Analysis of Ice Formation and Winter Flooding on Flat Creek, Wyoming, Between November 2018 and March 2019

Edward Kempema, Ph.D.
Presented to the
Flat Creek Water Improvement District
April 12, 2020

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Summary Points

- The 2018-2019 winter produced relatively severe ice conditions that choked long reaches of the Flat Creek channel.
- Ice choking of the channel lead to incipient flooding that required clearing of the channel on an estimated 12 different days.
- Even with the relatively sever ice conditions seen during the 2018-2019 winter, managed use of Thaw Well #2 protected the downstream reach to at least Stellaria Lane Bridge. However, for severe multiday anchor ice cycles, the thaw well must be operated for more than four hours per day. Longer pumping periods are necessary to clear the channel as far as the Stellaria Lane bridge.
- During a severe ice choking event, it may take up to two days for Thaw Well #2 pumping to clear ice and reduce water levels at the Stellaria Lane bridge. The thaw wells cannot be used to stop an imminent flooding event. Instead, they need to be managed to minimize the amount of ice that forms during multiday ice cycles.
- The Reolink internet cameras make it possible to view evolving ice and flow conditions in real time. This ability has not been integrated into an ice management system (with either thaw wells or excavators) but it is worthwhile to consider this in the future.
- Time-lapse cameras (collecting images every 15 to 30 minutes) are useful for recording the evolution of ice formation and flow impacts at multiple locations along Flat Creek. These images can supplement and confirm water level and water temperature measurements.
- Multiday ice cycles follow a regular progression of initial anchor ice formation on the stream bed that grows to the water surface. Aufeis (icings) then form and continue to raise the water level. Ice will continue to grow until either the weather changes or excavators are deployed to clear the channel. When weather warms to near the freezing, the ice in the Flat Creek channel either melts or drifts off. This is a dynamic process, all the ice through town can be gone in a single day. This melting sets the stage for the next episode of ice growth.
- Flat Creek winter water temperatures and ice processes are not unique. Fish Creek, located just west of Jackson, is similar in size to Flat Creek. Due to a slightly higher groundwater influx, Fish Creek at Wilson rarely if ever freezes.
- Flat Creek's thermal conditions combined with Jackson's weather preclude the formation of a continuous, floating ice cover that will protect the Creek from ice-induced flooding.
- Managed discharge of warm groundwater is the best way to manage or mitigate ice-induced flooding in Flat Creek. However, there may be periods when thaw well discharge cannot offset weather conditions and ice chokes the channel. In that situation, excavators will need to be deployed to clear ice from the channel.
- Thaw Well #2 should be used as a test bed to determine best management practices for managing ice-induced flooding in Flat Creek. Future work should be focused on developing this management/operational plan.

Introduction

The 2018-2019 winter marked the fourth year of ice-related data collection along Flat Creek through Jackson. The methods used during the 2018-2019 winter were very similar to the methods used during previous winters, and are described in a report authored by Alder Environmental (2019, hereafter AE2019). The major changes for the 2018-2019 winter compared to previous winters were (1) installing real-time video web cams at three locations along the creek; (2) installing two Solinst real-time water level and temperature recorders upstream and downstream of the Wort Diversion/Thaw Well #2; and (3) changing the locations of the water temperature and level recorders (AE2019). Water level recorders were concentrated in the area from Garaman Park downstream to High School Road, with the goal of documenting water level variations in the vicinity of the Wort Diversion and downstream of Thaw Well #2 (TW2). A major goal of the data collection effort during the 2018-2019 winter was to determine how managed use of Thaw Well #2 affected ice and water level conditions downstream of the thaw well.

Summary of 2018-2019 Winter Conditions

The 2018-2019 winter was the coldest of the four-year monitoring period. Air temperatures were recorded by the Forest Service meteorological station in Jackson (JKNW4, see AE2019 for location). A summary comparison of winter conditions is shown in Figure 1, a plot of accumulated freezing degree days (AFDD) for the past four winters. AFDD are calculated by summing up the mean daily air temperatures (multiplied by -1 to get a positive slope on the graph), with a starting point for the season when temperatures remain below freezing (Kempema and Ettema, 2018). The 2018-2019 AFDD season started earlier and persisted for considerably longer than the previous five winters (Figure 1).

Figure 2 shows the Creek's response to winter conditions, with stage (water levels) at the six water level/water temperature stations shown in the top panel (station locations are shown in Appendix 1). All the water levels shown in this report are relative, that is, the first recorded water depth for each logger station is subtracted from all subsequent measurements at that station. This graph does not show true water depths. Rather, the graph shows relative changes from an arbitrary water level for each water level station. This is a tradeoff that makes it easier to view relative changes in water levels along the Creek. The bottom panel in Figure 2 shows air temperatures in bar graph form. This provides an intuitive view of the severity of the winter (compared to Figure 1) and shows that there were several multiday periods when the average air temperature never rose above -10 ^{o}C (-23 ^{o}F).

The gross water level response for the 2018-2019 winter was similar to previous years (Figure 2). Water temperatures at station LT18.1, located upstream of the Cache Street Bridge (Table 1) remained above freezing throughout the winter due to the warm-water influx of spring water into the Creek on the Elk Refuge. Starting in mid-November, cold nights supercooled the water from station LT18.2 downstream and drove anchor ice growth, which in turn raised water levels. From early December until mid-January, cold snaps drove multiday anchor-ice cycles (MDCs) that raised water level from 0.5 to > 1 m (1.6 to 3.2 feet) in downstream reaches of the Creek. This created potential flooding conditions that required excavators to clear ice from the channel, discussed in more detail below. By comparison, early and late in the ice season, supercooling and small water level rises and falls occurred on a diel basis. Water levels rose at night when anchor ice formed on the bed and dropping during the day when a combination of warm air temperatures and incoming solar radiation (insolation) heated the water, released attached anchor ice, and opened the Creek channel. When more persistent, colder fronts passed through the

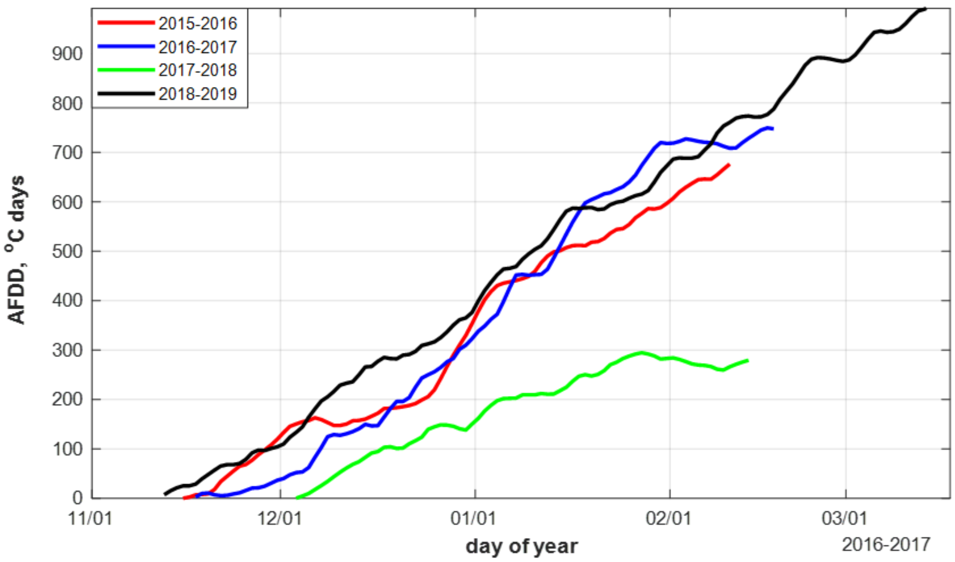

Figure 1. Plot of accumulated freezing degree days (AFDD) for the winters of 2015 through 2019. The steeper slope for the winter up until mid-January 2019 is an indication that air temperatures were consistently colder during that period. In addition, the sub-freezing air temperatures continued well into March 2019.

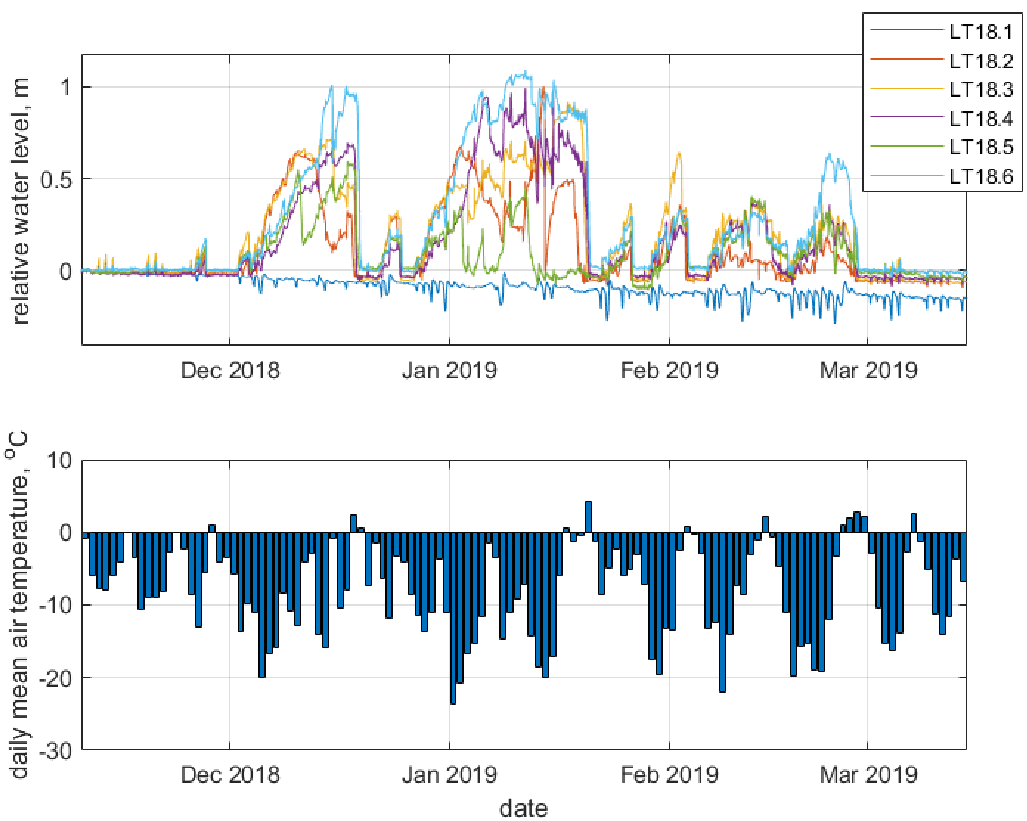

Figure 2. Top: water levels measured at six locations along Flat Creek during the 2018 – 2019 winter. The station numbers increase downstream (see Appendix A). Bottom: Average daily air temperatures during the 2018–2019 winter. Prolonged cold spells during December and January created multiday anchor ice cycles that raised water levels up to ~1 m (3.3 feet), creating potential flooding hazards.

Figure 3. These four panels taken from the time-series camera located at the Crabtree Lane bike path bridge in Garaman Park (station C18.5) illustrate the dynamic nature of ice conditions along Flat Creek. Warming air temperatures on January 19 and 20 precipitated a complete collapse of the anchor ice dam just upstream of the bike bridge as warm water from the Elk Refuge flowed downstream. Water level behind the dam dropped about 1 m (3.3 feet). This event cleared all the ice from the Flat Creek channel in a matter of hours. The jumbled ice rubble in the background was excavated from the Creek on January 15, 2020. The excavator could not reach the ice dam.

region, multi-day anchor ice cycles occurred (MDCs, described in Kempema and Ettema, 2018) and significantly raise the water level. These MDCs and their associated large water level increases were especially prevalent from early December through mid-January and raised water levels over 1 m (3.3 feet) at some downstream locations on the Creek (Figure 2). This pattern has been observed during previous winters. Similar magnitude cold fronts later in the winter do not have the same effect on water levels, as noted by creek-side residents since before the beginning of this study in 2015. This is attributed to the effect of increased solar radiation arriving at the stream as the year progresses due to increasing sun angles and longer days. The increased sun angle increases insolation at the Creek as it rise above Snow King Mountain for longer periods. Figure 2 illustrates the delicate thermal balance that controls the attachment of anchor ice, as either a carpet or as discreet ice weirs or ice dams, to the bed. For example, increased average air temperatures on December 18 and January 20 resulted in complete removal or melting of the ice structures in the Creek channel, leading to reduced water levels along the entire study reach (Figure 3). This complete removal was accompanied by the 0^{o}C isotherm migrating downstream in the "zipper effect" described by Kempema and Ettema (2018) and was confirmed by the time-lapse photo series, which show ice-free channels after these events, although there is considerable ice still present as overbank accumulations above the stream level (Figure 3).

Ice-related flooding was relatively severe during the 2018-2019 winter. My best estimate is that one or more excavators were deployed on 12 different days to remove ice blockages on the Creek during the 2018-2019 winter (Appendix B, Table B1). This estimate, along with estimates for the four previous winters are based on observations from Alder Engineering, conversations with streamside residents and stakeholders, newspaper accounts, and online discussion groups. The 12 days of excavator deployment is by far the greatest number of days that are recorded for a single winter season(see Kempema and Ettema 2018 for a discussion of previous years' excavators deployments). It would be very useful to have a more accurate record of when and where excavators were deployed, based on contractors' invoices, to document where the most severe ice problems occur.

Mr. Zeim of the Town's engineering department documented ice removal along the creek during the December incipient flooding events. He reported that there was extensive ice and high water levels along large portions of the Creek during the period of December 13-16. A number of ice dams were removed from the Creek between Mr. Klyn's property and the Smith's market at this time. Removal of ice from around the "island tree" by Eagle Village condos released ice to float downstream, which ". . .clogged some downstream spots. This had no noticeable negative effects on the stream." Several dams removed between the post office and the Creekside condos during the same period lowered water levels. The effect of thes efforts can be seen as small drops in water level at stations LT18.3 and LT18.4 on these dates. A more detailed account of Mr. Zeim's observations are available in AE2019.

I had a telephone conversation with Mr. Carlin Gerard of the Teton Conservation District on April 1, 2019. Mr. Gerard reported that it was a very bad year for ice in the Creek. Mr. Gerard was out on January 14, 2019, when excavators removed ice from the streambed for "about ½ mile bellow Klyn's". Mr. Gerard was careful to point out that this was an estimate of the distance, but that large amounts of ice that had completely choked the channel had to be removed by an excavator. This made an impressive pile on the riverbank (e.g Figure 3). The excavators started removing ice from upstream at this location, but this created an ice jam so they then moved downstream and worked their way upstream, eventually clearing the channel.

Based on the water level records, excavation notes, and witness observations, it is clear that the 2018-2019 was a severe ice year that produced the potential for extensive flooding along several different portions of the Creek. Potential floods were avoided by deploying excavators to clear ice blockages (see cover figure). Anchor ice carpets with overlying aufeis (icing) deposits completely choked large stretches of the Creek through town in December and January. However, review of the time-lapse camera records shows that an extensive open water channel was maintained along the creek through the winter. The only sure exception was camera station C6, located at the Stellaria Street bridge. The Creek in the field of view of this camera was completely ice- and snow-covered on January 17, 2019. Snow blocked the camera view until the morning of the January 20; the channel at this location opened up as the day progressed. This is the same event that cleared the entire channel through town (Figures 2 &3). There were undoubtedly other reaches of the Creek where a complete ice cover formed, but enough open water was maintained to form channel-choking ice throughout the winter.

The ice (and potential flooding) conditions seen during the 2018-2019 winter appear to be very similar to those of the 2014-2015 winter (discussed in Kempema and Ettema, 2018). As in previous years of this study, the camera records and eye-witness accounts show that the Flat Creek channel can be choked with ice that grows from the bed upward until water flows out of the channel.

Table 1. Water level/temperature (LT18.#) and selected water temperature (T18.#) stations. All station positions are referenced by distance to Thaw Well #2, locations of the stations are shown in Appendix A.

Station[1]	Distance from TW#2 (m)[2]	Distance from TW#2 (feet)[2]	Description[3]
LT18.1	-4500	-14750	Upstream of N. Cache Street Bridge
LT18.2	-640	-2100	Garaman bike path, E. side Village Creek
LT18.3	-110.5	-360	Above Wort Diversion, Creekside Village Garaman Pathway
LT18.4	-35	-115	Upstream of Thaw Well #2, Garaman Park
T18.11	169	550	2110 Hidden Ranch Lane, Vacant Lot
LT18.5	382	1250	Upstream Stellaria Lane Bridge
T18.12	645	2100	Just upstream of Broadway Bridge
T18.13	818	2680	Upstream of Eagle Village bike path bridge
LT18.6	958	3140	Upstream of Eagle Village bike path bridge

[1]LT: combined water level and temperature station, T: water temperature station
[2]Negative values are distances upstream of Thaw Well #2 (TW#2), distances measured in Google Earth
[3]Taken from AE2019, see Appendix A for positions.

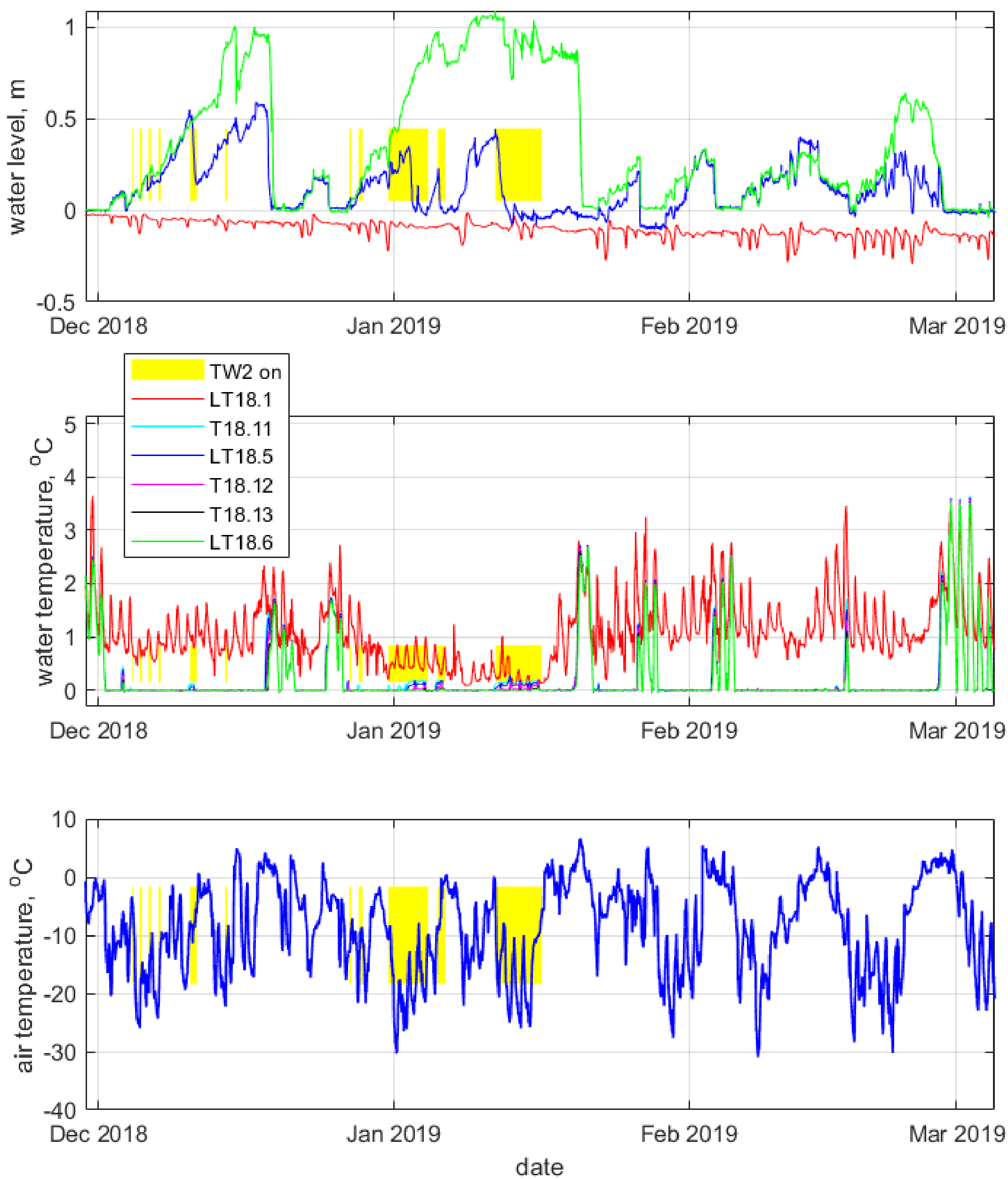

Figure 4. Top: water levels at stations LT18.1 (Cache Street bridge), LT18.5 (Stellaria Lane), and LT18.6 (Eagle Village bike bridge). Water levels at Cache Street are not affected by ice, while the downstream stations are subject to multiday ice cycles that raised water levels significantly. The yellow bars represent periods when Thaw Well #2 was pumping. Use of the thaw well reduced ice and water levels at Stellaria Lane during multiday anchor ice cycles in December and January. Middle: water temperatures downstream of Thaw Well #2. See Table 1 and Appendix 1 for thaw well and water temperature station locations. Bottom: air temperatures measured at U.S. Forest Service station JKNW4.

Flat Creek Water Levels and Thaw Well #2 Effects

Thaw well #2 (TW#2) ran for a total of 286 hours during the 2018-2019 winter, for periods ranging from 2 hours 45 minutes to 116 hours (Appendix B, Table B2). Figure 4 shows the water level increases associated with multi-day anchor ice cycles (MDCs) that occurred during December 2018 and January 2019. Two water level stations (LT18.5 & LT 18.6) and three temperature stations (T11, T12, & T13) were located downstream of Thaw Well #2 (Appendix A). These data are shown in Figure 4, along with air temperatures. Thaw well operation for a few hours each day between December 4 and 7 had little effect on rising water levels at station LT18.5, located just upstream of the Stellaria Lane bridge. Operation of TW#2 for 17 hours on December 10-11 resulted in a 0.3 m (>1 foot) drop in water level at Stellaria Lane, but there was no effect at station LT18.6 located 580 m further downstream. Between December 4 and December 10, the increasing water levels at stations LT18.2 through LT18.6 were very similar (Figure 2), suggesting that accumulations of anchor ice carpet on the bed is driving the water level increases (Nafziger et al. 2017). The water levels start diverging on December 11. Rapid drops of 0.42 m (1.4 feet) and 0.33 m (1.1 feet) at stations LT18.22 and LT18.3 located upstream of TW#2 on December 15 are most likely the result of excavators removing ice, as noted in Mr. Seim's report (Figure 2, and AE2019) The drop in water at station LT18.5 was driven by warm water discharge from TW#2. On December 10, water temperatures at T18.11 reached 0.13 ^{o}C, LT18.5 reached 0.08 ^{o}C, and T18.1212 reached 0.02 ^{o}C, showing that heat from TW#2 water was reaching these sites (this is difficult to see on Figure 4). The rapid increase in water level at station LT18.6 between December 13 and 15 (Figure 4) suggests released anchor ice might be causing local damming as reported by Mr. Zeim, but this increase did not threaten infrastructure.

The impacts of TW#2 during the second multiday anchor ice cycle, which began on December 27, confirms the interpretation of the December events. Intermittent operation of the thaw well for a total of 235 hours over a 15 day period held the water level increase to about 0.44 m (1.4 feet) at Stellaria Lane (LT18.5), while water levels at LT18.4, about 15 m (50 feet) upstream of TW2 discharge, and LT18.6, 580 m (1900 feet) feet down stream of Stellaria Lane rose 0.96 m (3.1 feet) and 1.08 m (3.5 feet), respectively (Figures 2 and 3). The LT18.2 water level record is highly variable between January 3 and January 19, marked most notably by a 1 m drop in water level on January 14 between 6 and 11:30 AM (Figure 4). The reason for this is not clear but excavators were deployed on January 14 and 15 (Table B1). However, there was also a concurrent increase in water temperature to 0.03^{o}C at 5 AM on January 14. Unfortunately, the time lapse camera at this location failed early on the morning of January 14, so the exact cause of this drop cannot be determined.

Figure 4 clearly shows the effects of Thaw Well #2 use. Four-hour pumping cycles had little effect on ice choking the channel during multiday anchor ice cycles in December and January. However, 17 hours of pumping on December 11/12 dropped water levels 0.41 m (1.35 feet). Choking of the channel started again when the pump was turned off but was mitigated on December 20 when the entire creek cleared. During the second MDC in January, it took from December 31 until January 2 for Thaw Well #2 discharge to reduce ice choking of the channel at Stellaria Lane. The reason for this relatively long response time is not clear, but it does illustrate the fact that thaw well pumping is not an instantaneous cure for anchor-ice induced flooding. Thaw well operation has to be actively managed to reduce anchor-ice related flooding potential during multiday anchor ice cycles.

The water level records collected over the last four years do provide some other useful information on ice-driven flooding potential in Flat Creek. Multiday anchor ice cycles and their associated flooding are most likely to occur during the months of December and January. Temperatures that would produce MDCs during the New Year result in diel anchor ice formation and release events in February and March, with a relatively small rise in water level during the night, and a decrease in water level (and associated rise in water temperature) during the following day. The reason for this is most likely increased insolation associated with longer days and higher sun angles.

The conclusion reached here is that managed, intermittent use of Thaw Well #2 protects the downstream reach at least as far as Stellaria Lane even during relatively severe multiday anchor ice cycles, as evidenced by the ~0.40 m (~1.5 feet) reduction in water level at this site relative to the adjacent up- and down-stream water level stations in December. This protection ends somewhere between Stellaria Lane and Broadway. “Protects” as used here, does not imply that there is no anchor ice formation and concomitant water level increase during a multiday ice cycle, instead, anchor ice formation/retention is reduced enough to not completely choke the creek channel. It is likely that other thaw wells that are operated in a similar fashion with have a similar effect on downstream ice.

Discussion

Real time cameras, time lapse cameras, and multiday anchor ice cycles

Three Reolink real-time cameras were purchased by the FCWID in 2018. These cameras were deployed by Alder Engineering at the Creekside condos, Eagle Village, and Mr. Klyn’s property. These cameras make it possible to view and record selected sites along the Creek in real time via an internet connection. They do require access to the internet; Alder Engineering arranged to connect the cameras to creek side residents’ internet service during a trial deployment. These cameras made it possible to view evolving ice conditions along the creek. They were not used to make decisions about thaw well operation, although it may be possible to do this in the future.

Advantages of the Reolink camera system include the ability to remotely check ice conditions at any time and to collect still images and video clips of the creek. The cameras work well in low light, making it possible to see ice conditions at night. Downsides of the Reolink system includes the necessity of a power supply and internet connection and the lack of the ability to collect time series images (e.g., an image every 15 minutes). A user has to be logged in to the system in order to record images. The Reolink cameras were deployed from buildings at elevations of up to ~20 feet above the Creek. This showed the utility of high viewing angles and longitudinal views of the Creek bed for viewing ice features. (Past time-lapse camera deployments were mounted next to the creek channel and generally oriented to look in the upstream direction.)

Figure 5 is an example use the Reolink system to monitor ice evolution and water level increases in the Creek by recording development and decay of a multiday anchor ice cycle. Multi-day anchor ice cycles follow a very regular pattern of ice development. The progression is shown by a series of images collected at Mr. Klyn’s property with the Reolink system during a multiday ice cycle spanning January 12-19, 2019 (letters refer to figure 4 images):

A. Initial formation of an anchor-ice carpet covered essentially the entire creek bed. This carpet did not grow at a uniform rate; ice thickening was quicker on shoals, weir crests, and other obstructions to flow. Anchor-ice accumulation raised water levels.
B. The anchor-ice carpet grew to the water surface. Accumulating anchor ice raised the local water level. Localized aufeis (icings) start growing at the air/water interface, increasing ice thickness
C. The anchor ice carpet grew to intercept the water surface. Persistent anchor ice covering the whole creek channel emerged from the flow. At the same time, water level slowly rose and inundated low-lying areas and froze to form dense, compact aufeis deposits (icings) along the banks and in low-lying areas (see Figure 3 for exposed icings). This process is the same as described by Turcotte and Morse (2011). As the creek channel is choked, thin layers of water flowed across the icing covering the channel froze, thickening the icing upwards and increasing channel choking. As a result of water flowing across the icing, heat loss is not significantly reduced as more ice forms (Turcotte and Morse 2011).
D. Ice continued to rise and choke the channel. More and more of the channel is covered by a form of merged ice (Tremblay et al. 2014). The merged ice consisted of a lower layer of porous anchor ice and an upper dense aufeis layer. Ice filled the entire channel. This ice will keep will keep growing upward until one of two things (E or F) occurs:
E. As the weather warms, the 0°C isotherm and the ice melting/release front migrate downstream. There are very few large boulders in Flat Creek, and the channel is wide, so surface ice and icings collapse into the channel as the submerged ice melts. Collapsed ice also melts, and the channel becomes essentially ice-free (this is illustrated in Figure 3). This sequence sets the stage to restart ice growth.
F. Water level reaches a critical stage and excavators are deployed to remove ice. Strategic removal of ice lowers the water level until warm water arriving from upstream melts the remaining ice. In both of these cases, the creek is set for another round of channel choking. However, the situation is exacerbated because ice remnants fill low-lying regions along the bank and decrease channel storage capacity (Figure 3 and Figure 5 E&F).

The sequence outlined above may be broken at any step. For example, the daily cycles of anchor-ice formation and release that occur early and late in the season are essentially steps A, B, and E of this sequence. As noted, anchor-ice carpets are ubiquitous, but they grow at different rates. Anchor-ice dams are very common features in the creek and tend to form on existing rock weirs. Depending on conditions, the anchor ice dams may grow to the point where they need to be mechanically breached to reduce flooding before the rest of the channel is completely choked. This would requiring deploying excavators at step C in the sequence, before the entire channel is ice choked..

While the Reolink cameras are useful for spot-checking creek conditions, the Wingscape time series cameras have proved very useful for monitoring conditions throughout the winter. Seven of these "game"cameras have been deployed along the creek during the winters of 2016-2019. These cameras are self-contained, inconspicuous, and set-and-forget. Placed along problem areas of the Creek, they recorded an image every 15-30 minutes. These images have been very useful for determining the dynamic nature of ice conditions along the Creek. Figure 3 illustrates this by showing the rapid decay as warm water undermined an anchor ice dam just upstream of the Crabtree Lane bike bridge in Garaman Park. Other time lapse cameras along the Creek recorded the same ice decay; this event marked the end of potential flood-producing multi-day anchor ice cycles along the Creek during this winter season, although smaller-magnitude ice events still occurred throughout February. The time lapse cameras are extremely useful for monitoring changes in different reaches of the Creek throughout the winter season.

Figure 4. A to E: Progression of channel choking as anchor ice grows from the streambed upward to the water surface. A: Ice-free channel lined by border ice; B: anchor-ice growth to air-water interface and initial icing formation; C & D: icing covers more of the water surface as ice chokes channel; E: melting of channel ice. F: Excavator clears anchor ice and icing from the stream channel on 17 December 2018. The icing stratigraphy is visible in the vertical ice face upstream of the excavator. Flow is left to right.

The two camera systems, along with the water level and water temperature instruments make up a measurement system that has made it possible to understand the dynamic nature of ice formation and potential ice-related flooding along the Creek. They can and should be used in the future to document changes in the ice regime as new mitigation methods are incorporated into the Flat Creek winter flood protection system.

Some thoughts on Jackson-area winter water temperatures

Eddy-Miller et al. (2009) conducted an extensive study of the interactions of shallow groundwater and surface water in Fish Creek west of Jackson. They found a groundwater connection between the Snake

River and Fish Creek that delivers relatively warm groundwater to Fish Creek throughout the year. Streamflow data collected between 1994 and 2008 at USGS gaging station 13016450 at Wilson show that the stream was ". . . rarely ice covered, indicating groundwater inflow upstream or at the station during the winter months." These observations make it worthwhile considering how Fish Creek at Wilson responded to the 2018-2019 winter season. Plots of the 2018-2019 winter water level and temperature in Fish Creek are very similar to the FCWID station LT18.1 (Figure 6, compare with Figure 2), located just upstream of the Cache Street bridge. Like LT18.1, the Wilson gaging station is situated in a location where an influx of relatively warm ground water limits ice formation and protects the stream from catastrophic anchor-ice flooding events. There is evidence of supercooling, anchor ice formation, and an associated increase in water level in early December and January at the Fish Creek gaging station, but these appear to be relatively small diel events that do not raise water level above ~0.15 m (6").

In addition to Fish Creek, Cache Creek at USGS gaging station 13018300 (Cache Creek near Jackson, WY) recorded above-freezing water temperatures through much of the 2018-2019 winter (Figure 6). Cache Creek has a very small discharge, so it is probable that ice and snow bridges insulate the creek during the winter. The take-away story here is that Flat Creek is always influenced by warm-water inputs, from the Elk Refuge, Cache Creek, and probably other unidentified sources. To be clear, the Cache Creek gage is about 6.5 km upstream of the discharge point into Flat Creek, and the water cools as it flows down to Flat Creek. We don't have information on Cache Creek water temperatures at the confluence with Flat Creek, although occasionally during the last four winters above-freezing water temperatures have been observed at water temperature stations in Flat Creek directly below the Cache Creek confluence. Flat Creek also has relatively warm spring inputs downstream of Jackson that markedly reduce the risk of ice-related flooding (Brian Remlinger, personal communication). The amount of heat input by groundwater flow, both upstream and downstream of Jackson, is not known. However, it is clear that there are multiple warm groundwater inputs into these small streams in the Jackson Hole region. Recent studies of small streams in other regions suggest these steams are normal in this respect, i.e. warm baseflow supply mountain streams during the winter.

Fish Creek at Wilson (Figure 6) and the upper end of Flat Creek at station LT18.1 (Figure 1) both have enough geothermal or "groundwater" heat available throughout the winter to resist the multiday anchor ice cycles. However, downstream portions of Flat Creek are subject to multiday ice cycles and potential flooding. This is shown in Figure 7, a comparison of USGS water temperatures measured at Fish Creek near Wilson and Flat Creek at High School Road during the 2019-2020 winter. Fish Creek had short freezing periods (hours), while Flat Creek had multiday freezing cycles punctuated by short periods of warming that removed or melted ice from the entire Creek. Judiciously adding heat to Flat Creek, in the form of warm groundwater, will go a long way to reducing ice-induced flooding along downstream portions of the Creek, as shown by the effects of TW2 at station LT18.5. As pointed out by Daly (2003) the benefit of adding heat is greatest at the injection point, and decreases downstream. The goal of the FCWID now should be to determine where, when, and how much groundwater (heat) needs to be added to the Creek to minimize the risk of ice-induced flooding through town. The goal should not be to suppress all ice formation in the Creek, as implied by Daly (2003). Instead, a dynamic management plan that focuses on minimizing ice formation and accumulation during multiday anchor ice events should be developed.

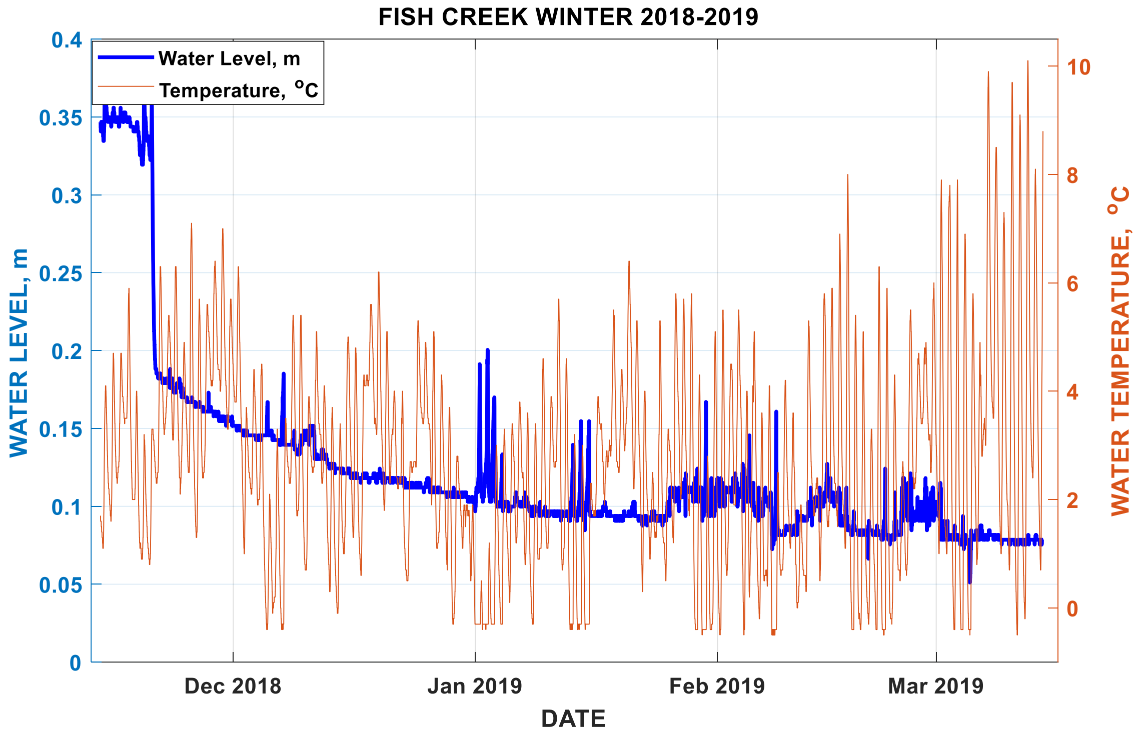

Figure 6. Water level and temperature from the USGS gaging station 13016450, Fish Creek at Wilson, WY. The water level and water temperature records for this station are very similar to the FCWID level station LT18.1, upstream of the Cache Street bridge. It appears that there were short, diel periods of anchor ice formation and release January and early February.

Predicting anchor-ice related flooding events

One of the desired goals of this study has been to develop a simple method to predict anchor-ice related flooding events along Flat Creek. In last year's WID report, Kempema and Ettema (2018) suggested that a modified accumulated freezing degree day (AFDD) approach might be useful for predicting potential anchor ice flooding conditions. The AFDD method is an empirical approach used to estimate the increasing thickness of a growing, solid surface ice cover. Kempema and Ettema (2018) suggested that modifying this to include the surface area of Flat Creek along with a to-be-determined coefficient relating ice volume to AFDD. To test the possibility of this approach, I retrieved weather data for the period from 2013 through 2019 winters from station JKNW4 and searched for information on when ice conditions were severe enough to require mechanical removal on Flat Creek (TableB1, Appendix 1). My assumption is that deploying an excavator was an indication of incipient flooding. As a test, I calculated 3- and 5-day AFDD totals (sums of the average air temperatures for the previous 3 and 5 days, respectively). I then plotted these data for non-excavator days and for excavator days, the results are shown in Figure 8. Red stars in the figure represent AFDD values for days when excavators were not used, blue diamonds represent antecedent air temperature totals for days when excavators were deployed. The 5-day and 3-day AFDD's are shown on the right axes of these plots, the left axes show the season total (i.e., a repeat of the data in Figure 1). There is no clear relationship between incipient flooding events (excavator deployment) and the AFDD totals for the previous several days. There are several possible reasons for this. The most logical explanation is that ice-induced flooding is a very dynamic, poorly understood phenomena. This dynamic nature is shown in Figures 2, 3, and 4. It is not possible to account for all of thermal influences on stream flow with a simple, empirical equation, particularly when we know that groundwater is affecting the system. However, Figure 8 does reinforce what creek-side residents have known since before this study started. That is, anchor-ice induced flooding risk is greatest during December and January when the days are short, the sun angle is low, and much of Flat Creek through Jackson is shaded by Snow King Mountain. The most likely time for an anchor-ice induced flooding event is during a prolonged cold snap in December or January, when anchor ice carpets, weirs, and dams form on the streambed, choking the flow.

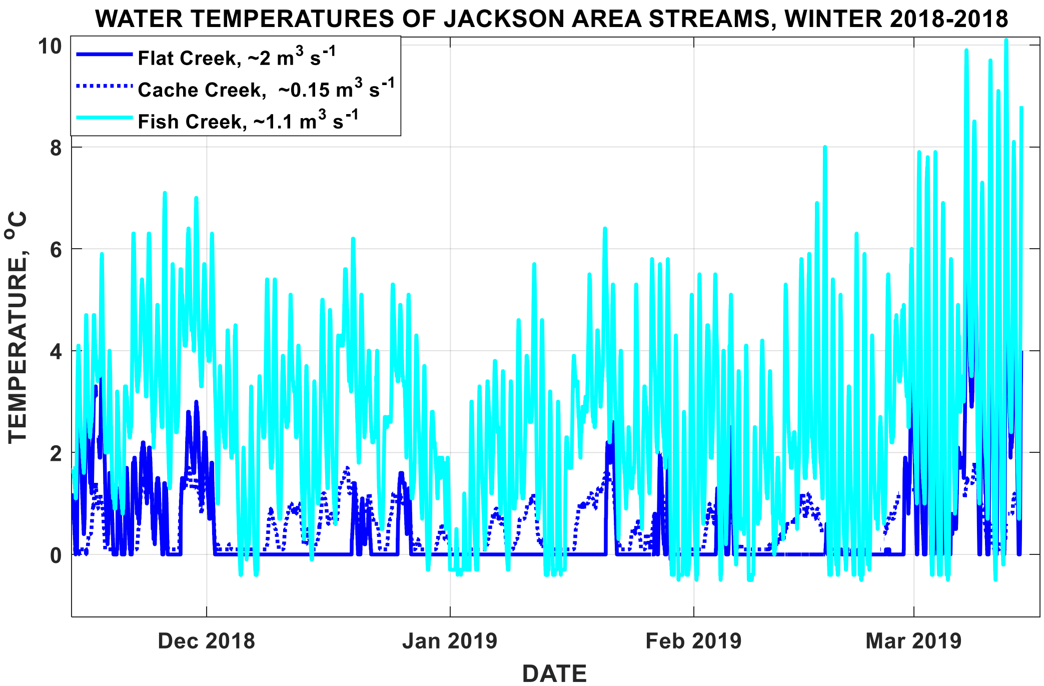

Figure 7. Comparison of USGS-measured water temperatures at Flat Creek (USGS 13018350), Fish Creek (USGS 13016450), and Cache Creek (USGS 130183) during the 2018-2019 winter. The difference in water temperatures through time are intriguing, considering all of these creeks are subject to similar winter air temperaturesThe conversation factor is 1 cubic meter per second = 35.3 cfs.

Conclusion

Based on four years of data collection and analysis, the best solution for reducing ice-induced flooding in Flat Creek is to judiciously add heat, in the form of groundwater, to the Creek to reduce (not eliminate) ice formation and associated water level increases during multiday anchor ice events. This conclusion is driven by the observation thatFlat Creek is impacted by a continuous warm-water influx from the Elk Refuge, Cache Creek, and other unidentified heat sources discussed in previous reports to the FCWID. This warm water and the winter weather patterns interact with the result that in will never be possible to develop a permanent floating ice cover that protects the creek from winter flooding. Ice grows in the creek from the bed upward choking the channel and displacing streamflow upward during cold snaps. Subsequent warm weather (near freezing temperatures) causes this ice to decay and melt from the channel, resetting the system for ice growth and channel choking during the next cold snap.

Thaw Well #2 is the WID's best test bed for developing the information and techniques needed to decide where to place new thaw wells, and to determine how to operate these wells in the future. Upcoming data collection should focus on water temperature and level sensors in the area downstream of Thaw Well #2. The goal of future data collection should be to continue to determine how far downstream the Thaw Well #2 warm-water plume extends under different discharge, time, and weather conditions. The results of these determinations can then be used to develop plans for additional thaw well placements and operations.

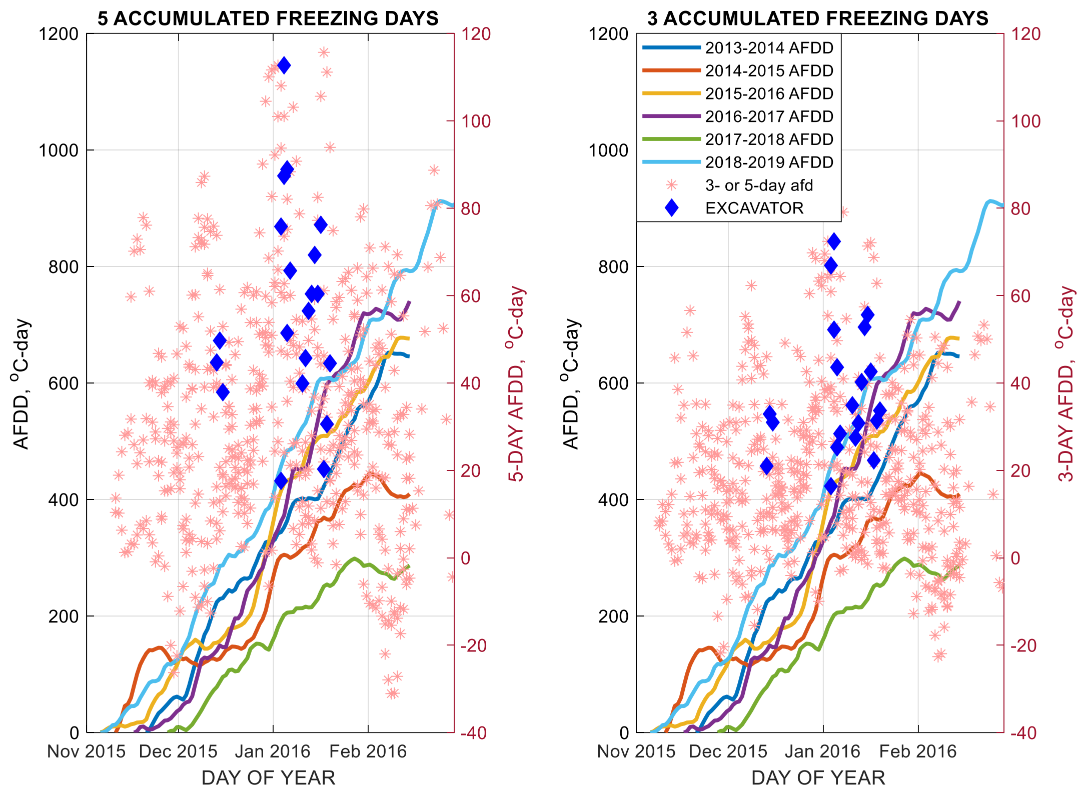

Figure 8. 5-day (left) and 3-day (right) accumulated freezing degree day totals for the winters of 2013-2019. Red stars represent AFDD totals for days when excavators were not deployed during this 6 year period, blue dots represent antecedent air temperatures on days when excavators were deployed. By inference, the use of excavators indicates incipient flooding. There is no clear relationship between antecedent air temperatures and conditions that require excavators to clear ice from the Creek channel. This figure does validate the idea that ice-related flooding (as defined by excavator use) only occurs during the months of December and January.

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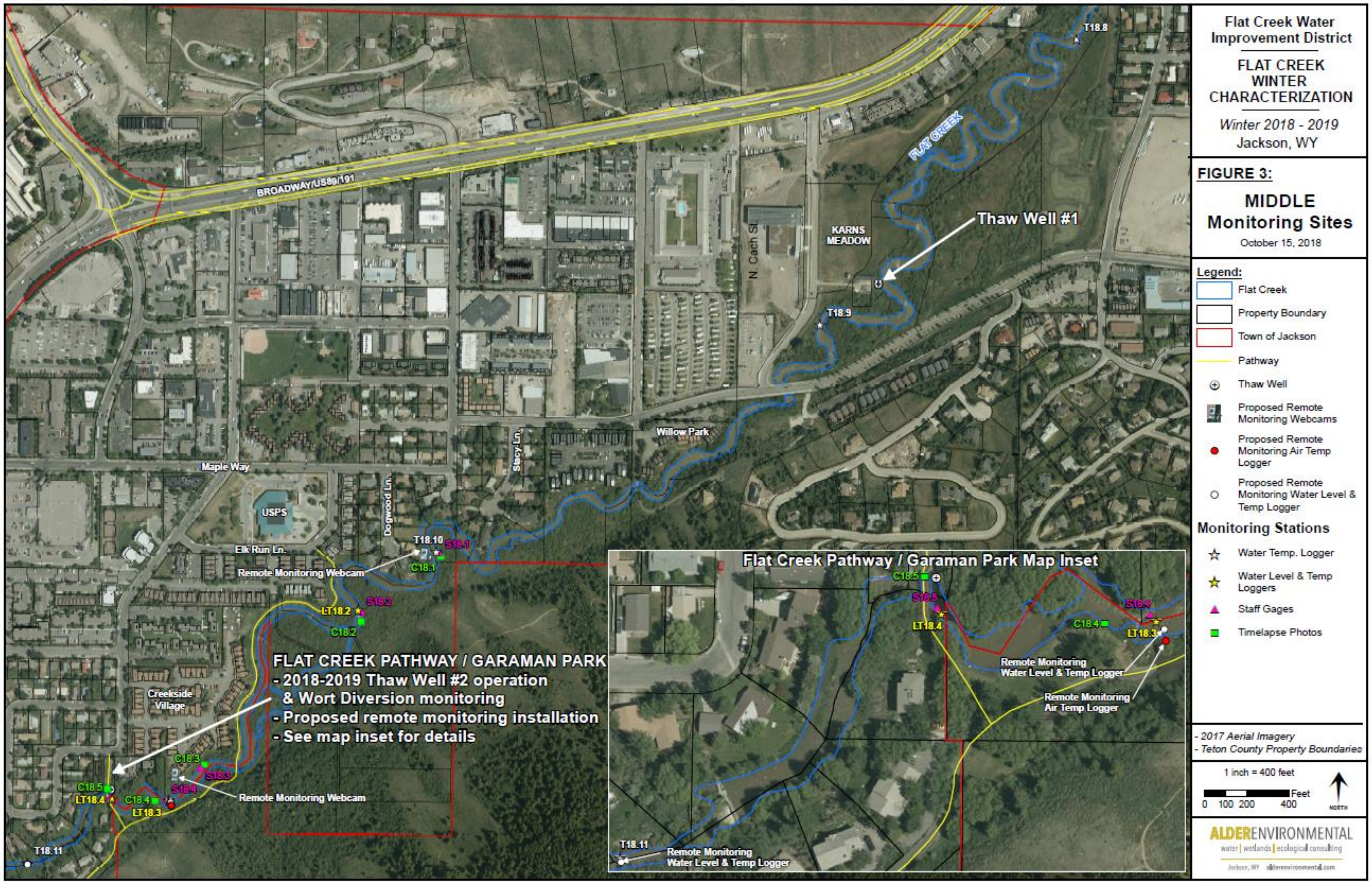
Appendix A

Google Earth images showing the locations of instrument packages deployed in Flat Creek during the winter of 2018-2019.


Flat Creek Water Improvement District
FLAT CREEK WINTER CHARACTERIZATION
Winter 2018 - 2019
Jackson, WY
FIGURE 3:
MIDDLE Monitoring Sites
October 15, 2018
Legend:
Flat Creek
Property Boundary
Town of Jackson
Pathway
Thaw Well
Proposed Remote Monitoring Webcams
Proposed Remote Monitoring Air Temp Logger
Proposed Remote Monitoring Water Level & Temp Logger
Monitoring Stations
Water Temp. Logger
Water Level & Temp Loggers
Staff Gages
Timelapse Photos
- 2017 Aerial Imagery
- Teton County Property Boundaries
1 inch = 400 feet
0 100 200 400 Feet
NORTH
ALDERENVIRONMENTAL
BROADWAY/US89/191
FLAT CREEK
Thaw Well #1
KARNS MEADOW
N. Cach St.
T18.8
T18.9
T18.10
T18.11
Willow Park
Maple Way
USPS
Elk Run Ln.
Dogwood Ln.
Stacy Ln.
Creekside Village
Remote Monitoring Webcam
FLAT CREEK PATHWAY / GARAMAN PARK
- 2018-2019 Thaw Well #2 operation
& Wort Diversion monitoring
- Proposed remote monitoring installation
- See map inset for details
Flat Creek Pathway / Garaman Park Map Inset
Remote Monitoring Water Level & Temp Logger
Remote Monitoring Air Temp Logger
C18.1
C18.2
C18.3
C18.4
C18.5
S18.1
S18.2
S18.3
S18.4
S18.5
LT18.2
LT18.3
LT18.4


Flat Creek Water Improvement District
FLAT CREEK WINTER CHARACTERIZATION
Winter 2018 - 2019
Jackson, WY
FIGURE 4:
SOUTH Monitoring Sites
October 15, 2018
Legend:
Flat Creek
Property Boundary
Town of Jackson
Pathway
Thaw Well
Proposed Remote Monitoring Webcams
Proposed Remote Monitoring Air Temp Logger
Proposed Remote Monitoring Water Level & Temp Logger
Monitoring Stations
Water Temp. Logger
Water Level & Temp Loggers
Staff Gages
Timelapse Photos
- 2017 Aerial Imagery
- Teton County Property Boundaries
1 inch = 300 feet
0 75 150 300 Feet
NORTH
ALDERENVIRONMENTAL
water | wetlands | ecological consulting
FLAT CREEK
T18.11
Stellaria Ln.
LT18.5
C18.6
Hidden Ranch Loop
BROADWAY/US89/191
T18.12
T18.13
Remote Monitoring Webcam
Berger Ln.
LT18.6
C18.7
S18.7
USGS Gage
Gregory Ln.
Smith's
High School Rd.
Thaw Well #3

Appendix B

Table B12. Best estimates of days when excavators were deployed between fall 2014 and spring 2019 to remove ice blockages from Flat Creek.

Excavator deployment dates	AF3Day	AF5Day
1/3/2014	16.40	17.60
1/17/2014	22.3	20.3
1/18/2014	31.4	30.6
1/19/2014	33.7	44.5
1/4/2016	72.4	112.7
1/5/2016	25.28	51.44
1/13/2018	21	44.7
1/14/2018	32.9	49.7
1/15/2018	31	37.9
12/13/2018	21.1	44.67
12/15/2018	33.87	37.91
1/3/2019	66.9	75.8
1/5/2019	43.6	88.9
1/6/2019	28.4	65.7
1/10/2019	34.9	39.9
1/11/2019	27.5	45.7
1/12/2019	30.8	56.5
1/13/2019	40.2	60.4
1/14/2019	52.8	69.3
1/15/2019	55.6	60.4
1/16/2019	42.6	76.2

Table B2. Thaw Well #2 operation during the 2018-2019 winter.

Date/Time ON	Date/Time OFF	Hours On (hh:mm)
12/4/2018 13:45	12/4/2018 16:30	2:45
12/5/2018 7:45	12/5/2018 12:45	5:00
12/6/2018 7:30	12/6/2018 12:15	4:45
12/7/2018 7:45	12/7/2018 13:25	5:40
12/10/2018 14:45	12/11/2018 7:45	17:00
12/14/2018 7:50	12/14/2018 11:38	3:48
12/27/2018 8:10	12/27/2018 12:25	4:15
12/28/2018 8:25	12/28/2018 16:30	8:05
12/31/2018 10:30	1/4/2019 14:20	99:50
1/5/2019 14:20	1/6/2019 9:30	19:10
1/11/2019 16:30	1/16/2019 12:30	116:00