DATE: January 26, 2018
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SUBJECT: REPORT ON SITE VISIT TO FLAT CREEK, JACKSON, WY

INTRODUCTION

The purpose of this short report is to provide a review of the ice conditions and water levels I observed along Flat Creek, Jackson, Wyoming during January 1-4, 2018. Additionally, this report offers a preliminary analysis of what I observed. The analysis leads to a set of conclusions and the outline of an approach to ice management along the creek.

I present and discuss weather data from station JKNW4 and water level and temperature data from the USGS gaging station #13018350, located just upstream of the High School Road bridge. Much of this report is based on inferences gleaned from the USGS gage record, which is the only real-time source of water level and temperature data available at this time. These data will be augmented when the six water level data loggers, 13 water temperature data loggers, and six time-series cameras that were installed by AE in November are recovered at the end of the present ice season. To be kept in mind is that the analysis of this larger data set may modify the conclusions presented here.

During the period January 1 through 4, I observed ice conditions along Flat Creek and evaluated potential ice-related flooding along the creek, which flows through Jackson, Wyoming. On January 1 between 4:00 and 5:20 PM, I walked the bike path from High School Road to the pedestrian bridge at the upstream end of Garaman Park. On January 2 and 3, I accompanied Brian Remlinger and Kevin Poole on Alder Environmental's (AE's) designated walking routes (Alder Environmental, 2017). The observations, along with time I spent at AE's office, gave me an insightful occasion to assess how ice forms and affects water levels along the creek, and to bring into focus methods for managing ice formation and water levels. In this regard, an important part of my visit entailed discussing the extensive data and observations that AE had collected during the last three winters. On January 4, Carlin Girard of the Teton Conservation District and I visited the Creek to view and review ice conditions. In addition to covering large portions of AE's designated walking routes, we made stops on North Cache Street at the lower end of the Elk Refuge.

Since my site visit, I have discussed my observations with Dr. Rob Ettema. Together, we have conducted the preliminary analysis, drawn conclusions from the analysis, and suggest the outline of an approach to managing ice along Flat Creek as it passes through Jackson.

FLAT CREEK'S PHYSICAL AND ICE CHARACTERISTICS

The physical characteristics of Flat Creek play an immediate role in ice formation along the creek. In a plan to rehabilitate Flat Creek, Thomas and Lora Wesche (2003) concisely describe the physical characteristics of the creek through Jackson:

> *"The 3.5 miles of Flat Creek flowing through the Town of Jackson can generally be characterized as wide, shallow, single threaded, moderately meandering, low gradient and stable (Figure 2). Channel width ranges from about 25 up to 75 feet, with over 75 percent of the wetted surface area comprised of water depths of less than 1.0 feet. Sinuosity (ratio of channel length to valley length) varies from about 1.4 in the Karns Meadow section down to 1.0 (straight) in several sections that have been channelized and confined by urban development. Few islands and bars are present and the channel gradient is 0.6 percent. The channel itself is exceptionally stable, characterized by well-vegetated stream banks and a paved substrate of small to large cobble." (Wesche and Wesche, 2003)*

The 18-year, average daily discharge measured at High School Road (UWGS 13018350, Flat Creek below Cache Creek near Jackson, Wyoming) ranges from 60-70cfs during the ice season, which runs from about December 1 through February 15.

Wesche and Wesche (2003) point out that Flat Creek thorough Jackson ". . . is an idea frazil generator." This comment is borne out by my observations. Widespread frazil generation during cold, surface-ice-free periods leads to extensive anchor ice formation, which is a prominent ice characteristic of the creek.

Anchor ice formation and subsequent release create a number of potential ice-related flooding scenarios that Jackson has been trying to mitigate for years. Mitigation efforts have included the following actions:

1. Discharging warm water into the creek to melt ice (Daly, 2003);
2. Placing weirs and other in-stream improvements into the Creek to reduce flow velocity and promote surface-ice cover growth while simultaneously improving instream habitat (for example Leemon and Wesche, 2012; Wesche, 2002; Wesche and Wesche, 2003); and,
3. Using backhoe excavators to remove ice dams when flooding was imminent (Brian Remlinger, personal communication).

Alder Engineering collected water temperature and level at several locations along the creek during the winters of 2015-2016 and 2016-2017. Kempema and Ettema (Kempema and Ettema, 2016, 2017) analyzed these data and found that water temperatures and the ice cover along the creek are strongly influenced by the above-freezing, spring-fed water at the creek's source, the springs in the Elk Refuge. This warm water melts ice throughout the winter, preventing the development of a continuous, floating ice cover.

WEATHER, WATER AND ICE CONDITIONS DURING WINTER 2017-2018

It is evident that the creek's relatively large aspect ratio (width/depth) and steep grade cause the creek's water to be very thermally responsive to weather conditions and to heat input from sources of groundwater contiguous with the creek.

To date, winter 2017-2018 has been relatively mild. This weather situation has resulted in somewhat different ice conditions along the creek compared to last year (see Kempema and Ettema, 2017 for a discussion of last year's ice regime). However, <u>the same basic ice-formation processes</u> are evident during both winters.

It is useful to recount the main weather and water conditions prevailing at the creek this winter. My site visit occurred from January 1 through 4, 2018. As described above, conditions during this period closely matched typical early freeze-up conditions normally seen in late November or early December, i.e. air temperatures dropped to well below freezing and Flat Creek had little or no ice.

Daily air temperature records from weather station JKNW4, along with water level and temperature records from the USGS gaging station upstream of the High School Road Bridge (USGS gage number 13018350) are shown in Figure 1. The period from December 1, 2017 through January 5, 2017 can be broken into two phases. From December 1 thorough 21, daytime high temperatures cluster around the freezing point, and night-time lows range into the single digits (^{o}F). As a result, water temperatures cooled to the freezing point at night, and rose to above 33^{o}F (0.5^{o}C) during the day. These diurnal water temperature variations are matched by inversely-correlated water level changes; i.e., when water temperature was at the freezing point, the water level rose by up to 0.2 feet, but when the temperature rose, water level dropped. This trend was characterized by the occurrence of open water with supercooling and anchor ice generation along the creek at night, followed by anchor ice melting or release during the day. On December 21, a cold front passed through the area, with air temperatures reaching a minimum of -14^{o}F on December 24. This cold front generated widespread anchor ice formation along the entire creek bed that stayed in place until the evening of December 29 (Brian Remlinger, personal communication), even though air temperature rose above the freezing point by early morning on December 27 (Figure 1).

Water level dropped precipitously at about 6:30 PM on the 29th, followed by rising water temperatures at about 11:30 PM (Figure 1). By the next day, essentially all anchor ice and border ice had been flushed out of the Creek along AE's designated walking routes (Brian Remlinger, personal communication). At this time, we only have levels and temperatures from the USGS gage for late December and early January. However, AE downloaded the 6 Hobo pressure loggers that are deployed along the Creek on December 13. Comparison of the USGS gage record with the Hobo data from December 1 through 13 show similar temperature and water level trends, strongly suggesting that the source of the warm water arriving at High School Road was from upstream of north Cache Street, approximately 3.7 miles (6 km) upstream of the gaging station.

It appears that upstream anchor ice and border ice acts as a buffer, keeping the water at the freezing point and maintaining local ice (either border or anchor ice) until the upstream ice is melted; thus, a rise in water temperature at the USGS site indicates essentially ice-free conditions upstream. This supposition is reinforced by Brian Remlinger's observation that essentially all ice along the designated walking routes was gone by December 30. Analysis of the upstream temperature and pressure logger data collected by AE from upstream of the USGS gage will allow confirmation of this deduction.

Air and water temperatures dropped again on December 30, and water levels began to rise on December 31. This set the stage for the site visit: essentially no ice was present, air temperatures ranged from near 0^{o}F to near freezing during the site visit, and the water temperature at the USGS gage dropped to the freezing point. The USGS gage shows an increasing trend in water level that peaked on the morning of January 5 at 2.65 feet. The water level increase was not uniformly upward, instead there is a complex daily variation in water level associated with changing air temperatures, insolation, and river ice conditions. On January 6, water level dropped precipitously back to about 1.8 feet (Figure 1). This water level drop coincided with an increase in water temperature to 36^{o}F (2.4^{o}C). On January 6, the ice weir on a rock-weir diversion structure upstream of Garaman Park completely melted out (Bill Wotkyns, personal communication). This, along with the temperature rise recorded at the USGS site, suggests that Flat Creek was once again essentially ice free.

A summary of the major ice and water conditions observed during my site visit are listed below:

- Flat Creek went from ice-free conditions on December 30 (Brian Remlinger, personal communication) to a completely anchor-ice carpeted creek bed on January 1 and 2. This anchor-ice carpet was observed on the lower section of the designated walking route, from High School Road to the pedestrian bridge upstream of Garaman Park, on the evening of January 1. On January 2, the entire designated walking route was traversed; essentially all of the visible creek bed was carpeted in anchor ice (Figure 2). Significant anchor-ice free portions of the bed were observed on the left side of the Creek below the Kelly Tube (~600 square feet, these are very rough estimates), on the right side of the Creek below Virginia Lane (~ 400 square feet), and in the channel above the 2^{nd} pedestrian bridge upstream of High School Road (~2500 square feet). This last location had a complete anchor ice cover in the morning that had released by the time we returned at 2:15 PM (Figure 3).
- I entered the water at the three anchor-ice free locations mentioned above to observe anchor ice that was still in place upstream and downstream. The anchor-ice carpet at all three of these locations was 4 to 8 inches thick (10 to 20 cm) and composed of 1-3 mm diameter, irregular, thin, disk-shaped ice crystals. The biggest apparent difference in the anchor-ice masses at the three sites was the degree of hardness or induration. At Kelly Tube and Virginia Lane, it was relatively easy to dislodge anchor ice from the bed, or to push a finger into anchor ice masses. At the downstream pedestrian bridge, the anchor ice was strong enough to bear my weight in many places, and had to be kicked to free it from the bed.
- Although anchor ice was ubiquitous, it did not have a uniform thickness along the Creek. All of the observed rock over pour structures and rock weirs along the designated walking routes had associated anchor ice weirs that raised upstream water levels (Figure 4). Due to safety concerns, I was not able to directly measure the ice thicknesses of any of these weirs. There is a fundamental difference between an anchor ice weir and an anchor ice dam. Weirs are composed of accumulated frazil and slush ice, and are completely under the water surface. In contrast, anchor-ice dams form when ice weirs breach the air/water interface. Anchor-ice dams

have cores composed of anchor-ice weirs that are sheathed in a hard ice surface that forms at the water/air interface. As a result, anchor ice dams are much more resistant to thermal or mechanical erosion compared to anchor-ice weirs. The cold freeze up conditions during 2016-2017 winter created numerous anchor-ice dams, but conditions during this year's site visit promoted anchor-ice weir formation. Presumably, if air temperatures had remained well below freezing, some of the observed anchor-ice weirs would have morphed into anchor ice dams, which may grow by means of accretion of drifting anchor ice and growth of aufeis (freezing of thin flows of water trickling over the anchor-ice dam). Anchor-ice weir formation was not restricted to in-stream improvement structures. They also formed at other places along the creek. By January 3, AE had mapped the locations of more than 30 anchor-ice weirs or dams along the Creek, their locations and history should be analyzed at the end of the ice season.

- Anchor ice weirs raise upstream water levels, which may lead to overbank flooding. The worst flooding observed during the site visit occurred around an anchor-ice weir that developed on a rock weir for the 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 infrastructure and a track hoe was hired to remove the anchor-ice weir. The track hoe was not able to reach the weir, but did clear accumulated slush ice from upstream. The next day the dam was thermally eroded, which mitigated the flooding threat (Bill Wotkyns, personal communication).
- A second area of significant overbank flooding occurred along the JH Community Pathway around 100 to 120 yards downstream of the Pathway intersection with Elk Run Lane. Icings associated with this over bank flooding increased about 8" in thickness between January 2 and January 4 (Figure 5). This location provided a good illustration of how overbank icings form. These icings form as thin sheets of water freeze as they flow over existing ice layers, creating a very dense, grounded ice mass. Unlike anchor ice attached to the stream bed, these ice masses resist melting during warm-weather periods, filling space that might otherwise accommodate subsequent overbank flooding.
- Anchor ice was released from some of the bed starting on the afternoon of January 2. Large masses of anchor ice, covering several square yards to several 10's of square yards would rise from bed (Figure 6). It is not clear why anchor ice released from some portions of the bed, but not others. As this anchor ice drifted downstream, it would become disaggregated by flow turbulence, breaking up into smaller and smaller flocs until completely disaggregated. It appeared that the majority of the released, drifting anchor ice passed over existing anchor ice weirs, although a recently-released, relatively dense anchor ice mass did choke the channel upstream of the Garaman Park diversion structure for 150 or 200 feet, and contributed to local overbank flooding (Figure 7). Surprisingly, once this mass choked the stream, the majority of subsequent anchor ice arriving from upstream appeared to pass under the mass and over the anchor ice weir. Relatively little slush ice grew upstream once the initial mass was emplaced.
- Thaw Well #2 was started at 10:40 on January 2. It ran for about 3 hours at ~½ speed. The warm thaw-well discharge cleared the anchor ice from the river right side of the channel for about 200 feet downstream of the thaw well (as far as we could see from the Crabtree Lane pedestrian bridge). This resulted water level drop of about 1 foot along this reach. The next morning, the left side of the channel below the thaw well was still carpeted with anchor ice, but there was little or no new anchor ice where the release had occurred the previous afternoon. Although it

was impossible to determine why anchor ice naturally released from some parts of the bed and not others during the course of the site visit, it is clear that the presence of warm water results in the almost immediate release of attached anchor ice.

- Based on observations made along the designated walking routes, the existing in-stream improvements do little or nothing to support surface ice cover growth. Ideally, these improvements slow the current enough to allow surface ice to grow at the air-water interface, rather than in the water column (frazil) or on the bed (anchor ice). The widespread carpet of anchor ice, seen upstream and downstream of all the in-stream improvements we could approach, along with the lack of significant surface ice growth during the four-day site visit show that frazil and anchor ice are the predominate ice types formed during the prevailing weather conditions. An alternative method of surface ice growth enhanced by the instream improvements might be juxtaposition, where released anchor ice and slush ice arriving from upstream are trapped by the in-stream improvement structures, bridging the creek and freezing into a continuous surface ice cover. The only place this was observed was a short section of the creek upstream of the Garaman Park diversion (Figure 7, discussed above). These observations indicate that expecting to grow an ice cover by juxtaposition in a shallow, steep, fast-flowing creek like Flat Creek is unsound, because slush ice arriving from upstream will pass under the existing ice cover and choke the creek channel, potentially resulting in rapid, catastrophic overbank flooding.

DISCUSSION

My site visit illuminated the ice and flow conditions that exist along Flat Creek during the winter months, and leads to several conclusions and an ice-management approach that the FCWID should consider further.

Flat Creek is relatively wide and shallow, and therefore responds rather quickly to changes in air temperature. Much of the creek, even with the instream improvements, flows with water depths less than 1 foot deep. The shallow depth and large aspect ratio (width to depth ratio), combined with relatively high slopes and current speeds create turbulent hydrodynamic conditions. These flow conditions, together with the creek's thermal responsiveness, promote frazil and anchor ice rather the formation of a stable surface ice cover.

Stabilization of ice formation (of any form) along the creek is disrupted by the continuous input of relatively warm water from the springs in the Elk Refuge. Consequently, during most winters a significant reach of open water occurs that has the potential to generate frazil and anchor ice (with related flooding) when the inevitable cold front blows through. As documented in previous FCWID-funded studies (Kempema and Ettema, 2016, 2017), the downstream end of this open-water reach will migrate upstream and downstream in response to changing weather conditions. This winter represents one extreme, when, apparently, no persistent surface ice cover has developed anywhere along the town reach. As a result, water level increases associated with anchor ice formation are occurring on a regular basis (Figure 1). Last year, in contrast, was characterized by an almost continuous surface ice cover through the town reach. This surface ice cover stayed in place until the thaw wells were activated.

The presence of ice, whether anchor ice or surface ice, raises water levels in a stream or river. A floating, surface ice cover raises the water level in two ways. First, the presence of floating ice takes up space in the channel, raising the water level. A simple analogy is adding ice cubes to a nearly-full glass of water; the water level will flow over the lip of the glass. Second, a floating ice increases the wetted perimeter of the stream, which increases frictional drag and raises the water level.

Anchor ice on the stream bed also raises water levels by filling available channel space. However, anchor ice does not increase the wetted perimeter because it covers the already-existing bed. Anchor ice does have additional effects on water level, notably by altering channel roughness or flow-resistance. It does not accumulate as a uniform thickness on the bed, instead it preferentially collects on high spots like rocks protruding above the bed and rock weirs, creating backwater conditions that may cause flooding. These backwater effects drove the flooding observed at Garaman Park and downstream of Elk Run Lane during the site visit. In addition, anchor ice tends to release from the bed in large masses. The sudden release of large masses of anchor ice effectively rapidly increase stream discharge (consisting of water + floating, released anchor ice) that can quickly raise water levels when air temperatures rise, creating what Jasek et al. (2015) termed Anchor-Ice Waves (AIWaves). Jasek et al. (2015) indicate that AIWaves may raise water level by 30% in the Peace River in Canada. The USGS gage record (Figure 1 bottom) suggests that AIWaves may have occurred in Flat Creek. The sharp double spikes seen in water level during middays on December 31 through January 4 suggest AIWave formation. However, these double spikes, along with the daily increase in water level seen from December 5 through 18, may be the result of released anchor ice choking the channel and raising local stage (with no increase in discharge) rather than true AIWaves as described by Jasek et al. (2105). It should be noted that we could not directly detect the ~0.2 feet increase in stage that was recorded during these events. Also, when ice is present (particularly anchor ice), it is very difficult to determine whether changes in water level are due to changes in discharge (water flowrate) or the presence of ice.

Based on my site visit, Dr. Ettema and I draw the following conclusions regarding ice formation and water flow along Flat Creek:

1. The creek's relatively wide shallow morphology makes the creek thermally very responsive to air-temperature fluctuations.
2. It is likely that Snow King Mountain exerts an important influence on the creek's daytime thermal condition, because the mountain blocks insolation heat from entering the creek.
3. The creek's inflow from the Elk refuge and the creek's morphology, together, strongly promote frazil and anchor ice formation.
4. Anchor-ice formation and release often results in localized ice-jamming and subsequent ice growth (notably by aufeis) that locally chokes water flow along the creek.
5. The several structures placed as part of the in-stream improvements to the creek inadequately take into account the creek's thermal behavior and the way ice forms along the creek. The structures do not (cannot) promote a surface ice cover formation or reduce anchor-ice formation. Instead, the structures often become locations where anchor-ice dams form.
6. Management of ice formation and potential flooding primarily requires consideration of the creek's thermal characteristics.

OUTLINE OF AN ICE-MANAGEMENT APPROACH

The conclusions mentioned above suggest the need for a multi-part approach to ice management along Flat Creek. The approach is outlined below:

1. **Manage the creek's thermal condition**. The likely feasible way to do this via the judicious use of the existing thaw-wells. The purpose here is to produce the situation Figure 1 shows for the period of December 1 through 22, whereby thaw-well use promoted the daily release of anchor-ice at key locations along the creek. My observations indicate that small amounts of released anchor ice can be flushed through the creek without jamming. Note that complete elimination of anchor ice is infeasible.

   Thaw-well use should involve water release at <u>key locations</u> where it will have greatest benefit. For example, the discharge point for Thaw Well #2 could be moved about 100 yards upstream of its present location so as to discharge warm water above the rock weir known to form an ice dam.

   Further, thaw-well use should be at <u>key times</u> related to forecasted weather conditions. Likely, these key times need only be for several hours duration and then only during the period December 1 through February 15, when ice formation is known to be potentially problematic.

2. To the extent possible, **remove or modify locations (often creek-improvement structures) where anchor-ice weirs dams commonly occur**, so that such ice dams occur much less frequently (or not at all). This part of the approach requires that FCWID identify the locations where anchor-ice dams commonly occur.

   For example, the diversion rock weir at Garaman Park is a location where, during the last two winters, ice dams commonly occurred and caused localized flooding that threatened nearby creek-side condos.

3. At locations where the FCWID is resigned to the formation of anchor-ice dams, **have a backhoe excavator available** so as to mechanically remove or reduce the dam. This part may be considered a last resort, but is realistic, given the creek's proximity to dwellings (houses, etc.).

   An alternative or additional action (where feasible) could be to construct relatively low levees around certain dwellings, protecting them from flooding.

This approach entails a set of considerations FCWID must evaluate. However, I encourage FCWID to think through the practical and economic issues associated with the approach outlined above.

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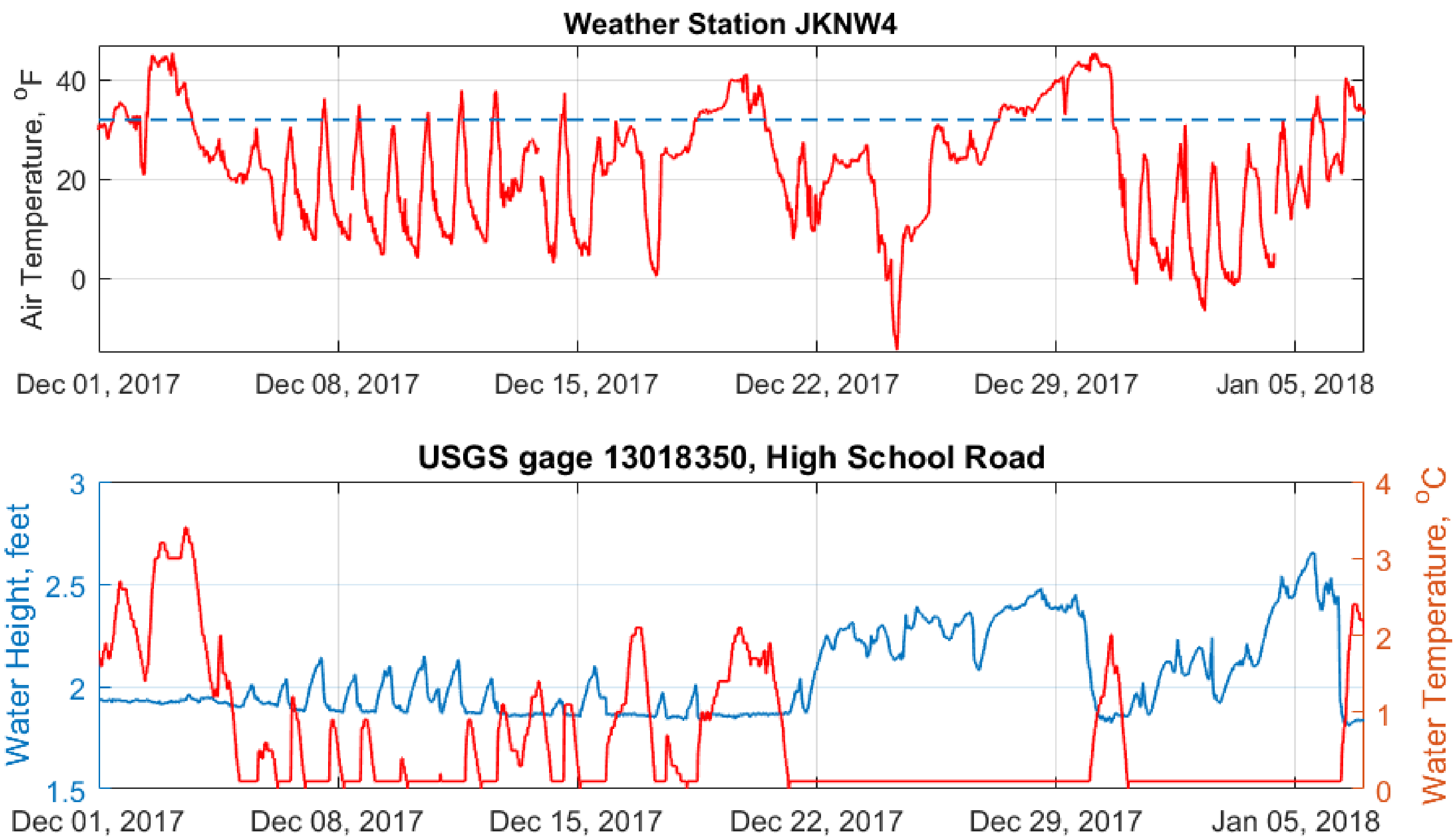

Figure 1. TOP: Air temperatures from weather station JKNW4 from the period of December 1, 2017 through January 5, 2018. The dotted blue horizontal line is at 32°F. BOTTOM: Water level and temperature measured at USGS gaging station 13018350, located just above the High School Road Bridge. There is an inverse relationship between water level and water temperature at this site. When water temperature drops to zero, water level rises in response to ice formation. Above freezing water temperatures result in a drop in water level, presumably due to melting and/or release of all upstream ice. Note that air temperature is in °F while water temperature is in °C..

Figure 2. Typical anchor ice coverage on the bed of Flat Creek on the morning of January 2, 2018. Essentially all of the bed observed bed was covered with a 4" to 8" (10-20 cm) thick layer of anchor ice. The emergent ice masses visible in the left center of the figure indicate that this anchor ice mass has grown by accretion of anchor ice drifting down from upstream in addition to in situ growth.

Figure 3. On January 1 and the morning of January 2, the entire bed in this region was carpeted in anchor ice. On the afternoon of January 2, the anchor ice on the left side of the image had released from the bed (dark area) and drifted downstream as slush ice. By the afternoon of January 4, this entire cross section was anchor-ice free. View looking upstream from 2nd pedestrian upstream of High School Road.

Figure 4. Changes in an anchor ice weir between January 2 at 10:13 AM (TOP) and January 4 at 11:56 AM (BOTTOM). This anchor-ice weir has grown and become partially emergent in 50 hours, and is beginning to transition from an anchor-ice weir to an anchor-ice dam. Water levels have increased both upstream and downstream of the dam, as seen by the flooded rocks in the center of the image above the ice-covered rock over pour structure, and the flooded grass in the lower left of the image below the rock over pour. There is very little change in the amount of border ice cover growth during this period. The T-stake on the left contains a time-lapse camera.

Figure 5. *Significant overbank flooding along the JH Community Pathway downstream of Elk Run Lane. The park bench seat is estimated to be about 16” high, water level rose 6” to 8” between January 2 and 4 due to an anchor ice weir that formed on an existing rock over pour structure to the left of the photograph.*

Figure 6. Released anchor ice drifting downstream (right side of image) and accumulating in low-velocity zones (left side of image). The relatively large mass of drifting ice is recently-released anchor ice. As it continues to drift downstream, it will become more disaggregated and dispersed across the creek surface. If cold air temperatures persist, the deposited slush ice on the left side of the image will freeze into a surface ice cover that could eventually bridge the Creek.

Figure 7. TOP: An anchor-ice weir (transitioning into an anchor-ice dam) on an existing rock weir diversion in Garaman Park. BOTTOM: A juxtaposed surface ice accumulation, consisting of released anchor ice, located upstream of the anchor ice dam shown in the top image. The approximately 150-feet long ice accumulation chocked the channel over a 5-minute period on January 2.