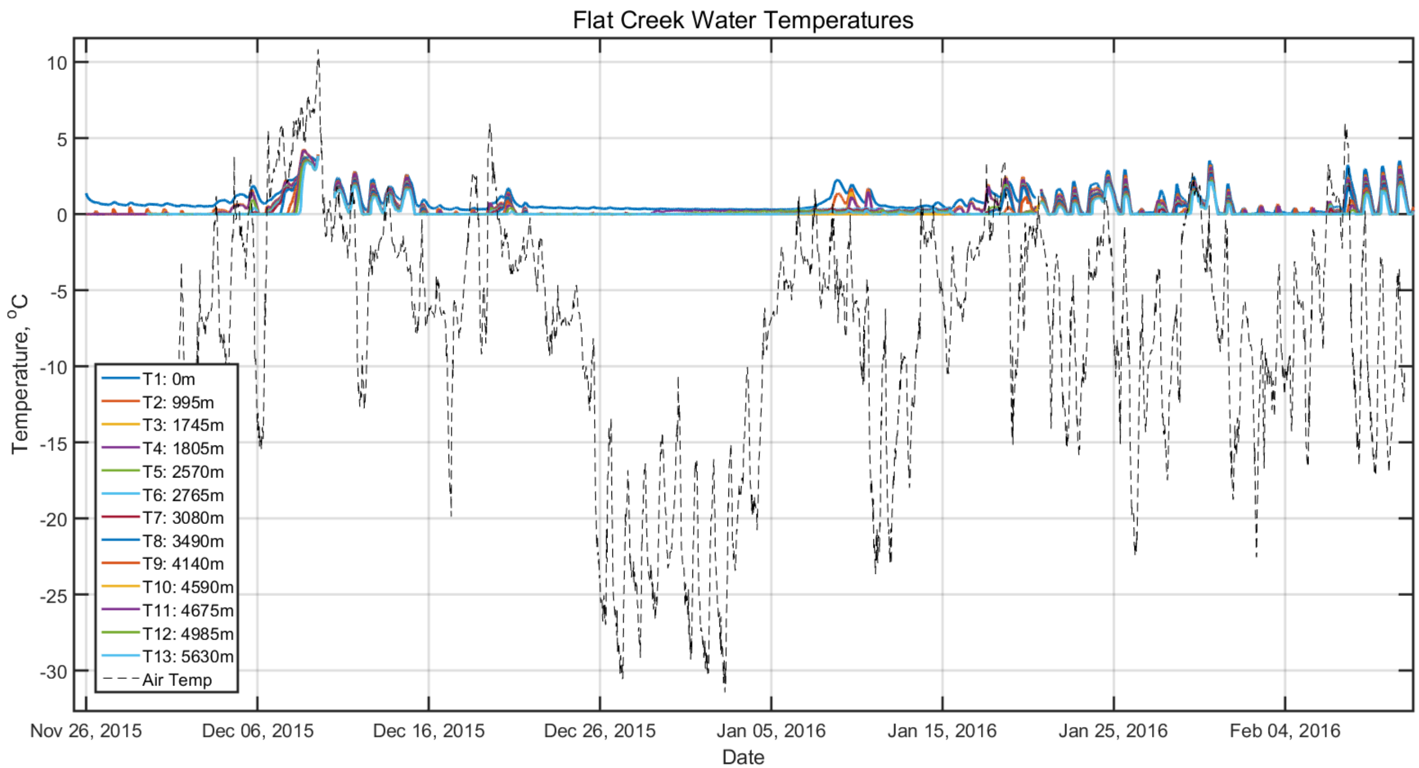


*Figure 5. Water and air temperatures along Flat Creek during winter 2015-2016. The water temperatures show a strong correlation with air temperatures on daily and longer cycles. When air temperatures rose above -5°C (23°F), all water temperature records show daily warming trends, often followed by nighttime supercooling events. The numbers in the figure key are distances in meters downstream from temperature station T1.*

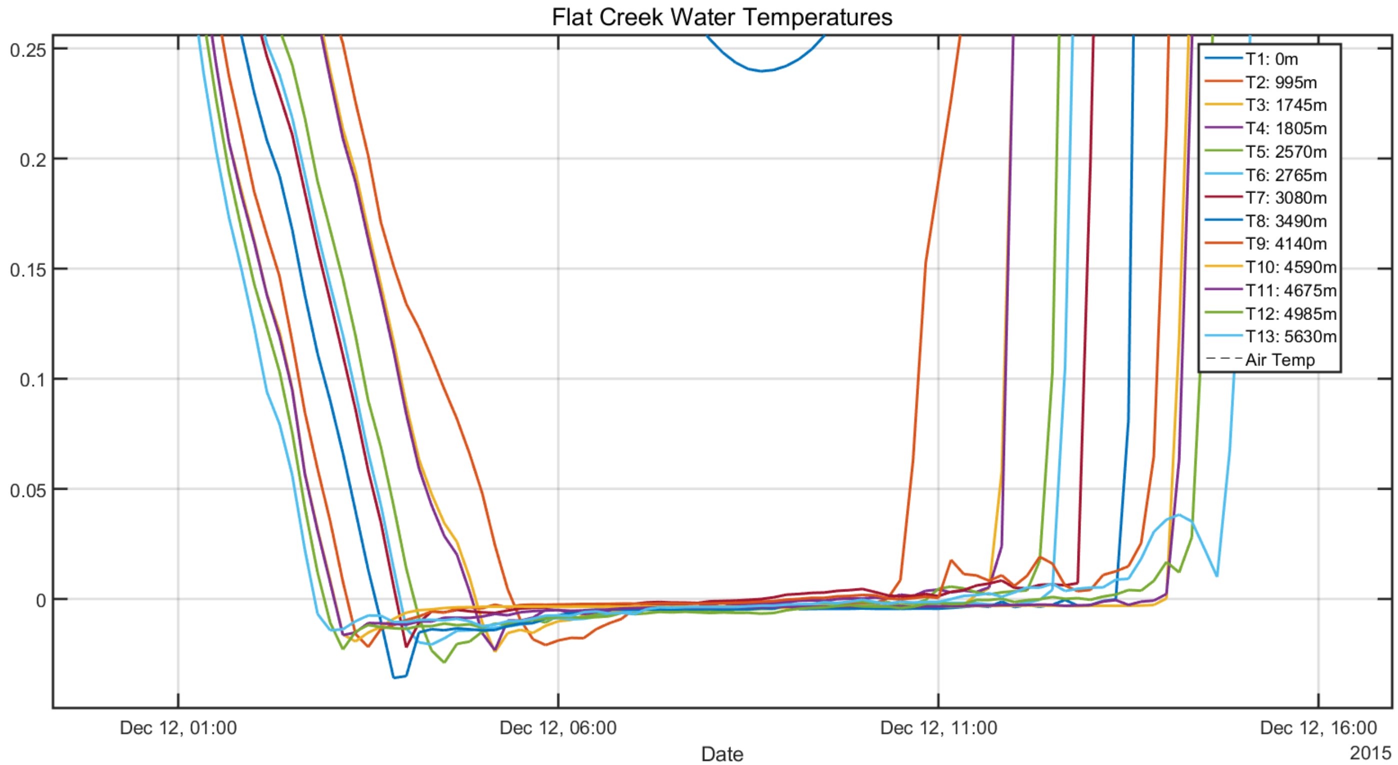


*Figure 6. Close up of water temperatures on December 12, 2015 showing the super-cooling front advancing upstream for T13 to T2, a distance of 4,630 m, in about 5 hours. Water along the entire reach rose to the freezing point by 9 AM. This record suggests that frazil and derivative ice types formed for about 6 hours at T13, but only for 3 hours at T2. The rapid temperature rise during the day suggests that any attached anchor ice in the creek released, and probably melted, through the course of the day. Air temperature reached a minimum of -12.6°C (9.5°F) on the night of December 12.*

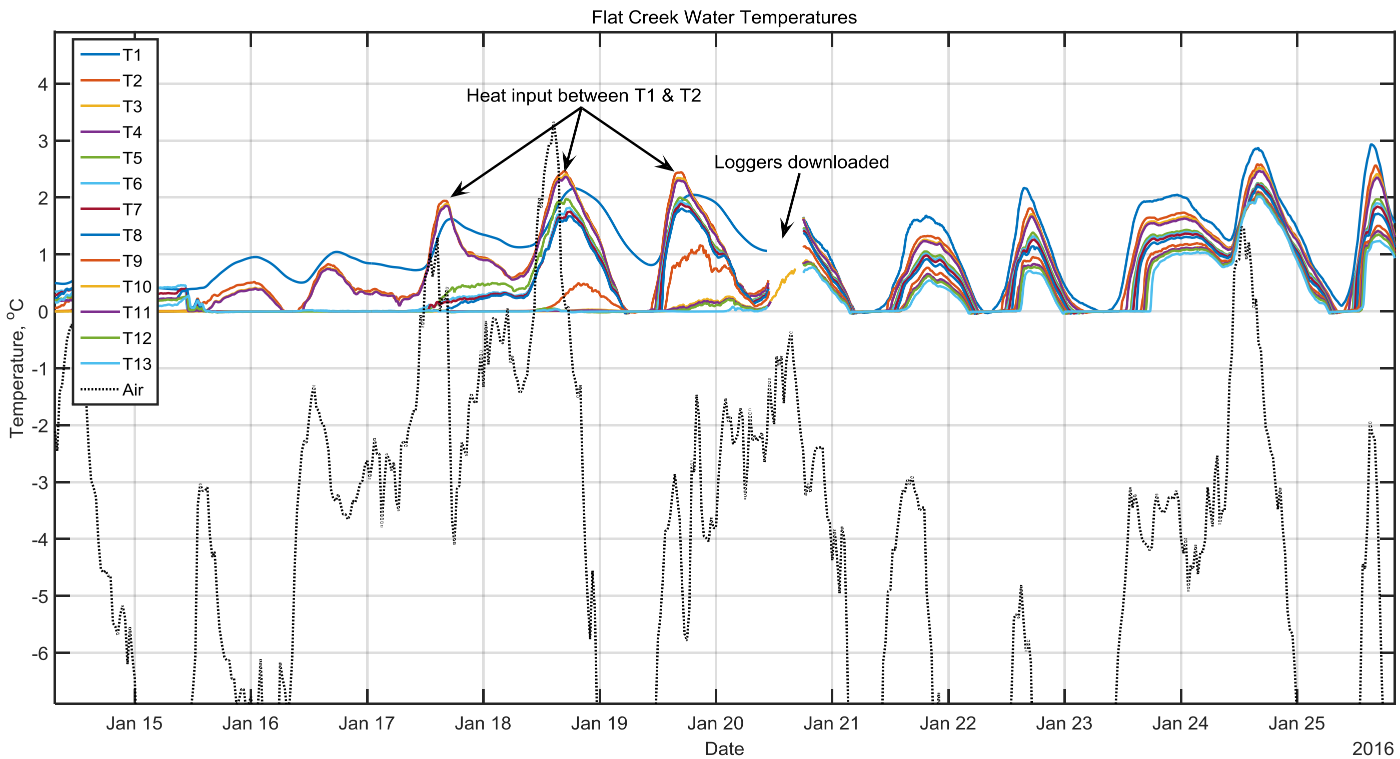


*Figure 7. Water and air temperatures between January 14 and 25 (minimum air temperatures not shown). The high temperatures recorded at stations T2, T3, and T4 on January 17 thorough 19 indicate a heat source coming into the Creek between T1 and T2 (and possibly between T2 and T3). The most likely heat source is surface runoff from melting ice in Jackson. The warming daytime water temperatures through this entire record, when daytime air temperatures rarely reached 0°C, show the importance of solar radiation in warming the water, even when air temperatures are below freezing.*

## Photo logs

Alder Environmental established 19 photo points (AE 2016), locations in the FCWID boundaries where pictures looking upstream and downstream were collected every time the creek was visited. AE personnel also collected 'spot photos,' single photos of interesting features seen along the creek. These images provide a very good record of the types of ice found in the creek, including anchor ice (both attached and released), ice weirs, ice dams, suspended ice, and aufeis (Figure 8).

The photos provide a glimpse of the dynamic nature of the ice in the creek, and confirm, to us, that the creek is acting like a typical small stream during freezeup (with the caveat that "freezeup" may last all winter in Flat Creek). However, in their present state, the photos are not very useful for detailed analysis, because it is difficult to arrange the photos at a given photo point in time-order. It would be useful to arrange the photos into files by photo point, with photo names listed by date. Then, it would be fairly simple to review the photos taken at a given location and form an overall picture of ice formation along the creek. An electronic addendum to this report (Addendum 1) shows the 16 digital photos collected at photo point 10 looking upstream. This addendum shows the utility of arranging the photos by location along with the dynamic nature of ice in the creek. It would be worthwhile to arrange all of the 2015-2016 images in this fashion. In addition, the photos in this image show the utility of placing game cameras along the stream to collect images at a higher frequency.

We have perused all of the photos to gain an understanding of ice and flow conditions in the creek. The present photos are somewhat deficient, because the exact same site was not occupied for consecutive photos. We recommend that during the upcoming winter, six to eight game cameras be placed along the river to record images at 15- to 30-minute intervals throughout the day. This would enable a semi-quantitative analysis of the photo logs, comparing, for example, ice dam breaches with specific air and water temperatures. A suitable camera, that is an update to a camera we've used in the past, is the Moultrie Wingscapes Timelapse Cam (http://www.wingscapes.com/wingscapes-timelapsecam-camera). Six cameras, with batteries and SD cards, but not mounting hardware, will cost about $900. However, AE personnel visiting the creek should continue to take 'spot photos' of any interesting ice or hydrologic features they observe.

## In-stream structures

The few published studies of freeze-up processes on small to medium size streams (mainly in Canada) show that ice dams initially form at locations of abrupt change in channel geometry: cascades, steps in step-pool channels, at rapids with large rocks or emergent boulders, and at the heads of riffles. In this regard, in-stream structures can be prime locations for ice-dam formation. This aspect is something that must be further investigated for Flat Creek.

Active or growing ice dams raise water levels, leading to backwater formation and potential overbank flooding (Figure 3). A rise in water level can cause a continuous cascade of water to flow over an ice dam, creating a dense ice structure that can grow upward at rates of up to 2 cm/hour. If an ice dam rises above channel boundaries, thick, dense accumulations of overbank ice can form. With warming weather trends, ice dams can breach, but they can reactivate during subsequent cold snaps, resulting in renewed flooding. Figure 8, and the photo on the cover of this report, shows an ice dam on Flat Creek. Further investigation of Flat Creek should determine how, how often, and where such ice dams develop.

It is worth considering the recent study by Turcotte et al. (2013), who studied the growth of 30 ice dams in a watershed in Quebec. They found that ice dams grew upward, and therefore water level behind the dams increased, at rates of 0.5 to 3 cm/hr, rates they believe are characteristic of all steep channels (including Flat Creek). These rates are a factor of 10 slower than water level increases associated with the upstream progression of an ice front with hanging ice dam development. Figure 3, taken from Turcotte et al. (2013) illustrates their understanding as to how an ice dam forms.

*Figure 8. Aufeis formation at P7. The view is upstream on January 11, 2016. The characteristic steps formed by thin layers of water freezing as they flow over the ice cover are visible in the center of the image. Aufeis was only visible in four of the 54 photos taken along the river on this day, indicating aufeis formation at this site was likely driven by water flowing over an anchor ice dam. Most of the river had open water at relatively low stage, often with anchor ice on the bed.*

Ice dams and ice-cover progression with hanging ice dam formation both affect upstream water levels. The slow rate of ice dam rise versus hanging ice dam development suggests that it may be possible to distinguish between these two mechanisms by monitoring water levels. Ice dam growth is slow (on the order of 6 to 10 inches a night (Turcotte et al. 2013), so there is some warning of an approaching flood. Based on photographs presented by AE 2016, ice dams are relatively narrow structures (Figure 9 and Addendum 1). This raises the interesting possibility that, if ice dams are the predominant flood-inducing mechanism on Flat Creek, it may be possible to mitigate flooding by breaching the dams. This occurs naturally when the weather warms, allowing the water to warm and breach the dams naturally. The dam breach will refreeze with renewed cold air temperatures.

The data set collected by AE 2016 incudes 213 ice dam features. Based on what is visible in with the ArcGIS Database, not all in-stream structures in Flat Creek formed ice dams, and not all ice dams formed on in-stream structures. AE 2016 reports 34 ice-dam observations with estimated heights of 2 feet or more, including eight with estimated heights of 3 to 4 feet. Most, if not all of the highest ice dams are located on top of in-stream structures, and are reported to be formed of anchor ice. It is not clear whether this was attached, in situ anchor ice or released anchor ice.

Ice dams are relatively easy to identify along Flat Creek (Figure 9, Addendum 1, and cover photo). In contrast, hanging ice dams are relatively hard to identify, because they collect under an existing ice cover. Ice dams commonly form in backwaters where stream slope decreases. Rock and log structures were placed in Flat Creek to reduce current speeds and enhance the development of a surface ice cover. However, the combination of instream structures combined with a continuous warm water supply from upstream suggests that there may often be significant frazil and released anchor ice accumulation, in the form of hanging ice dams, upstream of these instream flow structures. These hanging ice dams may fill the channel, causing the water to run across the ice surface, forming aufeis. The 2015-2016 data, along with undated photos supplied by Mr. Wotkyns, suggest that aufeis formation may be a major contributor to flooding in the creek at times.

If hanging ice dams and associated aufeis formation are the predominant flooding mechanism, it will be difficult to clear ice from the channel while cold conditions persist. Homeowners along Flat Creek may have insights into which of these mechanisms dominate in Flat Creek through the FCWID. Additionally, a useful task for next winter will be to monitor ice dam formation along the creek.

Tuthill (Tuthill, 2008a; Tuthill, 2008b) found that in-stream structures like weirs can increase the likelihood of ice dam formation by straining frazil and released anchor ice from the flow. At the same time, the backwater created by slower currents can create hanging dams that can fill the channel and lead to flooding. In Flat Creek, with a consistent open-water reach and frazil and anchor ice production upstream, it is not clear what effects in-stream structures have on ice-related flooding. This is an area that needs more study, and it is important to recover any information on the location, type, and height of any in-stream improvements along the entire course of the creek.

## Thaw-well operation

Daly (2002, 2005) made an in-depth, HEC-RAS based, computer-model study of the effects of the thaw wells on ice suppression in Flat Creek. His study showed that thaw wells could help mitigate ice-related flooding. The extent to which they could help depends of several factors, including how water from the wells is mixed within the river, and how the heat transfer coefficient (water to air) is affected by such features as ice dams.

Daly calculated the length of river that would be protected for flows of 40 to 100 cfs (cubic feet per second) for air temperatures ranging from 20$^{o}$F to -30$^{o}$F. The model results showed that thaw well #2 would protect the creek from freezing for distances of approximately 600 feet to 3800 feet (180 m to 1160 m) downstream from the well under those conditions. We do not have the creek morphologic data to repeat this study, and think that it would be redundant to do so. However, we can compare the measured temperatures to Daly's results. Thaw well 2 (TW2) ran from December 28 at 12:00 PM to January 15 at 10:30 AM. Daly assumed a well temperature of 7.8$^{o}$C, while seven temperature measurements made in the 2015/2016 season averaged 7.9$^{o}$C. Figure 10 shows that the warm thaw well water was first discernable at T11, 72m (236 feet) downstream of TW2, at 21:30 on January 28, and at T12, 437m (1400 feet) downstream, on December 30 at 13:00. During that time, air temperatures ranged from -26.7$^{o}$C to -10.61$^{o}$C (-16$^{o}$F to 13$^{o}$F), with an average near -18$^{o}$C (0$^{o}$F). Daly's results suggest TW2 would protect for a distance of about 1000 feet downstream at this average temperature. The model results fall roughly in the range of the measured water temperatures, but the measured temperatures show the surprisingly long time it takes for this warm water to be felt downstream, probably because the water is cooled by melting ice as it transits towards T12. T13, located 1030m (3380 feet) downstream show a rising temperature limb on January 6, but by this time the average daily air temperature had risen to above -5$^{o}$C, so it is hard to determine whether this temperature rise represents heat input from the thaw well.

Thaw well 1 (TW1) was turned on at 10:30 AM on January 5. Temperature stations T6, 176 m (580 feet) downstream of TW1, and T7, 437 m (1430 feet) show water temperature increases within 1 hour, with T6 temperatures rising much more rapidly than T7 (Figure 10). The photo log for January 6 shows a significant, almost continuous ice cover from T6 to T11, where TW2 discharges. This indicates that the heat introduced by the thaw well moved rapidly downstream, probably under the existing ice cover. It also raises the question of whether TW1 and TW2 should have been turned on when they were. The ice cover between TW1 and TW2 would have been better maintained if TW was not turned on, and it may be that the ice cover would have extended well past TW2 if that thaw well was not in use. On January 6, an open water channel extended from TW 2 all the way to photo point P17, a distance of 850 m (2800 feet). These observations show the utility of the combined photo and temperature logs, and also show the utility of collecting photos at higher frequency to correlate ice cover with air temperatures and other warm-water inputs like the thaw wells.

To be considered further is the efficient operation of the thaw wells. Thaw well operation in 2015-2016, as in previous years (Mr. Buckstaff, personal communication, 9/2016) consisted of turning the wells on and letting them run for extended periods. Considering the dynamic nature of the water temperature changes and ice formation in Flat Creek, the best management practice will probably consist of judicious use of the thaw wells for relatively short periods of time. More work is necessary to determine how the thaw wells are best used.

*Figure 9. A breached ice dam on Flat Creek, 12/4/2015. Photo site P10 upstream. This ice dam is located on an in-stream improvement structure that acts as a step in ice-free flows. AE 2016 reports the estimated ice dam height as 3 feet. There is an accumulation of what appears to be slush ice upstream of the ice dam, suggesting the presence of a hanging ice dam in that area.*

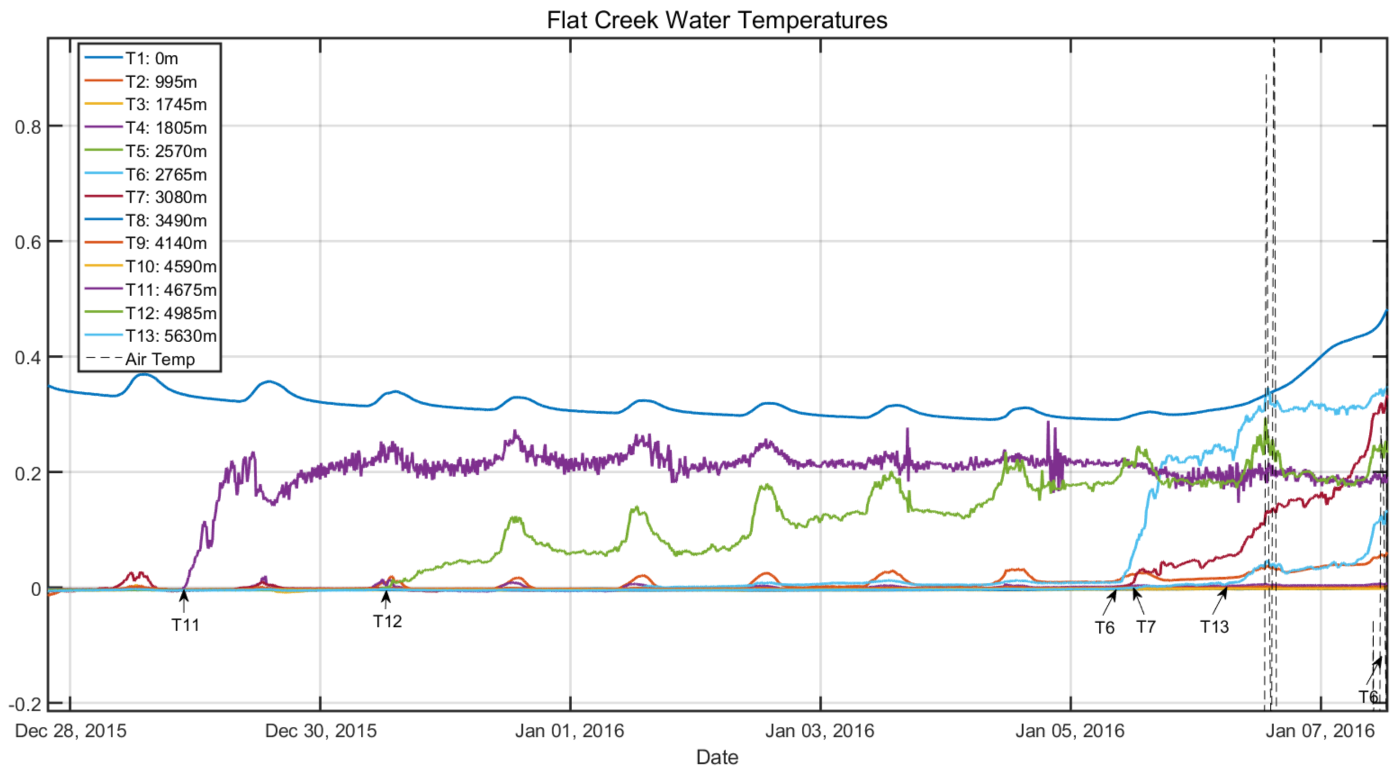


*Figure 10. Thaw well effects on downstream water temperatures.*

## Ice-Management Approaches

A useful way to discuss optional approaches for controlling ice formation in Flat Creek through the FCWID of Jackson is to look at the variables influencing the length, $L$, of channel required for an ice cover to form. The following equation (in metric units) relates the variables and consequently serves to framework for assessing the options:

$$L \approx \frac{\rho C_p q}{H_{wa}}\left[ln\left(\frac{-T_a}{T_{wo} - T_a}\right)\right]$$

Here, $L$ = the distance of open water or channel length needed for an ice cover to form; $H_{wa}$ = heat transfer coefficient stemming from the heat-budget analysis, $T_a$ = air temperature, and $T_w$ = water temperature, with $T_{w0}$ = the temperature of water at the start of the reach; $C_p$ = specific heat capacity of water; $q$ = water discharge per unit width of channel; and, $\rho$ = water density. This equation can be used to evaluate the effect of the warm water entering town from the Elk Refuge, or to evaluate thaw well performance.

The two theoretical approaches to reduce the amount of ice formed in a channel reach of length $L_R$ are:

1. Manage flow and thermal conditions so that $L > L_{R,}$ *so no ice forms through the reach*; or,
2. Minimize *L to promote formation of a floating ice cover*, doing so in a way that enables water to pass along Flat Creek with an acceptable water level profile.

Table 2 summarizes possible variable adjustments and associated actions involved in implementing management approaches 1 and 2 when air temperature is constant, as are the values of $C_p$ and $\rho$.

We do not suggest that concrete actions be taken at this point in time. Neither approach offers assurance as being a practicable means of eliminating ice-related flooding along Flat Creek in the FCWID. Each approach has attendant considerations. However, we suggest that the approaches outlined be thought through so as to identify whether any action, or group of actions, is potentially feasible and worth investigating further.

Moreover, we believe that ice management, if deemed feasible, will have to be an active procedure involving more-or-less continuous monitoring of winter weather and stream conditions. It will be important to anticipate the onset of frigid weather, and to be aware of water temperature along the creek. In this regard, monitoring air and water temperature is a necessary action whichever approach is used. We note in this regard, for example, Gholamreza-Kashi (2016) developed a model for predicting frazil-related freezing events along a reach of a small river. The model is based on a combination of river discharge and air temperatures expressed as Degree Days of Freezing (DDF). DDF is defined as the mean daily air temperature below freezing. For example, if the mean temperature is -8°C for a day, the DDF is -8°C. The model is based on analysis of historical data and meant to be applied with weather forecasts to predict freezing events. Gholamreza-Kashi uses the accumulated FFD over a five-day period to predict flooding. This method shows potential as a frazil-related flood forecasting tool which might be applied to Flat Creek. The method uses readily available meteorological data – air temperature, to predict possible ice-related flooding. However, conditions will be unique for each watershed or stream reach, and the predictive capability for Flat Creek will have to be determined.

On balance, we are doubtful that Approach 1 is workable, because increasing water discharge may exacerbate the flooding potential, as more water has to be passed along the creek. Also, decreasing heat transfer from water to air is much more difficult to achieve than is increasing heat transfer from water to air. This is essentially the approach tried in Flat Creek between 2001 and 2004, when in-stream structures were added to encourage the growth of a surface ice cover (the best way to reduce heat loss to the atmosphere) while at the same time improving stream habitat.

A fallback action to be considered, if the means for controlling water discharge and temperature are rather constrained, is to provide access to mechanical means for disrupting or removing ice dams and opening a flow path (that is, excavators). This action should be examined by the FCWID.

Table 2. Approach, adjustment of variables, and actions to reduce the volume of ice formed in Flat Creek through the FCWID.

| Approach | Variable Adjustment | Possible Action to be Considered |
|---|---|---|
| Approach 1<br><br>Set $L > L_R$ | Increase warm water discharge, $q$ | Water discharge would have to be added to the channel by means of groundwater pumps, or releasing water impounded upstream of the FCWID. |
| | Increase initial temperature of water, $T_{w0}$ | Heat would have to be added to the channel by means of water provided by groundwater pumps, or release of water impounded upstream of the FCWID.<br>Alternatively, |
| | Decrease heat transfer to air, $H_{wa}$, along the channel | Flow would need to be substantially slowed and turbulence-generating structures removed from the channel. |
| Approach 2<br><br>Minimize $L$ | Decrease water discharge, $q$ | Water would have to be impounded or diverted during frigid weather |
| | Decrease initial temperature of water, $T_{w0}$ | Before entering the channel, water would have to be exposed to frigid air. This could be done via increased shallowing and mixing of the flow upstream of the channel. |
| | Increase heat transfer to air, $H_{wa}$, along the channel | Once water enters the upstream end of the channel (upstream of the FCWID), heat loss could be increased by modifying the shape and height of the instream improvement habitat structures. |

## Observation and Data Needs

The mitigation approaches, along with the observations and data collected by AE during winter 2015-2016, prompt the need for further observations and data. Our analysis leads us to suggest the following three sets of additional information needs

1. Determine the possibilities and limitations associated with the mitigation approaches and actions listed in Table 2;
2. Further monitoring of Flat Creek through the FCWID and in the Elk Refuge; and,
3. Ice-formation data from sources beyond Flat Creek.

### Ice management actions

There likely are practical and various other constraints attendant to the actions Table 2 lists. These constraints must be evaluated. This task is best done by the FCWID, with our input as needed.

### Monitoring of Flat Creek

AE's winter 2015-2016 monitoring yielded useful insights that should be augmented by the following supplementary field monitoring we suggest be undertaken during winter 2016-2017:

1. Deploy the RBR temperature loggers to develop a longer-term record of water temperatures in the Creek during winter. Station T1 is a critical station for determining the incoming water temperatures. One or more of loggers should be placed in the slow moving water upstream of north Cache Street bridge to determine the temperature structure of the water column;
2. Deploy six to eight submersible pressure gages along the creek through town, focusing on the area within the FCWID. These gages should be deployed in conjunction with the temperature loggers. They should be concentrated in the FCWID, mostly upstream of rock weirs where large ice dams were identified last winter. However, one should also be placed at Station T1 to monitor upstream water levels. A similar pressure recorder will need to be placed in air to allow for barometric corrections of the pressure records. Staff gages should be placed near the pressure/temperature loggers, and read weekly during the winter;
3. Six to eight "game cameras" should be deployed along the Creek to get time-series photographic records of ice formation, coverage, and changes through the course of the ice season. These should be concentrated in the FWCID reach, but, again, one should be placed upstream of the north Cache Street bridge looking towards the creek in the Elk Refuge. The primary purpose of the camera at this location is to monitor whether an ice cover forms over the relatively warm, slow moving water upstream of Highway 189. Additional cameras could be deployed in consultation with the FCWID and AE;
4. Comparison of the two hobo air temperature records with the records from Station JKNW4 show similar trends with minor differences in minimum and maximum daily temperatures. Based on this, it is not necessary to place the Hobo air temperature loggers out again, because any future predictive capabilities can be based on the JKNW4 record;
5. The creek should be observed throughout the upcoming ice season, with observations similar to last year's being recorded;
6. In addition, attempts should be made to measure the thickness and type of ice making up an ice cover. In particular, care should be taken to identify aufeis and hanging ice dams;
7. We recommend that Dr. Ed Kempema visit Flat Creek during late December 2016 or January 2017 when ice is actively forming along Flat Creek. His direct observations of ice formation, and

discussion with FCWID and AE personnel will help confirm the viability or limitations of mitigation approaches; and
8. There is useful information in the photo log collected by AE in 2015-2016, but this information is relatively difficult to access in its present forms. It would be very useful if all of the photo-point data could be regrouped into files by point, with times associated (See Addendum 1). For example, all of the P11 upstream data are grouped together in a file, with time stamps in the file name to make viewing consecutive images easier. It would then be a simple, relatively short process to go through all of the photos to see how conditions along the river change through time.

### Data from other sources

In addition to the proposed field monitoring of Flat Creek, there are additional data of prospective use:

1. Daly (2002) and an unpublished online report (Flat Creek-Phase III-Presentation 2004.ppt) mention that creek surveying and hydraulic modelling were done sometime between2001-2004. Sundry Flat Creek stakeholders may have copies of these survey data, particularly a longitudinal profile and cross-section profiles;
2. Examine possible records of the locations and descriptions of all the instream improvements placed in the river between 2001 and 2004. It will be informative to know if there any justification, relating to ice, as to why specific instream improvements were placed where they were. Any descriptions of in stream improvements or river restoration structures would be very useful to review, particularly geographic coordinates and improvement descriptions; and,
3. Records of when and where ice-related flooding has occurred along the creek in previous years.

It will be more efficient, in the long run, to review any and all historical records on ice-related freezing rather than regenerating the data in the future. For example, multiyear flooding records may identify critical points where flooding recurs regularly, or a specific pattern to the flooding phenomena. Analysis of historical records will help design future measurement programs and may provide insights into the mechanisms of ice-related flooding.

## Conclusions and Recommendations

The monitoring work by Alder Environmental during the winter of 2015-2016 (AE 2016) identified the continuous inflow of relatively warm water from the Elk Refuge into Flat Creek as an important factor influencing ice-related winter flooding in Flat Creek. In addition, the photo record showed the complexity of ice types that affect water levels through town, and suggest that ice dams play a substantial role in ice-related flooding along Flat Creek.

The data collected by Alder Engineering during the 2015-2016 winter show that Flat Creek has a complex winter thermal and ice regime. At least three different types of ice structure may contribute to significantly increased water levels that lead to overbank flooding: (1) anchor ice formation that raises local bed elevation. Observations show that anchor ice can stay attached to the bed for several days in Flat Creek (Brian Remlinger and Sinclair Buckstaff, personal communications, August 2016). In addition, Mr. Buckstaff observed that anchor ice can thicken by 2-3 feet in one day, and that anchor-ice related flooding usually occurs during the late afternoon on his property; (2) Formation of anchor ice dams on top of existing anchor ice deposits. These dams are composed of denser (less porous) ice than anchor ice. They tend to breach, rather than release, during warming trends, and are reactivated by during following cold snaps; and, (3) hanging ice dams composed of frazil and released anchor ice that fill the channel and lead to aufeis formations. The data collected last winter do not show which of these ice features, if any, is the most likely to cause flooding. The goal of our recommendations is to gain a clearer understanding of the ice types that lead to flooding along the creek.

We believe the FCWID is taking the correct approach to understand and mitigate ice-related, winter flooding along Flat Creek. The monitoring information gathered by AE and this report are necessary steps in reliably addressing the cause of flooding and identifying viable mitigation approaches.

Table 2 lists the main approaches and their commensurate actions for possibly mitigating ice-related flooding. The main actions to further investigate areas follow:

1. Reduce the water temperature of flow entering the upstream end of the reach;
2. Reduce water discharge into the reach; and,
3. Eliminate ice dam and ice jam formation along the reach.

Additionally, the mechanical means should be considered for removing ice at locations of ice and flow congestion. An important aspect of mechanical removal is providing access for mechanical equipment to remove ice.

An important action with all mitigation efforts is to correlate air and water temperatures, such that air temperature is a useful indicator metric for anticipating the possible onset of ice-related flooding. Fairly recent studies indicate that this idea is practical on some rivers.

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# Addendum 1

Photo addendum to “Preliminary Analysis of Ice-Related Flooding on Flat Creek, Wyoming, Winter 2015-2016” by Edward Kempema and Rob Ettema, October 14, 2016.

This addendum contains 16 digital photos collected at Photo Point 10 looking upstream (AE 2016). The purpose of the addendum is to show the utility of time-series photos in illustrating the dynamic nature of ice and water levels in Flat Creek during the winter.

Figure A1. 12/02/15, P10U_20151202: A breached ice dam is visible in the middle of the figure. Border ice has formed both upstream and downstream of the ice dam. Upstream of the ice dam there appears to be accumulated slush ice making up a continuous ice cover across the creek. There may be a hanging ice dam below this slush ice.

Figure A2. 12/04/2015, P10U_20151204: Very similar to previous image (12/02). This image was taken at a slightly different position relative to the previous image, so the breach in the ice dam is not obscured.  It looks like water levels are slightly elevated below the ice dam, relative to the 12/02 image. A staff gage is visible at the left corner of this image

Figure A3. 12/08/15, P10U_20151208: The ice dam and continuous ice cover are gone, exposing the rock weir underlying the dam. Water level (stage) is down through the whole visible reach, creating suspended border ice upstream of the weir and tilted, collapsed border ice downstream of the weir.

Figure A4. 12/16/2015, P10U_20151216: The ice cover has changed very little from the previous photograph. However, it appears that ice and/or snow slush is accumulating as an ice weir on top of the rock weir, resulting in slightly higher stage upstream. There doesn’t appear to be a change in stage below the weir. Snow is congealing into a floating ice cover in the lower right of the picture, below the weir.

Figure A5. 12/18/2015, P10U_20151218: Border ice is growing out from both creek banks upstream of the rock weir. There is a significant accumulation of anchor ice in the channel downstream of the weir, although water level in this area is still below December 4 levels.

Figure A6. 12/23/2015, P10U_20151223: Border ice width has increased downstream of the weir, but unchanged upstream of the weir. The ice weir height has increased, with a concurrent increase in stage upstream of the weir. It is impossible to tell if there is still anchor ice on the bed below the ice weir.

Figure A7. 12/28/2015, P10U_20151228: Continuous surface ice cover formation upstream of the weir, and almost complete ice cover development downstream. With this ice cover, little or no anchor ice could form locally. However, released anchor ice and frazil slush arriving from upstream potentially may be trapped by the ice dam/rock weir, raising water level and causing flooding upstream. On 12/04, the ice level on the staff gage was ~0.9 feet, this image shows a level of ~0.5 feet, a drop of 0.4 feet.

Figure A8. 2015/12/30, P10U_20151230: An example of an ice cover that inhibits (local) frazil and anchor ice growth. This is the cover the in-stream improvements were made to promote. However, the dark spot in the new snow at the base of the dam in the center of the picture may indicate that the ice dam is increasing in height though overtopping (see figure 3 in text), which would also raise stage upstream of the dam. The undisturbed snow on top of the ice indicates no substantial rise in stage has occurred at this time.

Figure A9. 01/02/2016, P10U_20160102: Very similar to previous image, but there is a reduction in the size of the open water lead in the right center of the image. Dark spots at base of dam suggest overtopping of the dam, but there appears to be little, if any, increase in the height of the ice dam compared to the previous photograph. The gray color of the ice downstream of the ice dam suggests stage has increased slightly, resulting in water inundating the snow cover visible in the previous image.

Figure A10. 01/06/2016, P10U_20160106: Again, very similar to previous image, with no discernable changes upstream of the ice dam. More inundated ice below the ice dam indicates that water levels in this area have continued to rise. This increase in water level most likely reflects changing ice conditions downstream of the photograph rather than an increase in creek discharge.

Figure A11. 01/11/2016, P10U_20160111: A complete surface ice cover, exactly what is needed to prevent frazil and anchor ice formation. Water levels above and below the ice dam appear to be same as in the previous image.

Figure A12. 01/14/2016, P10U_20160114: Ice cover is still complete, but has started to settle due to reduced stage and/or discharge.

Figure A13. 01/26/2016, P10U_20160126: Essentially back to the same conditions seen on 12/23, with a more continuous, but apparently melting, ice cover above the breached dam. Water level is down both above and below the partially breached ice dam.

Figure A14. 01.29/2016, P10U_20160129: This image shows continued melting of the ice cover. The surface ice cover is gone, and the ice dam is disintegrating. Ice dams are persistent features because they are made of dense, low porosity ice. They are among the last ice features in the channel to melt, but will be outlasted by suspended border ice. River stage is down through the entire field of view of the image.

Figure A15. 02/02/2016, P10U_20160202: Significant increase in ice dam height and creek stage above the ice dam, along with formation of a continuous floating ice cover. It may be that the ice dam is still growing upward at this point. There is very little change in stage below the dam, suggesting the dam grew through accumulation of advected slush and released anchor ice formed further upstream. Although not the highest stage of this ice season, this is the type of event that could lead to flooding upstream of the ice dam. Between January 29 and February 1, daytime high temperatures were near $0^{o}$C, raising water temperatures along the whole study reach to at least $0.6^{o}$C during daytime on 02/01. This implies there was essentially no ice in the creek channel. A short-lived cold snap during the night of 02/01 dropped air temperatures to $-18.8^{o}$C ($-2^{o}$F) supercooled the water, and most likely led to extensive anchor ice formation along with the growth of the ice dam at this location. If many spots along the stream show similar ice growth (as is likely), this set of conditions (remnant ice dams, mostly ice-free channel, and relatively warm weather followed by a cold snap, would be a trigger in a predictive model to watch for potential flooding.

Figure A16. 02/04/2016, P10U_20160204: The ice dam has been breached, dropping the water level upstream and leaving a suspended ice cover. The stage downstream of the dam looks essentially the same as in the previous image. A comparison of this image with the last shows how flooding can be a very local phenomena, with water levels varying by several feet over distances of a few hundred feet horizontally along the creek.