Analysis of Ice Formation and Winter Flooding on Flat Creek, Wyoming, Between November 2015 and February 2018

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for
Flat Creek Water Improvement District
Jackson, Wyoming

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Table of Contents

Cover photo: Anchor ice dam on an exsisting rock weir near Creekside Village Condominiums on January 4, 2018. Image from Alder Engineering.

List of Figures

List of Tables

Summary

This report is the culmination of a three-year study undertaken to understand the physical processes that control ice formation and ice-generated flooding in Flat Creek. The ultimate goal of the study was to develop a plan to minimize the risk of winter flooding through Jackson, Wyoming. Pertinent river-ice research is presented to describe ice formation in fluvial systems, and to describe the state of knowledge of small-stream ice processes. Data collected by Alder Environmental during winters spanning the period from November 2015 through February 2018 are summarized, and major findings are presented. Historical ice-driven flood records and accounts are used to flesh out a picture of winter flooding on Flat Creek. A simple heat-budget analysis, using a combination of a linearized heat budget and accumulated freezing degree days is used to show that “small” heat sources (e.g., groundwater and frictional heat) are major components of Flat Creek’s winter energy balance. These sources supply more heat to the creek than can be lost to the atmosphere over the course of the winter. As a result of this heat and other factors, it is very difficult to form a stable, floating ice cover along Flat Creek. Instead, frazil and anchor ice are the predominant ice types in the creek. The writers identified two types of ice jam that create the largest flooding risk in Flat Creek: long, channel filling accumulations of merged, attached anchor ice and surface ice that choke the creek, and anchor ice dams. Based on the analysis and observations, it is suggested that the WID use a conservative ice management plan that uses a combination of injected heat (thaw wells) and mechanical means (excavators) to minimize the risk of winter flooding in Flat Creek. Included in this plan are a list of several identified choke points that should be modified to reduce local flood risk.

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 to monitor water and ice conditions in Flat Creek through the Town of Jackson during winter 2015-2016. This monitoring was continued through the winters of 2016-2017 and 2017-2018. Of focal interest was the reach of Flat Creek within the FCWID boundaries. This report analyzes the findings of AE's monitoring program and recommends further considerations toward mitigating ice-related flooding.

Our report focuses especially on the following questions associated with Alder Environmental's monitoring work and our knowledge of ice-related flooding in situations similar to Jackson's:

1. What ice-formation and ice-driven flooding processes do the observations and data show?
2. Are there significant gaps in the observations and data, and, relatedly, what observations and data should be collected in future winters?
3. What viable options exist for mitigating the adverse consequences of winter flooding?

We intend this report to be viewed as a substantial component of a longer-term project aimed at managing hydrologic, hydraulic, and thermal conditions in Flat Creek with the goal of reducing ice-induced winter flooding. In this regard, this report focuses on identifying and defining a practicable option for managing ice formation so as to mitigate flooding. The option involves minimizing the volume of ice formed in the reach and having the means (thermal and mechanical) to ease flow choking at key locations along the reach.

Observation and Data Sources

The observations and data herein analyzed come from a variety of sources:

- Alder Engineering's 2015-2018 winter monitoring studies, which include measurements of water temperatures, air temperatures, water levels (stage), water volumes (discharge), thaw-well operations, and ice conditions along the creek. The measurements and links to a GIS database are described in the reports "*Flat Creek Winter Characterization Study, Methods and Data Summary, Data Deliverables*" by Alder Environmental (2016, hereafter AE 2016); "*Flat Creek Winter Characterization Study, Methods & Data Summary Deliverables*" (2017) and "*Flat Creek Winter Characterization Study 2017-2018, Methods & Data Summary Deliverables*" (2018). Directions to access all three years of data in the GIS database are available in the 2018 report. The utility of the online GIS database developed by Alder Engineering is difficult to overemphasize. This online gateway provides geo-referenced, graphical access to much of the data collected during the three years of the study, including locations of thaw wells, ice dams, anchor ice accumulations, overbank flooding, and hundreds of photographs. This website should be among the first references consulted by anyone interested in Flat Creek ice problems.
- The data collected by Alder Environmental between November 2015 and February 2017 have been analyzed by the authors of this report, and are available in two previous reports submitted to the FCWID (Kempema and Ettema, 2016, 2017). These reports are summarized here, and the results reported in the reports are compared to the winter 2017/2018 data.

- Dr. Kempema visited Flat Creek in January 2017 and January 2018, when he met with Alder Environmental personal and made direct observations of Flat Creek ice conditions. A summary of his observations are included in this report.
- In addition to analysis of the last three winter's data, data included in this report includes historical information recovered from interviews with Jackson residents and found in newspaper and online resources. These sources provide a historical perspective and additional information about ice processes in the creek.

Ice-Formation Processes in Flat Creek

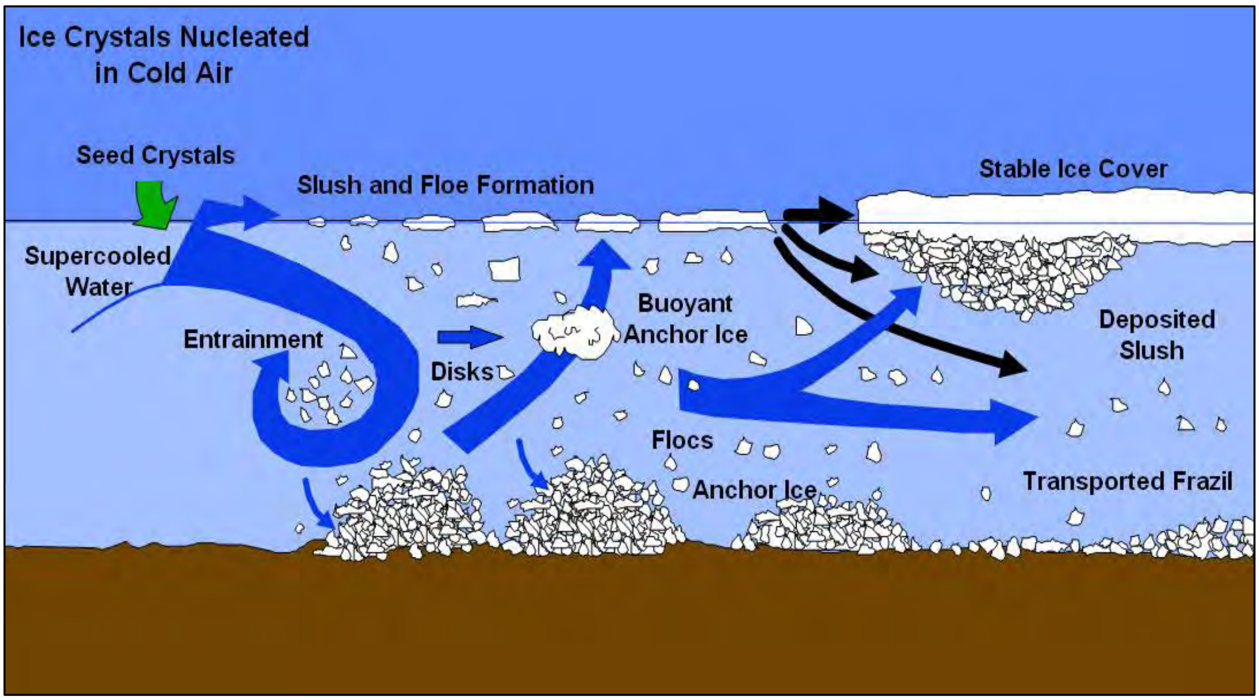

Figure 1. Forms of dynamic ice in flowing water include frazil disks and flocs, attached and released anchor ice, floating slush ice floes, and stable ice cover formation. Ice transported from upstream (frazil, released anchor ice, and floes) may accumulate on the underside of a stable ice cover as an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

Figure 1 illustrates our understanding of river ice formation, based mainly on observations from medium and large rivers; it is an understanding shared by leading river-ice hydraulicians. Although this figure is 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; Turcotte et al., 2014b; Turcotte et al., 2013). Flat Creek, being less than 45 feet (15m) wide, shallow (winter flow is typically less than 1 foot (0.3m) deep), relatively steep (slope = 0.0055, Daly, 2002), and having coarse bed sediment (gravels and cobbles), is a "small stream." Besides comparatively small flow rates, the main differences in freeze-up processes in

[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.

small streams arise because channel boundaries and large roughness elements (e.g., rock outcrops and boulders) can directly interact with ice formation processes and, thereby, with water flow. Figure 2 shows the effect that ice cover formation has on rivers of various sizes. This figure illustrates three important points about ice formation:

1. A shallower channel is thermally far more responsive to changes in heat fluxes (from weather and groundwater) than is a deeper channel;
2. For a given discharge, all ice formation increases the flow depth, because of added flow resistance; and,
3. An ice cover of a given thickness has a much greater impact on a shallow stream than on a large river.

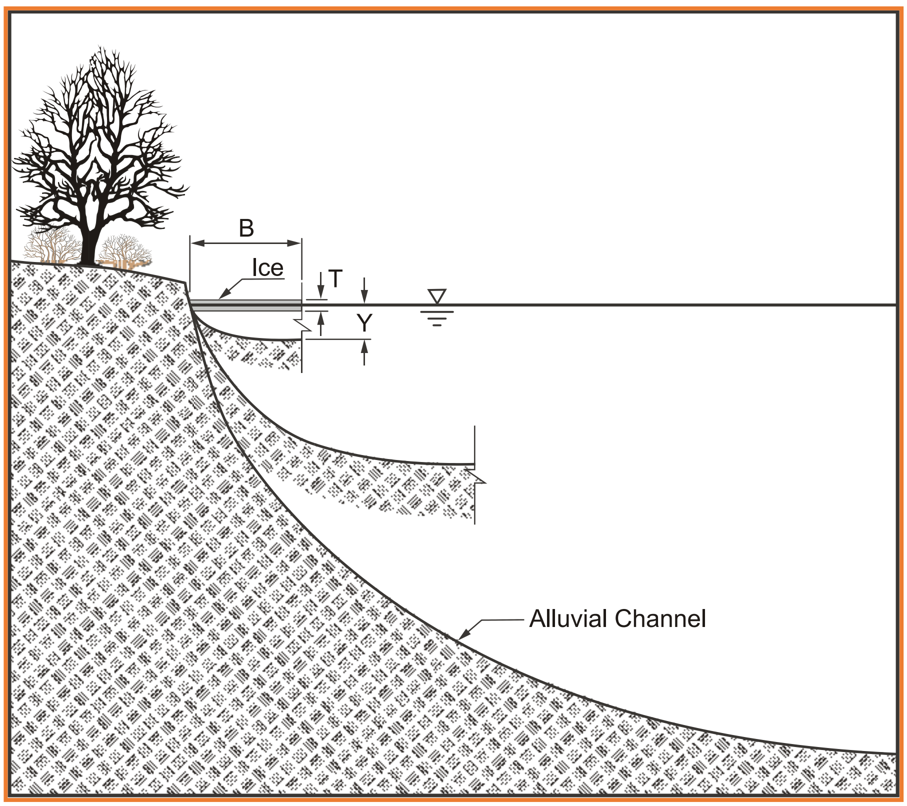

Figure 2. Diagram illustrating the effect that ice of a given thickness, T, has on different sized alluvial channels. B is distance from the bank, Y is the water depth, and the inverted triangle represents the water surface. For a small, shallow stream like Flat Creek, all ice has a very large effect on the flow depth. This effect is amplified when ice of given thickness also lines the channel's banks and bed, as further illustrated below in Figures 3 and 4. From Ettema (2007).

Anchor ice formation in small streams

Flat Creek is a small stream. It is about 30 feet (10 m) wide, shallow (more than 75% of the creek through Jackson is less than 1 foot (0.25 m) deep, Wesche and Wesche, 2003), has a slope of 0.55% (Daly, 2002), and a winter discharge of about 70 cubic feet per second (cfs, ~2m^3/s). The relatively small size of Flat Creek makes it difficult to compare ice processes in the creek to much of the fluvial ice processes literature published before about 2000. Up until about the turn of the millennium, studies of ice formation in rivers focused mainly on larger systems, with flows greater than about 10 m^3/s (350 cfs). This focus on larger flows was driven by the fact that infrastructure and engineering structures affected by ice were mainly located on larger rivers. In the past 10 years, however, scientists and engineers have recognized that ice-related processes in small streams are significantly different from those observed in in large rivers (Kempema et al., 2008; Lind et al., 2016; Stickler and Alfredsen, 2009; Tremblay et al., 2014; Turcotte and Morse, 2011, 2013; Turcotte and Morse, 2017; Turcotte et al., 2014b; Turcotte et al., 2013).

In this section, we review published research findings directly relevant to ice formation in small streams. We believe this fairly extensive review is directly useful for understanding ice formation in Flat Creek and, thereby, in identifying ways to avert potential problems associated with ice formation.

A substantial portion of the published research is from Canada. Benoit Turcotte, Brian Morse, and their colleagues at Université Laval, Quebec, have probably made the largest contribution to our understanding of small-stream freeze-up processes (Dubé et al., 2014; Turcotte and Morse, 2011, 2013; Turcotte and Morse, 2017; Turcotte et al., 2011a; Turcotte et al., 2014a, b; Turcotte et al., 2011b; Turcotte et al., 2013). They promote 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 (Figure 3).

Supercooling water and frazil generation associated with freezing air temperatures trigger anchor ice formation. Anchor ice accumulations create backwater effects, especially when they cover significant portions of the bed or create ice "weirs" in the flow. The next 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 become hard, strong structures. Ice dams, as their name implies, block flow in a channel and raise upstream water levels. Growing, or active, ice dams form by freezing of successive, thin layers of water overtopping the dam. Ice weirs and ice dams are widespread along Flat Creek during winter flooding events.

Turcotte et al. (2013) point out that anchor ice and ice dams are the most recognized types of ice affecting freezing gravel-bed channels. Anchor ice accumulations alter bed roughness and choke channels, raising local water levels. Ice dams, composed of anchor ice and aufeis (icing) accumulations, occupy the entire width and depth of the channel and are described as "channel blockage" features. Turcotte et al. describe three stages of ice dam formation:

1. The active stage, when air temperatures are below freezing and ice dams build up through a combination of anchor ice accumulation and local aufeis development;
2. The passive stage, when the heat budget is positive and the ice dams are no longer increasing in height or width; and,
3. The breached stage, when the anchor ice dam is breached or perforated, usually by a relatively narrow opening.

The transition from passive to breached stages can occur in an hour or less, resulting in draining of water retained behind the dam. Turcotte et al. point out that the breached stage is not associated with seasonal breakup. Instead, this stage is an essential part of the freeze-up process. Because of the narrow opening in breached ice dams, such dams can rapidly become active again when the next cold weather front passes through. Typically, ice dams slow the flow enough to encourage development of a surface ice cover upstream of the ice dam (this is not true for Flat Creek). When water drains from behind an ice dam, the ice cover may remain, if thick enough or suitably supported. This suspended ice cover, which is not in contact with the water surface, creates an insulating layer that protects the water from further freezing. If the channel upstream of an ice dam lacks supporting rocks, the surface ice layer collapses back into creek and either floats away or melts, depending on the net energy flux in the system.

Figure 3 shows a longitudinal profile of Turcotte and Morse's (2011) model of anchor ice, ice dam, and suspended ice cover growth in a gravel bedded stream. This model is a reasonable representation of freeze-up processes occurring in Flat Creek. We have modified this figure to better represent Flat Creek conditions by designating the emergent boulders as cross-sections of rock weirs. This figure shows how anchor ice accumulations form preferentially on large rocks extending into the flow, how the ice accumulates through time, and how the anchor ice eventually emerges through the water surface, creating ice dams. As anchor ice accumulates water level also rises. When ice dams are breached, water level falls (although not to pre-ice levels), exposing the ice dam remnants to the atmosphere. Panels f and g of Figure 3 are probably least applicable to Flat Creek conditions because they over represent the amount of suspended ice that forms in Flat Creek. Small remnants of suspended ice attached to the creek banks are common features in Flat Creek, but these remnants usually don't cover a very large portion of creek surface, because the suspended ice cover collapses into the river and melts.

Figure 4 (also from Turcotte and Morse, 2011) illustrates ice growth in a channel upstream of an active anchor ice dam. As the ice dam height increases, anchor ice continues to choke the bed (light blue in figure), while aufeis and surface ice growth form hard, compact ice wedges (dark blue) along the channel border. Both of these ice types choke the channel cross section and raise local water levels. Turcotte et al. (2014) note that even though border ice growth out from the channel margins decreases the open-water area, as long as water level continues to rise, there is no change in heat loss to the atmosphere (assuming constant weather conditions) because the growing border ice is constantly flooded by thin layers of water that cover the ice surface and continue to lose heat to the atmosphere at a constant rate.

Ice dams and border icings continue to grow upward and outward until one of three things happen. First, floating surface ice may grow to cover the entire water surface, halting anchor ice growth. Second, the net energy flux may change from negative to positive (due to sunrise, warming weather trend, or heat input from another source), resulting in cessation of ice growth and/or melting of the existing ice cover. This is the situation that leads to breaching of existing anchor ice dams. Turcotte et al. (2013) found that ice dams stopped growing and eventually breached when heat fluxes became positive. They report that ice dams breached at air temperatures ranging from -2^{o}C to -20^{o}C, indicating that heat fluxes (other than heat exchange between the stream and the atmosphere) varied greatly from one place to another in a watershed. Third, with continued net heat loss and maintenance of an open water channel, anchor ice, ice dams, and border icings will continue to grow until ice dams grow to reach the channel depth, at which time there will be overbank flow, with flooding and ice formation in low lying areas. In this situation, overbank flooding may occur upstream of an ice dam due to backwater effects while simultaneously downstream flooding occurs because of water being diverted outside of the channel. Turcotte and Morse (2013) found that ice dams grow at 1-3 cm/hour (~1 inch/hour) and can remain active for several days. Upper limits on ice dam growth are limited by the duration of a cold weather event or by the local channel depth. Once an ice dam grows to the top of the channel, water flows over or around the dam, so the dam cannot grow any higher. Flow around the ice dam is represented on the left side of the bottom panel of Figure 4, where there is a slope away from the thick border ice accumulation.

Turcotte et al. (2013) discuss the formation and implications of ice dams in detail. They found that anchor ice and ice dams result in significant storage of stream water, and thereby may substantially reduce water discharge. They conclude that ice dams formed in steep channels represent an underrated freezeup flood threat to infrastructure because the ice-related flooding process is not properly understood and categorized. Because of water stored behind ice dams, there is the potential of releasing javes, or ice jam release waves, when ice dams are suddenly breached (Beltaos, 2007). Turcotte et al. observed that ice dams initially form on cascades, at each step of a step-pool channel, at the head of riffles, and where large rocks emerge from the flow, and point out that all these sites correspond to areas of lateral channel blockage and/or water velocity increases. Turcotte and Morse (2011) found that boulders or stone clusters that reduce channel cross section by as little as 5% may collect anchor ice and thereby lead to ice-dam formation.

Turcotte et al. (2013) outline possible methods to mitigate ice-dam induced flooding. They state that the mechanical breaching of an ice dam can temporarily reduce upstream water levels. They point out that an ice dam cannot grow upward unless it also extends across the entire channel. They also suggest continuously warming some of the water upstream of the site where an unwanted ice dam forms. In this regard, they indicate the following equation to evaluate the amount of energy (Ω_h, Watts) required to maintain the water temperature (T_w) above the freezing point over a targeted, partial channel width (W_{tar}):

$$\Omega_h = (T_{Wtar} - T_w)\frac{QW_{tar}\rho_w C_p}{W_s} - E_{net}\left(\frac{W_{tar} - L_{plume}}{2}\right) \qquad \text{Equation 1}$$

Tw is the initial water temperature (0°C or supercooled), T_{Wtar} is the target water temperature at the ice dam location, Q is stream discharge, ρ_w is water density, C_p is the specific heat capacity of water, W_s is the surface width of the stream, E_{net} is the net heat energy budget, and L_{plume} is the length of a triangular-shaped warm water plume or the distance between the heat source (with water diffusing downstream) and the ice dam. Turcotte et al. point out that the heat source must be positioned far enough above the ice dam to prevent the development of “icing dikes” around the heat source that reduce its effectiveness. This distance exceeds “a few meters.”

Nafziger et al. (2017) studied anchor ice formation and release events on two regulated and one unregulated stream in northeastern Canada. Theses streams have slopes, widths, and discharges similar to Flat Creek. They used a combination of water temperature, water stage, and time-series digital photography to identify 161 anchor-ice formation and release events. These events comprised both single-day and multi-day anchor ice events. Single-day events resulted in a diel rising stage when water supercooled and anchor ice formed at night and decreasing stage when water warmed and anchor ice released during daylight hours.

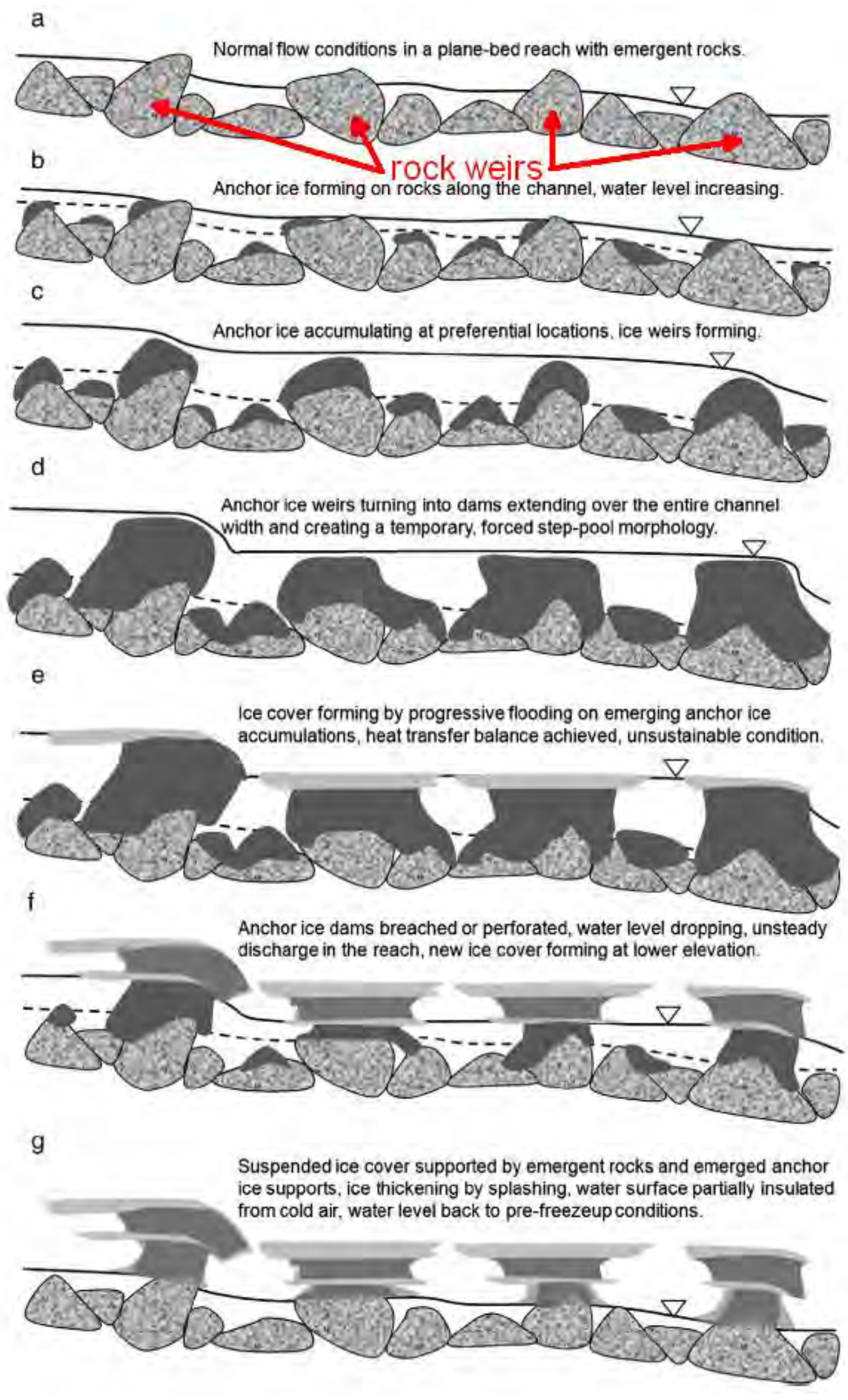

Figure 3. Turcotte and Morse (2011) illustrate their interpretation of ice cover formation in a longitudinal stream profile. This figure is a good representation of anchor ice dam formation in Flat Creek. Dark grey represents anchor-anchor-ice accumulation, light grey is surface ice growth. The solid black line with triangle represents the water elevation, the dotted line represents the initial water elevation. Discharge is assumed to be constant.

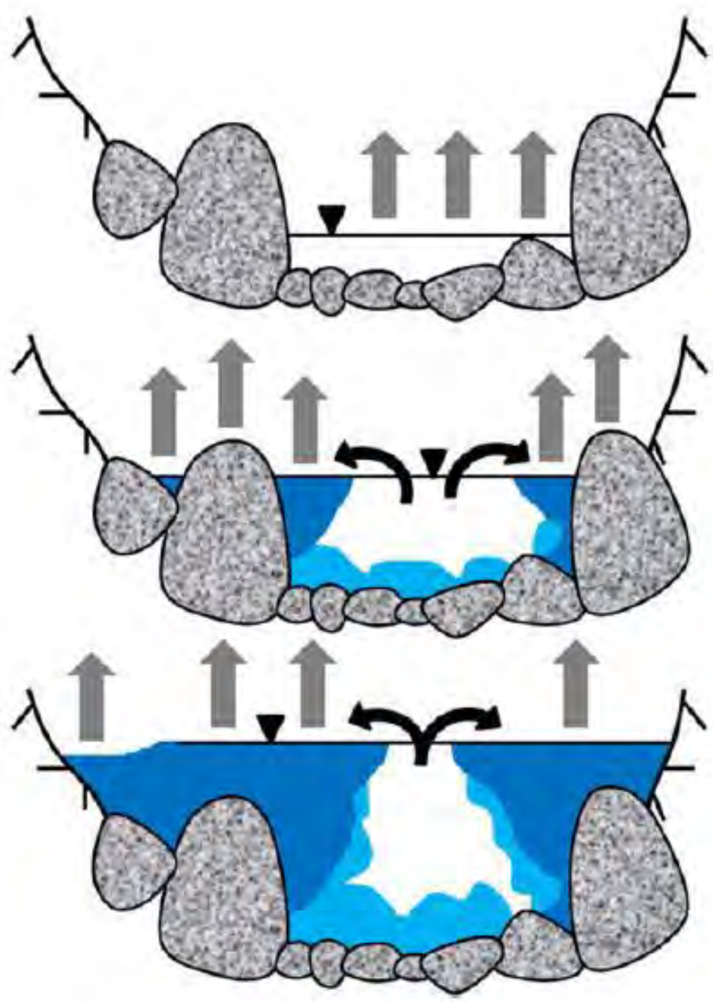

Figure 4. A conceptual model of ice formation in a channel cross section upstream of an anchor ice dam where water is constantly flooding newly formed ice surfaces. The dark blue zones represent dense border ice formed as water levels rise and flood existing ice (black arrows). The light blue represents anchor ice deposits. The gray arrows represent heat loss from the creek to the atmosphere; the bold line with a triangle represents the water surface, which rises as ice accumulations choke the channel. The left side of the bottom panel represents water rising above the level of the downstream bank, leading to overbank flooding. (This figure is from Turcotte et al. 2014, and is used with their permission.)

Additionally, Nafziger et al. (2017) classified stream anchor ice deposits into three morphological categories:

1. *Weir morphology* consisting of narrow accumulations of anchor ice that stretch across the channel, usually at the crest of a riffle, in a weir-like manner;
2. C*arpet morphology*, accumulations of anchor ice that cover, or carpet, the channel bed along significant longitudinal distances; and,
3. *Patchy morphology*, consisting of distributed, unconnected patches of anchor ice on the stream bed.

They used changes in water stage and photographic records to identify the beginning and end of anchor-ice formation events. On mornings following anchor-ice formation events, anchor ice accumulations on the bed either released, stayed in place to form multi-day accumulations, or were incorporated into the surface ice cover of the streams. Nafziger et al. report that 98% of anchor ice accumulations released on days when there was a net heat gain to the water and the air temperature was above -15^{o}C (5^{o}F). This observation indicates strong thermal control on anchor-ice release from the stream bed. Nafziger et al. also found that regulated and unregulated streams have different ice regimes. Anchor ice only formed in unregulated stream during shoulder seasons; i.e., before and after the formation of a surface ice cover during winter. In contrast, regulated streams maintained surface ice covers for shorter periods of times, and experienced greater number of anchor ice events, with the number of anchor ice events increasing with downstream distance from the dam. The latter behavior is attributable to the continuous or frequent release of relatively warm water from upstream impoundments (water whose temperature is above the freezing point).

Tremblay et al. (2014) conducted a study of anchor ice formation and ice rafting in the Stokes River, Quebec during the winter of 2012-2013. Their 140 m long study reach varied from 6-12 m in width and had an average bed slope of 0.95%. The river bed is composed of gravel with a mean grain size of 5.8 cm, and consists of wide, shallow riffles, glides, and two "deep" pools. Tremblay et al. identify two types of anchor ice cycles:

1. Diurnal cycles, where anchor ice formed overnight and was released during the following morning; and,
2. Multi-day cycles (MDCs), where anchor ice formed and continued to grow over several days.

They report that anchor ice formed during diurnal events tended to be poorly attached to the bed and of relatively low density (<633 kg/m^3). In contrast, MDC anchor ice increased in thickness over several days, and had densities ranging from 633-920 kg/m^3. MDC anchor ice masses were harder and more firmly attached to the bed. As anchor ice thickened, in places it formed anchor ice dams that emerged from the water surface and merged with the surface ice cover. Anchor ice dam formation initially raised upstream water levels to the height of the dam (0.3 to 0.4 m). In addition to anchor ice dams, thickening anchor-ice masses merged with surface ice, which increased the total ice thickness and increased the potential for severe ice jam formation. MDCs ended when water temperatures rose to above the freezing point, resulting in release of anchor ice from the bed and the formation of thin "channels" or breaches through the ice dams that drained upstream water. Tremblay et al. suggest that multi-day anchor ice events occur primarily in rivers draining small, steep watersheds. They note that, even though multi day anchor ice cycles have been more widely recognized in recent years, they are still poorly described in the literature.

Lind et al. (2016) studied 25 boreal streams with slopes >0.5% in northern Sweden to determine the hydrologic and thermal controls on ice formation. They developed a conceptual data base describing the likelihood of anchor ice, surface ice, and/or suspended ice development based on an analysis of 22 different variables. Suspended ice is common small, steep streams; it is a derivative form of the surface ice cover that remains suspended above the water surface when water levels drop because breaching of anchor ice dams or reduction in stream flow. Lind et al. concluded that ice formation is a complex process controlled by interactions between numerous hydraulic, climatic, and geomorphic variables. Warm groundwater influx prevented anchor ice formation, while high turbulence and course substrate promoted anchor ice growth. They found that frequent freezing and thawing events decrease the stability of surface ice and stimulates anchor ice growth. They also found that anchor ice dams created the most significant increases in winter water levels in their study. In about ½ of the study reaches, ice-induced flooding events approached or exceeded peak spring flood levels, often resulting in overbank flooding. Surprisingly, Lind et al. report anchor ice formed at velocities above 0.3 m/s (about 1 foot/s). This is much lower than previously reported velocities of, for example, Hirayama et al. (2002) of 0.7 to 0.9 m/s ~2-3 feet/s). The difference in observed velocities may be due to the size of the rivers studied, Lind et al's study focused on relatively small, steep streams with small discharges, shallow and narrow flows, and course substrates, resulting in highly turbulent flows.

Figure 5. View of a breached anchor ice dam with an upstream suspended ice cover on Flat Creek (photo taken on 2/4/2016). The breached dam is about 3 feet high and is located on an existing rock weir. Anchor ice dams are common on Flat Creek, suspended ice covers are rare. The suspended ice cover in this image fell into the creek soon after the anchor ice dam breached.

The role of heat in ice formation and decay

Ice formation processes are controlled by heat fluxes, the flow of heat into and out of the water column from various sources, which are in turn governed by local incoming solar radiation, weather conditions, and flow conditions in the stream. Ideally, some form of heat (or energy) flux equation is used to define all of the energy sources and sinks that affect ice growth and decay in a small stream like Flat Creek.

Ashton (1986; 2013), for example, discusses the combinations of factors influencing the heat regime of a stream. He mentions, inclusively, the physical properties of water, the mechanical forces exerted by flowing water and thermal exchanges between the atmosphere, the water, the ice, and the stream bed. These sources and sinks include advective (conveyed by flow) and conductive heat transfer, precipitation, short wave radiation, long wave radiation, friction, and groundwater inputs into the stream. After an exhaustive discussion of heat source, sinks, and transfer, he concludes that under open-water flow conditions, the main heat fluxes are sensible and latent heat transfers. Short-wave radiation (sunlight) and longwave radiation (black-box radiation) are small and opposing heat flux components in during winter, but short wave radiation becomes an important heat source in the spring.

Ashton also mentions “secondary” (small) heat fluxes such as friction, bed sediments, groundwater inflow, and ice-penetrating short wave radiation, and identifies conditions where they should not be ignored. Ideally, it should be possible to develop an equation that takes account of all these fluxes to determine the amount of ice that grows or melts for a given set of conditions. However, it is usually impossible to identify the magnitudes of all of these heat sources and sinks, as they vary in time and location. As a result, simplifying assumptions are made, resulting in two common approaches for determining the energy fluxes: a linear heat transfer model or a cumulative degree day approach (Hicks, 2016).

The linearized heat-transfer approach lumps all of the temperature-dependent terms together and approximates them as linear functions for quantifying the rate of heat transfer. Net incoming solar radiation can be included explicitly (Hicks, 2016), but two heat transfer coefficients and a constant must be calibrated with site-specific data. If these values are not available in detail, the heat-transfer equation for open-water conditions simply takes the form:

$$\phi_{wa} = H_{wa}(T_w - T_a) \qquad \text{Equation 2}$$

where φ_{wa} (W/m^2) is the heat flux between water and air, H_{wa} (W/(m^2 °C)) is a linear heat transfer coefficient, T_w is the water temperature (°C), and T_a is the air temperature (°C). For an ice-covered flow, the appropriate equations become

$$\phi_{wi} = H_{wi}(T_w - T_i) \qquad \text{Equation 3}$$

and

$$\phi_{ai} = H_{ai}(T_i - T_a) \qquad \text{Equation 4}$$

where the subscripts “*wi*” and “*ai”* respectively refer to water-ice and air-ice interfaces and “*i*” refers to heat flow through the ice. Hicks (2016) points out a number of difficulties associated with using these methods to calculate heat fluxes and associated changes in ice volumes. Heat transfer coefficients are expressed in terms of W/(m^2 °C), so the open-water and ice-covered areas of the flow must be known. In addition, the temperatures of the water, ice, and atmosphere must be determined. This problem is exacerbated in small streams with growing anchor ice dams, because flooded border ice heat fluxes are equivalent to the open-water flux over the same area (Turcotte and Morse, 2013).

When ice forms, water temperature can be assumed to be at the freezing point and air temperature, which varies with time, can easily be recorded. Determining ice growth rates under an existing ice cover are more challenging, because it is difficult to determine the appropriate ice temperature, T_i. With subzero air temperatures, the temperature through the ice cover varies from 0°C at the ice-water interface to the air temperature at the ice surface. Fortunately, a continuous ice cover inhibits anchor ice formation, so we can ignore ice growth associated with heat loss through an ice cover, although this term may be important for removing the advective heat flux associated with groundwater heat advected from the Elk Refuge. Hicks (2016) reports that heat transfer coefficients in these equations range from about 8 to 20 W/(m^2 °C). In this report, we use a constant, reasonably conservative value of 25 W/(m^2 °C) for H_{wa}, as recommended by Daly (2002).

This linear approach also ignores “small” heat fluxes into and out of the stream, including warm groundwater input and friction. However, several authors (Ashton, 2013; Dube et al., 2015; Stickler and Alfredsen, 2009; Tremblay et al., 2014; Turcotte and Morse, 2011, 2013; Turcotte and Morse, 2017) have pointed out the relatively greater importance of groundwater input into relatively small streams.

A second common approach used to determine the thickness of an ice cover is the cumulative degree-day approach (Hicks, 2013). This method assumes that the temperature-dependent heat transfer terms that dominate fluxes can be represented by accumulated degree-days. The accumulated freezing degree days (AFDD) are calculated by summing up the mean daily air temperatures, starting when mean air temperatures remain below the freezing point. The equation for calculating the thickness of a surface ice cover is

$$t_i = \alpha\sqrt{AFDD} \qquad \text{Equation 5}$$

where t_i is the ice thickness and α is a calibrated, site-specific coefficient. Although the degree-day method is empirical, it remains quite useful. Notably, Kempema and Ettema (2017) discuss modifying this relationship slightly to determine the ice volume produced in Flat Creek; i.e.

$$\text{Vol. of Ice} = Area\left(\alpha\sqrt{AFDD}\right) \qquad \text{Equation 6}$$

where α is a (yet to be determined) coefficient relating the volume of ice formation to *AFDD.* The utility of the AFDD method in Flat Creek is as a tool to predict potential cold weather periods when ice-induced flooding may occur, rather than as an active management ice management tool.

Although the linear heat-transfer model is probably the best approach to apply to Flat Creek at this point, it should be noted that Dube et al. (2015) have tackled the problem of developing a physically-based numerical ice-dam growth and water level model that includes a complete heat budget for a single step-pool sequence in Lepine Creek, Quebec, Canada. This model is complex, but successfully quantified many of the winter heat flux components of a step-pool channel. Dube et al. believe that a simplified version of this model could be incorporated into an existing ice/hydrodynamic model that could be used to predict ice dam and water levels during freeze-up periods. Though no such model exists at this moment, it can be envisioned that such a model will be available within, say, about five years.

Winter Observations, Data, and Results from 2015 through 2018

Winter 2015/2016 and Winter 2016/2017 Summary

Between November 2015 and mid-February 2016, 13 data loggers were placed in Flat Creek between Cache Street and High School Road to record water temperatures at 5 minute intervals during the winter months. Air temperature data was also collected. In addition, Alder Engineering personnel regularly walked sections of the creek within the FCWID to map ice distributions, ice types, overbank flooding, and to collect photographs. The primary results from this study are that anchor ice is ubiquitous in Flat Creek, water temperatures and ice conditions vary continuously with weather conditions, and that there are multiple warm water sources in the creek that persist throughout the winter. The largest warm water (heat) source is Flat Creek itself, which is spring fed. The heat flux associated with warm water, combined with flow characteristics, inhibits the formation of a persistent surface ice cover on the creek. Instead, ice, predominately frazil and anchor ice, form when air temperatures drop. When air temperatures rise, the net heat flux is enough to warm the water, releasing anchor ice from the bed and eventually melting all of the ice in the stream channel. This process is good, because removing ice from the channel lowers water level, but it also sets the stage for a new round of anchor ice formation and another ice-induced flooding event when the next cold weather front passes through.

The winter 2016-2017 field effort built on and closely matched the methods developed during the field effort conducted during winter 2015-2016. Alder Environmental (2016, 2017) provide detailed descriptions of sampling methods, sampling locations, and descriptions of the data collected. Figures 1 to 4 from the appendix of Alder Environmental 2017 report are included in Appendix 1 to this report, and can be used to identify sampling station and thaw well locations discussed in the text. A major data-collection change for the 2016-2017 field effort was adding six submersible pressure loggers to measure water level at various locations along the creek, along with seven time-series cameras ("game cameras") that collected digital images at approximately 15 minute intervals through the winter. Also, rather than placing air temperature data loggers along the Creek, all weather data were retrieved from the weather station JKNW4. These changes were made based on the previous winter's results.

The 2016/2017 winter data records reinforce the 2015/2016 winter observations. Major findings from these two years of records include:

- Water temperatures respond rapidly to both air temperatures and incident sunlight when there are significant stretches of open water. The creek may warm by several degrees above freezing during the day and still supercool and form anchor ice at night. Even during the coldest parts of the year, creek water may warm by several tenths of a degree when air temperatures rise above 23°F (-5°C). Inspection of the 2016-2017 time sequence photo records show that the creek surface must be ice-free for the water column to warm by this amount. These relatively large temperature variations are a result of the shallow, turbulent nature of the flow in the creek.
- There were multiple supercooling and anchor ice formation events leading to increased water levels during both winters.
- The water temperature records from both years indicate that multiple, varying sources of warm water flow into the creek from the National Elk Refuge downstream to at least Karns Meadow. The exact locations of all of these warm-water sources have not been identified, but include springs on the Elk Refuge, springs and surface runoff in Jackson, and Cache Creek discharge.
- The 13 temperature loggers located between Cache Street and High School Road show a recurring "zippering" temperature structure:
    - When there is no ice cover on the creek and the air temperature drops, a supercooling front advances upstream from temperature logger station 13 to temperature logger station 2. A frazil- and anchor-ice front advances upstream along with this temperature front. As a result, the downstream end of the stream reach experiences longer periods of supercooling and more frazil and anchor ice formation than upstream.
    - When air temperatures warm during the day, warm water advances back downstream from the temperature logger 1 station to temperature logger 13 station, melting ice as it progresses.
    - These advancing and retreating temperature fronts were observed numerous times during both winters, and illustrate the dynamic nature of temperature variations and ice formation when no ice is present.

- An essentially continuous surface ice cover formed along the WID portion of Flat Creek upstream of Thaw Well #2 during the winter of 2016/2017. This ice cover, along with a relatively thick snow layer on top of the ice, lasted through January 2018. However, continuous, long-lasting, surface ice covers like this are unusual events on Flat Creek (Brian Remlinger, personal communication 8/2018). All existing data and historical records indicate that promoting surface ice cover formation is not a viable winter flood management technique along the creek.
- Even during relatively cold winters like 2016/2017[2], continuous discharge from Thaw Well #2 is capable of keeping the creek channel essentially ice free for at least 440 yards (400 m) downstream of the Garaman Park bicycle bridge. However, this unmanaged thaw well operation pushes anchor ice formation downstream in a haphazard manner, resulting in increased water levels and flood risk downstream of the Highway 89 Bridge. These data, along with Daly's 2002 analysis, suggest that an additional thaw well installed upstream of the Highway 89 bridge, combined with an active management plan, will significantly reduce the ice-induced flooding risk from Thaw Well #2 to High School Road.
- The 2015/2016 and 2016/2017 photo stations, water temperature loggers, and water level loggers show a complex history of ice cover extent, ice choking, water temperatures, and water level variations during the course of the winter. The sources of relatively warm water inputs into the river, combined with natural swings in air temperatures, create a complex, varying ice regime in Flat Creek. This ice regime in turn creates complex, varying changes in water levels along the creek that are difficult to predict.

Winter 2017/2018 Summary

The WID/Alder Environmental data collection scheme for winter 2017/2018 was very similar to the 2016/2017 winter, with a similar suite of instruments and observations being collected. The major difference between the two winters is that the focus of the study shifted to the lower reaches of Flat Creek, so temperature loggers and water level loggers were concentrated in the downstream section of the creek. Table 1 describes the relative locations of data loggers during the 2017/2018 winter. Appendix 1 contains aerial photos with the locations of the loggers during the 2016/2017 and the 2017/2018 winters, these locations can also be compared on Alder Environmental's GIS website (Alder Environmental, 2018).

The 2017/2018 winter was much warmer than the previous two winters (Figure 6). During the winters of 2015/2016 and 2016/2017, the accumulated freezing degree days were relatively similar, at 630°C-days and 718°C-days, respectively. The maximum AFDD in 2017/1018 winter summed to 295°C-days, a relatively modest total. However, there were three significant cold periods during this winter, from 12/5 to 12/15, 12/20 to 12/27, and 12/30 to 1/5, when significant amounts of anchor ice formed. Figure 7 shows air temperatures in the top panel, along with water temperatures and levels at level stations L17.2 and L17.6. Figure 8 is a close-up of the bottom panel of Figure 7, showing details of the inverse relationship between the water temperature and water level. This figure illustrates how, as water temperatures warm, water levels drop. The period from 12/4 to 12/15 was characterized by diel anchor ice formation and release events that raised water levels by up to 0.7 feet (0.2 m) at night when water

[2] https://www.usclimatedata.com/ lists records that the average air temperature in Jackson in December 2016 was 5.7°F below normal. During January 2018 the average daily air temperature was 11.2°F below normal.

supercooled and ice formed. Water levels decreased during the day when air and water temperatures rose and anchor ice either melted or released from the bed and drifted downstream. The two later, longer cold periods consisted of multi-day anchor ice cycles (MDCs) that were characterized by anchor ice accumulations staying attached and continuing to grow and raise water levels for several days. Although there was a diel, quasi-sinusoidal variation in air temperature, air temperatures stayed below the freezing point. All of the water level stations showed increasing water levels during these two periods (summarized in Table 2), but the greatest increase in water level was observed at station L17.2, which was located about 40 feet (12 m) upstream of the rock weir south of Elk Run Lane on the Garaman bike path. Table 2 lists the maximum measured water levels reached during each of these multi-day anchor ice cycles.

Table 1. Relative locations of temperature and water level loggers during winter 2017/2018. Also see Appendix 1.

Logger station ID	Descriptive location	Distance between stations (m)	Distance between stations (ft)	Distance from Cache Street (m)	Distance from Cache Street (ft)
T17.1/L17.1[1]	US[2] of N Cache Street Bridge	-		0	0
T17.2	Gill Street, 45’ US of rock weir	1000	3280	1000	3280
T17.3	35’ upstream of Garaman Park bicycle bridge	810	2657	1810	9217
T17.4	DS[2] end of Karns Meadow	1005	3296	2815	18450
T17.5	Stacy Lane	720	2362	3535	30045
T17.6/L17.2	45’ US of rock weir south or Elk Run Lane	650	2132	4185	43772
T17.7/L17.3	35’ US of TW2	460	1509	4645	59007
T17.8	US Crabtree Lane	75	246	4720	74489
T17.9	DS Crabtree Lane	105	344	4825	90315
T17.10/L17.4	US Stellaria Lane Bridge	210	689	5035	106830
TT17.11	US H89 Bridge	275	902	5310	124246
T17.12/L17.5	US side of bike bridge S of Highway 89	165	541	5475	142204
T17.13/L17.6	80’ US of bike path bridge (& island) north of Smiths	140	459	5615	160622

[1]T represents an RBR temperature logger station, L is an Onset water level logger
[2]US = upstream. DS = down stream

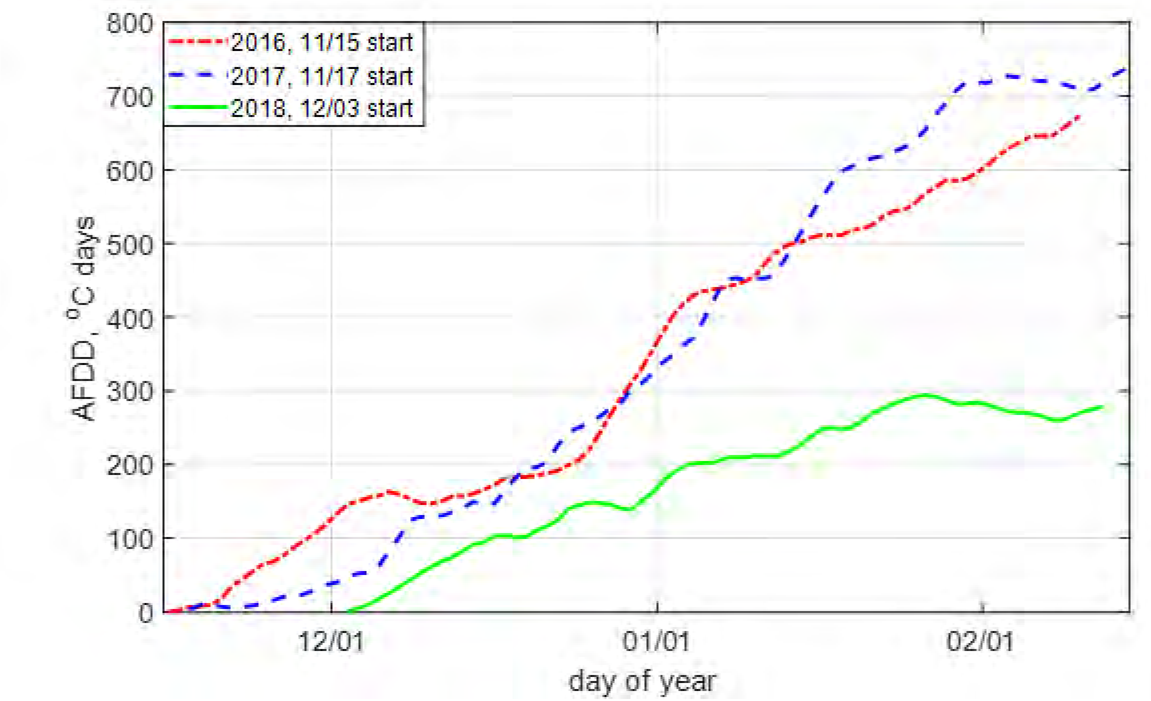

Figure 6. Plot of accumulated freezing degree days (AFDD) for winters of 2015-2018. The dates listed in the figure legend are the start time for AFFD. Winter totals are 11/15/2015 to 2/10/2016: 677 AFDD, 11/17/2016 to 2/16/2017: 750 AFDD, 12/3/2017 to 1/20/2018: 295 AFDD.

Table 2. Maximum water levels recorded during the two multi-day anchor ice cycles that occurred during the winter of 2017/2018. Negative values indicate a drop in water level.

Level Logger Station	Δh_{max} Dec 22- Dec 29 ft (m)	Δh_{max} Dec 31-Jan 6 ft (m)
L17.1	-0.16 (-0.05)	-0.13 (-0.04)
L17.2	2.52 (0.77)	2.56 (0.78)
L17.3	0.85 (0.26)	1.15 (0.35)
L17.4	0.66 (0.20)	1.31 (0.40)
L17.5	0.82 (0.25)	0.98 (0.30)
L17.6	0.91 (0.28)	1.35 (0.41)

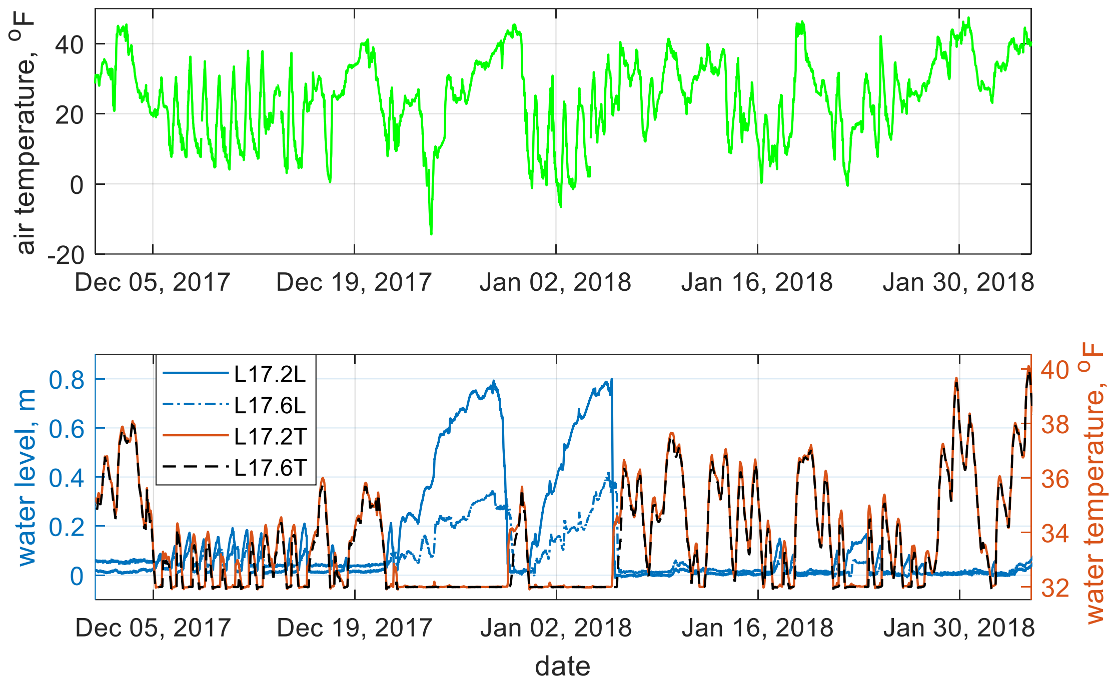

Figure 7. Top: winter 2018 Jackson air temperatures. Bottom: water levels (blue) and water temperatures at level logger stations L17.2 and L17.6 during the 2017/2018 winter.

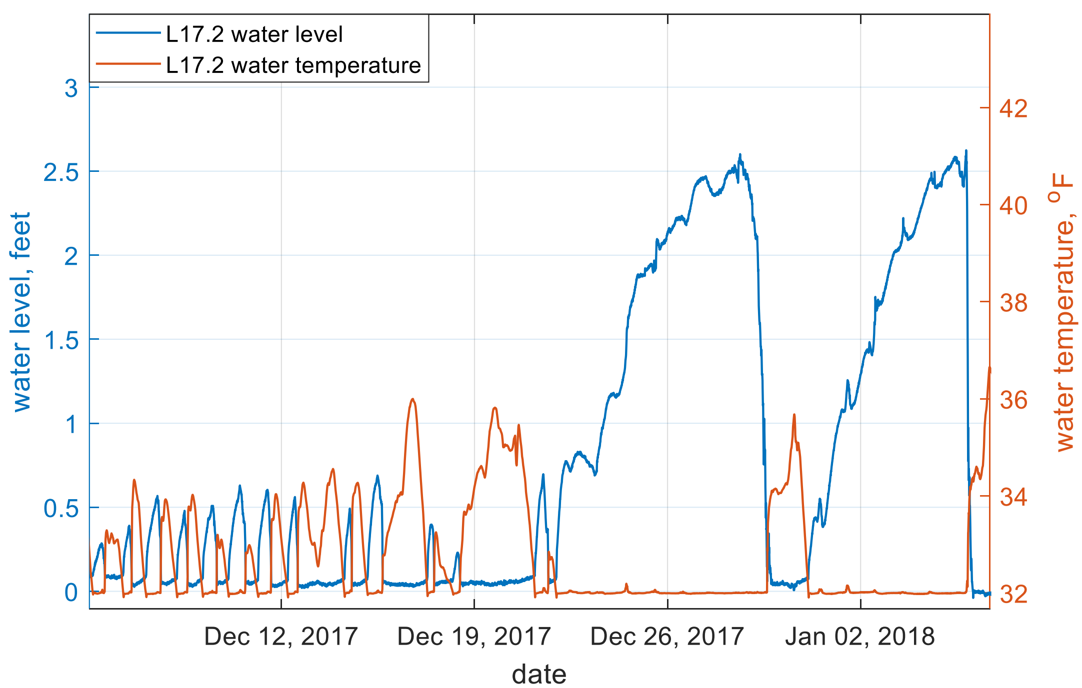

Figure 8. Expanded view of a portion of the bottom panel of Figure 7 illustrating the inverse relationship between water temperature and water level.

The temperature and water levels measured during the 2017/2018 winter show similar trends to the previous two winters. Graphs of air temperature, water temperature, and water level for each instrument station are included in Appendix 2. As noted in previous years, the water temperature at Cache Street stayed above the freezing point all winter and water level did not appear to be affected by ice. All downstream instrument stations experienced both supercooling and anchor ice formation. However, several of the temperature stations recorded temperature measurement greater that those recorded at station T17.1 (Appendix 1 for location) at the same time, indicating that there are other sources of heat entering the creek. Although water level station L17.2 experienced the greatest measured increase in water levels, there was no threat to infrastructure at this location. However, anchor ice dams on rock weirs above and below this station did flood the bike path and threaten residences along the creek.

Dr. Kempema visited Flat Creek from January 1 to January 4, 2018. His visit coincided with one of the multi-day anchor ice cycles, so he was able to observe much of the process. He spent a large amount of his time walking the creek and observing ice conditions. These walks occurred almost entirely along Alder Engineering's designated walking paths, although Dr. Kempema also visited Cache Street to make observations. During this period, essentially the entire creek bed was carpeted with anchor ice. Dr. Kempema entered the creek at three locations on January 2 and found that the anchor ice carpet was 4 to 8 inches (10-20 cm) thick and composed of accumulations of 1-3mm diameter frazil ice crystals frozen solidly together. The strength of the anchor-ice carpet increased in a downstream direction. Near the Smith's market, it was strong enough to support a person's weight.

Although essentially the entire creek bed was carpeted by ice between January 1 and 5, the most spectacular manifestations of this ice event were the anchor ice dams and weirs that formed in the creek on every observed rock weir, and in other places. The worst flooding observed during the site visit occurred around an anchor-ice dam that developed on a rock weir for the Wort Diversion in Garaman Park. This anchor-ice weir grew over a period of six days, from December 31 through January 5. By January 5, overbank water levels were threatening condominiums and an excavator was dispatched to remove the anchor-ice dam. The excavator was not able to reach the dam, but did clear accumulated ice from upstream, which reduced water levels and the flood threat. The next day the ice dam thermally eroded, which mitigated the flooding threat (Bill Wotkyns, personal communication). Although there were several more diel supercooling event through January, this was the last major ice-induced flooding event during the winter.

Anchor ice carpets, weirs, and dams are eye-catching features of Flat Creek. However, as water loses heat to the atmosphere, border ice also grows out from the creek edges. By January 4, 2018, border ice grew to several meters wide in several places along the creek (perpendicular to the flow), and thickened by flooding and aufeis formation (Figure 3). However, the only place where a continuous surface ice cover was observed was upstream of the Wort Diversion, where released anchor ice collected and congealed into a continuous ice cover less than 100 m long. The January 1-5 event was the last major icing event of the 2017/2018 winter. After this event the photo logs show little or no border ice, while the water level data shows only relatively small diel anchor ice formation and release events.

A result of the relatively mild winter is that thaw well use was limited to Thaw Well #2 being operated for a total of 25.8 hours over the course of the winter.

Understanding ice formation and ice-related flooding on Flat Creek

The photo stations, water-temperature loggers, water level loggers, observations, and mapping information collected over the past three winters show a complex history of water temperatures, ice types, ice cover extent, ice choking, and water levels during the course of each winter. The inputs of relatively warm water combined with natural swings in air temperatures create a complex, varying ice regime in Flat Creek during the winter season. This ice regime in turn creates complex changes in water levels that are difficult to predict.

The U.S. Army Corps of Engineers *Ice Engineering Manual* (USACE, 2006) stresses the difficulty of predicting ice jams and ice-related flooding. It also stresses the need to evaluate historical ice, meteorological, and hydrologic records to develop predictive measures to address these issues. In this section of the report, the authors pull together the observations collected during the last three winters, along with historical records to describe ice conditions and ice-driven flooding in Flat Creek.

Heat fluxes

As discussed in the literature review, ice formation requires a net loss of energy, or heat, from the water body to the surrounding environment. In the case of rivers and streams, the heat sources and sinks include the advective heat loss to the atmosphere, short- and long-wave radiation, groundwater, precipitation, and heat supplied from the stream's bed. Our report mentions (see "The role of heat in ice formation and decay") that the complete heat flux equation is usually simplified by ignoring groundwater, friction, and other "small" heat sources, and then linearizing the heat transfer equation by use of a heat transfer coefficient. In this section we discuss the relative magnitudes of some terms that are normally ignored, but must be considered in Flat Creek. We do this by comparing heat loss values to ice growth rates predicted by an AFDD analysis.

Heat loss to the atmosphere is a primary driver of ice formation. It is possible to estimate the thickness of a floating, surface ice cover with Equation 5, the Stefan equation (Hicks, 2016):

$$t_i = \alpha\sqrt{AFDD} \qquad \text{Equation 5}$$

where t_i is the ice thickness, α is a site-specific coefficient, and *AFDD* is the accumulated freezing degree day. Cumulative Flat Creek AFDD values for study winters are shown in Figure 6. Hicks (2016) lists a range of values for α; by using a value for an "average river" of 0.014 it is possible to estimate the theoretical thickness of a floating cover in Flat Creek. Multiplying ice thickness by stream surface area gives an estimate of the ice volume produced during a given winter. These values are summarized in Table 3. These theoretical values are not directly convertible to anchor ice carpet or ice dam volumes because of density differences in different ice types (anchor ice typically has around 50% porosity), but they do provide a way of comparing ice conditions during different winters.

Table 3. Estimated thickness of a surface ice cover on Flat Creek based on Stefan equation.

Winter	Measured AFDD °C-days (# of days)	Estimated surface ice thickness from Stefan Equation ft/yr (m/year)
2015/2016	677	1.2 (0.36)
2016/2017	750	1.25 (0.38)
2017/2018	295	0.8 (0.24)

Short- and long-wave radiation measurements were not collected during the study. These are important terms in the heat budget, and are measured in some studies, but they are often either ignored or wrapped into the heat transfer coefficient in the linearized form of the energy budget. Anecdotal evidence from Jackson residents, and from Dr. Kempema's winter visit, suggests that the shadow cast by Snow King Mountain affects anchor-ice retention on Flat Creek from around West Karns Avenue to Stellaria Lane. The shadow shades Flat Creek from short-wave radiation (direct sunlight) for much of the winter and thereby enables persistent multi-day anchor ice cycles along this section of the creek. The Laramie River near Laramie shares many characteristics with Flat Creek, including slope, discharge, and winter weather patterns. However, it flows across a wide, grass-covered flood plain, so it gets direct insolation almost every day. By way of comparison, the Laramie river typically experiences diel cycles of anchor ice formation and release during the shoulder seasons (early December and late February), with 8-inch thick (0.2m) accumulations forming over much of the bed on cold, clear nights, then releasing when the sun strikes the water in the morning. During mid-winter, the Laramie River is usually almost completely ice covered.

Multi-day anchor ice cycles are rare (Kempema and Ettema, 2011; Nafziger et al., 2017). Flat Creek, though, experiences multi-day anchor ice cycles with each subsequent cold spell. Recognizing this problem, Graham and Girard (2016) performed a solar radiation analysis along Flat Creek through Jackson for the period of December 1, 2015, through February 29, 2016. This analysis was performed using the ArcGIS Area Solar Radiation Tool and a 10 m DEM for topography. They report that Flat Creek at the base of Snow King Mountain received three times <u>less</u> direct solar radiation than other areas of the creek during this period. The incoming insolation along the Creek ranged from 30,000 to 105,000 Watt-hrs/m^2. It would be interesting to do this analysis at 1 week intervals over the same time period, to see how solar radiation changes as the sun angle changes through the winter season. Also, although this information is somewhat conjectural, it is very obvious that incoming solar radiation has a large effect on anchor ice release. Again, by way of comparison, on the Laramie River, attached anchor ice is usually completely gone within 3 hours of the morning sun hitting the water.

The first year of the study identified a persistent advective heat flux into the creek through town in the form of warm water at the Cache Street Bridge. This warm water results from the spring-creek nature of Flat Creek, where warm groundwater rises in the Elk Refuge and flows through town. The presence of this advective groundwater heat flux was confirmed during the next two years of the study (Figures A2.2 and A2.3 in Appendix 2). This heat must be removed from the water before ice can form. The writers use the analysis and values Daly (2002) used in his thaw well analysis to determine how far downstream from the Cache Street Bridge this added heat protects the creek from ice formation (or, more precisely, to identify the position of the 0°C isotherm, assuming the creek is well mixed). For this calculation, we assume an initial, constant water temperature at the bridge of 33°F (0.55°C) and two discharges, 40 cfs and 100 cfs (1.1 and 2.8 m^3/s). Figure 9 shows the results. The distance travelled before water reaches the freezing point is a function of stream discharge and air temperature. Larger flows, at the same temperature, require a longer time (and therefore distance) to remove the “excess” heat from the water. The heat loss rate is a function of air temperature. The greater the temperature differential between air and water, the faster the heat is removed. This plot is made with the assumption that air temperature is held constant; in fact, the air temperature varies almost continuously, so the heat loss rate and distance travelled before freezing also vary. The changes in air temperature, along with this relatively large and constant heat input, cause the “zippering” of freezing and thawing fronts advancing upstream and downstream throughout most winters (Kempema and Ettema, 2016, 2017).

Another way to consider the effect of warm water influx from the Elk Refuge into Flat Creek is to determine the amount of ice that is melted by the heat carried within the water. Assuming a continuous flow of 40 cfs (1.13 m^3/s) at 33°F (0.56°C), water at the Cache Street Bridge delivers enough heat to melt about 750 cubic yards of ice per day (690 m^3/day). At a 100 cfs flow rate, the melted ice volume increases to 1875 cubic yards per day (1725 m^3/day). These values are based on a heat capacity of water (C_p) of 4.184 kJ/(kg °C), the latent heat of fusion of water (L_{fw}) of 334 kJ/kg, and an ice density ρ_i of 920 kg/m^3. These can be converted into melting or ice suppression thicknesses by dividing the volume by the area of the creek (about 57,000 m^2 through town). This results in an estimated 0.5 inch to 1.25 inches of ice suppression or melting per day (1.2-3 cm/day). This is much greater than the estimated growth rate (Table 3). However, anchor ice does not usually melt in place. Warming the surrounding water to the freezing point causes anchor ice to release from the bed and drift downstream, being effectively flushed from the system. These values are presented for illustrative purposes. In reality the situation is much more complex. Complexities include continually varying air and water temperatures (Figure A2.2). As air temperature varies, the amount of heat loss from water to air also varies, which accounts for the daily variations observed in water temperature (Figure A2.3). However, having positive heat fluxes coming into the creek, either at the upstream end at the Elk Refuge, or along gaining stream reaches, continuously melts ice in the creek (or effectively suppresses ice growth), whether anchor ice or border ice exists. If enough ice is melted, the open water channel is reestablished, setting the stage for more anchor ice formation. As discussed previously, frazil and anchor ice are the first types of ice to form in turbulent flows, so the reestablishment of open water sets the stage for new potential anchor-ice flooding events during the next cold spell.

If water in Flat Creek arrived at Cache Street at the freezing point during most of the winter (the assumption made in Daly’s (2002) thaw well analysis), it would seem to make sense to promote surface-ice cover formation to reduce ice-related flooding events. However, the data gathered over the past three winters shows that Flat Creek is very dynamic, with the freezing front (or zero degree isotherm) advancing up- and down-stream through the reach during winter. Formation of a sustainable surface ice cover is very difficult. As a result, multiple anchor-ice events occur annually.

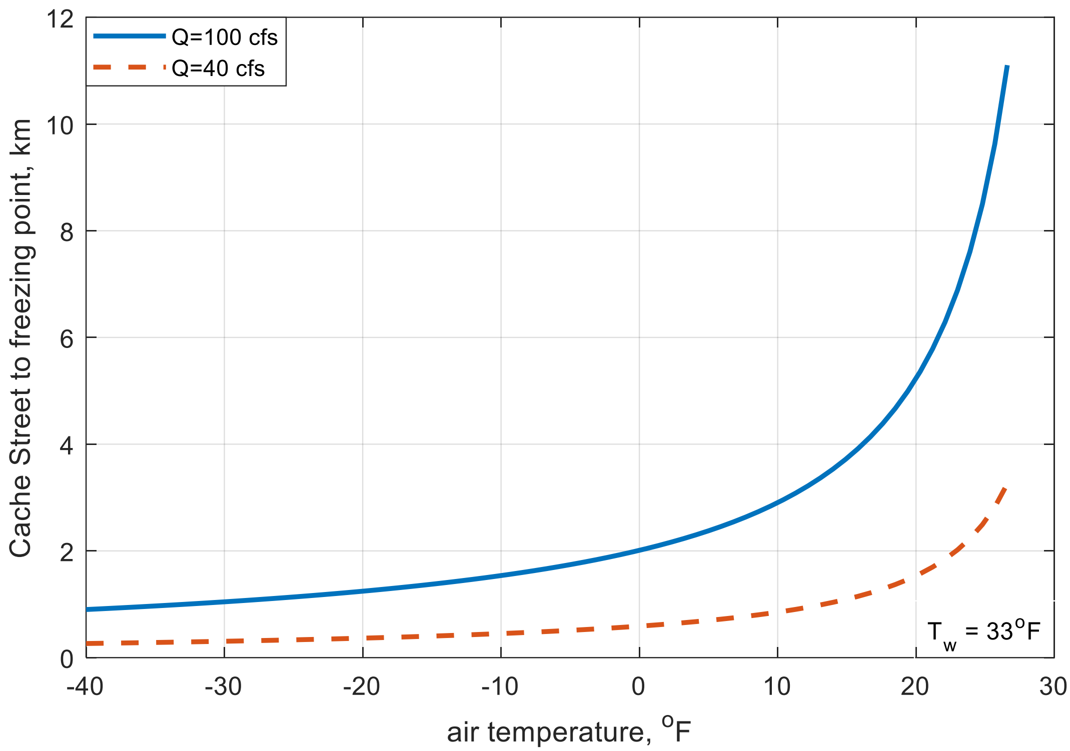

Figure 9. Distance from the Cache Street Bridge to the initiation of ice formation for different air temperatures and stream discharges (Q). This figure was constructed using the water depths and current velocities determined by Daly's (2002) HEC-RAS-modelled analysis of Flat Creek. The water temperature at the Cache Street Bridge is assumed to be 33°F (0.55 °C).

Other heat sources entering the creek were inferred, but their locations were not identified during the three-year data collection effort. These inferred sources show up as warmer temperatures at downstream temperature logger stations as compared to upstream stations (Figure A1.2). The exact causes of most of these temperature anomalies are not clear, although it is clear that Cache Creek is a potential heat source (Kempema and Ettema, 2017); and Brian Remlinger identified a warm-water spring in the lower section of Karns Meadows. Dr. Kempema also identified some anchor-ice free sections of creek bed during the January 2018 visit that may be warm water seeps. The writers strongly urge using caution in going beyond saying that there are unknown heat sources into the creek. The fact that the temperature loggers only record the high temperature anomalies when water temperatures are above the freezing point (and air temperatures tend to be high) suggests that many of these sources may represent surface runoff (attributable to local snow melt or rain).

Thaw well use and effects

The amount of ice suppression afforded by thaw well use is a straightforward calculation (Kempema and Ettema, 2015). Summaries of thaw well operation during the past three winters are presented in Table 4. During the 2016/2017 winter, Thaw Well #2 operated for 41 days at 60% of design capacity. The average water temperature of TW #2 water was slightly above 8.5 °C, and the thaw well discharge was 550 gallons per minute (gpm, 1.23 cfs or 0.0347 m^3/s). The amount of heat TW #2 added to the river per hour can be determined using

$$E_{tw} = Q_{tw} T_{tw} C_p \left(\frac{3600\ s}{hour}\right) \qquad \text{Equation 7}$$

where E_{tw} is the energy introduced by Thaw Well #2, Q_{tw} is the thaw well discharge, T_{tw} is the thaw well water temperature, and C_p is the heat capacity of water (4.184 kJ/(kg °C). Using the values above, Thaw Well #2 injects 4444 kJ/hour of energy into the creek. Dividing this value by λ and ρ_{ice} provides a Thaw Well #2 ice suppression rate of 13.3 m^3/hour. This can be converted to an ice melt or ice suppression rate for the area between the thaw well and High School Road. The creek distance from the thaw well to High School Road is 1370 m, with a width of 10 m. Using these values predicts about 1 m (3.28 feet) of ice suppression over the 41 days when the thaw well was operational. This is about three times the predicted ice growth based on the AFDD analysis mentioned above (Table 3).

The heat injected by Thaw Well #2 is constant as long as the pump is running, regardless of air temperature, and this heat must be removed from the water column before ice can form. The rate this heat is moved from the water to the atmosphere is a function of air temperature. The air temperature and heat flux to the atmosphere varies throughout the day. Less ice will form at higher temperatures, so discharged thaw well water will be more efficient. The energy injected into the creek from Thaw Well #2 supplements the energy supplied by warm water entering the creek at Cache Street and other warm water sources that move the freezing front up and down the creek throughout the winter.

It should be remembered that it is not necessary to melt all the ice in the creek to mitigate anchor-ice induced flooding. Anchor ice will release from the bed when creek water temperature rises above the freezing point. Anchor ice dams will also breach. The addition of warm water accelerates this effect, enabling anchor ice to release from the bed and flush downstream past High School Bridge.

In preparing this report, we became aware of two online news reports that claim thaw-well operation withdraws 300 to 320 million gallons of water from the underlying aquifer each winter. This volume of water consumption would require running all three thaw wells at design capacity for about 90 days each winter. To our knowledge, this has never been done. The thaw well operation records for the winters from November 2015 through February 2018 are summarized in Table 4. Maximum water use during this period was 56 million gallons of water during 41 days of use during the relatively severe 2016/2017 winter. 23.6 million gallons of this water (42%) was discharged at Thaw Well #3, which enters the creek directly above the High School Road Bridge, the downstream end of built-up infrastructure. Thaw Well #3 discharge most likely protects upstream infrastructure from ice-related flooding by inhibiting ice jam formation at the bridge. However, this could be accomplished with a much smaller, managed discharge plan for Thaw Well #3.

Another thing learned this past winter is that the thaw wells are controlled by frequency drives that regulate pump speed and discharge. The 2016/2017 thaw well pumping records show that Thaw Wells #2 and #3 are operated at 65% to 70% of design capacity, pumping at 550 gpm and 450 gpm, respectively. Thaw Well #1 is also, apparently, not operated at design capacity. Barring other information, it should be assumed that this well also operates at about 65% of design capacity. Brian Remlinger related that a Town employee explained that operating the wells at design capacity dewatered the wells, which threatened pump failure (personal communication, June 2018).

Table 4. Summary of thaw-well operation between November 2015 and February 2018

Thaw well number	Design capacity, (gpm)		Operating capacity during 2016/17 (gpm)	Days used during 2015/16 winter	Total water used 2015/16 (million gallons)	Days used during 2016/17 winter	Total water used 2016/17 (million gallons)[2]	Days used during 2017/18 winter	Total water used 2017/18 (million gallons)[2]
1	1000		Not given	11	15.8[1]	0	0	0	0
2	800		550	18	14.4[2]	41	32.4	1[2,3]	0.36[3]
3	700		450	18	12.5[2]	34	23.6	0	0
	Total winter water use (million gallons)				42.7		56		0.36

[1] Calculated using design capacity, operating capacity is not known, so this is an overestimate
[2] TW #2 operated for a total of 25.8 hours between 1/3/2017 and 1/22/2017 at the operating capacity
[3]Calculated with stated operating capacity

It is interesting to note that operating Thaw Well #2 at 68% capacity (550 gpm) maintained an open-water channel essentially all the way to the High School Road Bridge during the 2017/2018 winter. However, large anchor ice dams created high water levels and overbank icings from Highway 89 Bridge downstream to High School Road as a result of the open water area (Kempema and Ettema, 2017).

The discussion above is not meant to diminish the concern that thaw well use may have a negative impact on the aquifer. We simply want to make sure that correct information is available to the public, so that informed decisions can be made. It is also heartening to learn that the thaw wells are equipped with frequency drives that allow the discharge rate of each well to be varied over a large range. We strongly believe that the thermal solution to the Flat Creek winter flooding problem requires managed thaw well operation to obtain the best results. The presence of frequency drives on the thaw wells means that both the length of time and the discharge volume of each well can be varied to minimize the flooding probability.

In summary, this section of our report indicates the sound prospect that adding relatively warm water to the creek at selected locations should reduce the amount of water supercooling, thereby reducing the volume of frazil and anchor ice growth, and enabling anchor ice to more easily detach from the creek's bed. These actions should reduce the potential for ice-related flooding. We consider streams like Flat Creek to be very thermally responsive (change temperature quickly) to inputs and losses of heat.

Effects of instream improvements and vegetation

It is useful to consider the effects on ice accumulation exerted by the use of instream improvements of stream habitat.

Since 2004, instream environmental improvements have been added to a significant portion of Flat Creek through the town of Jackson. The improvements were added in a series of four phases (Wesche, 2002, 2005, 2009, 2012; Wesche and Wesche, 2003). Completed instream improvements on Flat Creek include a mixture of J-hook vanes, rock over pour structures (rock weirs), double rock deflectors, log spurs, excavated pools, and bank cover deflectors. In addition to potentially reducing ice-related flooding, these structures were installed to improve aquatic habitat in the Creek. Instream improvements on the reaches of Flat Creek from Snow King Avenue to Stacy Lane and from Thaw Well #2 down to the Highway 89 Bridge were planned (Wesche, 2012) but never completed. This offers the opportunity compare anchor ice accumulations in areas with and without instream improvements. Unfortunately, the area from Thaw Well #2 to below Stellaria Lane was not included in the winter walking path data collection efforts, so ice conditions along this reach are not known. There is a question whether completing the proposed instream improvements will reduce the ice-induced flooding risk through this reach. This is not a straightforward question to answer. During the 2017-2018 winter, 32 unique anchor ice dams were observed along the study reaches within the WID. Ten of these ice dams occurred along the reach from Snow King Road to Stacy Lane (31%), the area with no instream improvements. During winter 2016-2017, six of 30 recorded (20%) anchor ice dams occurred in the same reach, while during the 2015-2016 winter 10 out of 41 (24%) recorded anchor ice dams occurred there. The “improvement-free” reach from Snow King Avenue to Stacy Lane accounts for about 20% of the observed study reach (Figures 10 and 11). This suggests that the installed instream improvements have either no or very little effect on the number of anchor ice dams formed along a given creek reach. By acting as preferential sites for anchor-ice accumulations rock weirs do, to some extent, control the position of anchor ice dams.

Rock weirs and other instream improvements do, to some extent, control the position of anchor ice dams by acting as preferential ice accumulations sites. Anchor ice dams are the most visible anchor ice morphology in Flat Creek (Figure 5). A major consideration in managing ice along Flat Creek is to ascertain if instream improvement structures that trigger problematic ice dams should be removed. The consensus from the literature is that anchor ice dams tend to form in the same location every year, and that ice dams form on flow obstructions. The data from Flat Creek is ambiguous on this topic. It is clear that some features, including rock weirs, are sites of repeated ice-dam formation. However, there are also variations in the anchor ice dam distributions between years that reflect varying weather and hydrologic conditions and ice dams are not restricted to rock weirs (Figures 10 and 11). Some of these apparent variations probably arise from the way data collection methods evolved during the study period, but some of the observed variations are real. As a result, based on observational data it is relatively easy to predict that the Wort Diversion structure, for example, is a recurrent problem area. It is more much more difficult to predict the effect that removing the diversion structure will have on local anchor-ice accumulation and associated flood potential. Monitoring should be carried out after any changes to the stream bed to determine how the changes affect ice accumulation and winter water levels. It should also be kept in mind that flooding may be driven by anchor ice accumulation along any portion of the creek, and not all flooding is associated with ice dams. Several of the identified recurrent anchor ice dam locations are addressed in more detail in management section of this report.

Anchor ice literature tends to list “preferred” locations for recurrent anchor ice dam formation, including channel constrictions, heads of riffles, areas with emergent boulders, and shoals. Another generalized observation is that anchor ice forms preferentially on coarse substrates. The whole cobble-bedded channel of Flat Creek provides an excellent substrate for anchor ice formation, as seen by the extensive anchor ice carpets that form thereon. However, it is clear that rock weirs and emergent rocks concentrate anchor ice accumulation, and form locations of recurrent anchor ice dams. This issue can best be seen by visiting Alder Environmental’s Flat Creek ArcGIS webpage and turning on and off the image of an anchor ice dam so as to expose the rock weir locations on the creek bed. While there appears to be a significant correlation between anchor ice dam and rock weir locations, not all anchor ice dams form on rock weirs or other instream improvements. This observation is reinforced by the observation that there are roughly the same concentrations of anchor-ice dams in improved and unimproved portions of the creek, as discussed above. The key notion is that some channel features, including instream improvements, are more efficient at accumulating anchor ice and creating anchor ice dams.

Anchor ice dams grow at multiple locations along the creek during prolonged cold spells, and either breach or melt out in the intervening warm spells. However, the ice dams are not the only risk factor during cold periods. At the same time that anchor ice dams are forming, anchor ice carpets up to at least 8 inches thick cover the majority of the creek bed, and border ice wedges grow up and out from the creek edges (Figure 4). All of these ice morphologies work in concert to choke the creek bed and raise water levels. The critical flood risk period occurs when extended cold periods create multi-day ice cycles that produce large amounts of ice (predominately different forms of anchor ice and aufeis) in the creek.

There is very little information published on how instream improvements actually affect the ice regime of a stream. Tuthill (2008) offers a good review of the effects of instream improvements on ice regime. He points out that installation of an instream improvement structure like a weir or rock over pour may constrict the flow, leading to freeze-up ice jams. He also notes that the effect of an instream improvement, either positive or negative, may be hard to predict, and that instream improvement structures must be placed with care in order minimize their potential ice-induced flooding impact. We would argue that instream improvements need to be evaluated on a site-by-site basis. Additionally, most groups doing such improvements do not consider the improvements' effects on ice formation or movement. Consequently, there is a significant question as to the role of instream improvement structures, such as those listed above, in ice-related flooding. The question acutely applies to Flat Creek.

The U.S. Army Corps of Engineers' Ice Engineering Manual (USACE, 2006), a leading opus on ice jams, discusses the causes of ice jams. Listed features that affect ice-jam formation include changes in slope, confluences, river bends, and channel features (including instream improvements). Page 275 of the Manual states: "*Removing or building a dam may cause problems. In many parts of the country, small dams that once functioned for hydropower have fallen into disrepair. Communities may remove them as part of a beautification scheme or to improve fish habitat. However, the effects of an existing dam on ice conditions should be considered before removing or substantially altering it. It is possible that the old dams control ice by delaying ice breakup or by providing storage for ice debris. Dam construction can also affect ice conditions in a river by creating a jam initiation point. On the other hand, the presence of a dam and its pool may be beneficial if frazil ice production and transport decrease as a result of ice cover growth on the pool.*" If one substituted "instream improvement" for "dam" in this quote, it would be directly applicable to Flat Creek. The instream improvements in Flat Creek were placed with the stated dual goals of improving aquatic habitat and reducing ice formation and winter flooding. Evidently, little effort went into evaluating the extent of the improvements' impact on ice formation in the creek during the construction phase.

At this point, the writers do not have enough data to say in quantitative terms the extents to which existing instream improvements reduce or increase the risk of ice-related flooding in Flat Creek. It is clear that the installed rock weirs do act as anchor points for ice dam initiation that, thereby, heighten risks for upstream flooding. Many of the ice jams mapped along the creek during the last three winters were associated with rock weirs (Alder Environmental, 2016, 2017, 2018). This observation suggests that the instream improvements increase the risk of flooding at some locations.

However, this lack does not impede our assessment on the effects exerted by the instream structures. Based on the last three winters of observations, the writers posit that the existing instream improvements also may reduce the overall flooding impact of ice by creating a series of relatively small accumulation sites rather than a single, large ice-accumulation (and jam) site. In concept, the instream improvements may create a series of relatively low-head anchor ice dams, rather than one large constriction at a natural choke point. Unfortunately, there is not enough evidence, either from the literature or from the writers' observations, to confirm or reject this concept. What is clear is that the installed improvements do <u>not</u> work effectively to promote surface ice formation, thereby decreasing the risk of anchor ice formation. It is also clear that removing some structures will locally decrease the risk of flooding. Decisions to remove or retain these structures should be made on a case-by-case basis, and could be an objective of the coming winter's observations.

A question that came up during preparation of this report is whether vegetation on the streambed increases anchor ice accumulation. There is very little detailed information in the literature on this topic. Piotrvich (1956) notes that frazil will stick to wood in supercooled water. Foulds and Wigle (1977) report frazil adhering to "rock, weeds, and underwater structures." Recent literature focuses on ice effects on instream vegetation rather than vegetation effects on ice. Meribani et al. (2014) report that some plans resist ice formation. Presumably, this means that they would resist anchor ice accumulation. Lind et al. (2014) found that anchor ice attaches to instream vegetation and wood, and note that anchor ice affects instream vegetation by promoting the growth of ice-resistant plants. They also report that plant diversity increases in anchor-ice impacted stream reaches compared to reaches without anchor ice accumulation. Based on the literature, it is not clear whether dense vegetation mats increase or decrease the probability of anchor ice accumulation. Based on our observations of anchor ice attached to wood and plant debris in oceans, lakes, and rivers, we think that any object projecting into the water column, including plants, is a preferred site for anchor ice accumulation.

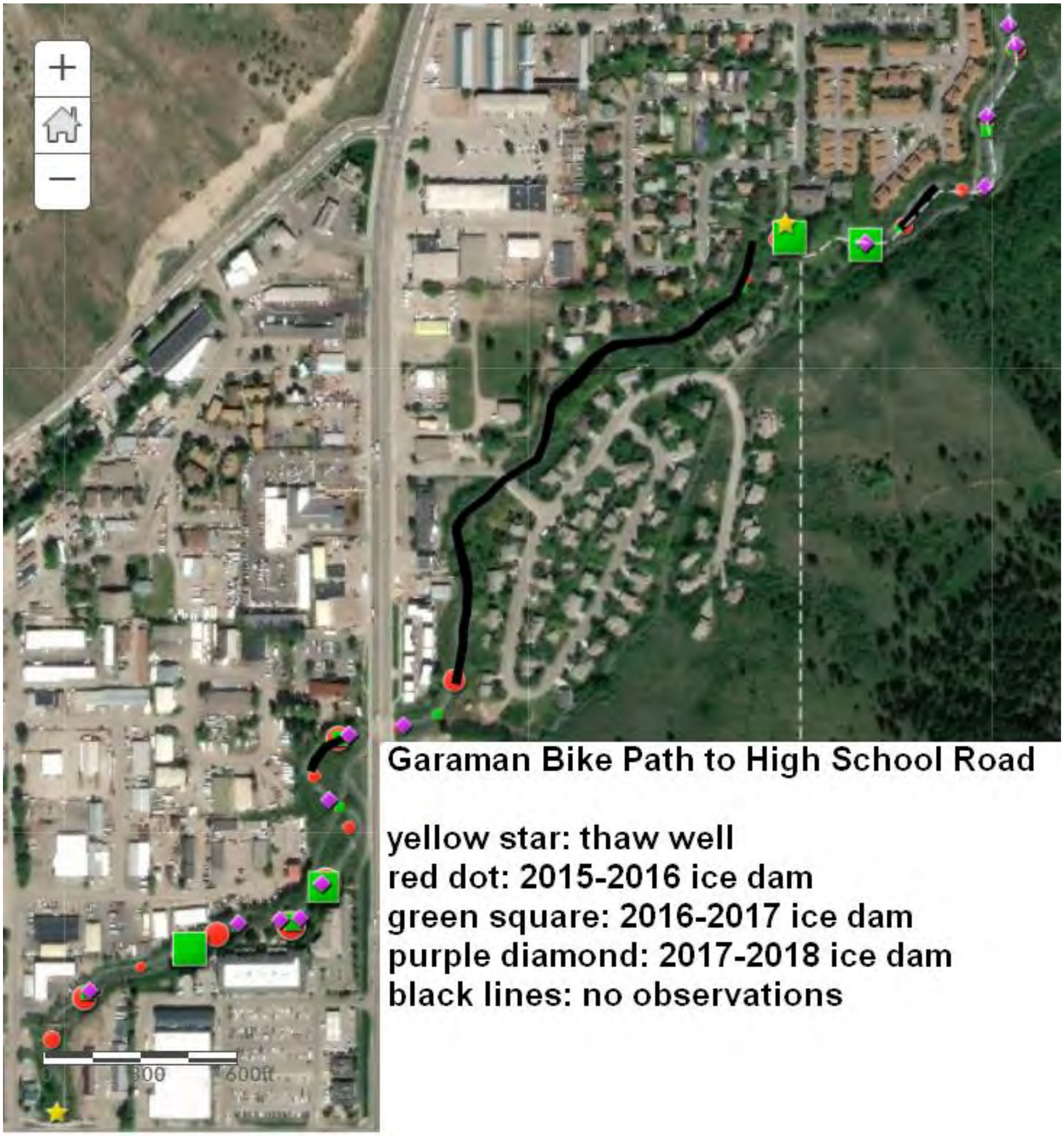

Figure 10. Anchor ice dams mapped between the Garaman Bike Path and High School Road between November 2015 and February 2018. This figure was generated from Alder Engineering's ArcGIS website (2018). The variation in marker size for the 2015-2016 and 2016-2017 data represent the relative number of observations of each individual anchor ice dam.

Figure 11. Anchor ice dams mapped between Karns Meadow and the Garaman Bike Path between November 2015 and February 2018. This figure was generated from Alder Engineering's ArcGIS website (2018). The variation in marker size for the 2015-2016 and 2016-2017 data represent the relative number of observations of each individual anchor ice dam.

Historical ice-induced flooding and damage to infrastructure

Information sources on ice-induced flooding in the Flat Creek include historical records, newspaper accounts, and interviews with waterfront residents. These sources potentially provide useful qualitative information regarding ice-related flooding along Flat Creek, especially the locations of the flooding.

However, the writers recovered very little information from reliable historical records. The only written record found addressing pre-development ice problems was from Jim Stanford on January 23, 2014, recorded in the comments section of the website of the *Jackson Hole Underground*. The article describes January, 2014 flooding in the creek (http://www.jhunderground.com/2014/01/21/flat-creek-flood-fight/#more-25202):

"First, regarding the history, I asked fisherman and former Town Councilman Paul Bruun about it over the weekend, and Paul said the creek has been flooding, up and down, as long as anyone can remember. I'm told the town has a letter from Mayor Ralph Gill in the 1970s advising a creekside developer he

would be on his own to fight floods. Farther downstream, the Lockhart-Gill family has been dealing with flooding on their ranch for several generations."

In April and June 2018, Dr. Kempema talked with Mr. Maurice Horn, a longtime Jackson resident, about ice-related flooding. Some four decades ago, Mr. Horn moved into a creekside property on Crabtree Lane, just upstream of the Leek Diversion. There was very little development along this stream reach in 1979, based on historical aerial photographs[3]. Mr. Horn resided on Crabtree Lane until 1993, and he reports that ice-induced high water levels were common during that time, although his house has never flooded. The worst winter he remembered was in 1992, when high water levels required clearing ice from most of the creek through Jackson. During this event, water rose at Mr. Horn's business property (1090 S. Highway 89, NE corner of 89 and Stellaria Lane) to the point where water was 3 inches high on the building door. FEMA puts this property in the area of 0.2% annual flood (500 year annual flood).

The history of efforts to mitigate ice-related flooding also sheds some light on ice-related flooding itself. The first recorded attempts to stop ice-related flooding occurred in the late 1990s, when the Town installed three thaw wells to discharge warm water into the creek (personal communication, Mr. Sinclair Buckstaff Jr., 1/2017). The goal of these wells was to add heat to the creek and inhibit ice formation. The thaw wells did not perform as well as expected, so Dr. Steve Daly of the U.S. Corps of Engineers Cold Regions Research and Engineering Laboratory visited Flat Creek in November 2001. 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. Daly determined that the existing thaw wells could mitigate ice-related flooding for distances of about 500 to 5,000 feet downstream of the well, depending on stream discharge and air temperature. The extent of thaw well coverage depends on several factors, including how water from the thaw wells is mixed within the river and how the heat transfer coefficient (water to air) is affected by such features as ice dams. The smallest protection distance determined by Daly occurred with his minimum assumed air temperatures of -30°F. Downstream protection distance increases as air temperature increases. Daly made a number of suggestions to minimize ice-induce flooding, including installing ice control structures (levees or floodwalls) along the creek, doing nothing, installing at least two more thaw wells, developing guidelines for operating the existing thaw wells, developing an action plan to be implemented when flooding is imminent, using mechanical methods to remove ice from the channel, or taking measures to produce a stationary, floating ice cover. Daly's thaw-well analysis was based on the assumptions that creek water at the upstream end of Town was near the freezing point and that the goal was to eliminate all frazil and anchor ice formation in the Creek.

Based on Daly's recommendations, starting in 2004 a number of instream improvements, including rock over pours (rock weirs), j-vanes, and rock double deflectors were installed in the creek, with the goal of reducing flow velocities, thereby promoting surface ice growth and inhibiting anchor ice and ice dam formation. The first instream improvements, including eight rock over pours (weirs), two rock transverse sills, and a rock double deflector were installed in a section of Flat Creek immediately upstream of High School Road (Wesche, 2005). Wesche reported that the instream improvements worked well until

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[3] Teton County map server, https://maps.greenwoodmap.com/tetonwy/mapserver/map#zcr=9/2435957/1408276/0&lyrs=a1977,state_fed,water,placelabels&filter=(pidn%20in('22-40-16-06-1-09-002'))

November 29, 2004, when extremely cold weather produced anchor ice upstream of the installation area. When air temperatures warmed, this anchor ice released and was carried downstream and jammed against some of the new improvement structures, causing flooding which necessitated removal of some of the rock structures from the creek. It was concluded that the cause of flooding was a combination of unexpected cold weather, release of anchor ice formed in an unrestored section floating downstream and jamming, and the fact that Thaw Well #2 was not turned on. It was believed that the problem would resolve when upstream sections of the creek were restored. In a December 6, 2004, email, Mr. B. Wotkyns reported that this event caused flooding in Berger and Martin Lanes. No buildings were damaged due to the quick response of the Jackson Public Works Department. Berger and Martin Lanes are in FEMA flood zone X, with a 0.2% or less change of flooding on an annual basis (500 year flood).

Newspaper and web coverage usually follows major flooding events, when excavators are dispatched to remove ice blockages. News accounts indicate that ice-related flooding is common along the whole built-up length of Flat Creek. Excavators are deployed somewhere along the creek almost every year to remove ice blockages. Occasionally, news reports give specifics on where ice blockages occur or some sense of the magnitude of the problem. For example, the website[4] of the *Jackson Hole News and Guide* has an article by Ben Graham describing a flooding event in early January 2014. This article states that several inches of water covered Shelby Lane, requiring deployment of two excavators to remove ice from the creek. An excavator was also used during this time to clear ice from the creek near Berger Lane where the creek was overflowing its banks.

An article on the *Jackson Hole Underground website*[5] states that on January 17, 2014, water levels between Stacy Lane and Crabtree Lane rose 3 feet in a matter of hours. On January 19, there were five backhoes working in the creek to clear ice blockages. A photograph published with this article (Figure 12) shows one of the excavators clearing the creek. The photo, along with the report that five excavators had to work to clear ice from the creek, imply that there was not a single, or even a series, of relatively narrow, channel spanning anchor ice dam(s) that could be easily cleared to lower water levels. Figure 13 is another unattributed photograph showing an excavator clearing ice from the Flat Creek channel. Once again, the ice the excavator is clearing appears to be very competent and appears to cover a significant length of the channel. No readily identifiable anchor ice dam (e.g., Figure 5) is visible in either figure (or other figures that the writers have seen of excavators clearing ice in Flat Creek). Instead, it appears that the excavators are clearing sections of ice that completely choke or clog the creek channel. Some ice accumulations appear to have clogged long reaches of the creek. This evidence suggests the ice clogs were caused by merged anchor ice and surface ice that filled long sections of the channel.

The two web resources mentioned above raise some interesting questions, shed light on the complex nature of ice-driven flooding in Flat Creek, and show that the last three years of FCWID-funded study of

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[4] http://www.jhnewsandguide.com/news/town_county/neighborhood-town-battle-flat-creek-flooding/article_74f9a992-3b45-5ee1-bf57-11d7cbec49d4.html#user-comment-area dated January 4, 2014

[5] http://www.jhunderground.com/tag/flat-creek/, dated January 21, 2014.

the problem have not identified all of the winter flooding threats on the creek. The downstream sites (Shelby Lane and Berger Lane) flooded in early January, yet there apparently was no flooding problem a few hundred yards upstream. However, 10 days later there was a major, rapid flooding event upstream, from Stacy Lane to Crabtree Lane, with ice up to 3-feet thick being reported. These observations reinforce the concept that the creek is prone to ice-related flooding along the entire length through town.

Observations from people living or working along the creek are another source of information regarding ice-related flooding. During the course of this investigation, the writers became aware that excavators were used to clear ice accumulations that threatened the Town Creek Townhomes (West Deloney Ave, upstream of the FCWID boundary, and another location that is within FEMAs's 0.2% annual flood risk area) in January 2016. A photograph taken on January 6, 2016, shows the ice debris that was removed from the stream to reduce flooding risk (Figure 14). It is estimated that 50 to 100 yards of creek channel were cleared of ice at this location (Mr. Carlin Gerard, personal communication, January 2018). As shown in Figure 14, this is a long, channel-filling accumulation of ice that appears to have completely choked the channel. Ms. Meyring from Jackson Hole Properties, property managers for the townhomes, checked company records and found that they were billed for excavator services to clear the creek in January 2016 and three times during January and February 2007. The relatively frequent deployment of excavators here indicates this is a problem area. Ms. Meyring reports that, to the best of her knowledge, this is the furthest upstream location where ice chokes the channel and causes overbank flooding.

Figure 12. This photo shows an excavator clearing ice from the creek during mid-January, 2018. The location of this photo is not known. This photo implies that the offending ice jam was not a simple ice dam that was readily cleared. Instead, it looks like many yards of the creek channel had to be cleared of ice. This image is from the Jackson Hole Underground website (http://www.jhunderground.com/tag/flat-creek/) .

Figure 13. This photo shows an excavator clearing massive, stratified, apparently dense ice accumulations from Flat Creek. The photo location, date, and photographer are not known.

Figure 14. Shown here is a lengthy accumulation of dense, thick ice cleared from Flat Creek in early January, 2016. The excavator had to clear an estimated 50 m to 100 m of ice along the creek (Mr. Carlin Gerard, personal communication, January, 2018). Photo by Carlin Gerard, used with permission.

All of the above reports were "near misses," in that there was no reported damage to houses or other structures. The worst reported damage was flooding of roads or the bicycle path. Dr. Kempema interviewed Mr. Bill Wotkyns and Mr. Sinclair Buckstaff Jr., longtime creekside homeowners, and asked if they had any knowledge of structure damage along the creek. Mr. Wotkyns reported that houses along Shelby Lane had water in the crawl spaces in the past, but the ice blockage was cleared before water damaged any structures. Mr. Buckstaff, who lives just downstream of Garaman Park, reported that his house flooded on January 28, 2001, when water topped a berm on the upstream side of his house. Water reached four feet deep in the garage. This was a major event that flooded a large portion of Garaman Park upstream of the Buckstaff's residence (Figure 15). Garaman Park flooded again in 2011, threatening the Buckstaff residence. In this instance, excavators were deployed to break up the ice accumulation above the house before water overtopped the berm (Figures 16 & 17).

Figure 15. Photo 9 from Daly (2003) showing ice-induced flooding at Garaman Park in late January 2001.

Figure 16. An excavator is shown here clearing an ice accumulation from Flat Creek at Garaman Park in early 2011.

Figure 17. The excavator here is clearing ice out from Flat Creek near Garaman Park in January 2011 to relieve the risk of ice-induced flooding. The ice in the red circle appears to be a piece of merged anchor ice and border ice about 3 feet thick, which choked the creek channel.

These historical records suggest that the writers haven't seen all possible forms of ice-induced flooding during the three winters of active data collection (November 2015 through January 2018), and that there is still much to learn. They also show the importance of collecting information on ice accumulations that require mechanical clearing going forward (discussed in detail in Alder Environmental, 2017) in order to determine the type, location, and conditions associated with various ice jamming events. The ice jams described in this section are substantially different than the Wort Diversion ice dams mechanically removed in December 2016 and January 2018 (discussed in the previous section). The water retained by the ice dams drained quickly once the excavator had created a breach in the ice dam. The ice choking of the channel depicted in the photos in this section required much greater effort to clear.

Ice Management Actions

Ice management rationale

There is no single or simple action that can be taken to mitigate ice-related flooding along Flat Creek, because the creek's morphology makes the creek inherently thermally responsive to heat loss and prone to frazil and anchor-ice formation. Active management is needed, involving controlled heat input and, at times, the mechanical removal of ice.

After analyzing data from the 2015 through 2017 winters, the writers concluded that anchor ice dams pose the greatest risk for ice-related flooding along Flat Creek (2017). After another year of observation, data analysis, and study, the writers now conclude that a more severe risk is posed by the large volumes of merged anchor ice, surface ice and aufeis that choke the creek. These merged ice masses or carpets choke long stretches of the channel, producing the possibility of widespread flooding that is more difficult to mitigate than flooding originating at a specific point. Therefore, the essential rationale for ice management along Flat Creek is to minimize the volume of ice in the creek, and thereby avert choking of water flow. This rationale involves managing the temperature of water flow in the creek.

Kempema and Ettema (2017) present two mitigation approaches to reducing ice volume:

1. Reduce flow turbulence and heat loss by promoting the formation of a surface ice cover. When the instream improvement structures were installed between 2004 and 2009, it had been thought that they would promote ice-cover formation (Wesche and Wesche, 2003); and,
2. Add heat to the creek's water and mechanically remove ice. This approach has been taken during the last 15 to 20 years, by means of thaw well use and deploying backhoe excavators to remove ice from the stream channel.

There are no data or observations to support the idea that the instream improvements have done anything to reduce the amount of ice that forms in Flat Creek. Based on time-lapse photo logs and visits to the creek, the writers' impression is that when the open channel is exposed to frigid air, there is little or no difference in partitioning of surface ice and anchor ice growth above and below the existing instream improvements. The basic difficulty is that Flat Creek's relatively small flow volume combined with its wide, shallow channel aspect makes the creek very responsive to changes in thermal exchange with the atmosphere.

Frazil and anchor ice are the predominant ice forms in the creek. During cold periods these ice types form rapidly and choke the channel. When winter temperatures are relatively mild (daytime highs in the low teens or high twenties), ice forms at night and either melts or releases from the bed during daylight hours. Multi-day cold weather fronts, with highs in the low teens for several days, promote multi-day anchor ice cycles, where anchor ice continues to grow for many days, eventually forming ice carpets that merge with surface ice to choke long stretches of the creek channel, or forming anchor ice dams that grow slowly upward until they fill the channel and cause overbank flooding. When the cold front passes, positive heat fluxes, primarily from warm groundwater inflow into the creek from the Elk Refuge and other locations, and to a lesser extent from friction-generated heat, act to partially melt and mobilize ice in the creek channel, set the stage for potential ice-driven flooding events when the next cold front arrives.

The data show that the heat flux into the creek (notably the relatively warm water entering from the Elk Refuge) is too high to maintain an ice cover through most winters. For example, Table 3 shows that, for the last three ice seasons, the heat generated by creek flow was capable of melting three times as much ice as estimated to form on the basis of an estimation of accumulated freezing degree day (AFDD). For example, the heat added to the creek by 33°F water entering at the Cache Street Bridge is capable of melting about 5 times the amount of ice estimated to form during the winter. This point also can be stated as follows: based on the AFDD analysis, ice grew at an estimated 0.2 inches/day. During the ice season, frictional heat suppressed about 0.5 inches of ice per day, and heat supplied by 33°C water entering the creek at Cache Street suppressed between 0.5 and 1.25 inches of ice growth per for discharges of 40 cfs and 100 cfs, respectively. Typical winter flow rates are between 60 and 70 cfs. It is an interesting irony that higher wintertime discharges supply more heat at the upstream end of the creek, assuming the same incoming water temperature. However, other than stressing the importance of heat input to the creek, this point should not be taken too far, because increased flow rate also increases water-surface area of flow along the creek, and the heat input is dispersed broadly along the creek.

Thaw well discharge, on the other hand, is a concentrated source of heat. The writers calculated that Thaw Well #2 discharge during 41 days during the 2016/2017 season supplied enough heat to the creek to suppress 1.3 feet of ice growth between Garaman Park and High School Road. This is about the amount of ice growth predicted with the AFDD estimate. It is apparent that the thaw well did not completely protect this stretch, because there were significant ice dams and backwater effects from the Highway 89 Bridge downstream. However, the thaw well did a good job of keeping the creek channel clear almost all the way to the Highway 89 Bridge. The lesson here is that the judicious application of focused heat holds promise of countering ice formation and accumulation at key locations along Flat Creek.

To be sure, the estimates mentioned above are based on a number of assumptions and are averages spread out over the length of the creek and duration of the ice season. They are done to show the relative magnitudes of different heat fluxes into and out of the creek during winter. However, the “zippering effect” of supercooling moving upstream with cold air temperature and a warm water front advancing downstream during warmer (but not necessarily above-freezing) weather supports the results. In reality, the thermal responsiveness of the creek (a small body of water) causes cooling and warming of the creek to vary quickly in response to changes in air temperature. During cold periods, heat loss to the atmosphere far overwhelms the positive heat fluxes supplied by friction and groundwater. This is the situation that leads to water supercooling and anchor ice formation. The longer a cold spell lasts, the greater the flooding threat becomes. These considerations indicate the futility of trying to form a long-lasting, floating ice cover on Flat Creek.

Proposed ice-management system

The writers propose that the FCWID adopt an active management system. The system must utilize a combination of "smart" heat application (thaw wells) and mechanical extraction (excavators) to minimize ice volume in the creek and, thereby, avert the risk of winter flooding. Table 5 summarizes the management system, whose main features are elaborated in the bullet points below.

Table 5. Proposed Ice management system for Flat Creek

Approach	Action to be Considered
Reduce the volume of ice formation, and inhibit and ease choking of water flow (Apply heat or mechanical means)	Add heat, at key channel locations, by means of water provided by thaw-well pumps. The key locations are a short distance upstream of where potential ice dams form. The addition of heat may reduce the extent and magnitude of supercooling along the creek and reduce the volume of ice in the creek. Additionally, the judicious application of heat will limit the growth of merged ice accumulations and ice dams and help to breach existing ice features (Figure 4).
	At especially severe ice dam locations, it may be necessary to mechanically remove ice. This action has been successfully applied in earlier years by means of an excavator and evidently is relatively quick.

The key features of an active ice-management system include:

- ***Monitor water temperature***. It is essential that the creek's water temperature be monitored during the winter and that records be kept. Record keeping should include, at least, thaw-well operation notes; information on ice dams or ice choking events that lead to flooding or mitigation efforts (including measurements and pictures of the structure); type and outcome of the mitigation effort (with pictures); and mapping of flood extent when needed. Much of this information can be archived in CRREL's ice jam database for long-term storage (explained in Kempema and Ettema, 2017). A sample CRREL ice jam report is included in Appendix 4. The writers advise adapting this form to record winter conditions along the creek.
- ***Monitor air temperature***. An important component of active management is to monitor and relate air and water temperatures, as air temperature is a useful indicator for anticipating the possible onset of ice formation and implementing possible ice-management plans. Calculating AFFD values based on weather forecasts may be a way to predict multi-day anchor ice cycles that drive flooding. In this regard, the writers recommend that the WID identify a suitably knowledgeable local person to assist with this monitoring.
- ***Use thaw wells judiciously to control ice growth and accumulation***. As described above, over the course of the winter there is a heat input into the creek through Jackson. At times, this heat input is overwhelmed by heat loss to the atmosphere. It is at these times that that thaw wells will need to be used to reduce the volume of ice formed and to create breaches in severe

accumulations of ice. Managed use of thaw wells will require learning when and where they should be used. In particular, thaw wells use should concentrate on frigid weather estimated to produce multi-day anchor ice cycles.[6]

- ***Modify problematic structures or features that develop recurring, severe ice blockages***. Ice conditions should be documented before any structure is removed. Ice conditions should also be monitored during following winters to see how changes in the creek bed change local ice conditions. Candidate structures for removal or design modification include instream-improvement structures, water-diversion structures and large boulders. Modification may also include changes to the creek banks, such as placing levees or other structures to constrain flooding.
- ***Include the possibility of mechanical extraction***. Although the risk of ice-related flooding can be reduced, it can never be totally eliminated. Procedures should be put in place to request and deploy mechanical means (notably mechanical excavators) for removing ice at especially severe choke-point locations of ice and flow congestion. Important aspects of mechanical removal should include:
    - Pre-arrange contracts with excavator operators to minimize the time needed to deploy equipment when flooding is imminent;
    - Identify recurrent ice choke points by keeping an updated record of when and where excavators are deployed; and,
    - Pre-arrange access permission with landowners near identified choke points. The writers believe that there is an ice-induced flooding risk for all properties along the creek, so the FCWID needs permission to access the entire creek bed.
- ***Keep residents informed about the propensity for ice formation***. Because ice-elated flood risk can never be completely eliminated, there should be a notification and evacuation plan in place to notify creek-side residents of imminent flooding.

The proposed active management system emphasizes observation, record keeping, and communication. The writers are not proposing a continuation of the existing study. Instead, moving forward, the goal should be develop predictive and mitigative techniques that form the basis of an action plan that reduces ice-driven flooding going into the future. Getting this system up and going will require appointing a designated manager. The writers anticipate what will start as an "actively managed" system will likely become a "largely automated system" in coming years. Monitoring instrumentation and computer-based management should be automated (to the extent fiscally feasible). The following hardware components of the management system should be considered:

- Connected weather forecasting
- Automated air- and water-temperature measurements
- Automated water-level monitoring at key sites

[6] Thaw well use should balance maximum ice-management returns against minimum impacts to the aquifer. It should be remembered that news sources stating that 300 million gallons of water per year are being used for ice management are wrong.

- Telemetry to a central computer that manages the timing of thaw well operation.
- Remote operation of thaw wells

This system should be set up to operate from mid-November through mid-February every year. It will take some investigation to determine the best components needed to build an automated management system for Flat Creek, so it is beyond the scope of this report to make specific recommendations. However, we note that some components of a nascent system already exist. Meteorological data collected at ¼ hour increments at weather station JKNW4 are available from MesoWest (Alder Environmental, 2017). Water discharge, stage, and temperature are available from the USGS gaging station at High School Road (USGS 13018350, Flat Creek below Cache Creek, near Jackson, WY). The USGS usually disables real time discharge measurements as winter progress due to the influence of ice on the stage/discharge relationship. However, the inverse temperature/stage relationships that indicate diel anchor ice formation and release (Figure 8) can be used to determine when anchor ice has begun to form in the creek. Any predicted, long, cold weather spells after anchor ice has begun forming should be considered as a possible flood triggering event.

A third existing component of an ice management system are the thaw wells. From a practical standpoint, if Thaw Well #1 is permanently retired, only Thaw Well #2 is available to mitigate ice-related flooding in the WID. Moving forward, instrumentation to monitor water temperature and stage should be installed downstream (and possibly also upstream) of Thaw Well #2. The rational for this location is twofold. First, these instruments can be used to evaluate the effects of Thaw Well #2 operation on downstream ice and flooding conditions, and can be used to develop a best management plan for thaw well operation. Second, eventually this instrumentation can be integrated into the system that automatically operates the thaw well when needed. Experience gained around Thaw Well #2 can then be expanded outward to develop other components that will minimize ice-related flooding along the whole developed length of the creek.

Winter intensity and duration interact with channel characteristics (e.g. slope, width, depth, current speed, bottom substrate) to drive complex ice processes in rivers and streams. These process become more pervasive and complex as streams become smaller and steeper (Heggenes et al., 2018). Keep in mind that ice-related flooding is a fundamentally different problem compared to typical open-water floods. Open-water floods tend cover long stretches of a river system. In contrast, ice-induced flooding is a very local event that is independent of the flow volume. An ice dam may cause upstream flooding while lowering water levels downstream of the dam. Conversely, breaching a dam may lower upstream water levels while creating flood waves that propagate downstream. The complex nature of ice processes on Flat Creek will make it difficult to develop and implement a completely automated mitigation system.

Specific short-term actions

The previous section outlined a plan for long-term ice and winter flood management. Data collected during the last year three winters suggest some items that should be addressed in the short term to minimize winter flooding risk, in order of importance:

- ***Remove or modify the rock weir at the Wort Diversion***. The weir has been a problem area for many years and was one of few areas that required mechanical removal of an anchor ice dam during the last three years. The writers understand that negotiations are already underway to address this problem by removing the boulders and installing a stop-log that can be removed in the wintertime. The writers endorse this plan, but suggest placing water level loggers above and below any replacement structure during winter, along with a game camera aimed at the new structure, to record possible local, negative effects of the change.

- ***Modify a prominent shoal and step on river right a few yards downstream of the Highway 89 embankment by the Smith's market***. A large anchor ice dam has formed on the feature during the last 3 years. Removing the shoal may reduce flood risk on Berger Lane and Martin Lane.
- ***Modify a shoal comprising several large boulders (escaped riprap?) on river right a few yards below the Highway 89 Bridge***. It appears that anchor ice that forms preferentially on this shoal and the rocks, choking the channel and flooding the bike path. It would require very little effort to clear the boulders, which might alleviate the flooding.
- ***Instrument a resident-identified recurrent ice dam location near Stacy Lane during the 2018-2019 winter.*** This site has been identified as the "usual damming site" along the creek. The WID data shows that a 3 foot high anchor ice dam formed here during two of the last three winters. This site should be instrumented with a time lapse camera, water temperature logger, and water level logger during the upcoming winter with the goal of defining the magnitude of stage increase. This is a possible site for some type of mitigation effort in the future.
- ***Prevent the formation of merged, channel-choking ice accumulations at Town Creek Condominiums***. This creek reach should be especially monitored and included in the active management plan.
- ***On a longer time scale, install a thaw well on the creek somewhere between Stellaria Lane and the Highway 89 Bridge***. The 2016/2017 winter data showed that Thaw Well 2 protects the creek almost to the bridge, but unmanaged use of well increased downstream flood risk when thick anchor ice accumulations formed between the Highway 89 Bridge and High School Road (Kempema and Ettema, 2017).
- ***Other thaw well installations***. In the future, and as further experience is gained with existing thaw wells, the WID may consider developing additional thaw wells as a way to apply heat to especially difficult locations of the creek. Based on the existing data and the writer's understanding that Thaw Well #1 will no longer be used, it is probable that one or more thaw wells will be needed to reduce ice-related flooding from West Snow King Avenue downstream to Garaman Park. Homeowner reports and field observations show that there are significant choke points where persistent anchor-ice dams form at a natural channel constriction near Stacy Lane and at two rock weirs between Elk Run Lane and the Wort Diversion. It may be worthwhile to consider installing smaller thaw wells at specific locations rather than installing one relative large well to mitigate ice along a long section of the creek.

Concluding Comments

The writers have learned a great deal about ice conditions along Flat Creek during the last three winters, but have never seen an actual, major flooding event. Therefore, some questions remain to be answered; e.g., as to the specific dynamics of anchor ice formation, or the full role played by Snow King Mountain in limiting insolation to the creek during winter. The writers believe, though, that they have a comprehensive understanding of the basic wintertime behavior of the creek. In many respects, Flat Creek is representative of many small streams in the mountainous regions of the U.S. and elsewhere.

Accordingly, one of the most important things the writers learned is that there is nothing particularly unique about ice conditions along Flat Creek. The supercooling of creek water, warm groundwater influx, frazil generation, anchor ice, aufeis, and ice dams all occur in other mountain streams. One urban-development aspect of Flat Creek that requires greater attention in regions experiencing frigid winters is the need for appropriate zoning of residential development close to the creek.

The management plan proposed by the writers is a fairly conservative approach that builds on the WID's existing plan of removing threatening ice structures mechanically or by actively using heat from thaw wells to reduce ice buildup at critical points. It is anticipated that several more years of ice management along Flat Creek will lead to tuning of the essential plan.

The WID is encouraged to be alert for prospective ice-management methods, besides those the writers recommend. Such methods are continually under consideration and emerge as understanding of ice formation develops. For example, supercooling is reduced or eliminated when there are abundant ice crystals in the water column. In this regard, an as-yet untested method entails the use of snow-making equipment to spray ice (snow) into water during frigid weather conditions. Meanwhile, the U.S. Corps of Engineers (2006) Ice Engineering Manual is a good source of other methods to protect property from ice-related flooding. Appendix 3 of this report contains a table from the Manual listing other possible ice-mitigation methods and techniques.

Acknowledgements

The authors would like to thank all of the people who shared their knowledge of ice conditions, winter processes and flooding along Flat Creek. Mr. Bill Wotkyns and Mr. Sinclair Buckstaff Jr. were very patient answering my questions about flooding, anchor ice dams, and other ice forms along the creek. Mr. Buckstaff also critically reviewed a draft of this document. His comments were a great help in revising the manuscript. Mr. Horn was very generous with his time, and was very helpful in explaining previous winter flooding events. It is clear that these three gentlemen are keen observers of the creek. Ms. Wendy Meyring was very helpful confirming a rumor of an ice blockage near Deloney Ave that required mechanical removal in January 2016. She also went back through company records to search for excavator bills to confirm when other blockages occurred at the same location. Carlin Girard of TCD walked the creek with me in early January 2018. He raised interesting questions during that walk, and was also very helpful in answering my questions during later conversations. Mr. Brian Remlinger, Mr. Kevin Poole, and the crew at Alder Environmental braved the cold weather to collect the comprehensive data set on Flat Creek that we used in this study. They then assembled this massive data set into a very usable, online data base, with excellent documentation on how, where, and why things were done. They were always prompt and polite when I had questions and spent a considerable amount of time answering my questions and showing me around the creek. Thanks, guys!

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Appendix 1 figures include:

This series of seven figures shows data collection locations along Flat Creek for the period between November 2015 and February 2018. Thaw Well locations are also shown. Figures A1 through A4 are taken from Alder Environmental figures 1 to 4 (2017, Appendix A). Figures A5, A6, and A7 are from Alder Environmental (2018, Appendix A) These Google Earth images show the locations of water temperature loggers (T#), water level loggers (H# in this text, L# in Appendix figures), time lapse camera locations (C#), staff gages, and thaw well locations. These appended photos are at a high resolution, we suggest zooming in on the images in the electronic copy of this report in order to discern the station numbers. **A much better alternative to view sampling and ice observations along the creek is to log into the interactive ArcGIS database for Flat Creek developed by Alder Environmental (2018). This database can be accessed through:**

Weblink: http://arcg.is/1m1aHf (Previous winter data is included in this link as well)
Username: FCWID_2016
Password: frazil_2018
(both are case sensitive)

Detailed instructions for accessing the Flat Creek ArcGIS data base described above can be found in Alder Environmental (2018), available from the Flat Creek Water Improvement District

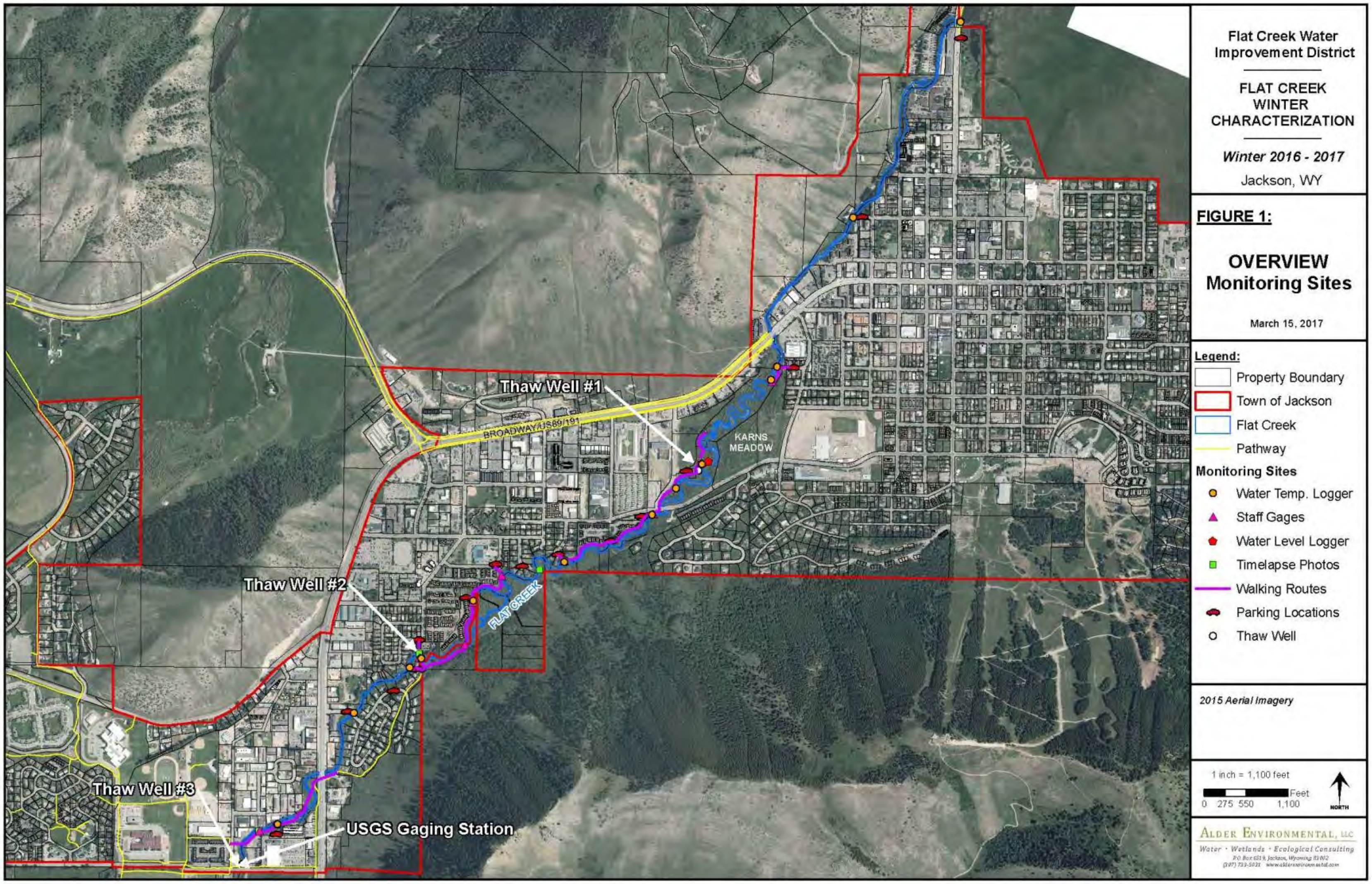


Figure A1.1. Flat Creek monitoring sites and thaw well locations 2015/2016 and 2016/2017.

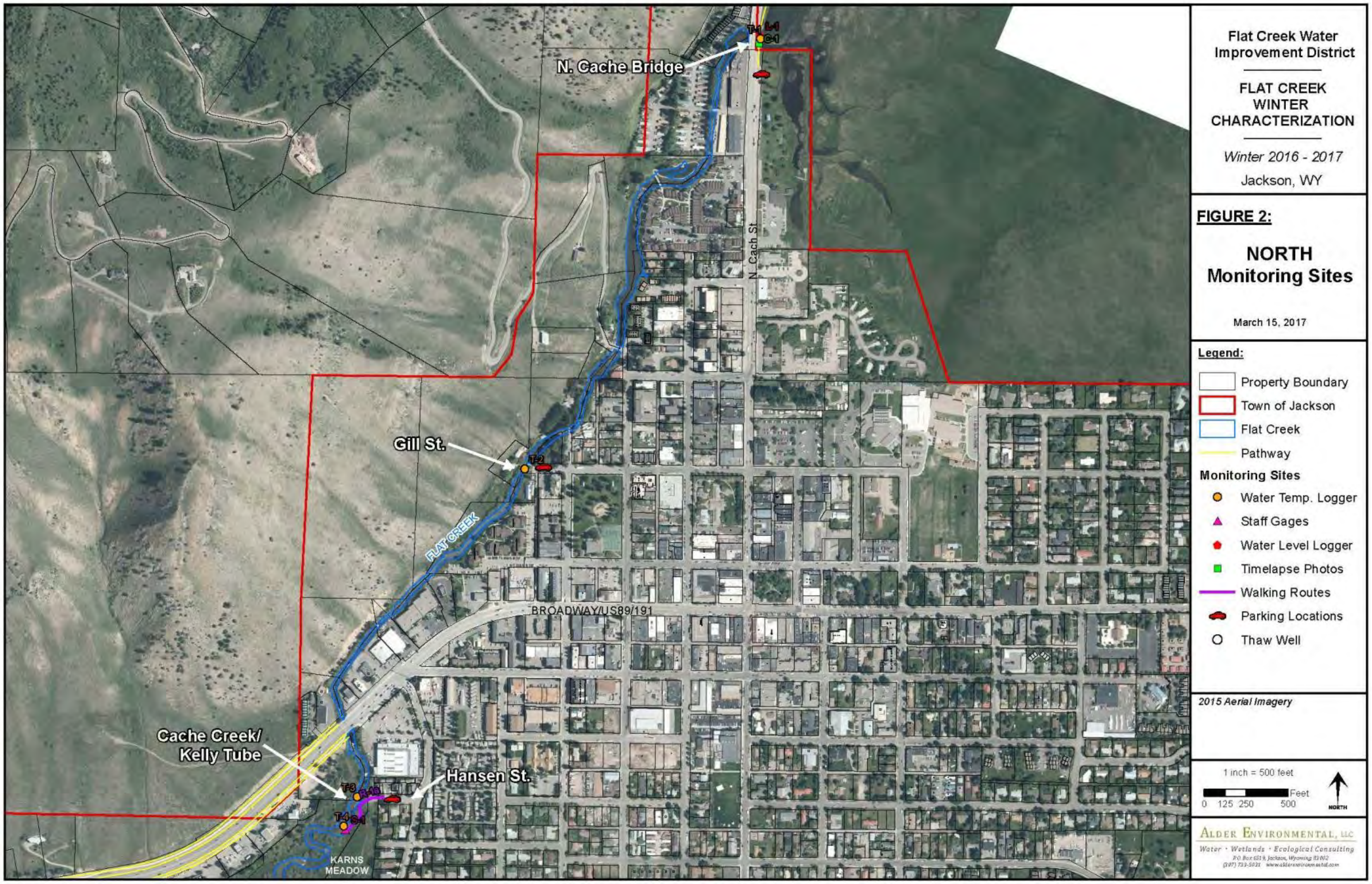


Figure A1.2. Flat Creek north section monitoring sites and thaw well locations 2015/2016 and 2016/2017.

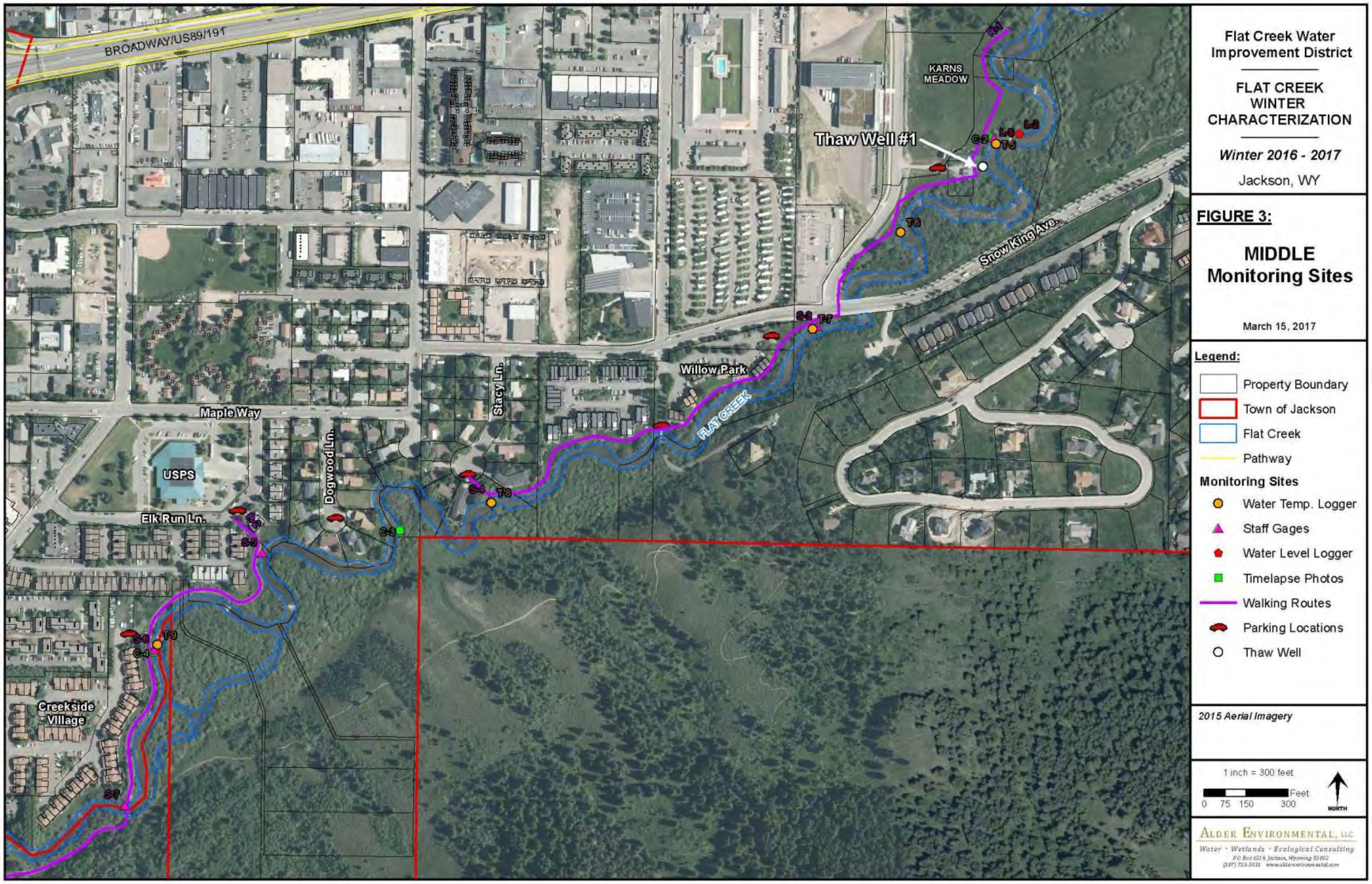


Figure A1.3. Flat Creek middle section monitoring sites and thaw well locations 2015/2016 and 2016/2017.

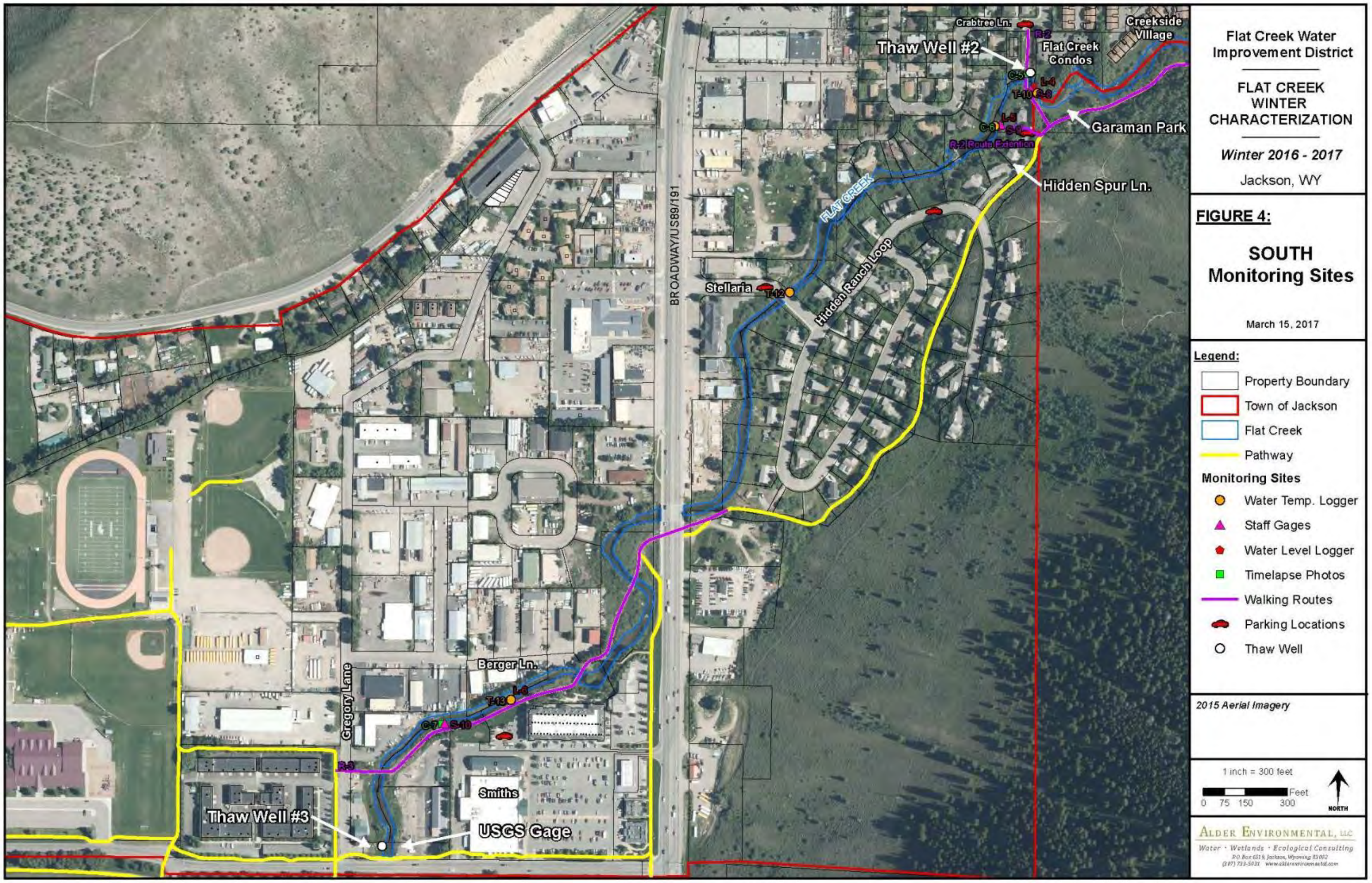


Figure 1.4. Flat Creek south section monitoring sites and thaw well locations 2015/2016 and 2016/2017.

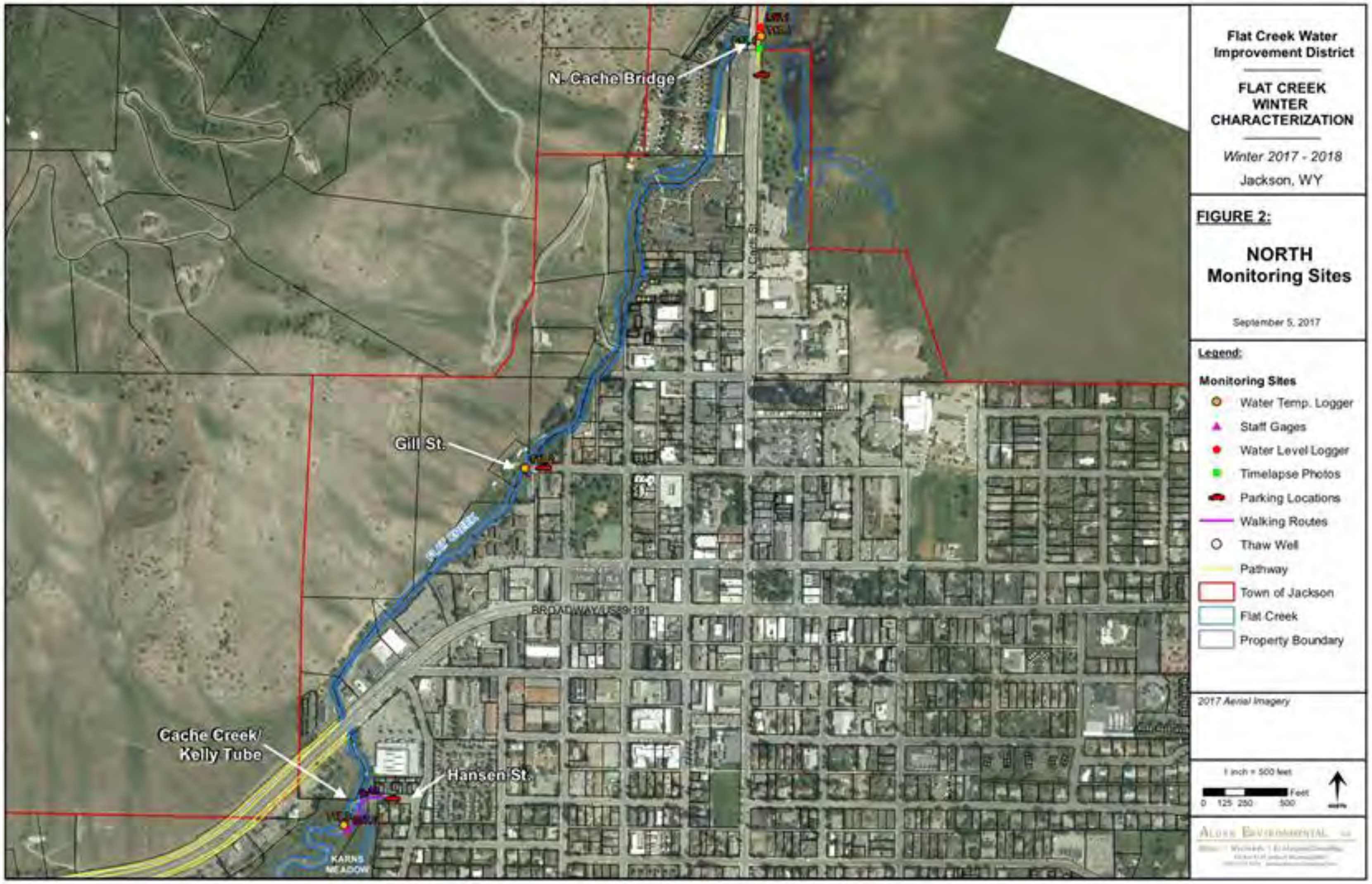


Figure A1.5. Flat Creek north section monitoring sites and thaw well locations 2017/2018.

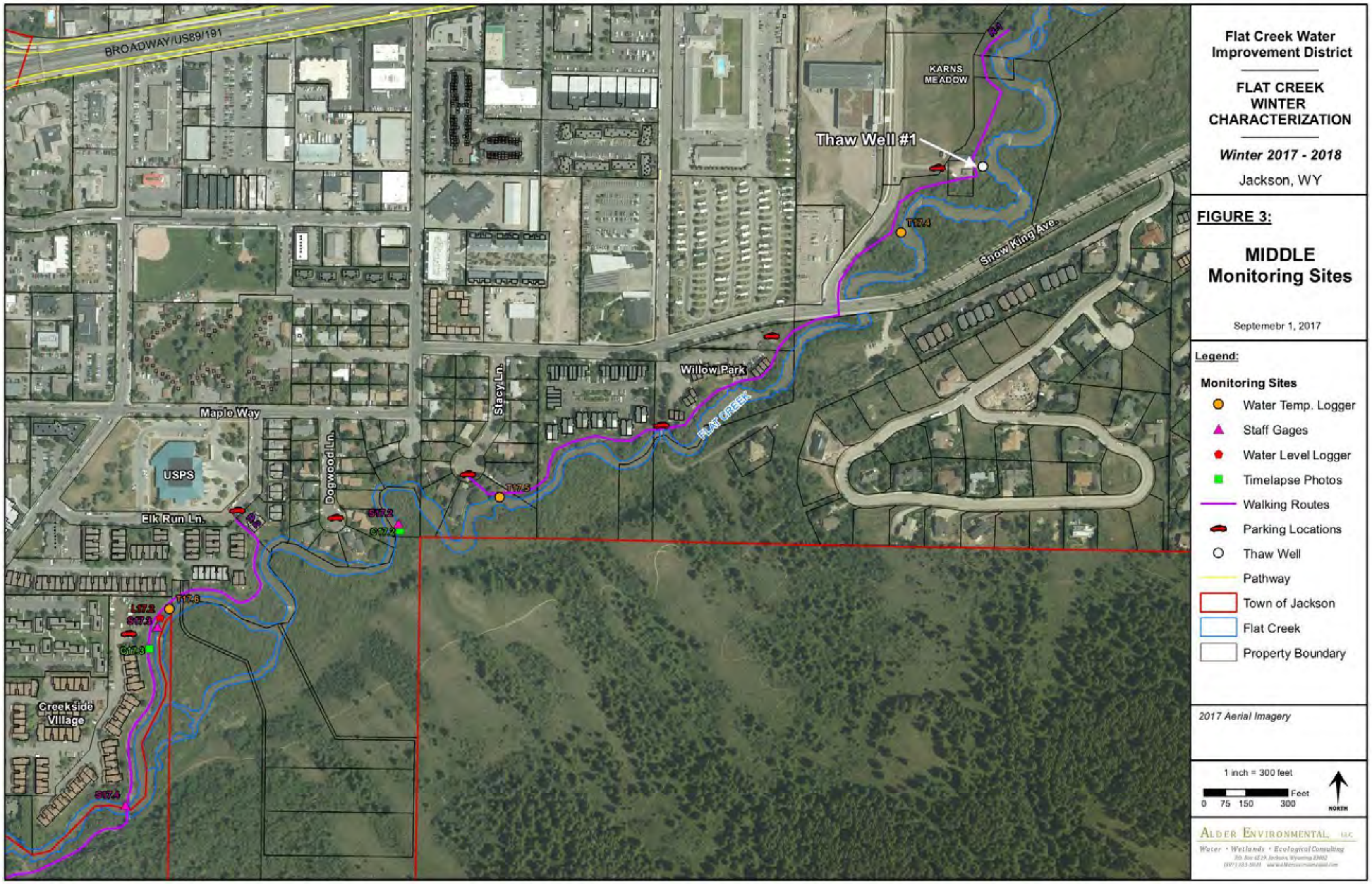


Figure A1.6. Flat Creek middle section monitoring sites and thaw well locations 2017/2018

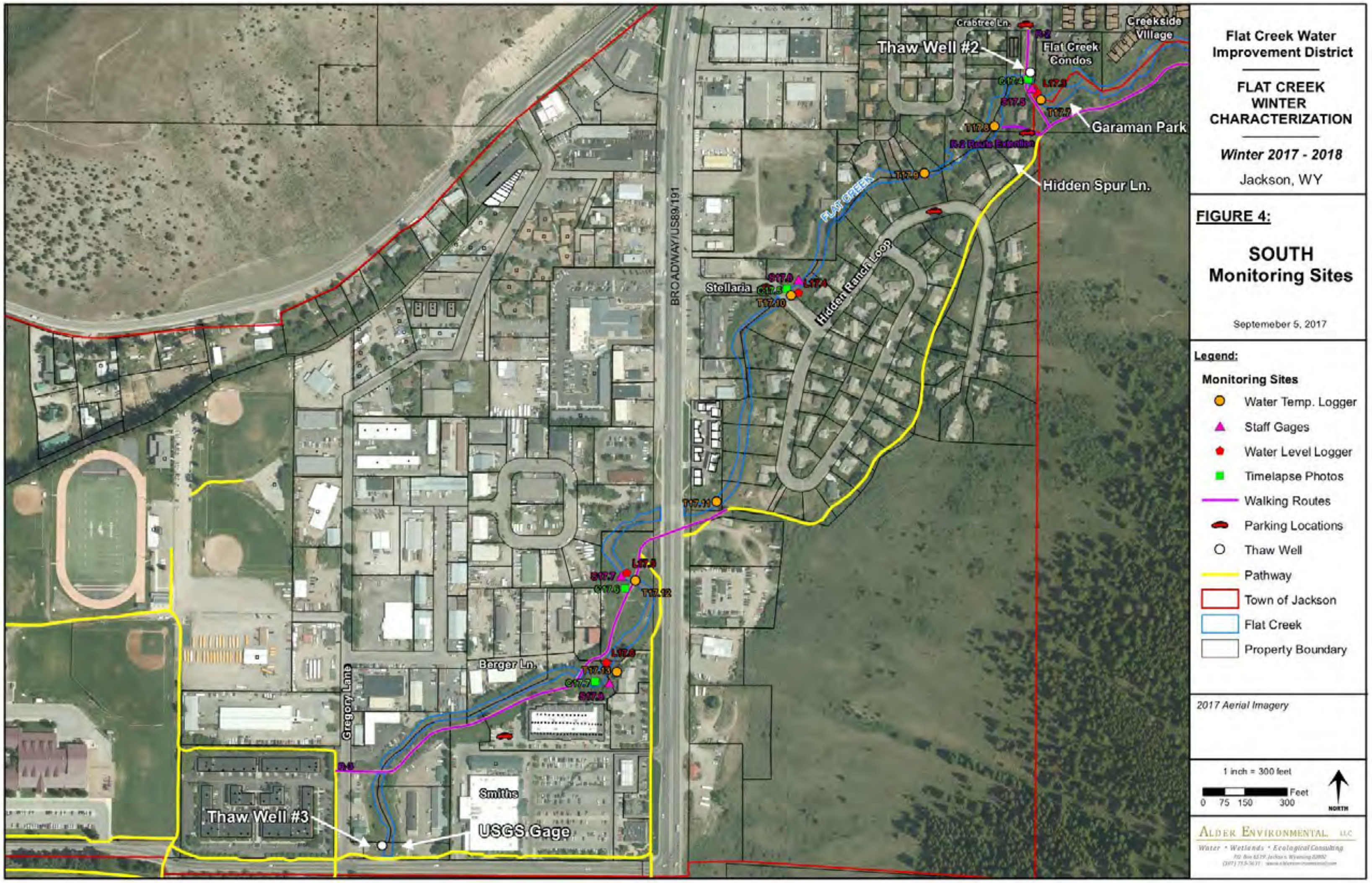


Figure A1.7. Flat Creek south section monitoring sites and thaw well locations 2017/2018

Appendix 2: Water levels and air and water temperatures during 2017/2018 winter

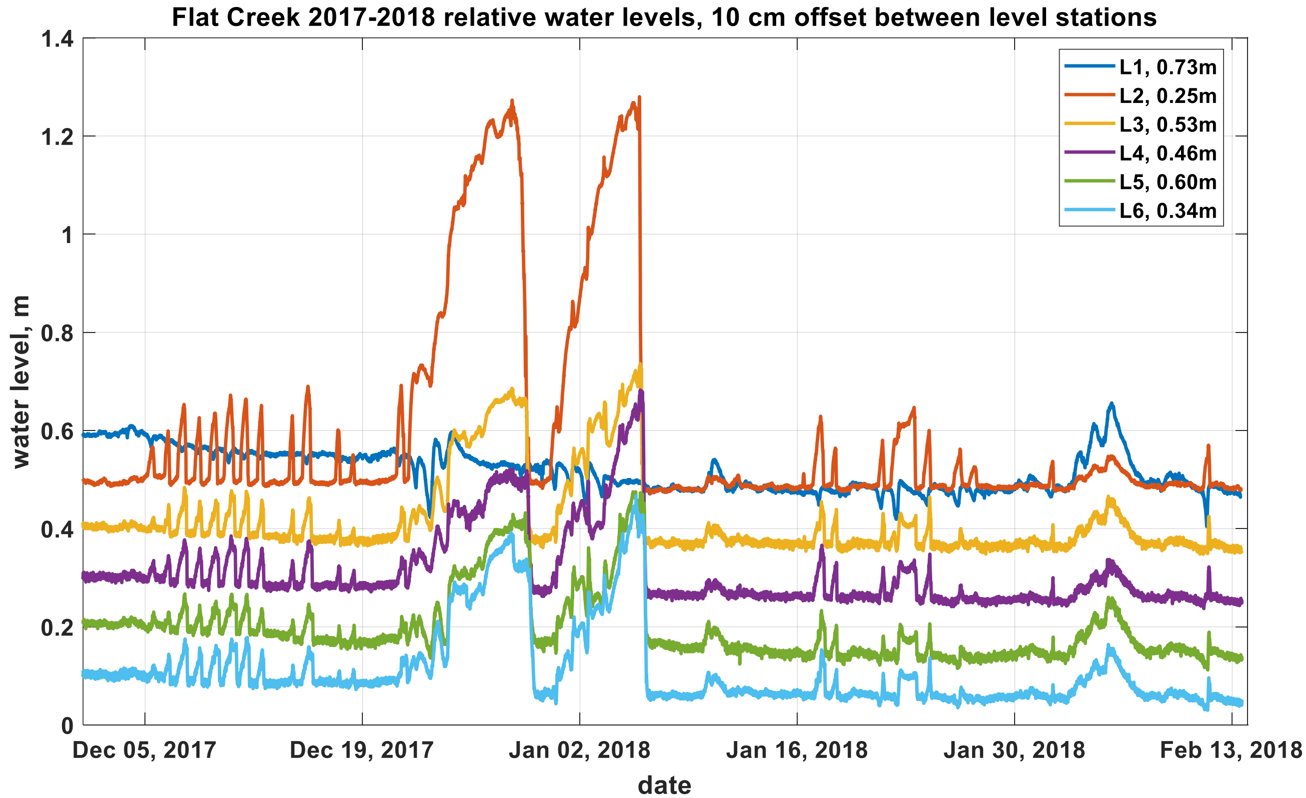


Figure A2.1. Relative water levels for Flat Creek water level stations 1 through 6 during winter 2017/2018 (see AE2018 for level locations). This data is processed by setting the water level on December 1, 2017 at midnight to 0 cm for each station, and then adding 10 cm between each subsequent station advancing upstream from L6. The initial water levels at each station are shown in the figure legend. Presenting the data this way allows comparison of relative water level changes, but not absolute changes between stations.

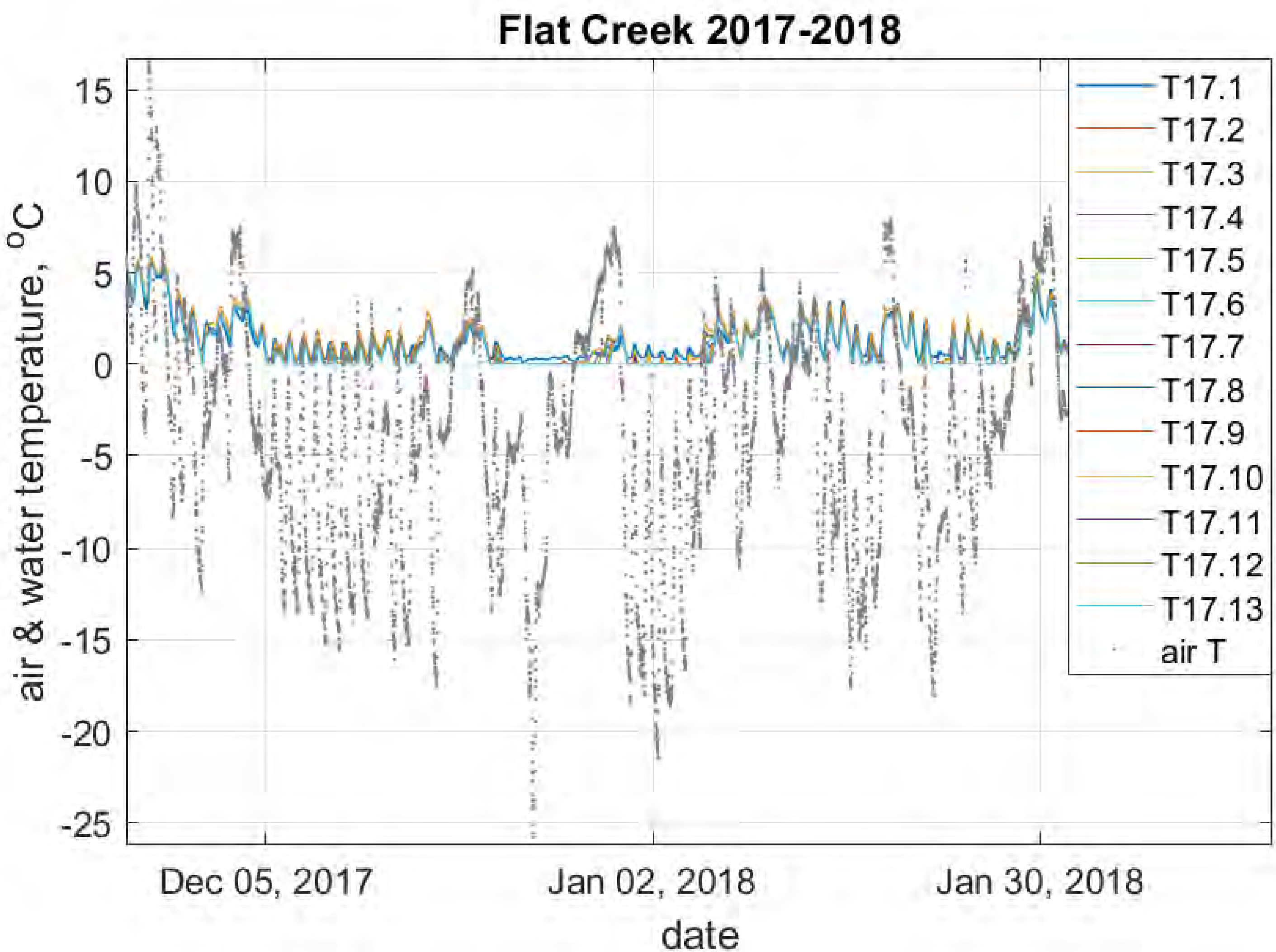


Figure A2.2. Graph showing air temperature at station JKNW4 and water temperatures measured at the 13 temperature loggers deployed during winter 2017/2018. See Appendix 1 for location of temperature logger stations.

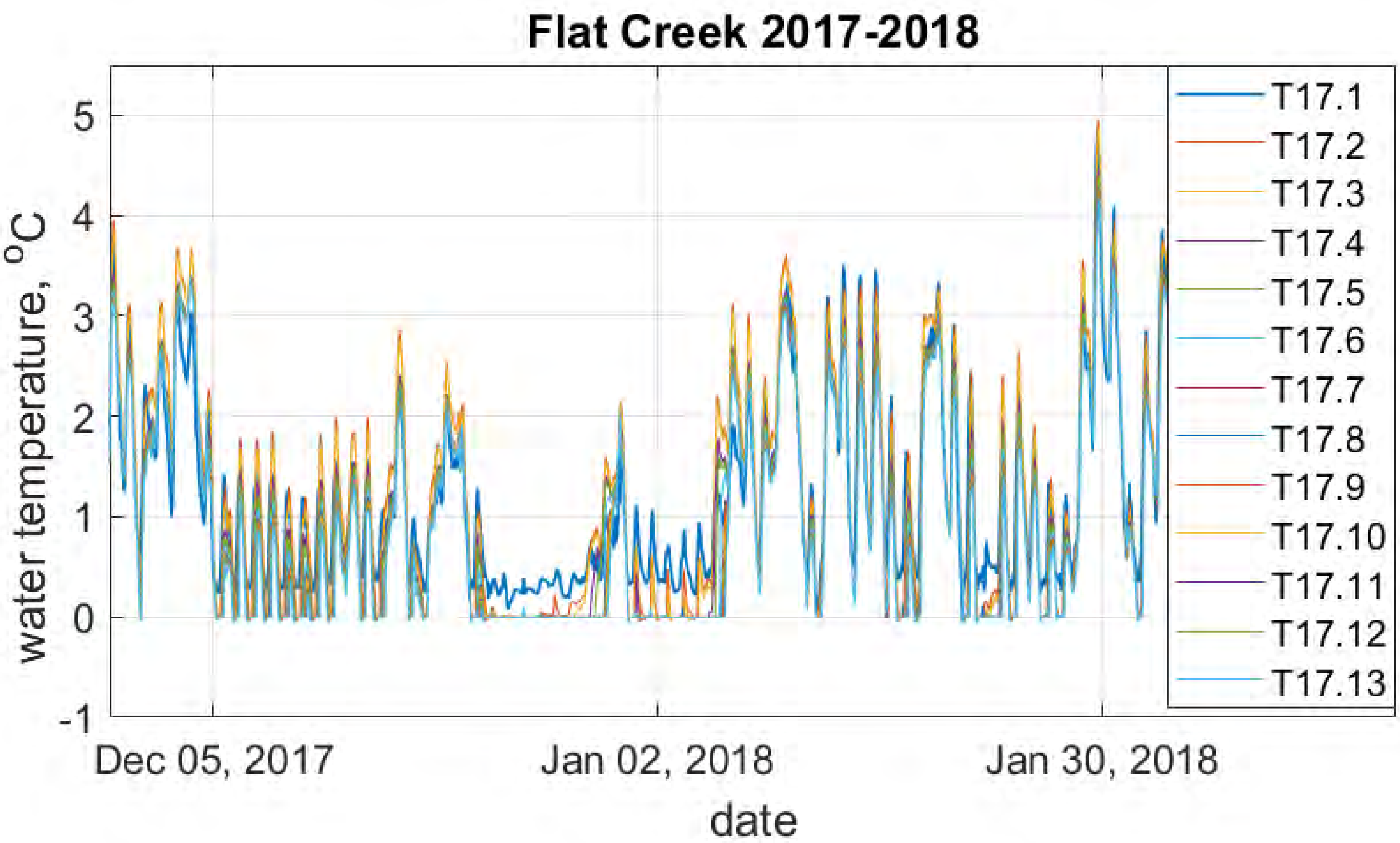


Figure A2.3. Water temperatures measured at 13 locations on Flat Creek between Cache Street and HighSchool Road during the 2017/2018 winter. Water temperatures remained relatively warm along the whole length of the study area during this winter. Temperature station 17.11, at Cache Street, remained above freezing all winter, but there were times when water temperatures at downstream stations exceeded temperatures at T171. All instrument stations downstream of T17.1 were subject to anchor ice formation. See Appendix 1 for location of the instrument stations.

Appendix 3: USACE ice jam mitigation strategies (2006)

Table 12-2
Ice Jam Mitigation Strategies and Applicable Techniques

Protect surrounding areas from flood damages
Dikes, levees, and floodwalls
Floodproofing
Floodplain land-use management
Sandbagging
Levee closing
Evacuation
Reduce ice supply
Thermal control
Revised operational procedures
Ice booms
Dams and weirs
Ice storage zones
Dusting
Ice retention
Increase river ice and water conveyance
Channel modifications
Revised operational procedures
Control ice breakup sequence
Detection and prediction
Ice booms
Ice cutting
Ice breaking
Revised operational procedures
Displace ice dam initiation location
Dams and weirs
Ice piers, boulders, and cribs
Ice booms
Ice breaking
Channel modifications
Remove ice
Thermal control
Ice breaking
Mechanical removal
Blasting

Appendix 4: CREEL Ice Observation Report

Example of the CRREL Ice Observation Report, used to record observations on ice jams or other ice-related problems and entering them into the CRREL ice jam data base. This form outlines all the possible observations that could be taken when observing an ice dam. After data on a particular ice jam is collected, it can be emailed to Joseph Rock (joseph.s.rocks@usace.army.mil) or mailed to Ice Jam Database Manager, CRREL, 72 Lyme Road, Hanover, NH 03755. The data will them be entered into CRREL's Ice Jam Database (http://icejams.crrel.usace.army.mil/) where it will be archived.

ICE REPORT

Section A

DATE: mm/dd/yy **TIME:** AM/PM

OBSERVERS NAME and CONTACT INFO:

RIVER/STREAM NAME: **NEAREST TOWN:**

LOCATION OF OBSERVATION: (attach a map if desired)

Area/Site# or Lat: Long:

Location of nearest roads:

Location of nearest bridge/landmark:

Distance to nearest Town: County:

Is this a changed condition: ◯ Yes ◯ No

Is flooding occurring, describe:

Is damaging occuring or has occurred? Describe:

Is there a Photo? ◯ Yes ◯ No File:

Photo description:

LOCAL WEATHER

Temperature:	Air: °F		Water: °F	
Precipitation:	Rain: in		Snow: in	
Wind:	Average Speed mph		Direction(pick one)	NW N NE / W ↑ E / SW S SE

RIVER CONDITION:

☐ Bankfull ft. ☐ Estimate less than bankfull ft. ☐ Nearest gage reading ft.

Section B

☐ **CHARACTER OF INTACT ICE COVER**

Location of downstream end of ice cover: Lat: Long:

or River mi: or Distance from observation location: mi

Location of upstream end of ice cover: Lat: Long:

or River mi: or Distance from observation location: mi

Surface roughness (check one):

☐ Smooth ☐ < 0.5 ft. ☐ < 1.0 ft. ☐ <1.5 ft. ☐ > 1.5 ft.

Evidence of decay ☐ Yes ☐ No ☐ Snow covered

If yes, check: ☐ Melting snow ☐ Melting ice ☐ Candled ice

Cracks in ice cover: ☐ Yes ☐ No

If yes, check: ☐ Parallel to shore, Distance from shore: ft. ☐ estimate ☐ measured

☐ Perpendicular to shore

Evidence of fracturing along banks: ◯ Yes ◯ No

If yes, check: ☐ (a) Ice thickness when fracture occurred: ft. ☐ estimate ☐ measured

☐ (b) Displacement: ft. ☐ estimate ☐ measured

☐ (c) Distance from shore ft. ☐ estimate ☐ measured

River Name: ____

ICE REPORT, continued

☐ **BREAKUP**

Cracks (check one): ☐ Parallel to shore, Distance from shore ____ ft. ☐ estimate ☐ measured

☐ Perpendicular to shore

Average distance between cracks ____ ft.

Water on top of ice: ☐ Pooled ☐ Flowing ☐ None

Time ice started to move: ____ AM/PM ____ mm/dd/yy

Time water was clear of ice: ____ AM/PM ____ mm/dd/yy

Post movement: Height of shear walls along bank: ____ ft.

☐ **ICE JAMS**

Cause (check one): ☐ Freezeup ☐ Aufeis ☐ Anchor Ice ☐ Breakup

☐ Combination ☐ Frozen-in-place ☐ Released ☐ Unknown

Condition at jam initiation point (check all that apply)

☐ Solid ice sheet ☐ Bend ☐ Bridge ☐ Island ☐ Constriction

☐ Reduction in water slope ☐ other: ____

Jam length: ____ mi (approx.)

Location of toe of jam (downstream end): Lat: ____ Long: ____

or River mi: ____ or Distance from observation location: ____ mi

Location of head of jam (upstream end): Lat: ____ Long: ____

or River mi: ____ or Distance from observation location: ____ mi

Estimated time of jam formation: ____ AM/PM ____ dd/mm/yy

Estimated time of jam release: ____ AM/PM ____ dd/mm/yy

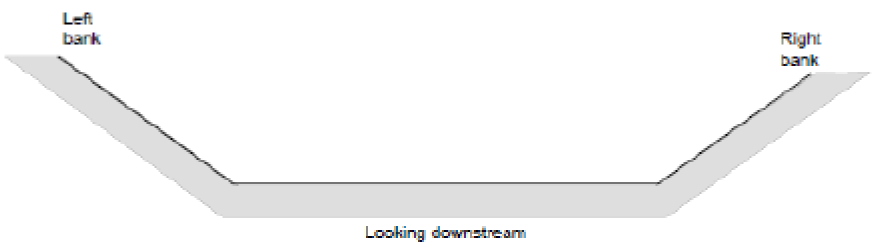
Height of shear walls along bank after jam release: ____ ft.

Can you estimate ice thickness: ____ in, How: ____

Can you identify a high water mark: ____

Section C

☐ **SKETCHES**: Include approximate scale, illustrate character of ice cover, ice coverage, water level, etc.



☐ **OTHER OBSERVATIONS/NOTES**

Comments on any aspect of ice quantity, quality, freezeup, breakup jamming, weather, etc.

____

Please email to: joseph.s.rocks@usace.army.mil or mail to Ice Jam Database Manager, CRREL, 72 Lyme Road, Hanover, NH 03755