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Fire and ice: Winter flooding in a Southern Rocky Mountain stream after a wildfire

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ABSTRACT

We observed a low-discharge flooding phenomenon on Little Beaver Creek, a tributary to the Cache la Poudre River in the Southern Rocky Mountains of Colorado, USA. Ice ranging in thickness from a few centimeters to 0.5 m occupied a large volume of the channel, forcing flows out of its banks. On two occasions, multiple consecutive days of uncharacteristically warm weather caused a spike in snowmelt, and bankfull stage was surpassed 60 days before peak runoff. The flow events occurred in late winter, six months after a wildfire had burned a large portion of the watershed at medium-to-high severity. Ash and other organic materials were mobilized during the overbank flows, and we observed evidence of recent ash deposition in the floodplain and high ash concentrations in the channel. During the same time period, camera footage captured the formation and collapse of a large accumulation of ice and snow at a log jam. Because climate change projections and recent observations indicate higher variability in weather patterns, wildfire regime, and precipitation events, winter flooding associated with ice, although not widely documented in small mountain streams, may become more common. Flooding and subsequent deposition of ash and other sediment can disrupt fluvial processes, impair the local biotic community, cause property damage, and impact drinking water sources.

1. Introduction

River ice occurs in a variety of river environments from large, low gradient rivers to small, steep mountain streams (Yang et al., 2020). Different processes lead to a range of ice morphologies (Turcotte and Morse, 2013), including anchor ice, surface ice, and ice dams. Anchor ice commonly forms when there is a combination of super cooled water (<0 °C) and high turbulence (Stickler and Alfredsen, 2009). Small frazil ice particles develop under these conditions and are transported toward the bed, where they adhere to sediment or other substrate, becoming anchor ice. With consistent exposure to below freezing temperatures, anchor ice grows and may cover large areas of the bed and occupy significant portions of the channel cross-sectional area. Anchor ice can affect habitat for native trout and other aquatic organisms (Harper and Farag, 2004; Lindstrom and Hubert, 2004). Hyporheic flow and other surface-groundwater interactions can also increase or decrease stream temperatures (Meisner et al., 1988) affecting anchor ice formation conditions.

A process known as rafting occurs when solar radiation and increasing air temperatures contribute to ice releasing, causing it to float to the surface. Ice rafting can cause significant sediment transport and change to bed topography when sediment particles remain encased as the ice floats to the surface and moves downstream (Kalke et al, 2015; Kempema and Ettema, 2011; Tremblay et al., 2014; Turcotte et al., 2017). Ice rafting has even been documented to transport particles larger than those mobilized during spring runoff in a river in the Southern Rocky Mountains (Kempema and Ettema, 2011).

The dynamics of surface ice can be equally complex. Aufeis, for example, develops as sheet-like masses of layered ice that form during the winter from successive flows of water on top of the cover ice (Morse and Wolfe, 2015). The overtopping water may come from perennial groundwater discharge at springs and aufeis forms where river base flow is sufficient to preclude winter freezing to the streambed (Clark and Lauriol, 1997).

Ice dams are likely to occur in steep channels (>0.3 %) and are a stage of suspended ice cover formation (Turcotte and Morse, 2013). The accumulation and emergence of anchor ice is followed by icing, as water flows over the emerged surface, and can grow quickly, choking the channel (Dubé et al., 2014; Turcotte et al., 2013). Though not limited to the occurrence at specific features within channels, they often do occur

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at gradient changes, riffles, around boulders, and at log jams. Ice dams can effectively block flow causing a backwater upstream and diverting flows out of the channel. Formation of ice dams is often followed by their breach or collapse as a result of warm air temperature. Ice dam failure releases the backwater and produces a sharp increase in discharge downstream and can cause flooding (Costa and Schuster, 1988a).

River ice can affect local stage-discharge relations by altering the quantity of river flow via multiple mechanisms whereby stage increases for a given discharge (Prowse and Beltaos, 2002; Ettema and Kepemema, 2012): cover ice that facilitates rising stage produced by a backwater; storage of water in river ice, with slow abstraction during freeze-over and rapid resupply during ice break-up; altered groundwater inflow caused by decreased hydraulic gradient (Weber et al., 2013); and decreased flow area in an ice-choked channel (Daly et al., 2019). Local stage-discharge relations in ice-free reaches may also be affected by upstream ice conditions. Large ice formations damming flow can produce a dramatic decrease in discharge downstream (Moore et al., 2002; Prowse and Carter, 2002; Shen and Liu, 2003). Water storage in ice-covered rivers can also result in temporal, winter-long discontinuities between stage and discharge, with annual peak stage during break-up and annual peak flow later in the runoff season (Prowse and Ferrick, 2002). Ice processes can generate the annual peak stage in some rivers, despite a discharge that is significantly lower than the maximum annual flow.

If surface ice breaks up abruptly rather than melting and thinning gradually, large blocks of ice can move downstream in congested transport and create temporary dams and associated outburst floods typically in medium and large rivers (Beltaos, 2007; Costa and Schuster, 1988b; Rokaya et al., 2018a). The abrasive effects of ice and ice jams and the hydraulic force of breakout floods can damage infrastructure and water distribution systems (Burrell et al., 2021; Gebre et al., 2013; Richard and Morse, 2008).

Finally, both anchor and cover ice influence winter habitat suitability for salmonids (Harper and Farag, 2004; Huusko et al., 2007; Lindstrom and Hubert, 2004; Prowse, 2001a, 2001b). Despite the relative importance of ice as a fundamental element of cold and temperate region hydrology, it is underrepresented in fluvial hydrology literature and may not be appropriately recognized in some river process studies.

Climate change is affecting the river ice regime of cold regions (Beltaos and Prowse, 2009; Huokuna et al., 2022; Rokaya et al., 2018b; Turcotte et al., 2019). There are many documented hydrologic responses to climate change that could affect the formation of river ice including the following: the timing of seasonal weather patterns and changes in air temperature are predicted to continue to shift (Stewart et al., 2004); stream temperature is predicted to rise (Leppi et al., 2012); the risk of rain on snow-caused flooding is predicted to increase (Musselman et al., 2018); and within the Rocky Mountains, the number of cold days is predicted to decrease (Stewart et al., 2004), among others. In western North America, snowmelt generated peak runoff is predicted to occur earlier in the year, temperatures are predicted to rise, and precipitation patterns are uncertain (Stewart et al., 2004). Stream flow metrics that define critical ecological thresholds such as baseflow and bankfull flow continue to change in ways that must be investigated to understand how watersheds will respond (Hauer et al., 1997). If river ice associated flood frequency and annual hydrograph characteristics are altered as a result of climate change, aquatic organism habitat may be negatively impacted.

Anthropogenic climate change and forest management practices have also caused a dramatic change in wildfire regimes in montane regions of western North America where continued change is predicted (Westerling and Bryant, 2008). In 2020, the western United States experienced one of the most catastrophic wildfire seasons on record with roughly 4 million ha burned (National Interagency Fire Center, 2021), and many of the wildfires occurred in the Cascade, Sierra Nevada, and Rocky Mountain Ranges. In the years after wildfires, rainfall and snowmelt runoff are magnified because of a change in hillslope properties and decreased canopy cover (Moody and Martin, 2001). Surface and groundwater interaction becomes disconnected and extreme flooding and debris flows are more likely (Neary et al., 2003). Common characteristics of mid-to high-elevation streams in the Rocky Mountains are high bed gradient, coarse bed material (Wohl and Merritt, 2005), and seasonal weather with winter months that experience below freezing temperatures. This environment is suitable for the formation of ice. The ice classification model by Turcotte and Morse (2013) suggests that predicted ice types in this environment include partial ice shells and suspended ice cover.

We are unaware of any study that has documented and analyzed the compounded effects of flooding over ice in the years after a wildfire. We observed several conditions leading to winter floods in a burned mountain stream: erratic weather conditions leading to the formation and break up of channel-choking ice; reduced canopy cover exposing snow to high solar radiation and ambient air temperature causing early snowmelt; and the development of ice dams at log jams. The observations summarized in this paper suggest that ice may be an important driver of overbank flows and sediment transport dynamics, particularly in mountain streams that experience large inputs of sediment or post-wildfire particulate organic matter. Here, we describe a series of hydrologic and geomorphic responses driven by ice formation and snow accumulation on Little Beaver Creek, Colorado, USA.

2. Study area

Little Beaver Creek (LBC) is a tributary of the Cache la Poudre River in northern Colorado, USA (Fig. 1). The watershed drains 38.5 km^2, ranges in elevation from 2280 to 3653 m, and has a flow regime characteristic of the Southern Rocky Mountains with high spring runoff and low baseflow during the autumn and winter. Summer flows are punctuated by occasional peaks caused by high intensity rainfall that can exceed discharge from snowmelt runoff. The area experiences a semiarid climate with mean annual precipitation of 52.6 cm and mean annual temperature of 3.3 °C for the period of record from 1990 to 2021 NCEI, 2022). The LBC watershed is underlain by Precambrian-age Silver Plume Granite (Nesse and Braddock, 1989). The active channel at the study site ranges in width from approximately 3 to 10 m. Valley floor width along the creek is mostly laterally confined to no more than a few bankfull widths across, but widens in areas where the gradient drops from roughly 2.5 % to 1 % and channel planform changes from step-pool to pool-riffle with active and abandoned beaver ponds (Ader et al., 2021). The creek averages 1.1 channel-spanning log jams per 100 m of valley length. The channel bed is composed of gravel to cobble material with a median grain size (d_{50}) of 40 mm at the study site.

The upland vegetation in the LBC watershed is primarily composed of mixed-conifer montane forest including Ponderosa pine (*Pinus ponderosa*), Engelmann spruce (*Picea engelmannii*), Douglas fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*). Some conifers are present in the riparian zone, but more common are willows (*Salix* spp.), birch (*Betula* spp.), and alder (*Alnus* spp.).

In 2020, 86 % of the Little Beaver Creek watershed burned at medium or high severity during the Cameron Peak Fire. LBC is the site of a multifaceted research project where the channel response to wildfire is being monitored (Wohl et al., 2022).

3. Methodology

3.1. Flow stage, temperature, and discharge measurements

We recorded flow stage and water temperature data from 8 August 2020 to 17 October 2021 with an Onset HOBO U20L-01 data logger. The logger was fixed to a rebar stake that was anchored to the stream bed. Absolute pressure (kPa) and temperature (°C) were recorded at 30-min intervals. A logger was also installed adjacent to the channel in open air, to correct for atmospheric pressure and measure air temperature. The

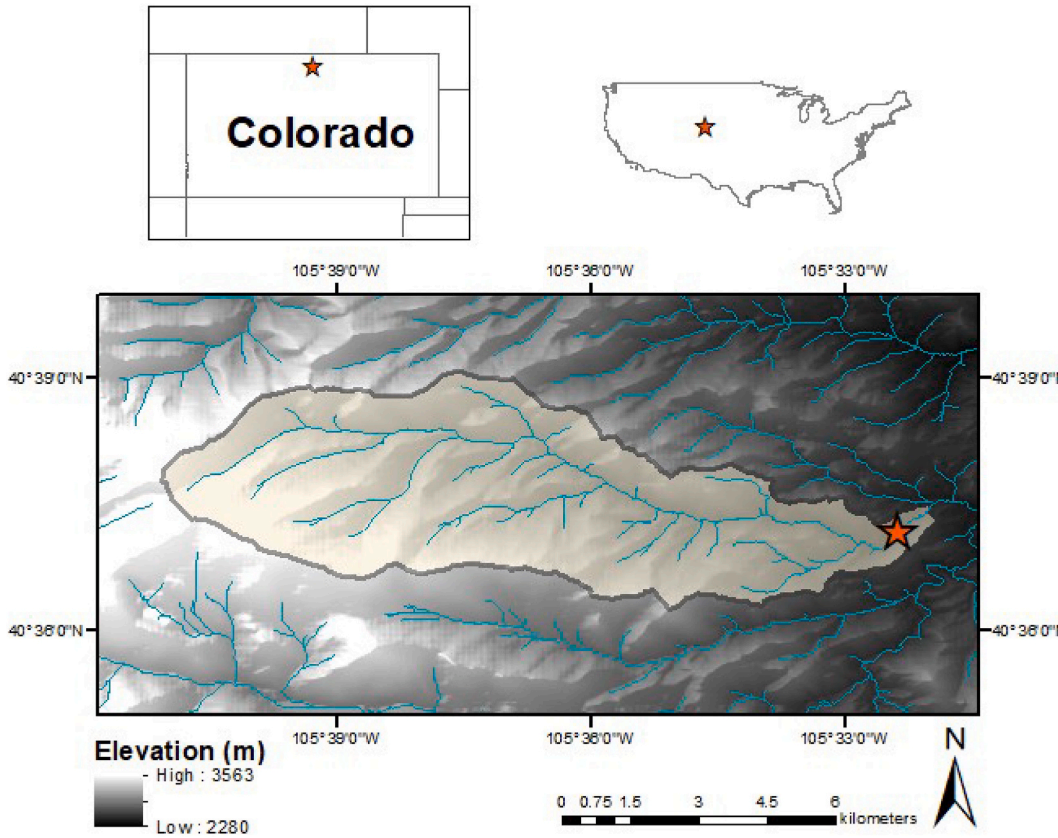

Fig. 1. Little Beaver Creek watershed. The star indicates the location where channel cross section measurements were made and flow over ice conditions measured.

resulting gauge pressure was converted to stage (cm) (Fig. 2) and discharge (m^3/s).

We measured discharge using a FlowTracker2 acoustic Doppler velocimeter (ADV) at six different flow rates from August 2020 to October 2021. The flow rate measurements range from 0.08 to 2.9 m^3/s. All flow rate and corresponding stage measurements were compared on a log-log scale to determine the stage-discharge relationship using a linear least squares regression. With this regression, we were then able

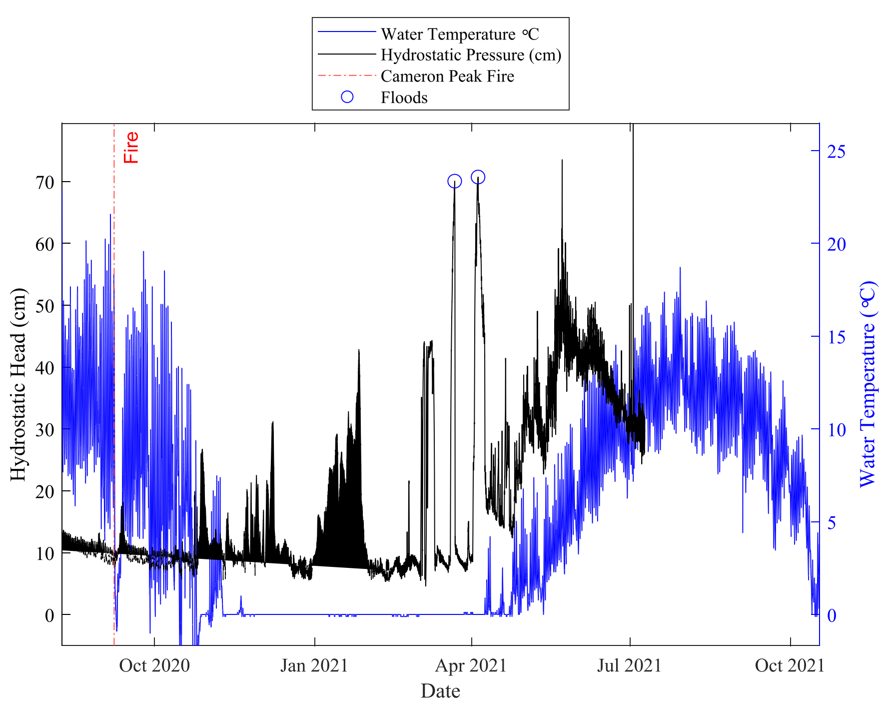

Fig. 2. Little Beaver Creek hydrograph. The dashed vertical line marks the date when the Cameron Peak Fire burned through the site. Flooding over ice occurred at the pressure sensor on 22 March and 4 April and is noted by the blue circles.

to determine the discharge for all instantaneous pressure measurements and develop a time series of discharge outside of the winter months the channel was free of ice. The discharge measurements and rating curve developed for ice-free conditions were developed as reference but are not directly compared with the winter hydrograph.

3.2. Field visit

We first observed the formation of ice at LBC on 17 November 2020. Cover ice was present in areas of low velocity, such as pools. The purpose of this visit was to observe the channel immediately after the wildfire. At this time, flow was low and clear, and we did not observe ash or particulate organic matter transport.

On 7 April 2021, following two floods that occurred during the periods of 20–22 March 2021 and 2–6 April 2021, we visited the site to collect pressure and temperature data from previously installed data loggers. Flow in LBC was opaque and had a sludge-like consistency with a high concentration of ash and small particles of charcoal and organic matter. Ice was not visible through the sludge and we did not discover it until wading into the stream. We hammered a piece of rebar through the ice at three locations along the cross section at the data logger and observed that the ice was frozen to the bed. The ice was very hard, smooth, and dense, and may have developed through various ice formation processes. Our observations lead us to believe the ice was surface ice, frozen to the bed and banks and submerged by snowmelt-generated runoff. We were unable to find the pressure sensor during this visit because it was encased in ice. We took approximate flow and ice depth measurements at the cross section. The ice surface appeared to be parallel with the water surface, indicating that its growth at this cross section had been primarily in the upward direction characteristic of aufeis when water repeatedly floods newly-frozen surfaces (Daly et al., 2019; Kempema et al., 2017; Turcotte et al., 2013). See Fig. S3 for a photo of the stream condition at this visit.

3.3. Total station survey

After the channel ice had melted, we used a Leica TC307 total station theodolite to survey the active channel geometry at the data logger (Fig. 3). We stretched a survey tape across the channel and noted the station of the reflective prism along the tape as we measured relative elevation with the theodolite. We recorded measurements at a 9 m wide cross section at approximately 0.5–1 m increments and surveyed at higher resolution where there was sharp change in bed topography. We compared these survey data with channel cross-section geometry information collected during prior discharge measurements to verify that minimal deposition <3 cm in height occurred near the left bank because of ice rafting or other sediment transport processes.

3.4. Photographic monitoring

We monitored channel conditions with a Bushnell Trophy Cam programmed to collect photos at hourly intervals or when a motion sensor was triggered. The camera had been installed to monitor post-fire channel change at a large wood jam but also captured the process of ice dam formation and failure immediately upstream from the jam. It was aimed at a water level gage in the channel approximately 10 m away. The game camera was located near the downstream extent of the burn area boundary in the LBC watershed. The photographs taken by this camera provide insight into the nature of ice dam formation and breakup, the turbidity levels during high flows, and the movement of logs within the jam during later phases of the 2021 runoff season.

4. Results

4.1. Hydrology and flow stage

From November 2020 to early April 2021, temperature measured by the stream sensor was 0 °C (Fig. 2). During this period, the pressure reading and calculated hydrostatic head were likely also affected by the formation of ice, snow accumulation, and melt represented by multiple stage increases >10 cm from late October through early March. Despite the uncertainty of flow depth during the period of below freezing temperatures, the data still provide meaningful information about the mechanisms responsible for winter floods. The data from the pressure sensor also provide a relative magnitude in comparison to spring runoff peak flow depth, which occurred on 25 May 2021, and summertime flash floods that resulted from post-fire hydrology and localized high intensity rainfall.

The largest flow stages that caused overbank flows during 2020–2021 were 70.1 cm on 22 March 2021, 70.7 cm on 4 April 2021, 73.7 cm on 25 May 2021, 79.4 cm on 2 July 2021, and 71.6 cm on 3 September 2021. Other spikes in hydrostatic head were observed during the months from November 2020 to April 2021 (Fig. 2). However, when compared with the game camera footage, it appears that the increased

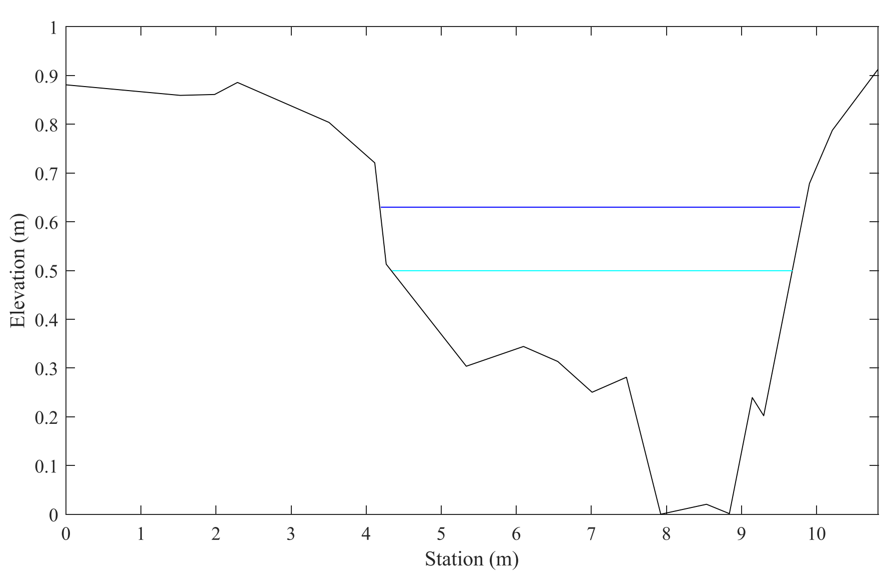

Fig. 3. Channel cross-section geometry and approximate water surface elevation (dark blue line) over measured anchor ice thickness (light blue line) on 7 April, day(s) after a large flood over ice event occurred. The anchor ice occupied approximately 30 % of the channel cross-sectional area.

pressure was not caused by depth of flow, but likely accumulated snow.

4.2. Hydraulics

The total channel cross-sectional area is approximately 3.2 m^2. On the date of the site visit, ice occupied nearly all of the lower 50 cm of the water column, and roughly 1.1 m^2 of channel cross-sectional area, resulting in a 34 % reduction of available channel flow area (Fig. 3). The ice in the channel was likely surface ice fused to the bed and banks and submerged by increased flow. Although it is difficult to estimate the roughness in the channel during the floods, the ice surface was hard and smooth at the location of the pressure sensor and in many places throughout the channel. Most studies investigating the hydraulic roughness of river ice are focused on the on the underside of ice cover and may neglect the hydraulic interaction of flow over the ice surface during floods. Laboratory experiments by Kerr et al. (2002) and a summary of river ice studies by Li (2012) suggest that anchor ice can produce both higher and lower roughness values than an ice-free bed. Kerr et al. (2002) show that as ice forms on gravel beds, it initially goes through a phase where roughness increases sharply, then follows a smoothing trend as bed ice coverage transitions from partial to full. As anchor ice continues to increase in thickness, roughness values continue to decrease. Kerr et al. (2002) reported Manning's roughness values as low as 0.02 for a fully covered gravel-bedded flume. Although we believe that anchor ice was not the primary morphology in the channel during the floods at LBC, these studies provide an interesting comparison that show potential ranges of hydraulic roughness values.

While wading in Little Beaver Creek to investigate ice thickness and morphology, the ice surface was extremely smooth with little surface topography. LBC is normally a hydraulically rough channel, with a cobble bed, steep slope, and dense vegetation along the channel margins. Using the surveyed channel cross-section geometry and flow measurements during the summer months, we calculated Manning's roughness values (n) in the range of 0.06–0.07 for flows from 1.2 to 2.38 m^3/s using the Manning equation for uniform flow: $= \left(AR^{\frac{2}{3}}\sqrt{S}\right)\Big/Q$, where A is the cross-sectional flow area, R is the hydraulic radius, S is the channel slope, and Q is the channel discharge. A simple visual observation of the submerged ice and comparison with the no-ice cobble bedded condition leads us to believe that local bed roughness could have been substantially lower during the winter floods at many locations. However, we assume that at the reach scale, conveyance likely decreased as a result of channel choking snow and ice conditions.

4.3. Ice formation

Photos from the game camera show the sequence of events that led to the accumulation of snow and ice and its collapse during 4–7 April 2020 (see Fig. 4 and supplemental files). One surprising observation from the photos shows how rapidly flow and ice and snow conditions changed. The game camera was pointed at a 1.5 m tall channel-spanning large wood jam 0.5 km upstream of the cross section where channel geometry and flow depth were monitored. During February and March, 1–2 m of snow and ice accumulated on the log jam and upstream channel surface. At 0900 h on 4 April 2021 (Fig. 4a) there was no visible flow over ice. By 1330 h that same day (Fig. 4b), flow had backed up and risen nearly to the crest of the ice and snow on the log jam, remaining elevated until 1500. At 1520 the stage immediately upstream from the jam began to recede and the water surface exhibited turbulent flow characteristics that suggest rapid flow, presumably beneath the log jam. The front of the ice collapsed just upstream from log jam by 1605, creating a 30–40 cm tall thermally-eroded ice surface that grew more exposed as stage fell until the water surface froze over during the night (between 2000 and 0500 the next morning). During a period of 9 h on 5 April (0600 to

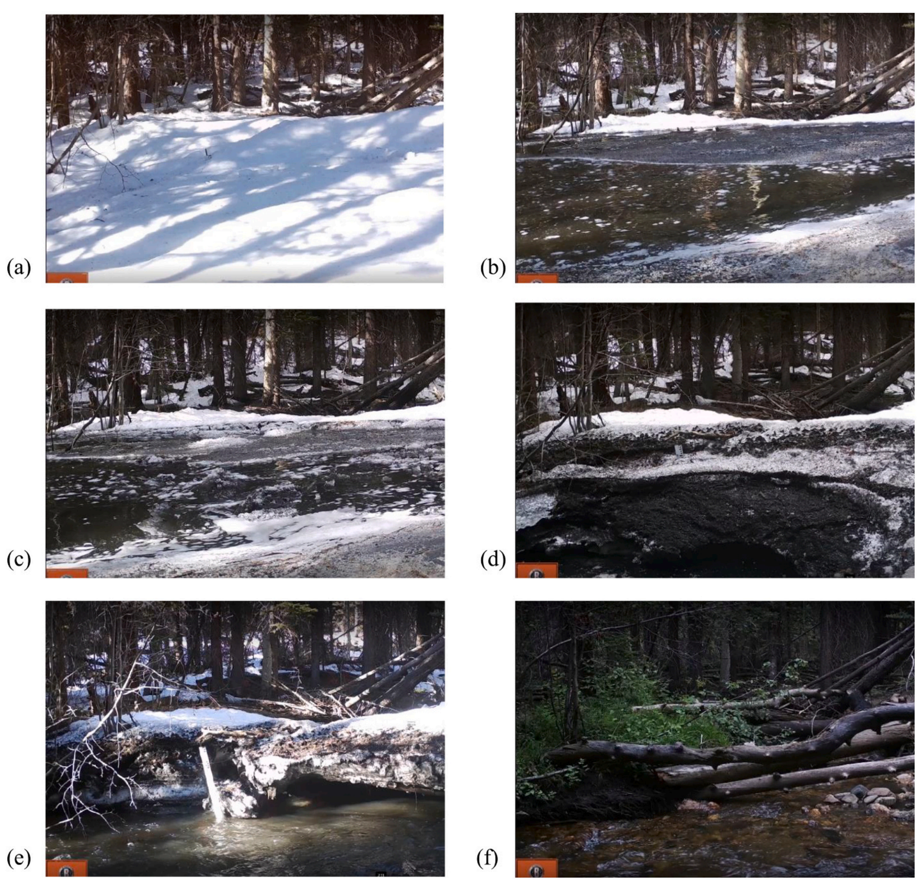

Fig. 4. Game camera images where a log jam was being monitored. Flow direction is left to right. An ice dam formed at this location and breached on 4 April 2021. (a) 0900 4 April 2021, morning of flood over ice. (b) 1500 4 April 2021, during flood over ice. Ponded flow is present upstream of ice dam. (c) 1523 4 April 2021, after ice dam failure, small standing waves present indicate increased velocity. (d) 6 April 2021 fine particulate organic matter and debris cover the collapsed ice dam as stage receded. (e) 8 April 2021, four days after flood. Ice remains perched on log jam with flow passing beneath. (f) August 2021, baseflow conditions.

1500), the water surface upstream from the log jam rose, submerging the ice surface by 1500 h. The water receded again that evening but did not freeze over during the night. Peak stage declined steadily during successive diurnal cycles until the ice cover upstream from the jam largely collapsed on 7 April (ice and snow cover remained on the jam itself). By 8 April, stage is so low that the lower side of the ice bridge on the jam is clearly visible, with water flowing beneath the bridge. Ice did not cover the channel again, despite repeated snowfalls and formation of marginal ice during the remainder of April.

It is possible that the rapid accumulation of flow at the jam on 4 April was the result of another ice dam breach farther upstream triggered by snowmelt runoff. In the days following the ice breach, flows dropped rapidly following the trend of ambient air temperature. As flows receded, ash fell out of suspension, covering the ice and snow still perched atop the remaining ice and log structure (Fig. 4c).

5. Discussion

5.1. Channel hydraulics

Using measurements taken in the field, we determined that the accumulation of ice occupied 34 % of cross-sectional area at the data logger. At the ice dam upstream, it appears that a much greater portion of the total channel cross section was occupied by snow and ice (nearly 100 %). If average cross-sectional flow velocity remained the same, or if channel roughness was unchanged from no-ice to iced conditions, less discharge would be needed to reach bankfull stage. However, because ice morphology has a range of associated roughness (similar to a sand bedded river with ripples, dunes, etc.), its state can largely impact flow conveyance such that a channel with its bed covered in low roughness ice accommodates flows that would cause flooding under no-ice conditions although generally ice processes increase roughness and reduce conveyance.

Although we did not measure flow or calculate channel roughness while ice occupied the channel, we can simulate the effects of a range of roughness values and resulting flow rates necessary to produce flooding. The flume experiment performed by Kerr et al. (2002) had a straight channel with plastic walls that eliminated roughness caused by planform and bank morphology/material, so changes in Manning's n were only attributed to grain roughness. To convey the no-ice, bankfull, volumetric flow rate of 2.5 m^3/s at LBC, total roughness would have to decrease from our measured average of 0.073 to an unrealistic 0.039. This far exceeds the 0.02 decrease in Manning's n from bare cobbles to cobbles covered in thick anchor ice (Kerr et al., 2002). We infer that during the floods on 22 March and 4 April 2021, flow rate was in fact less than no-ice bankfull discharge. If bed roughness had decreased by 0.02 with fully formed ice, similar to the conditions observed by Kerr et al. (2002), the total flow that could pass is 2.0 m^3/s, still much lower than bankfull flow. Thus, we can conclude that, under observed conditions, channel volume occupied by ice overcame the conditions of decreased roughness to cause flooding.

5.2. Broader hydrologic response

The post-fire ice-induced flooding that occurred at LBC is an event that has rarely been recorded in small streams at temperate latitudes, prompting several questions including: Have similar post-fire phenomena occurred elsewhere in western North America at a more catastrophic scale? Was this an isolated occurrence in the larger Cache la Poudre River watershed? What is the probability that such flooding will recur at the same site during the winter of 2022?

Many flow diversions exist on the Cache la Poudre River from the confluence of LBC to the nearest downstream gauging station. Consequently, any of the relatively small fluctuations in flow observed at USGS gages downstream of LBC (e.g., station 06752260) cannot be accurately linked to the flooding on 22 March and 4 April 2021.

Roaring Creek, also a tributary of the Cache la Poudre River at similar elevation to LBC, is another site with ongoing flow and stream temperature monitoring. On 22 March and 4 April 2021, flow spikes similar in relative magnitude to those in the LBC hydrograph occurred (Fig. S1). A significant portion of the Roaring Creek watershed also burned at high severity in the Cameron Peak Fire. An air temperature sensor was installed at the Roaring Creek monitoring site prior to the fire but burned and could not be recovered.

Average daily temperature on 3 April 2021, the day prior to flooding at LBC, was 10.0 °C warmer than the historical average. This high temperature likely extended over the entire Cache la Poudre River watershed. With such a dramatic response observed at two significant contributing watersheds in the Cache la Poudre River drainage, and unseasonably high temperatures observed at multiple locations, the lack of a dramatic response on the main stem of the Poudre River is interesting. The location of LBC within the greater Cameron Peak Burn scar is at a relatively low elevation. High temperatures observed there may have triggered the early snowmelt runoff, while other catchments that burned at high severity in the upper watershed may not have experienced air temperature sufficient to trigger floods at the scale that would be measureable in the main stem Poudre.

5.3. Mechanisms for flooding

We propose that the mechanisms responsible for the early season flooding at LBC are three-fold: (1) post-fire processes magnified snowmelt and runoff as a result of canopy cover loss and increased soil hydrophobicity; (2) air temperature fluctuating from many degrees below freezing to many degrees above freezing followed by a sustained warm spell triggered a large freeze-thaw event; and (3) large wood jams and accumulated sediment acted as structures on which ice could form and subsequently collapse, causing flooding. These conditions are distinctive but could certainly occur repeatedly in other forested and burned mountain watershed, but we are not aware of a similar event that has been documented in the literature.

5.3.1. Role of temperature fluctuations and ice dams

Previous research at Flat Creek, Wyoming and the Rio Blanco Diversion on the White River, Colorado, highlight the potential hydrologic role and associated hazards of large ice dams in flooding at LBC and other streams. At the White River, an ice dam formed atop a diversion structure and low discharge flows were pushed out of the channel flooding adjacent private property (Tuthill, 2008). At Flat Creek, a mountain stream in Jackson, Wyoming, USA, cold temperature has been documented as the main driver of anchor ice formation, constriction of channel flow area, and flooding at very low discharge (Daly, 2005; Kempema et al., 2017). Despite the use of thawing wells and other flood mitigation measures, stream temperature remains low enough that flooding has occurred on multiple occasions at a relatively low discharge. Following observed flooding at Flat Creek in 2005, Kempema et al. (2017) investigated the mechanisms by which flooding occurred at the same site. They describe ice weirs and dams that grow large enough to be exposed to air reaching 1 m in height. A successive breach of the ice dams caused by warm temperatures results in a surge of flow downstream, which can cause property damage in an urbanized area. The conditions observed at Flat Creek provide an interesting comparison to those at LBC.

We found clear evidence that the ice dam collapse captured by the game camera caused a flood pulse at LBC. The maximum flow depth that occurred on 4 April 2021 coincides with the timing of the dam collapse. However, flows remained higher than bankfull stage (~60 cm) at the sensor for another 24 h after this event. The flood that occurred on 22 March 2021 may have been related to an ice dam collapse that occurred between the sensor and the game camera. Although the portion of creek covered by the game camera remains completely snow-covered during this time, a collapse feature approximately 1 m in diameter and with no evidence of animal activity appears in the snow cover between 0800 and 0900 on 21 March, suggesting the potential for underlying changes in the ice cover and stream flow.

Weather patterns in Larimer County, Colorado, where LBC is located, show that in general, air temperature is following a warming trend (NCEI, 2022). However, the average monthly temperatures for March and April 2021 when the flooding occurred were not remarkably high or low. The departure from mean for those months was +0.28 °C. Although Flat Creek experienced flooding because of an extended period of cold temperatures, LBC experienced large fluctuations in daily mean air temperature ranging from −8 °C followed by consecutive days of unusually warm temperatures reaching 7 °C.

In Fig. 5, mean daily air temperature is plotted alongside hydrostatic head. Just prior to the two main floods, mean daily temperature reached at least 5 °C. The drastic swing in air temperature is an unusual occurrence and likely enhanced the ice dam breakup and flooding.

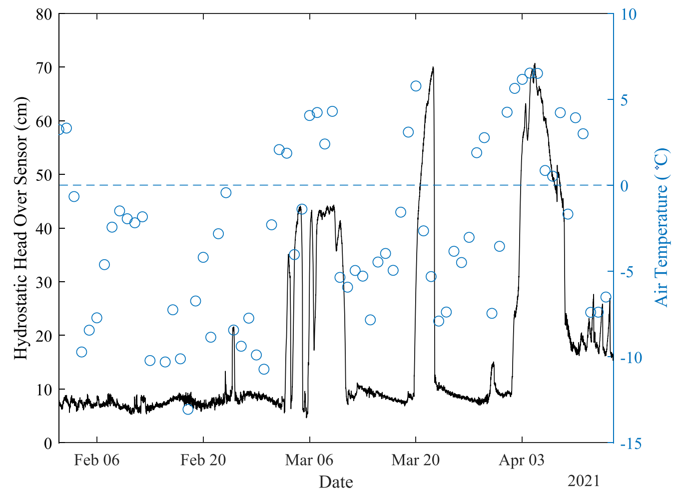

Fig. 5. Hydrostatic head time series at pressure sensor compared to air temperature readings. Leading up to the high flow events on 21 March and 3 April, mean daily air temperature exceeded 6 °C.

5.3.2. *Post-wildfire impact on hydrology*

Soil hydrophobicity and reduced infiltration are often a primary focus when investigating post wildfire hydrologic response (Shakesby and Doerr, 2006). This specific hillslope runoff process occurring under the snow likely contributed to a faster accumulation of flow in the channel, but in a region driven by snowmelt hydrology, loss of canopy cover must be considered. Temperature, radiation and humidity are all drivers of snowmelt (Hock, 1999; Kuhn, 1987), with solar radiation being the largest (Ellis et al., 2011). At both Little Beaver Creek and Roaring Creek, large areas near the pressure sensors were burned at medium to high severity and canopy cover was reduced significantly. Warm temperatures and high radiation likely occurred across the Poudre River watershed when LBC flooded, but only 15 % of the Poudre River watershed upstream of the confluence with the North Fork burned at medium or high severity compared to 86 % of the LBC watershed.

6. Conclusion

We observed evidence of low discharge flooding over ice at Little Beaver Creek, a tributary of the Cache la Poudre River in the Southern Rocky Mountains. The flood occurred in late winter, 60 days before spring runoff. A disturbance such as this may negatively impact aquatic habitat and organisms not suited to winter floods.

We have identified three primary mechanisms that were directly responsible for this phenomenon. Each mechanism is dynamically linked and in the case of (1) and (2) strongly enhances the others' effects. We propose them in order of our perceived relative importance: (1) Post-wildfire conditions magnified snowmelt including soil hydrophobicity and more importantly loss of canopy cover, exposing snow to higher-than-normal solar radiation. (2) Unusual weather patterns in March and April produced large swings of temperature, with consecutive days below freezing followed by consecutive days far warmer than freezing. (3) Channel structure including log jams that captured sediment, backed up flows and enhanced the processes of ice dam formation/failure.

In the last decade, western North America has experienced massive wildfires and post-fire hydrologic processes are widespread. Wildfires coupled with the increased weather variability resulting from climate change may generate the conditions favorable for more flooding related to ice-choked channels and should be monitored to mitigate potential flooding risks and better understand this poorly documented phenomenon.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2022.108370.

References

Ader, E., Wohl, E., McFadden, S., Singha, K., 2021. Logjams as a driver of transient storage in a mountain stream. Earth Surf. Process. Landf. 46, 701–711. https://doi.org/10.1002/esp.5057.

Beltaos, S., 2007. River ice breakup processes: recent advances and future directions. Can. J. Civ. Eng. 34, 703–716.

Beltaos, S., Prowse, T., 2009. River-ice hydrology in a shrinking cryosphere. Hydrol. Process. 23, 122–144. https://doi.org/10.1002/hyp.7165.

Burrell, B.C., Turcotte, B., Comfort, G., Groeneveld, J., 2021. Infrastructure And River Ice: An Overview. Presented at the 21st Workshop on the Hydraulics of Ice, Saskatoon, SK, CGU HS Committee on River Ice Processes and the Environment.

Clark, I.D., Lauriol, B., 1997. Aufeis of the Firth River Basin, Northern Yukon, Canada: insights into permafrost hydrogeology and karst. Arct. Alp. Res. 29, 240–252.

NCEI, 2022. Climate at a Glance | National Centers for Environmental Information (NCEI) [WWW Document], URL. https://www.ncdc.noaa.gov/cag/county/time-series/CO-069/tavg/2/4/1895-2021?base_prd=true&begbaseyear=1901&endbaseyear=2000 (accessed 1.21.22).

Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. Geol. Soc. Am. Bull. 100, 1054–1068.

Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. GSA Bull. 100, 1054–1068. https://doi.org/10.1130/0016-7606(1988)100<1054:TFAFON>2.3.CO;2.

Daly, S.F., 2005. Anchor Ice Flooding in Jackson, WY. Presented at the World Water and Environmental Resources Congress. In: American Society of Civil Engineers, Anchorage, AK, pp. 1–9. https://doi.org/10.1061/40792(173)240.

Daly, S., Rocks, J., Reilly-Collette, M., Gelvin, A., 2019. Ice Control to Prevent Flooding in Ship Creek. AlaskaEngineer Research and Development Center, U.S.. https://doi.org/10.21079/11681/33483

Dubé, M., Turcotte, B., Morse, B., 2014. Inner structure of anchor ice and ice dams in steep channels. Cold Reg. Sci. Technol. 106–107, 194–206. https://doi.org/10.1016/j.coldregions.2014.06.013.

Ellis, C.R., Pomeroy, J.W., Essery, R.L.H., Link, T.E., 2011. Effects of needleleaf forest cover on radiation and snowmelt dynamics in the Canadian Rocky Mountains. Can. J. For. Res. 41, 608–620. https://doi.org/10.1139/X10-227.

Ettema, R., Kepemema, E.W., 2012. River-ice effects on gravel-bed channels. In: Church, M., Biron, P.M., Roy, A.G. (Eds.), Gravel-bed Rivers. Ltd: John Wiley & Sons, pp. 523–540.
Gebre, S., Alfredsen, K., Lia, L., Stickler, M., Tesaker, E., 2013. Review of ice effects on hydropower systems. J. Cold Reg. Eng. 27, 196–222. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000059.
Harper, D.D., Farag, A.M., 2004. Winter habitat use by cutthroat trout in the Snake River near Jackson, Wyoming. Trans. Am. Fish. Soc. 133, 15–25. https://doi.org/10.1577/T02-072.
Hauer, F.R., Baron, J.S., Campbell, D.H., Fausch, K.D., Hostetler, S.W., Leavesley, G.H., Leavitt, P.R., Mcknight, D.M., Stanford, J.A., 1997. Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada. Hydrol. Process. 11, 903–924. https://doi.org/10.1002/(SICI)1099-1085(19970630)11:8<903::AID-HYP511>3.0.CO;2-7.
Hock, R., 1999. A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. J. Glaciol. 45, 101–111. https://doi.org/10.3189/S0022143000003087.
Huokuna, M., Morris, M., Beltaos, S., Burrell, B.C., 2022. Ice in reservoirs and regulated rivers. Int. J. River Basin Manag. 20, 1–16. https://doi.org/10.1080/15715124.2020.1719120.
Huusko, A., Greenberg, L., Stickler, M., Linnansaari, T., Nykänen, M., Vehanen, T., Koljonen, S., Louhi, P., Alfredsen, K., 2007. Life in the ice lane: the winter ecology of stream salmonids. River Res. Appl. 23, 469–491. https://doi.org/10.1002/rra.999.
Kalke et al., 2015. H. Kalke M. Loewen V. McFarlane M. Jasek, 2015. Observations of Anchor Ice Formation and Rafting of Sediments 18.
Kempema, E., Remlinger, B., Daly, S., Ettema, R., 2017. Ice-related, Urban Winter Flooding of Flat Creek, Jackson, Wyoming, 22.
Kempema, E.W., Ettema, R., 2011. Anchor ice rafting: observations from the Laramie river. River Res. Appl. 27, 1126–1135. https://doi.org/10.1002/rra.1450.
Kerr, D.J., Shen, H.T., Daly, S.F., 2002. Evolution and hydraulic resistance of anchor ice on gravel bed. Cold Reg. Sci. Technol. 35, 101–114. https://doi.org/10.1016/S0165-232X(02)00043-5.
Kuhn, M., 1987. Micro-meteorological conditions for snow melt. J. Glaciol. 33, 24–26. https://doi.org/10.3189/S002214300000530X.
Leppi, J.C., DeLuca, T.H., Harrar, S.W., Running, S.W., 2012. Impacts of climate change on August stream discharge in the Central-Rocky Mountains. Clim. Chang. 112, 997–1014. https://doi.org/10.1007/s10584-011-0235-1.
Li, 2012. Estimates of the Manning's coefficient for ice-covered rivers. In: Water Management, 165. Proceedings of the Institution of Civil Engineers, pp. 495–505. https://doi.org/10.1680/wama.11.00017.
Lindstrom, J.W., Hubert, W.A., 2004. Ice processes affect habitat use and movements of adult cutthroat trout and brook trout in a Wyoming Foothills Stream. N. Am. J. Fish Manag. 24, 1341–1352. https://doi.org/10.1577/M03-223.1.
Meisner, J.D., Rosenfeld, J.S., Regier, H.A., 1988. The role of groundwater in the impact of climate warming on stream salmonines. Fisheries 13, 2–8. https://doi.org/10.1577/1548-8446(1988)013<0002:TROGIT>2.0.CO;2.
Moody, J.A., Martin, D.A., 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surf. Process. Landf. 26, 1049–1070. https://doi.org/10.1002/esp.253.
Moore, R.D., Hamilton, A.S., Scibek, J., 2002. Winter streamflow variability, Yukon Territory, Canada. Hydrol. Process. 16, 763–778. https://doi.org/10.1002/hyp.372.
Morse, P.D., Wolfe, S.A., 2015. Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada. J. Geophys. Res. Earth Surf. 120, 1670–1686. https://doi.org/10.1002/2015JF003534.
Musselman, K.N., Lehner, F., Ikeda, K., Clark, M.P., Prein, A.F., Liu, C., Barlage, M., Rasmussen, R., 2018. Projected increases and shifts in rain-on-snow flood risk over western North America. Nat. Clim. Chang. 8, 808–812. https://doi.org/10.1038/s41558-018-0236-4.
Neary et al., 2003 D.G. Neary G.J. Gottfried, P.F. Ffolliott, 2003. POST-WILDFIRE WATERSHED FLOOD RESPONSES 9.
Nesse, W.D., Braddock, W.A., 1989. Geologic Map of the Pingree Park Quadrangle. Geologic Quadrangle, Larimer County, Colorado. https://doi.org/10.3133/gq1622.
Prowse, T.D., Beltaos, S., 2002. Climatic control of river-ice hydrology: a review. Hydrol. Process. 16, 805–822. https://doi.org/10.1002/hyp.369.
Prowse, T.D., 2001a. River-ice ecology. I: hydrologic, geomorphic, and water-quality aspects. J. Cold Reg. Eng. 15, 1–16. https://doi.org/10.1061/(ASCE)0887-381X(2001)15:1(1).
Prowse, T.D., 2001b. River-ice ecology. II: biological aspects. J. Cold Reg. Eng. 15, 17–33. https://doi.org/10.1061/(ASCE)0887-381X(2001)15:1(17).
Prowse, T.D., Carter, T., 2002. Significance of ice-induced storage to spring runoff: a case study of the Mackenzie River. Hydrol. Process. 16, 779–788. https://doi.org/10.1002/hyp.371.
Prowse, T.D., Ferrick, M.G., 2002. Hydrology of ice-covered rivers and lakes: scoping the subject. Hydrol. Process. 16, 759–762.
Richard, M., Morse, B., 2008. Multiple frazil ice blockages at a water intake in the St. Lawrence River. Cold Reg. Sci. Technol. 53, 131–149. https://doi.org/10.1016/j.coldregions.2007.10.003.
Rokaya, P., Budhathoki, S., Lindenschmidt, K.-E., 2018a. Ice-jam flood research: a scoping review. Nat. Hazards 94, 1439–1457.
Rokaya, P., Budhathoki, S., Lindenschmidt, K.-E., 2018b. Trends in the timing and magnitude of ice-jam floods in Canada. Sci. Rep. 8, 5834. https://doi.org/10.1038/s41598-018-24057-z.
Shakesby, R.A., Doerr, S.H., 2006. Wildfire as a hydrological and geomorphological agent. Earth Sci. Rev. 74, 269–307. https://doi.org/10.1016/j.earscirev.2005.10.006.
Shen, H.T., Liu, L., 2003. Shokotsu River ice jam formation. Cold Reg. Sci. Technol. 37, 35–49. https://doi.org/10.1016/S0165-232X(03)00034-X.
Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2004. Changes in snowmelt runoff timing in Western North America under a `Business as Usual' climate change scenario. Clim. Chang. 62, 217–232. https://doi.org/10.1023/B:CLIM.0000013702.22656.e8.
Stickler, M., Alfredsen, K.T., 2009. Anchor ice formation in streams: a field study. Hydrol. Process. 23, 2307–2315. https://doi.org/10.1002/hyp.7349.
Tremblay, P., Leconte, R., Jay Lacey, R.W., Bergeron, N., 2014. Multi-day anchor ice cycles and bedload transport in a gravel-bed stream. J. Hydrol. 519, 364–375. https://doi.org/10.1016/j.jhydrol.2014.06.036.
Turcotte, B., Alfredsen, K., Beltaos, S., Burrell, B., 2017. Ice-related Floods And Flood Delineation Along Streams And Small Rivers.
Turcotte, B., Burrell, B.C., Beltaos, S., She, Y., 2019. The impact of climate change on breakup ice jams in Canada: state of knowledge and research approaches. In: Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Canada. Available at: Http://Cripe.ca/Publications/Proceedings/20.
Turcotte, B., Morse, B., 2013. A global river ice classification model. J. Hydrol. 507, 134–148. https://doi.org/10.1016/j.jhydrol.2013.10.032.
Turcotte, B., Morse, B., Dubé, M., Anctil, F., 2013. Quantifying steep channel freezeup processes. Cold Reg. Sci. Technol. 94, 21–36. https://doi.org/10.1016/j.coldregions.2013.06.003.
Tuthill, A.M., 2008. Ice Jam at the Rio Blanco Diversion Weir on the White River in Colorado: A Case Study of In-stream Structures And Ice. ENGINEER RESEARCH AND DEVELOPMENT CENTER HANOVER NH COLD REGIONS RESEARCH.
Weber, M.D., Booth, E.G., Loheide, S.P., 2013. Dynamic ice formation in channels as a driver for stream-aquifer interactions. Geophys. Res. Lett. 40, 3408–3412.
Westerling, A.L., Bryant, B.P., 2008. Climate change and wildfire in California. Clim. Chang. 87, 231–249. https://doi.org/10.1007/s10584-007-9363-z.
National Interagency Fire Center, 2021. Wildfires and Acres | National Interagency Fire Center [WWW Document]. https://www.nifc.gov/fire-information/statistics/wildfires. (Accessed 21 January 2022).
Wohl, E., Marshall, A.E., Scamardo, J., White, D., Morrison, R.R., 2022. Biogeomorphic influences on river corridor resilience to wildfire disturbances in a mountain stream of the Southern Rockies, USA. Sci. Total Environ., 153321 https://doi.org/10.1016/j.scitotenv.2022.153321.
Wohl, E., Merritt, D., 2005. Prediction of mountain stream morphology. Water Resour. Res. 41 https://doi.org/10.1029/2004WR003779.
Yang, X., Pavelsky, T.M., Allen, G.H., 2020. The past and future of global river ice. Nature 577, 69–73. https://doi.org/10.1038/s41586-019-1848-1.