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Ice-Related, Urban Winter Flooding of Flat Creek, Jackson, Wyoming

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Flat Creek through Jackson, Wyoming has a long history of freezeup-related flooding events driven by frazil and anchor ice formation. These ice formation processes and associated flooding along the creek are typical features of the winter environment in small, spring-fed streams and rivers flowing through mountain valley and meadow locations in North America. Efforts to mitigate ice-related flooding along Flat Creek have been ongoing since before 2000. These efforts include installation of three thaw wells to minimize river supercooling and construction of more than 50 instream improvement structures designed to promote the formation of a stable ice cover. The wells and structures have not eliminated ice-related flooding problems in Flat Creek. The most effective flood mitigation technique has been to deploy excavators to remove offending ice from the stream channel when necessary. Excavator use is controversial because it is expensive and potentially harmful to the riparian corridor. Our paper briefly assesses previous flood mitigation efforts in Flat Creek, and then evaluates observations and data collected along Flat Creek during the winters of 2015-2016 and 2016-2017. It subsequently outlines a conceptual model for mitigating winter flooding along Flat Creek. Insights gleaned from Flat Creek help address ice-related flooding at similar mountain valley locations.

1. Introduction

Flat Creek through Jackson, Wyoming has a long, somewhat contentious, history of ice-related winter flooding. The flooding continues to be problematic because early zoning rules allow building development within a few meters of the creek. Remlinger (2006) reports that, after the adoption of the 1994 Teton County comprehensive plan, town planning regulations required setbacks of 6 m to 15 m from mean high water. As a result, a relatively minor increase in creek water level can put residential and commercial property at risk. Rising water levels are associated with frazil and anchor ice formation throughout winter. Our paper briefly assesses previous flood mitigation efforts in Flat Creek, evaluates observations and data collected along Flat Creek during the winters of 2015-2016 and 2016-2017, then outlines a conceptual model for mitigating winter flooding along Flat Creek. Insights gleaned from Flat Creek help address ice-related flooding at similar mountain valley locations.

An important contribution of our paper is its insight into ice formation and freeze-up flooding associated with ice formation in mountain streams. A key aspect of these processes is the substantial role played by groundwater flow into mountain streams.

Jackson has implemented a number of different plans to mitigate ice-related flooding over the last two decades. In 1999/2000, three thaw wells (wells used to introduce water at about 5°C to the creek) were drilled to reduce frazil ice formation along the creek through town (Nichols 2013). Beginning in 2003, Jackson worked with the Teton Conservation District (TCD) to construct a series of in-stream improvement structures to deepen and slow the creek, thereby promoting formation of a floating ice cover and mitigating frazil-driven flooding (Nichols 2013, Wesche 2002). Finally, through 2012 the town helped creek-side landowners by deploying excavators to remove choking ice deposits from the river. The use of excavators was a source of contention because of costs and liabilities born by Jackson. As a result, the Flat Creek Water Improvement District (FCWID) was formed in 2014 to address the wintertime, ice-related flooding threat. The FCWID and TCD funded data-collection efforts during the 2015-2016 and 2016-2017 winters. A unique feature of these data is the detailed, coupled measurements of water levels and temperatures along 6 km of the creek (Figures 1 and 2). These measurements, along with time-series of digital images, show the dynamic nature of ice conditions in a small creek as weather conditions change throughout the winter. The resulting data were analyzed to understand and help mitigate ice-related flooding in Jackson.

2. Freeze-up processes in small, mountain streams

Over the last 10 years the ice research community has recognized that freeze-up processes in small streams differ significantly from those in large rivers (Kempema et al 2008, Lind et al 2016, Stickler & Alfredsen 2009, Turcotte & Morse 2011, Turcotte & Morse 2013, Turcotte et al 2014, Turcotte et al 2013). Flat Creek, 10 m wide, shallow, relatively steep, and having a cobble bed, is a “small stream” set in a mountain valley. Important features of streams in mountain valleys include the presence of channel boundaries and large roughness elements (e.g., rock outcrops and boulders) that directly interact with ice formation processes and, thereby, with water flow. Additionally, a highly important feature is that such streams commonly drain groundwater from surrounding mountains.

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

Recent research findings (e.g., Turcotte et al., 2013, 2014) suggest using the concept of dynamic ice formation when describing mountain streams like Flat Creek. This concept rightly indicates that ice formation begins with the formation of frazil and anchor ice in fast-flowing channel segments. Frazil quickly triggers anchor ice formation. Then, anchor ice accumulations form and create backwater effects, especially when they cover significant portions of the bed or create ice "weirs" at shallow points in the river. A second stage of dynamic ice formation occurs when ice weirs emerge into air and evolve into ice dams during prolonged cold periods. Whereas submerged ice weirs are relatively porous and fragile accumulations of ice, emergent ice dams are hard, strong accumulations of ice. Ice dams, as their name implies, may choke flow in a channel by directly damming flow, or by accumulating frazil, released anchor ice, and aufeis upstream (Figure 3). Growing, or active, ice dams form by freezing of successive, thin layers of water overtopping the dam. Such ice dams are evident along much of Flat Creek during winter flooding events (Figure 4).

Ice dams can reach heights of about 1 m or more, choking flow and thereby creating significant backwater. Warming weather can cause ice dams to breach, releasing their stored water downstream (Figure 4). Alternating cold and warm spells during winter can generate alternating cycles of dam activation (growth) and beaching. Turcotte et al. (2013, 2014) and we find that ice dams are the most threatening, flood-provoking features on small streams during frigid winter weather.

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

$$V_{ice} = \frac{-T_{air} C_h A}{\rho_{ice} \lambda p_{ice}} * \frac{3600\ seconds}{hour} \qquad [1]$$

Here, V_{ice} is the volume of ice produced per hour, T_{air} = air temperature (^{o}C), C_h is a heat transfer coefficient from water to atmosphere, a commonly used value is 25 W/(m^2 ^{o}C), A is open-water area (m^2), ρ_i is the density of ice (920 kg/m^3), λ is the latent heat of fusion of ice (3.3 x 10^5 W/kg), and p_i is the slush/anchor ice porosity (0.5 is a reasonable value). Assuming a nighttime air temperature of -25 ^{o}C, in a 12 hour night a 100 m long by 10m wide reach of river open to the atmosphere can produce about 145 m^3 of slush ice. If all of this ice is deposited locally as anchor ice, it will raise the riverbed by about 14 cm, along with changing the bed roughness. To be kept in mind is that not all frazil forms anchor ice. Moreover, all anchor ice eventually releases from the bed and floats downstream until it comes to an obstruction or a low-velocity reach. A warm-water input that maintains a 100 m by 10 m ice-free lead will form large amounts of frazil and anchor ice with each passing cold front. This ice can choke the channel downstream, leading to flooding.

Ice that floats downstream accumulates on elements of channel morphology, such as riffles and boulder clusters, and engineered elements, such as stream-restoration structure, and thereby reduces the cross-sectional area of the channel. In extreme cases, the ice may completely block the channel, causing water to flow over and freeze on top of the existing ice cover, creating an aufeis. The main difference between ice dams and aufeis relate to considerations of stream length. Ice dams in small streams tend to be relatively thin features (< 5 m long). Aufeis, in contrast, can form long, channel filling deposits up to 100's of meters long that rest on the riverbed and cause significant flooding. Tuthill (2008) studied an ice jam that formed on the Rio Blanco River in Colorado in 2005 that formed a combined aufeis and slush ice accumulation that was more than 8 km long. This large jam/dam forced the entire river out of its channel, creating extensive flooding and thick ice accumulations in a rancher's alfalfa field. The jam began where frazil and released anchor ice collected on a rock weir that was placed to divert water into an irrigation canal.

Ice formation increases flow resistance and thereby elevates water levels. This effect is increased in small streams because the thickness of the ice cover can account for a significant portion of the stream depth. Moreover, the effect is exacerbated by the formation of dynamic ice forms such as ice dams, ice weirs, hanging ice dams, and aufeis. Consequently, overbank flooding may become especially severe in the winter, even when discharges are at a minimum.

3. Flat Creek hydrology and climate

Flat Creek watershed begins in the Gros Ventre Mountains northeast of Jackson and the valley of Jackson Hole, at elevations up to 3270 m above sea level. The creek flows approximately 58 km to its confluence with the Snake River at about 1800 m elevation. The study area through Jackson is at an elevation of roughly 1870 m. The creek is shallow, averages about 10 m in width, and has an average slope of 0.0055 through the Town of Jackson (Daly 2003). Median winter flows, based on 17 years of records of USGS gage 13018350, located on the southwest side of Jackson, range from 1.7 to 2 m^3s^{-1}. This includes the flow from Cache Creek, one of two major upstream tributaries, which contributes median winter flows of 0.11 to 0.17 m^3s^{-1} to the creek, based on 54 years of record (USGS gage 13018300, located 6.6 km upstream of the confluence). After exiting the Gros Ventre Mountains, Flat Creek flows across the relatively flat National Elk Refuge before entering Jackson. Remlinger (2006) observes that there are significant losses from Flat Creek to groundwater where the creek enters the upstream section of the Elk Refuge. This lost water returns to Flat Creek in the lower portion of the Elk Refuge. Remlinger (2006) indicates that from September through April, Flat Creek flows are almost entirely from groundwater and spring sources, several of which are located just upstream of Jackson. Another intermittent, sometimes significant, winter-season input into the creek is the runoff from snowmelt draining from Jackson directly into the creek, even during the coldest winter months.

Jackson experiences cold, snowy winters, with daily average high temperatures below freezing for three months a year, and daily average low temperatures below freezing for seven months per year (Table 1). Significant snowfall occurs between November and March. The regional climate provides conditions conducive to significant frazil and anchor ice formation from mid-November through February in most years.

4. Data collection

In fall 2015, FCWID contracted with Alder Environmental LLC (AE) to monitor water and ice conditions in Flat Creek through Jackson during winter 2015-2016. Of focal interest was the 6 km reach of Flat Creek in Jackson (Figure 1). AE's winter monitoring included regular observations of the creek, measurements of water temperatures at 13 locations measured with RBR soloT data loggers (accuracy ±0.002 ^{o}C), air temperatures from established weather stations, water levels measured at staff gages (stage), water discharges, thaw well operations, spot photos (photos of interest), and ice conditions along the creek. The data were collated into a GIS database containing locations of the various measurement stations, along with ice conditions seen along the creek. The measurements and GIS database are described in (Alder Environmental 2016, hereafter AE (2016)). Data collection continued through the 2016-2017 winter, with the addition of six water level data-loggers (Onset Hobo U20L-04, 0.4 cm accuracy) and seven game-camera stations, which imaged selected reaches of the creek at 15 minute intervals. The 2016-2017 winter data are summarized in Alder Environmental (2017, AE (2017)). Water levels and temperatures were measured at 5 minute intervals. The relative locations of the water temperature logging stations and water level logging stations, along with thaw well positions and operational history are listed in Tables 2 and 3. Figures 1 and 2 show the sampling station locations. The ensuing section of our paper analyzes the findings of AE's monitoring program, focusing primarily on water temperature and level records.

5. Flat Creek water temperature and stage

Thirteen RBR solo water temperature loggers were placed in Flat Creek for the period from November 26, 2015 through February 10, 2016. These high-accuracy loggers were placed along 5.9 km of Flat Creek in Jackson from the north Cache Street Bridge on the upstream side (T1) to the High School Road Bridge on the downstream side (T13, Figure 1, Table 2). The temperature loggers were installed in similar locations from November 17, 2016 through February 17, 2017 (Figure 2, Table 2).

Figure 5 shows records of water and air temperatures during winter 2015-2016. Except for a few nights in February 2016, the water temperature at T1 was always at least 0.25 ^{o}C above the freezing point. In hindsight, this should not be surprising, considering Remlinger's (2006) observation that Flat Creek flow is predominately spring water during winter. Spring water usually discharges at or near the average annual air temperature, which is 4.1 ^{o}C in Jackson (http://www.usclimatedata.com/climate/jackson/wyoming/united-states/uswy0088), so it appears the creek water has already cooled considerably before reaching T1. An ice cover formed upstream of station T1 at the Cache Street Bridge during the winter even with these relatively warm temperatures. The presence of an ice cover suggests that the flow is tranquil enough to stratify, with denser warm water near the bed separated from the ice by colder, less dense water. In this situation, the ice cover acts to insulate the warmer water underneath. The continuous flow of warm water measured at T1 suggests it may be difficult to form a continuous ice cover through town, where local slopes and mixing are higher.

The difficulty in developing a floating ice cover is also indicated by water temperature changes along the entire creek when air temperatures rose above -5 °C. When air temperatures were greater than -5 °C, water temperatures along the entire creek also rose; e.g., see Figure 5, December 3 to 21. Consequently, ice in contact with the water weakened and melted, creating open water and setting the stage for eventual renewed frazil and anchor ice formation when air temperatures dropped. This process is illustrated by the temperature curves shown in Figure 6. The atmosphere reached a high of 2 °C on December 11, while the nighttime low was -12 °C. Figure 6 shows a supercooling front advancing upstream from T13 to T2 as water temperatures dropped through the night. The characteristic temperature curves are an indication that frazil and anchor ice formed along the entire creek on this (and many other) nights. It seems counterintuitive, but it is likely that long cold spells, like the period from December 25 to January 4, are less likely to produce significant flooding than a warm spell followed by a very cold snap.

The temperature records show that warming weather had another effect on water temperature. When water temperatures rose above the freezing point, it was common for water temperatures at stations T2 through T4 to reach higher temperatures than at T1 (Figure 7). This trend indicates other heat sources influence the creek between T1 and T2, T3, and T4. Because the higher downstream temperatures are always associated with warming trends, it seems probable that the heat source is warm melt-water runoff from town, although other possible sources are groundwater inflow or warming of the water as it flows downstream. This hypothesis is supported by the photo logs, which show open water leads in ice-covered stream reaches directly below culverts discharging runoff water. The temperature records show that there is a consistent warm water source entering at the upstream end of the study reach on the Elk Refuge (Figure 5). Water at this source rarely, if ever, reached the freezing point during winter 2015-2016, and drives what we see as a complex, constantly changing, ice-and-water system in Flat Creek through Jackson during winter.

The 2016-2017 winter temperature record reinforces this conclusion by showing similar trends of incoming water at different temperatures entering the creek (Figures 7 and 8). The most eye-catching feature in Figure 8 is the precipitous drop in T1 temperature from approximately 1.8 °C to near freezing on December 15. This drop occurred when the logger was removed from the water for downloading and then redeployed. The technician who downloaded the instrument is not sure that he deployed the instrument in exactly the same position, but is sure that it is within 1 m of its original position. A pressure logger (H1) co-located with T1 shows a similar temperature drop, along with a 20 cm increase in water depth after the loggers were returned to the creek. The depth change indicates that the logger was placed in a slightly different position, and measured slightly different water characteristics.

From the start of data collection through December 3, 2016-2017 station T4 records anomalously low water temperatures at 0.25 to 0.5 °C less than expected compared to surrounding loggers. This changes during the period from December 3 to December 5, when T4 water is warmer than expected. T4 is below the Cache Creek water inflow, which was alternately warmer and colder than Flat Creek during this period, and in turn affected the water temperature in Flat Creek.

It is more difficult to explain the temperature record at T3 between December 23 and January 20. During this period, T3 water temperatures remain relatively steady near 0.1 ^{o}C, while upstream and downstream stations record near-freezing temperatures. This temperature anomaly was not seen during the 2015-2016 winter.

Thaw well operation has a strong warming effect on the creek directly below the wells, which was seen in both winters (Figures 5, 7, and 8). Thaw well 1 (TW1) was turned on at 10:30 AM on January 5, 2016. Temperature stations T6, 176 m downstream of TW1, and T7 at 437 m downstream, show water temperature increases within 1 hour, with T6 temperatures rising much more rapidly than T7. The photo log for January 6 shows a significant, almost continuous ice cover from T6 to T11, where TW2 discharges. This indicates that the heat introduced by the thaw well moved rapidly downstream under the existing ice cover. It also raises the question of whether TW1 and TW2 should have been turned on when they were. The ice cover between TW1 and TW2 would have been better maintained if TW1 was not turned on, and it may be that the ice cover would have extended well past TW2 if that thaw well was not in use. On January 6, an open-water channel, occupying the central band along the reach, extended from TW 2 a distance of 850 m downstream.

The 2016-2017 winter shows similar temperature trends when thaw well #2 (TW2) was on (Figure 8, Table 3). T11 and T12 water temperatures rose to above 0.05 ^{o}C in a few hours after the thaw well was started, and showed little sign of supercooled water during the time pumping continued. The water temperatures dropped quickly to near the freezing point when the pump discharge ceased. The T13 record, located 1067 m downstream from TW2, shows varying diel warming and supercooling events. The time-series photo record from downstream of T13 recorded a persistent, widening and narrowing open-water channel during the period that TW2 was in operation. The combined temperature record and photo log suggests a more-or-less continuous open-water channel was maintained during the period when the thaw well was operational. Thaw-well operation is discussed more in the next section.

Figure 9 shows water levels and temperatures measured at six locations along Flat Creek during winter 2016-2017. The data illustrate the effect of warm-water input, both natural and anthropogenic, on creek ice processes and associated water levels. Station H1, the most upstream monitoring location in this study, at North Cache Street bridge (Figure 2) experienced the smallest increase in stage during the winter. The maximum water level seen at H1 was 32 cm on February 10. At this time, the entire channel through the study reach was essentially ice free, and all downstream stations show a similar hydrograph. This suggests that this stage increase may have resulted from increased discharge associated with above-freezing temperatures rather than a flow-choking event. The highest water level seen during the ice season was 20 cm on January 9. The rise in water level on this day flooded an existing continuous ice cover upstream of Cache Road Bridge during this event.

All six water level stations experienced very similar water levels from November 11, when they were first deployed, until air temperatures dropped precipitously to -29 ^{o}C on the morning of

December 6 (Figure 9). From December 5 through December 14, stations H2, H4, H5 and H6 saw water level rise by about 50 cm. H3 water levels rose by 30 cm during the same period, while H1 stayed relative stable. Discharge from Thaw Well 2 into the creek upstream of stations H5 and H6 began on December 14 (Table 2), the discharge water had an average temperature of 8.6 ^{o}C during this period. The effects of warm-water discharge are seen immediately at station H5, 70 m downstream of TW2, where water levels start to drop at 14:15. At H6, 1067 m downstream of the thaw well, water levels begin dropping 25 hours after pumping began. However, air temperatures rose to 4 ^{o}C on December 15, resulting in water levels dropping by similar amounts upstream of the thaw well at stations H2 and H4. This level drop was accompanied by increases in water temperatures at the upstream stations (Figure 8). From December 18 until the first week in February, stations H2 and H3 experienced relatively slow, steady increase in stage, reaching a maximum of about 50 cm above their initial November water levels. During this same period, H4 water levels varied between 20 and 40 cm above its initial November level. All three of these stations developed an essentially continuous ice cover during this period. Water temperatures in this reach, except for station T3, stayed very near the freezing point until Jan 24. After this, temperature stations T1 through T4 began to show daytime warming, and T2 shows nighttime supercooling events. The slow increase in water levels at T2 and T3 may be an indication of channel choking by in situ ice growth (Figure 3), or may indicate choking by frazil and anchor ice arriving from an open-water site upstream.

In contrast to the upstream stations, H5 and H6 both showed relatively rapid increases in water level immediately after the thaw well pumping ceased on December 28, with stage increases reaching 2 cm hour^{-1} at H6 on the night of December 29. Thaw well #2 pumping was resumed on January 3 because of the 90 cm water level rise seen at H6. The effect of renewed pumping was seen at H5 as a rapid drop in water level, and at temperature stations T11 (co-located with H5) and T12, where water temperature stabilized at 0.1 to 0.2 ^{o}C while pumping continued until January 28. One result of the pumping is that the ice cover was completely melted from the channel around H5 for the rest of the winter. In contrast to H5, at H6 water levels continued to rise after thaw well pumping resumed, reaching a maximum of 1.3 m on January 8. H6 water level began dropping quickly when air temperatures rose from -32 to 3 ^{o}C on January 9, reaching a minimum level of 12 cm on January 11. On January 13, another cold front came through, with daily temperatures ranging from -15 to -30 ^{o}C. Water levels at H6 rose quickly as ice choked this reach, reaching a maximum of 1.1 m and then dropping back to mid-November levels when air temperatures rose to freezing on January 19. A narrow open-water channel persisted at this site throughout January. It is probable that thaw well discharge maintained this channel, and a wider open-water channel upstream.

The 2016-2017 photo stations, water temperature stations, and water level recorders show a complex history of ice cover extent, ice choking, water temperatures, and water levels 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 during the winter. This ice regime in turn creates complex changes in water levels that are difficult to predict.

5. Discussion and conclusion

The detailed insights described above elucidate freeze-up flooding of streams flowing through mountain valleys subject to substantial groundwater drainage. The flooding along Flat Creek is common and attributable to frequent freeze-melt cycles. Freezing chokes flow predominantly derived from groundwater drainage from the surrounding watershed, which raises local stage.

Daly (2003) conducted a HEC-RAS based computer-model study of the effects of the thaw wells on ice suppression in Flat Creek. His study, which did not consider groundwater input, showed that thaw wells could help mitigate ice-related flooding. The extent to which they help depends of several factors, including how water from the wells is mixed within the river, and how the heat-transfer coefficient (water to air) is affected by such features as ice dams. Daly estimates the length of river protected from freezing for flows of 1.1 to 2.8 m^3s^{-1} in air temperatures ranges from -21 ^oC to -37 ^oC. He shows that TW2 will protect the creek from freezing for distances of approximately 180 to 1160 m downstream under those conditions, which encompasses stations H5 and H6.

Our observed temperatures and water levels support Daly's results. For example, thaw well 2 ran from December 28, 2015 until January 15, 2016. Daly assumed a well-water temperature of 7.8 ^oC, while seven spot temperature measurements made in the 2015/2016 season averaged 7.9 ^oC. Figure 5 shows that the warm thaw well water was first discernable at T11, 70m downstream of TW2, at 21:30 on December 28, and at T12, 437m (1400 feet) downstream, on December 30 at 13:00. During that time, air temperatures ranged from -26.7 ^oC to -10.61 ^oC, with an average near -18 ^oC. Daly's results suggest TW2 would protect for a distance of about 300m downstream at this average temperature. The model results fall roughly in the range of the measured water temperatures. Water temperature began increasing at T13, located 1067 m downstream from TW2, on January 6, when the average daily air temperature had risen to above -5 ^oC.

The 2016-2017 water-level records also show the risk of unmonitored thaw well discharge. Sites upstream of thaw well #2 experienced a winter water level rise of up to 50 cm, but also developed snow-covered, essentially continuous ice cover by early January. Record snowfall during the winter of 2016-2017 may have contributed to the winter-long snow-insulated ice cover. This ice cover did not prevent water levels from increasing at sites H2 and H3 as ice continued to choke the channel, and occasionally flood the ice cover, but water-level increases were relatively modest at about 50 cm. In contrast, continuous thaw well pumping cleared the ice cover from station H5, where water level remained low. However, the open water formed by thaw well operation created an ice-free reach that acted as a frazil and anchor ice factory, creating frazil and anchor ice that choked the river in the area around H6, raising water levels up to 1.3 m above pre-ice conditions and creating potential flooding. We suggest judicious, closely monitored thaw well operation in the future, to clear accumulated frazil and anchor-ice masses from the channel while maintaining, as much as possible, an insulating surface ice cover.

Flat Creek in the Town of Jackson is a typical mountain-valley stream situated relatively near its headwaters. It receives significant, relatively warm groundwater inflow throughout the winter season. Because of this inflow, combined with the creek's steep slope, Flat Creek experiences complex, varying ice conditions throughout the winter. Instead of developing a relatively stable ice cover, Flat Creek continually freezes and melts as cold and warm fronts move through the Jackson region. This weather results in multiple frazil and anchor ice events occurring throughout winter. The events place local infrastructure at risk for freeze-up flooding. The addition of thaw-well discharge increases the complexity of the system, making flood predictions even more difficult. The present study illuminates the freeze-thaw processes and their links to heat sources, both natural and artificial; moreover, the study also demonstrated the value of monitoring.

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Table 1. Jackson, Wyoming monthly climate summary.*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average high, ^{o}C	-1.9	0.4	6.4	12.1	17.5	23.1	28	27.4	21.8	14.3	4.1	-2.2
Average low, ^{o}C	-14.7	-13.5	-7.4	-3.5	-0.4	2.9	5.3	4.3	0.1	-4	-8.6	-13.7
Average precipitation, mm	31	25	31	33	50	39	32	36	38	33	41	39
Average snowfall, cm	40.6	27.9	17.8	5.1	2.5	0	0	0	0	2.5	27.9	45.9

*from http://www.usclimatedata.com/climate/jackson/wyoming/united-states/uswy0088/2017/1

Table 2: Flat Creek relative station locations during 2015-2016 and 2016-2017 winters.

Station designation/instrumentation*	Along-river distance between stations (m)	Cumulative distance from Station T16.1 (m)
T16.1, T17.1, H17.1, C17.1	0	0
T16.2, T17.2	996	996
T16.3, T17.3	749	1745
T16.4, T17.4	60	1805
H17.2	733	2538
T16.5, T17.5, H17.3, C17.2	28	2566
TW1	30	2596
T16.6	170	2766
T17.6	51	2817
T16.7, T17.7	228	3045
T16.8, T17.8	462	3507
C17.3	239	3746
T16.9	402	4148
T17.9	36	4184
C17.4	9	4193
T16.10, T17.10, H17.4	401	4594
C17.5, TW2	24	4618
T16.11, T17.11, H17.5, C17.6	70	4688
T16.12, T17.12	314	5002
T16.13, T17.13, H17.6	683	5685
C17.7	107	5792
TW3	173	5965
USGS	18	5983

*T: temperature station, H: water level station, C: time lapse camera
TW: thaw well, USGS: USGS Gaging station
Digits left of period indicate year: 16: 2015-2016, 17: 2016-2017
Digits right of decimal point indicate instrument number

Table 3. Flat Creek thaw wells locations, discharges, water temperatures and dates of use.

Thaw Well Location		**Design Discharge (cfs, m^3s^{-1})**	**Measured Discharge 1/20/17 (cfs, $m^3 s^{-1}$)**
Thaw Well #1	Karns Meadow	2.2, 0.062	N/A
Thaw Well #2	Crabtree Lane	1.76, 0.050	1.21, 0.034
Thaw Well # 3	High School Road	1.54, 0.044	1.0, 0.028
Thaw Well	**Date/Time ON**	**Date/Time OFF**	**# of Days On**
Winter 2015 -2016 Operations			
#2	12/28/15 12:00	1/15/16 10:30	18
#3	12/28/15 12:00	1/15/16 10:30	18
#1	1/5/16 9:18	1/15/16 10:30	10
Winter 2016 -2017 Operations			
#1	Not used		0
#2	12/14/16 14:00	12/28/16 9:30	14
#3	12/14/16 13:35	12/28/16 10:10	7
#2	1/3/17 8:25	1/30/17 10:45	27
#3	1/3/17 8:40	1/30/17 11:15	27

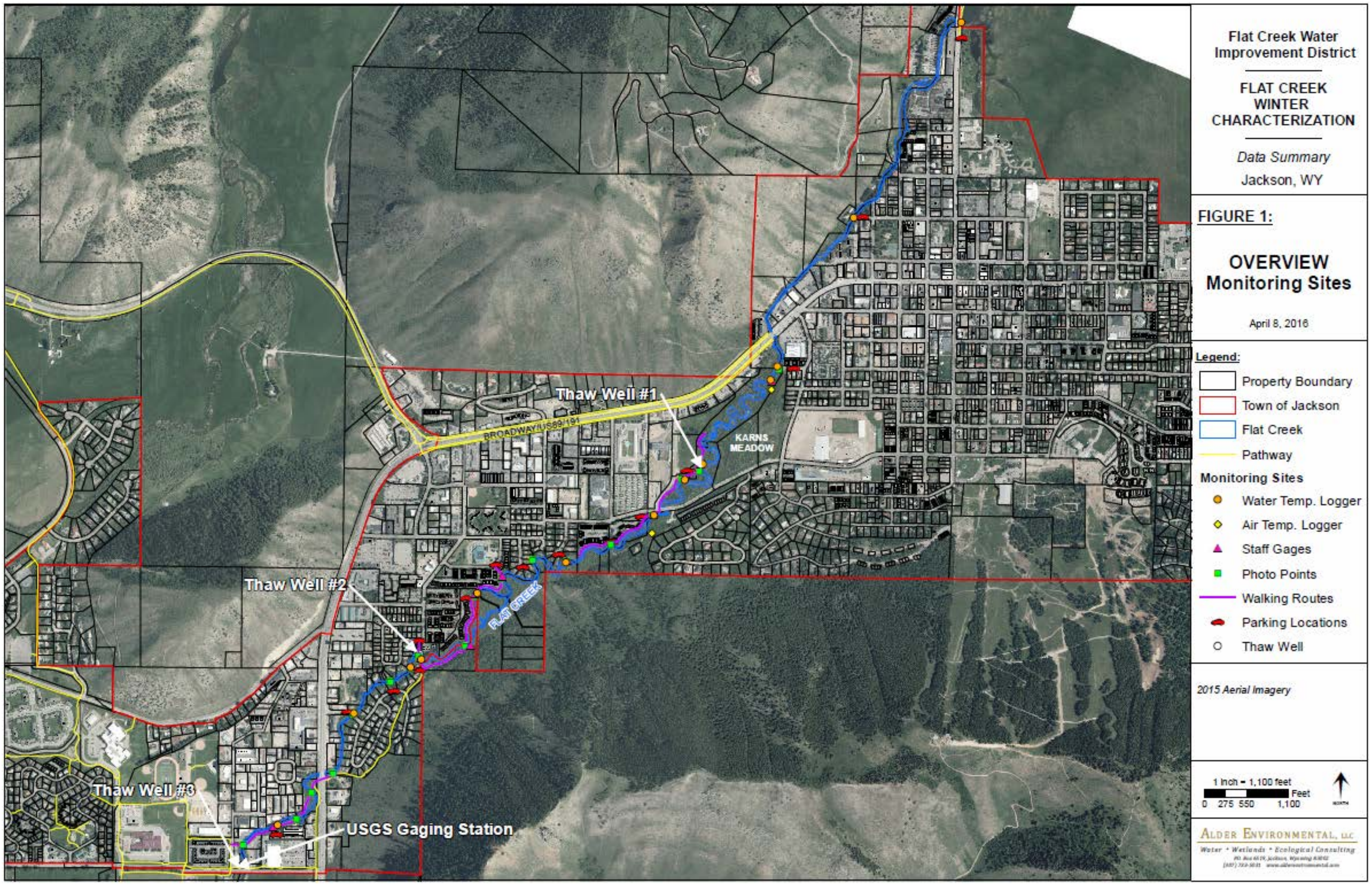

Figure 1. Flat Creek through Jackson, with sampling stations occupied during the 2015-2016 ice season. From Alder Environmental (2016), flow is from northeast to southwest.

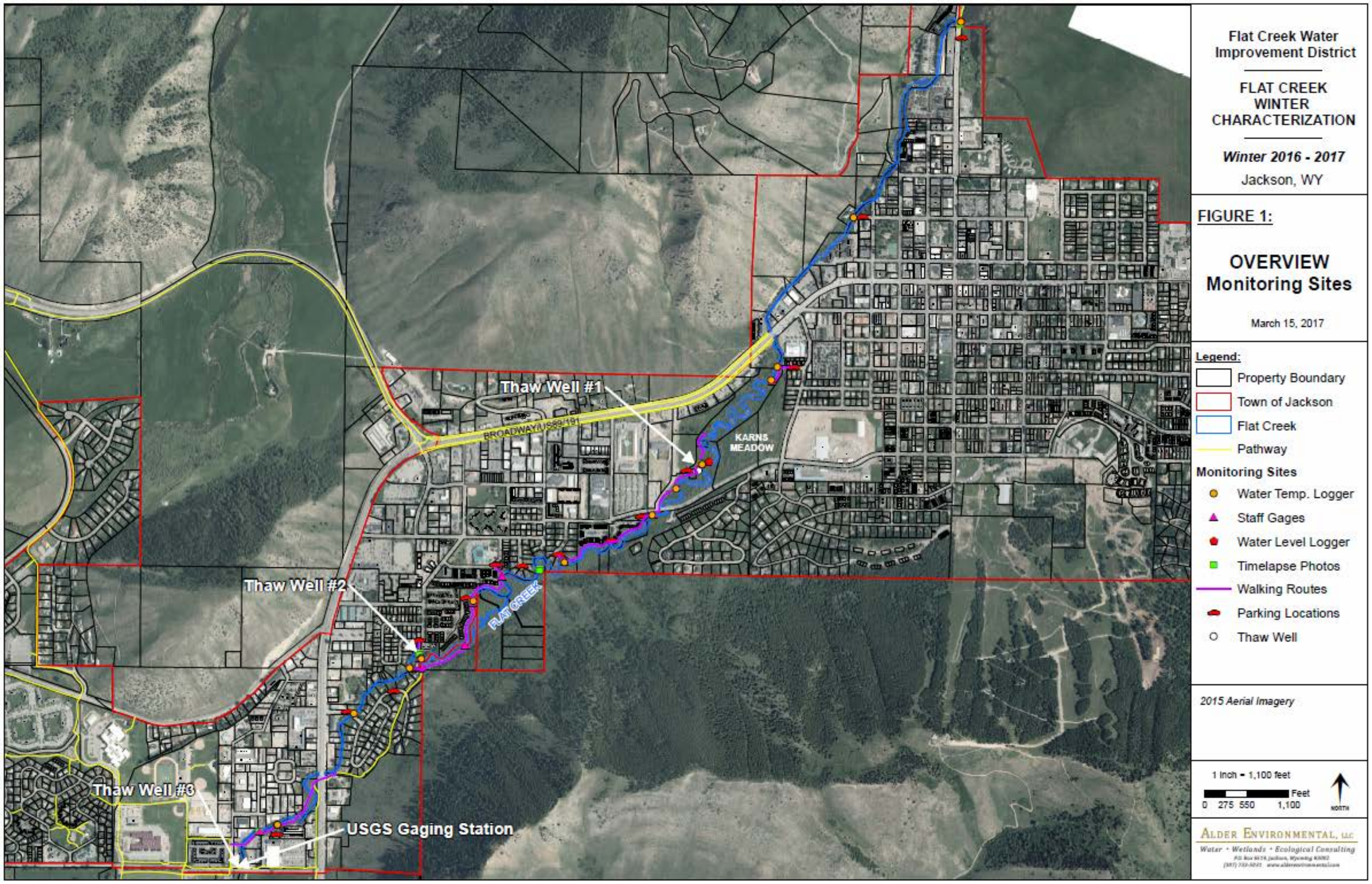

Figure 2. Overview of monitoring sites along Flat Creek during the 2016-2017 ice season. From Alder Environmental (2017).

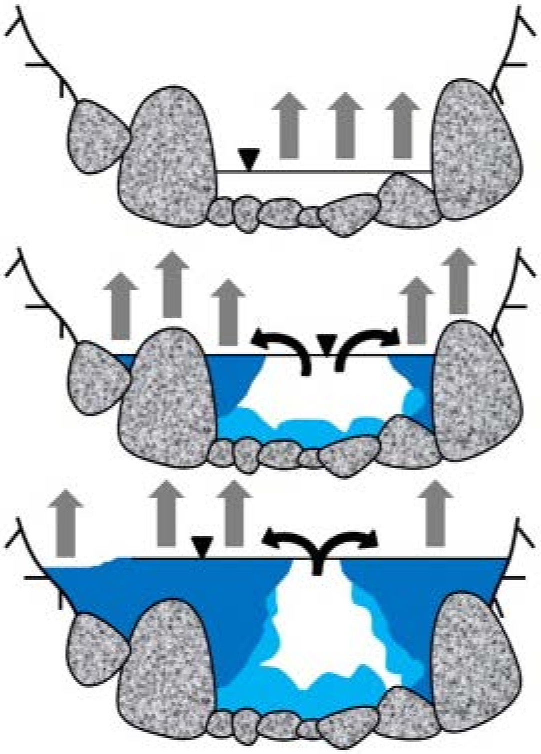

Figure 3. Shown here (from top to bottom) is the accumulation of ice formed upstream of an ice dam where water is constantly flooding newly-frozen ice surfaces. The upward pointing gray arrows represent heat loss from the stream to the atmosphere and the inverted triangle represents the water surface.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

Figure 4. A breached, 1-m-high ice dam on Flat Creek on February 4, 2016. The water level upstream has dropped, leaving a suspended ice cover. Flooding is localized upstream of the ice dam, with water levels varying by several feet over distances of a few hundred feet horizontally along the creek. This ice dam formed on a rock weir installed to mitigate ice-related flooding and improve in-stream habitat. Similar dams are common throughout the 6 km study reach during winter.

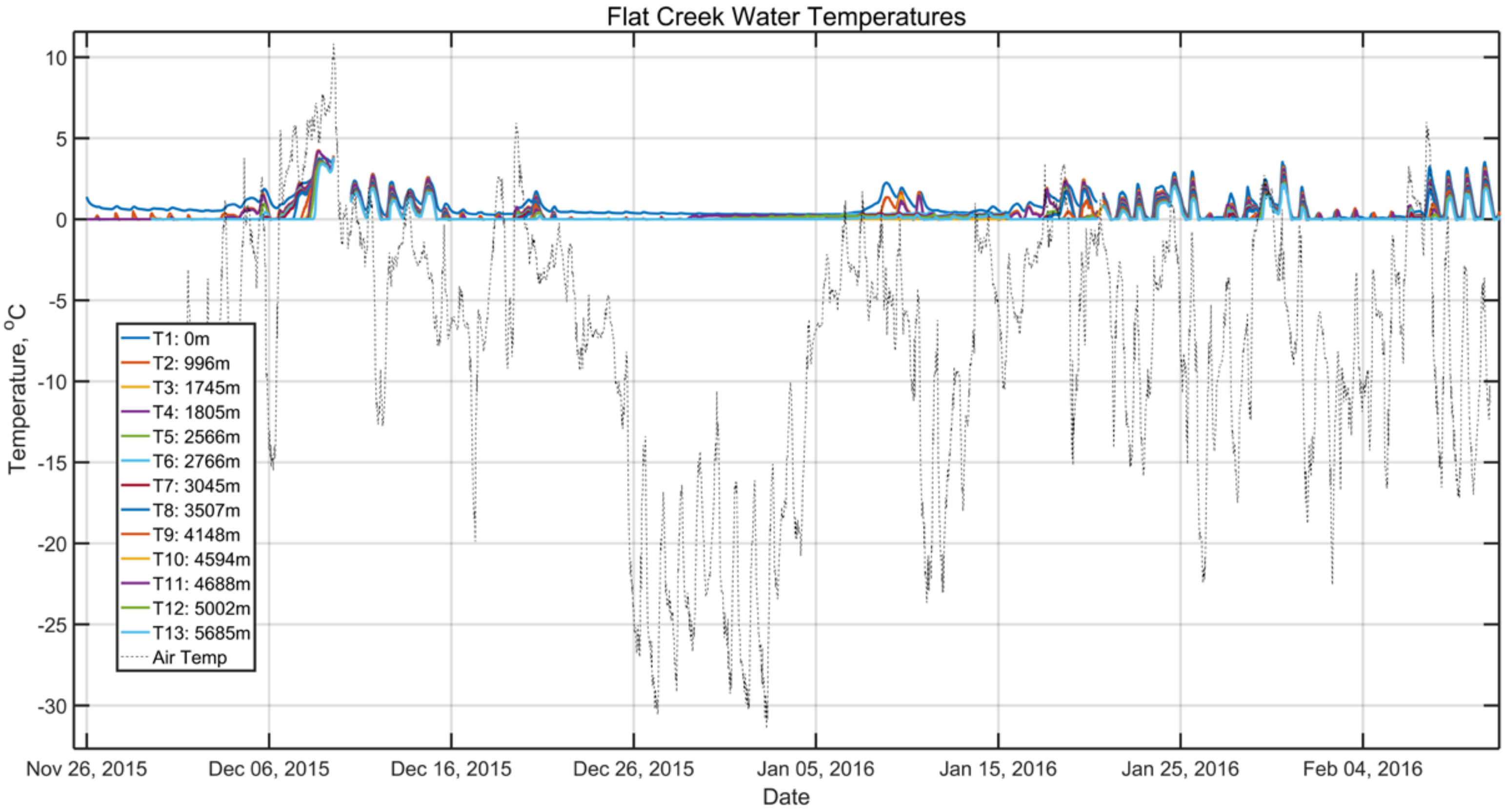

Figure 5. Water and air temperatures along Flat Creek during winter 2015-2016. Water temperatures correlate with air temperatures on daily and longer cycles. When air temperatures rose above -5 °C, all water temperature records show daily warming trends, often followed by nighttime supercooling events. The numbers in the figure key are distances in meters downstream from temperature logging station T1 (Table 2).

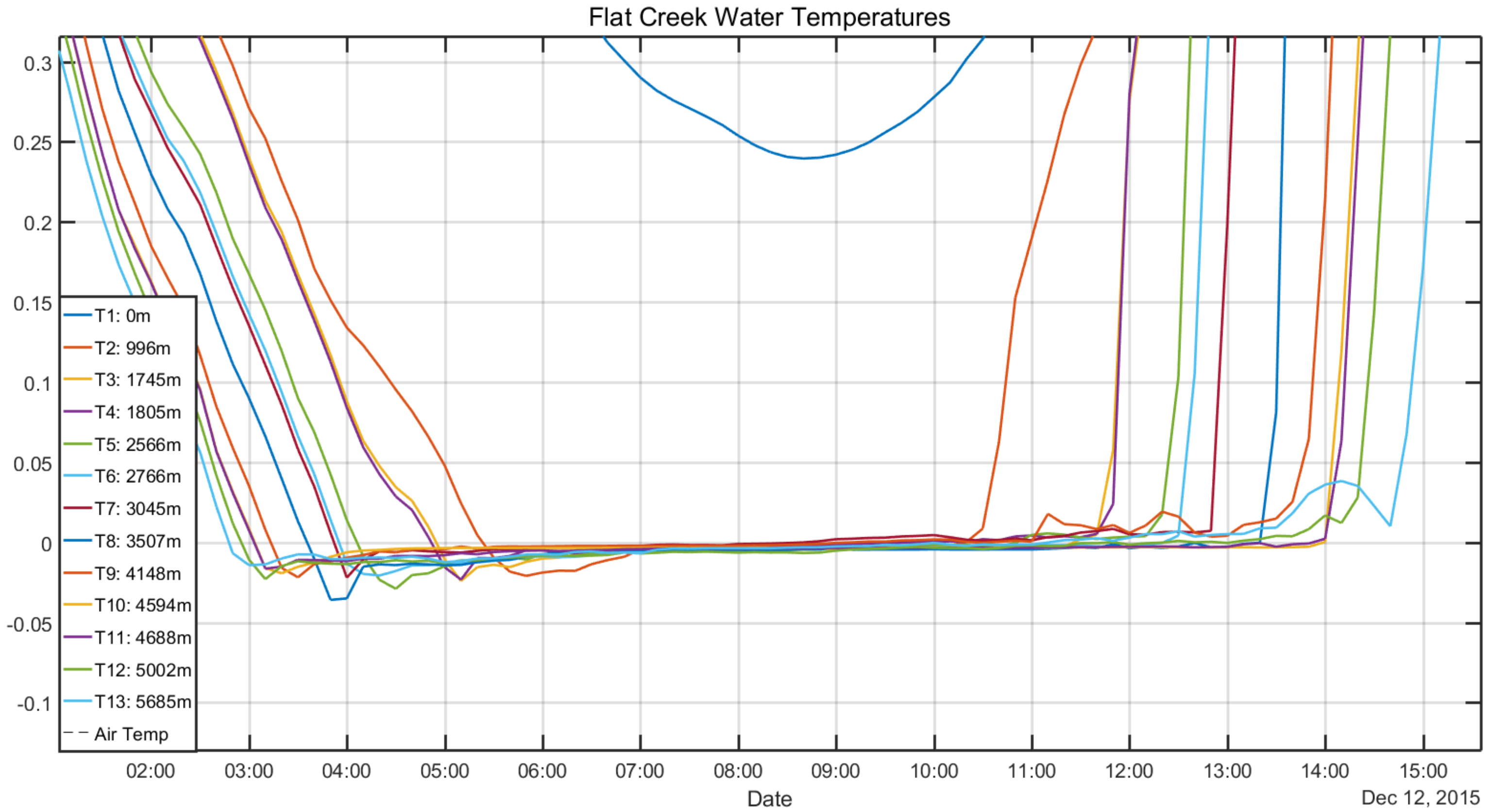

Figure 6. Fourteen-hour record of water temperatures on December 12, 2015 showing the supercooling front advancing upstream from T13 to T2, a distance of 4,689 m, in about 5 hours. Water along the entire reach rose to the freezing point by 9 AM. This record suggests that frazil and derivative ice types formed for about 6 hours at T13, but only for 3 hours at T2. The water at T1 never supercooled. The temperature rise during the day released, and probably melted, any attached anchor ice. The minimum air temperature this day was -12.6 ^{o}C at 06:00, air temperature then rose to a high of -2 ^{o}C at 14:30. This “supercooling zipper effect” of the supercooling front migrating upstream during the night, with a subsequent warm water front migrating downstream during the day, was common on days when air temperatures rose above -5^{o}C.

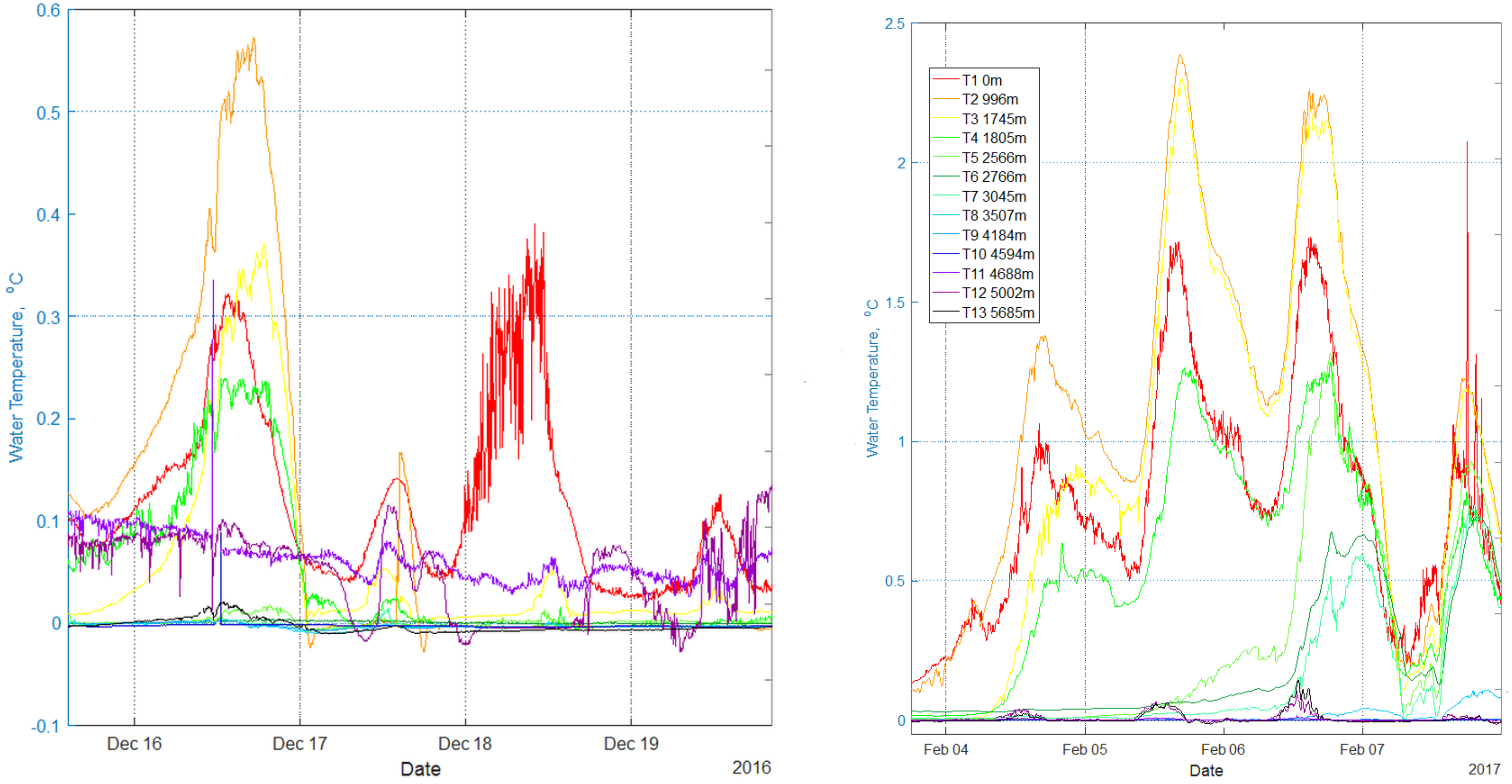

Figure 7. Two examples of temperatures at stations T2 and T3 rising to higher daytime temperatures than T1. This suggests a heat source entering the stream between T1 and T2. This heat source could be from surface runoff or a spring. Note scale difference on the two examples. Thaw well #2 was on from December 14 thorugh 28, its effect is cleary apparent in the T 11 and T12 temperature records in the left pannel, which stay well above freezing through the majority of this period, but don't undergo the daytime temperature spikes seen in T1, T2, and T3. T13 shows evidence of both warming and supercooling (with associated frazil formation) during the period the thaw well was operated.

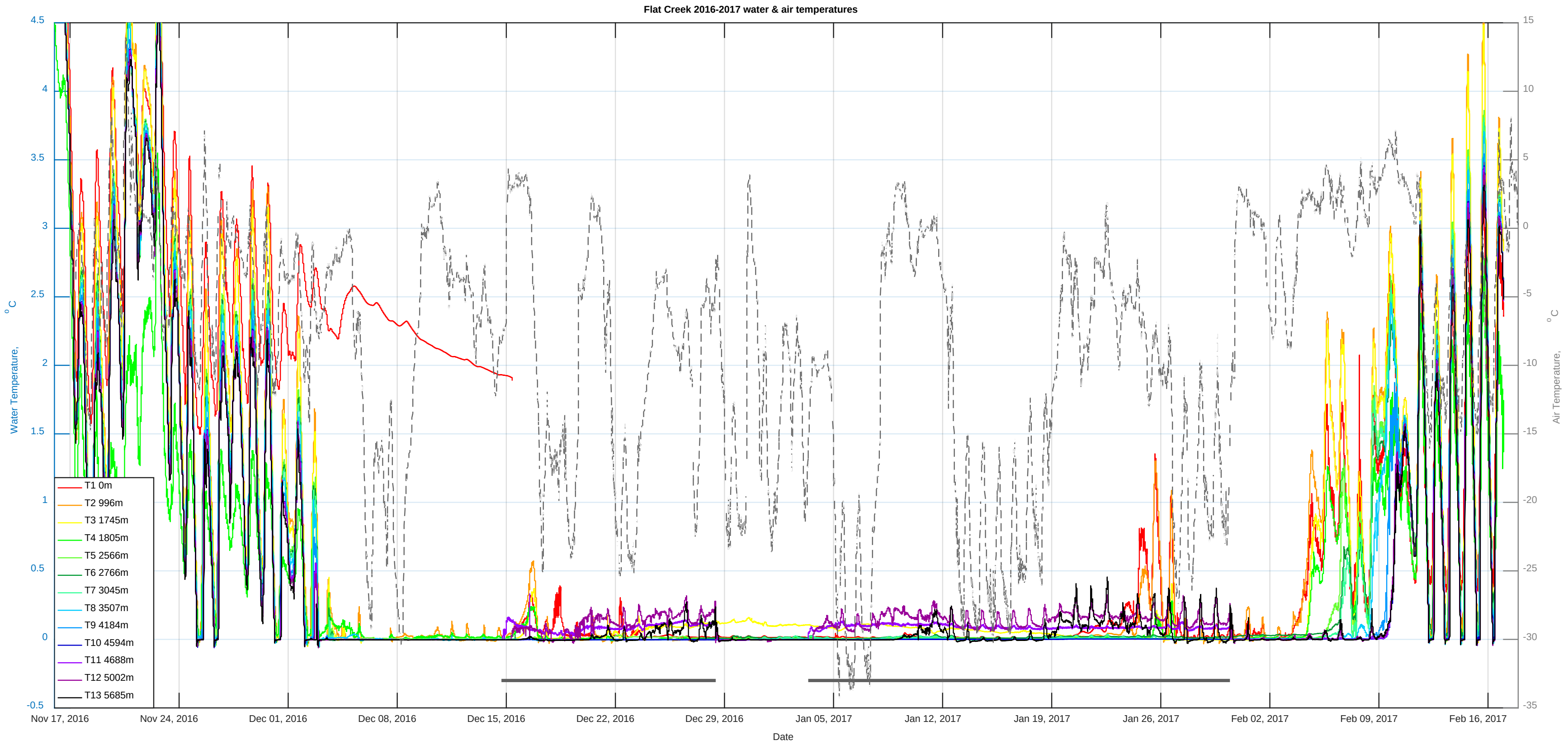

Figure 8. Water temperatures measured at 13 stations along Flat Creek through Jackson during the 2016-2017 winter with superimposed air temperature (right axis). The solid gray horizontal lines indicate times when thaw well 2 was turned on. The effect of the thaw well is seen in the T11, T12, and T13 temperature stations. This record is similar to the 2015-2016 record, with evidence of open water shown by positive daytime water temperatures and supercooling events during cold nights. There are also indications of warm-water input from various locations along the stream throughout the winter.

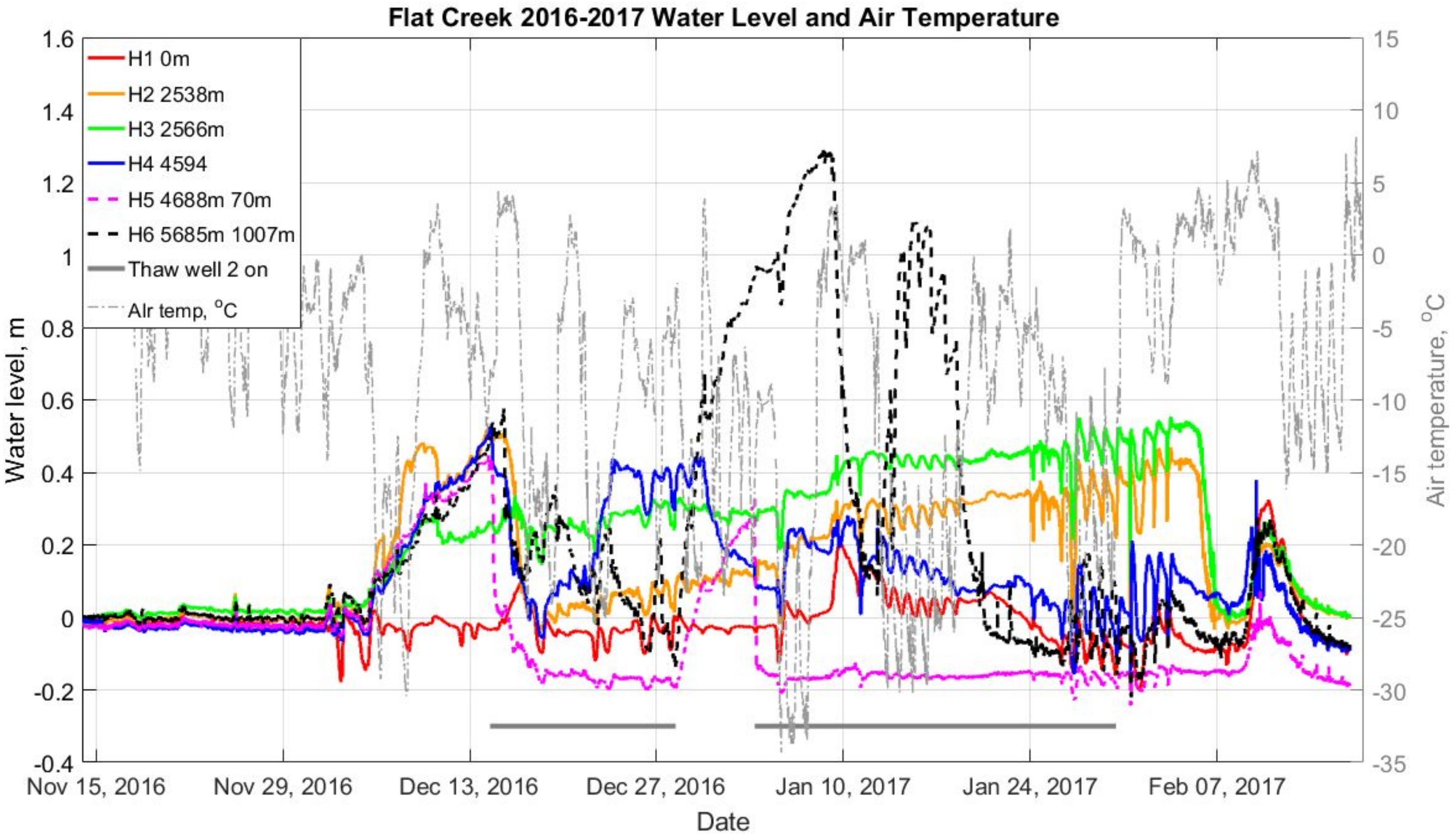

Figure 9. Water levels over the ~6 km study reach through Jackson with air temperature. The horizontal grey bars represent periods when thaw well #2 was operational. Key shows water level number (H#), distance downstream from H1 to instrument, and for H5 and H6, distance downstream from thaw well #2. Water levels are relative, with the zero for each instrument set to the level at 5 PM on November 17, 2016. Each instrument station cross section is different, so changes in water discharge will not change stage by the same amount at each station. Water level and water temperature sensors were co-located at each station except H2, which is located 28 m upstream of H3.