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Summary of Ice Jams and Mitigation Techniques in Alaska

Jeremy Giovando, Chandler Engel,
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Abstract

Ice is an important part of the Alaska ecosystems and can form through dynamic (e.g., frazil) or static (e.g., thermal) processes. In Alaska, both freeze-up and breakup ice jams occur, however breakup jams during the spring snowmelt period are most common. Historically there have been many river systems in Alaska that have chronic ice jam issues. These ice jams have resulted in several significant ice jam floods. There are ice jam mitigation techniques that can be used to either provide state and local emergency managers warnings of a potential ice jam or reduce the impacts of a jam. Common relatively low-cost mitigation methods that can be implemented prior to a jam forming are monitoring and detection of movement, mechanical or thermal weakening of the ice cover. Permanent measures are also effective and maybe the best option in specific locations. These measures include structures to keep flood waters from inundating areas (e.g., levee) or they can be designed to hold back ice fragments moving downstream (e.g., ice boom and pier structures). Climate change impacts to ice processes are important for Alaska and additional investigations will be needed to quantify the ecologic, hydrologic, and societal impacts.

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Preface

This study was conducted for US Army Corp of Engineers (USACE)–Alaska District, “Summary of Ice Jams and Mitigation Techniques in Alaska.” The technical monitor was Erin Stockdale, USACE-Alaska District.

The work was performed by the Terrain and Ice Engineering Group of the Remote Sensing/GIS Center of Expertise Branch of the Research and Engineering Division, US Army Engineer Research and Development Center–Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Meghan C. L. Quinn was group lead; and Mr. David C. Finnegan was center director. The acting deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and the director was Dr. Joseph L. Corriveau.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

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1 Introduction

Alaska is the largest state in the US and spans a north latitude range of 51° to 71°. The northern latitudes of Alaska result in relatively long winter conditions usually running from October through May. With winter conditions comes the freezing and thawing of rivers across the state. These freeze–thaw cycles are important dynamic ecosystem components, and influence people and infrastructure in many ways. The complete freezing of a river allows natural travel ways for some communities otherwise isolated during the rest of the year, offers the same for animal populations, and provides a plethora of recreational opportunities. However, river freezing and thawing, known as freeze-up and breakup, can also induce flooding events which can damage or destroy infrastructure, disrupt transportation, hinder river navigation, and sometimes cause loss of life. The primary inducers for flooding events during winter conditions are ice jams. River ice jams form when the flow of ice along a reach is obstructed by a stationary accumulation of ice (Beltaos 1995; USACE 2002). The two primary types of ice jams are freeze-up jams and breakup jams, the former being primarily composed of frazil ice, and the latter of fragmented ice blocks. The difference between these two ice jam types is discussed in Section 2, *Introduction to River Ice*, but both can be equally destructive. In 1989, the Cold Regions Research and Engineering Laboratory (CRREL) estimated annual damages because of ice jamming in the US at $100 million (Carlson et al. 1989), and more recently annual ice jam damages in North America have been reported at $300 million US dollars (Niziol 2020). In Alaska, damages from ice-jam induced flooding in 2009 were estimated at $29 million statewide (National Weather Service 2009), and in 2013, flooding from an ice jam on the Yukon River caused damages estimated at $86.5 million making it the fourth most costly ice-jam flood in North America between 1950 and 2018 (Kontar et al. 2015). Therefore, from the water resource engineering and emergency response standpoints, ice jams and ice jam induced floods are essential considerations. Monitoring river ice processes can help inform location and magnitude of potential ice jam floods, and effective flood mitigation can prevent loss or damage of property and life. This report discusses the state of the knowledge of ice jam monitoring and mitigation techniques as they apply to Alaska. Section 2 introduces river ice processes to provide a basic knowledge foundation for ice jams, Section 3 focuses on historical ice jams in Alaska including case studies, Sections 4 and 5 focus on the ice and ice jam monitoring and mitigation techniques, Section 6 briefly discusses engineering considerations for bridges and culverts with respect to ice, Section 7 discusses the effects of climate change on ice jams, and Section 8 summarizes the current research needs for improving ice forecasting, monitoring, and modeling in Alaska.

1.1 Background

This report builds on the knowledge of previous studies related to river ice and ice jams in Alaska. Because of the number of publications related to ice processes in Alaska it is not feasible given the scope of the current effort to thoroughly summarize all previous publications. We instead use the US Engineering Research and Development Center's (ERDC) reports as a touchstone in the literature and supplement these reports with recent peer-reviewed publications. The US Army Corps of Engineers (USACE) *Ice Engineering* manual (USACE 2002) contains technical notes for ice jams and ice jam induced floods applicable to Alaska. Therefore we use this reference as our foundational source for several chapters.

1.2 Objectives

The motivation for this report is to provide a general overview of ice jam knowledge in Alaska. River ice information is often scattered between peer-reviewed publications and government reports, and additionally, the information is also generalized and not specific for regions (i.e., Alaska). Therefore USACE-Alaska District has requested we bring together river ice information for Alaska from various sources into a single document. The objectives of this report are the following:

1. Summarize river ice formation processes in a manner which is understandable for a broad audience of readers.
2. Summarize ice jams for the state of Alaska.
3. Provide information about ice monitoring and mitigation techniques that can be used by local, state, and federal stakeholders in Alaska.

1.3 Approach

In this report, we first describe general ice processes to provide background for all readers regardless of their experience with river ice. We then summarize the historical ice jams for Alaska based on the information in the CRREL Ice Jam Database (IJDB). Finally, we provide a description of commonly used monitoring and mitigation techniques that have been used in cold regions across the world.

1.4 Scope

This report was prepared for Alaska District as part of the Silver Jackets program. Our focus is to provide ice formation for stakeholders with varying levels of experience in river ice processes. This includes local planners, state officials, and nongovernmental organizations who must consider ice characteristics in their projects and operational activities. The level of detail we have included in each section is intended to be a basic introduction. We have not exhaustively summarized all the publications and their findings related to each of the section topics. Instead, we aimed to provide key references which then would give readers a starting point for further exploration on a specific topic.

2 Introduction to River Ice

2.1 Objective

The objective of this section is to develop a basic understanding of river ice processes. The formation of different types of river ice formation is described, the processes of river ice breakup and thermal melt out will be introduced, and types of ice jams will be defined and discussed. These topics have important implications relating to ice observations, assessing flood risks, hazard mitigation and disaster response, and the engineering design of mitigation measures.

2.2 Ice formation

This section introduces the types of ice that form in rivers in cold regions, including Alaska. The formation of ice is affected the thermal process of heat transfer and its evolution is also greatly influenced by physical and mechanical processes. In general, the process of ice formation in natural settings begins with supercooled water and availability of seed ice crystals from outside of the water body.

2.2.1 Supercooling

In locations where the environmental conditions permit, water will lose heat and cool in temperature, eventually reaching and potentially exceeding the freezing point. We often think of the freezing point of water (0°C or 32°F[1] at atmospheric pressure) as a specific temperature where water transitions from liquid to solid ice. In fact, water can cool below the freezing point in laboratory settings by many degrees. In nature, fresh water has not been observed cooling more than about −0.1°C (31.8 °F) (Prowse 1995). When water is in this narrow band of temperature below the freezing point, it is referred to as supercooled water.

Supercooling of river water is possible when the air temperature is below freezing, and the river is not ice covered. Cold air is required for the transfer of heat from the water to the air through sensible heat exchange, where sensible heat refers to energy that you can feel—or sense—and

[1] For a full list of the spelled-out forms of the title abbreviations used in this document, please refer to US Government Publishing Office Style Manual, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 227–30, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

measure with a thermometer. Heat from the relatively warmer water moves to the colder air because of the thermal gradient. Wind can significantly increase the transfer of heat at the surface by providing a continuous supply of cold air. Also, supercooling often occurs when there is limited cloud cover. Clouds act as both a reflector of longwave radiation emitted by the river (McFarlane and Clark 2021) and a source of longwave radiation (Richard et al. 2015). The absence of clouds permits the longwave energy from the river to be lost to the atmosphere. The second criterion that the river be in an open water condition is partly because of an ice cover's interference with the heat transfer just discussed; the ice acts to insulate the water and results in the ice–water interface remaining at the freezing point. Once the ice cover is formed, additional heat loss from the water will cause the ice cover to thicken and supercooling temperatures will not exist under the ice unless it traveled from open water upstream.

Supercooled water is not particularly stable and is on the cusp of forming ice, but before river water changes from liquid to solid it needs an additional ingredient—seed crystals. Seed crystals act as base starting points—or nuclei—to which adjacent water freezes and ice crystals grow. This growth process is referred to as secondary nucleation, with the term primary nucleation being reserved for when seed crystals are initially formed, typically in the air around particles of dust or micro-organics. Snow is a common form of external seed crystal (Leppäranta 2015). More ice can grow from the original seeds and collisions between ice particles create new nucleation points. If the water body is quiescent, the seed crystals may immediately begin to form a buoyant ice cover. However, if the water is turbulent, as is usually the case in natural rivers or lakes exposed to wind, the ice crystals can become mixed into the water column. These two cases lead to very different ice formation processes which can be divided into dynamic or static ice cover formations.

2.2.2 Frazil ice

The evolution of frazil ice is shown in Figure 1. This evolution applies to most rivers because they are considered turbulent unless there is a backwater from something like a downstream water body or a dam which significantly reduces velocities (Ashton 1979). Since turbulence is predominant in rivers, when ice crystals form in supercooled river water, they will usually be mixed into the water column. The mixing is often sufficient to cause the entire depth of flow to be supercooled as well, allowing the seed crystals to grow throughout the entire depth, forming frazil ice. The details of frazil ice dynamics are quite complex and beyond the scope of this document, but others have thoroughly investigated the topic (Daly 1994; Hammar and Shen 1995). Frazil ice will tend to collect into clumps, or flocs, that are buoyant enough to overcome the turbulent mixing forces and rise to the surface to form a layer of slush. This slush will flow with the velocity of the river, initially in dark, loose masses (Figure 2). If ice production continues and the concentration of slush increases, it will begin to transform into more cohesive forms depending on the velocity and geometry of the river.

Figure 1. Evolution of frazil ice in natural water bodies. (Image reproduced from Daly 1994. Public domain.)

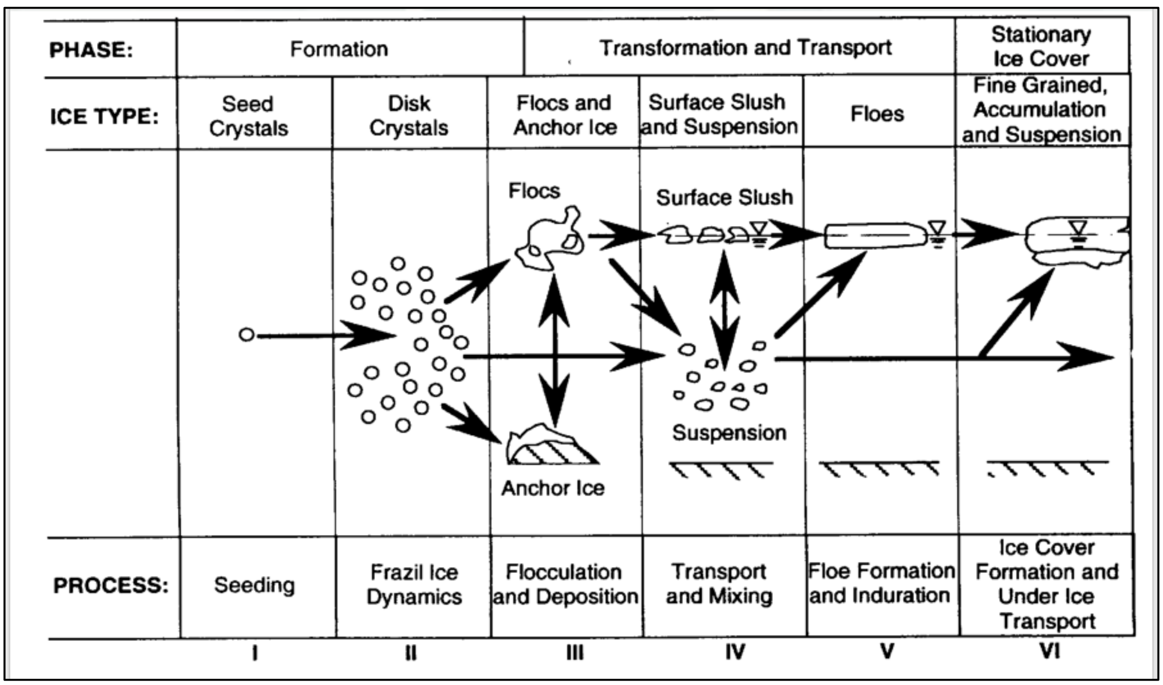


Figure 2. Frazil ice on the Nenana River, Alaska.

In slower moving systems the slush ice will form into pans, or small discs that have a raised round perimeter because of collisions with other pans. Sometimes this is referred to as pancake ice (Beltaos 1995). Individual pans may join into larger floes that will also continue downstream unless arrested by a stable ice cover, or some geometric feature of the river such as a bend or a constriction.

In faster moving river systems, turbulence will tend to keep the frazil suspended in the flow and large accumulations of ice can form in locations where velocities decrease such as at the entrance of a lake, or upstream of a channel constriction. The accumulating frazil can block flow, causing stages to rise and velocities to decrease encouraging more deposition.

If the substrate of the river bottom has cooled below the equilibrium freezing point, ice particles may adhere to the bed and either grow in place or accumulate more frazil particles forming anchor ice. Cooling of the river bottom will occur when contact with the supercooled water is the primary heat exchange mechanism. In areas with accretions due to groundwater inflow or other sources of slightly warmer water, anchor ice formation may not be as prevalent. When accumulation of anchor ice does occur, this can reduce the flow area of the channel and cause the river's stage to rise without any change to the flow rate. Frazil ice is a common form of ice in rivers. The formation and collection of frazil ice slush in the early winter is a key process that can lead to the formation of a continuous ice cover that may persist for the entire winter.

2.2.3 Dynamic ice cover formation

Dynamic ice cover formation refers to the process of forming a stationary ice cover from moving ice interacting with flowing water. Ice moving with the flow will tend to accumulate in bends and constrictions or when it encounters the upstream end of a stationary ice cover. Dynamic ice cover can be contrasted with static ice cover formation, discussed later in Section 2.2.4, which is more common on lakes and ponds. The formation of a static, or thermally grown initial ice cover spanning the channel will only occur if velocities are quite low.

In most rivers, ice initially forms close to the banks in slow moving water. Shallow, supercooled surface water that is not well mixed will develop a thin layer of ice when seeded. This ice, which commonly forms a ribbon along the margins of the river is called border ice (Figure 3). The ice will tend to thicken and grow laterally towards the center of the channel. Thermally driven lateral growth will continue on the margins of the border ice until flow velocities exceed the stability of new crystals. Lateral growth of border ice can result in the complete closure of the ice cover if hydraulic conditions permit. Typically, this will happen in slower moving rivers. It is very common to see frazil slush adhere to the edge of border ice especially on the outside river bends. The growth of border ice from the accumulation of passing slush is sometimes referred to as *buttering* (Figure 4).

Figure 3. Nenana River near Cantwell, Alaska. Border and anchor ice growth visible along banks and around rock features.

Figure 4. Frazil ice accumulation (buttering) in Yosemite Creek, Yosemite National Park, California. (Image reproduced from National Park Service 2010. Public domain.)

The narrowing open width of a channel experiencing border ice growth is prone to closure from frazil pans, commonly referred to as bridging the opening. The potential for an ice cover to close because of bridging is largely a function of the ice concentration, or the portion of the open water surface occupied by frazil ice pans. Bridging occurs in rivers without border ice growth, however the presence of ice on the river margins tends to increase ice concentrations and create narrow choke points where ice pans can get stuck. When ice concentrations reach 80%–90% the pans may not be able to freely move downstream and can become stationary (Hicks 2009).

Dynamic ice covers form from downstream to upstream, starting with some initiation point of stationary ice that forms a leading edge. There are several potential reasons for a leading edge to form, including lateral growth of border ice leading to closure, the presence of thermal growth of ice on a lake or reservoir downstream, accumulation of ice in a constriction or at a barrier such as a narrow bridge opening or a dam. Ice covers are sometimes intentionally initiated by ice booms (Foltyn and Tuthill 1996) or ice control structures (Tuthill 1995).

When moving ice encounters the leading edge a few things can happen depending on the physical properties of both the moving and stationary ice, and the hydraulic conditions of the river flow. In lower velocity rivers ice floes will simply stop and accumulate at the leading edge as they arrived in a *juxtaposed* collection of ice. As ice accumulates against the leading edge the floes transmit the shear force exerted by the water running beneath them on the stationary ice. This ice cover may not be totally stable, and the forces exerted on it from upstream can cause it to collapse, resulting in ice moving downstream toward the initiation point and a net thickening of the ice cover. This collapse-thickening process is referred to as *shoving* and can lead to a particular type of ice jam referred to as a *freeze-up jam* (Hicks 2009).

If velocities are high enough there is the potential for arriving floes to overturn and be pulled under the leading edge. The potential for underturning is a function of the floe geometry, the river velocity and the depth of flow. Once the floe is under the ice cover it may become stuck near the leading edge as it rides on the underside of the accumulated ice, but if the velocities are high enough it may progress downstream. If floes are continuously transported under the leading edge and downstream, the advance of the ice cover may stall. Loose runs of frazil ice can also be pulled under the leading edge and accumulate on the underside of the ice cover building up in accumulations in a process similar to sediment deposition, but somewhat upside-down (Shen and Wang 1995).

This process can be very dynamic and accumulations of ice passing under the leading edge may obstruct the channel downstream and result in higher stages and lower velocities at the leading edge. When velocities decline at the leading edge, ice may resume accumulating and extending the ice cover upstream. If the hydraulic conditions do not permit the continued growth of the cover upstream, the river may remain open for the entire winter. Locations along a river that do not grow a seasonal ice cover, such as sections of rapids, can produce frazil ice whenever meteorological conditions permit and may be the source of ice accumulation problems downstream (USACE 2002).

2.2.4 Static ice cover formation

In river reaches with low turbulent velocities, buoyant forces acting on ice crystals may be sufficient to prevent them from becoming entrained in the flow. This can result in the formation of *skim ice* which is thin ice that forms rapidly at the surface in a layer of supercooled water. Skim ice may be transported downstream in a “skim ice run” if there is a current or may remain stationary in quiescent reaches (Beltaos 2013). In slower moving water along the banks border ice (sometimes called shore ice) can grow by initially forming a thin layer of ice attached to the bank.

Both skim ice and border ice will continue to grow laterally across the water surface if meteorological and hydraulic conditions permit, specifically if the rate of heat loss to the atmosphere remains sufficiently high and the surface water velocities are low.

Continued low temperatures will cause the initially thin layers of ice to grow vertically down into the water column in a process called thermal ice growth. For the water on the underside of the ice cover to freeze, heat must be removed from the water through the ice cover itself. The rate of ice growth is a function of the thickness and conductivity of the ice. Snow on the ice surface will act as an insulator affecting the movement of heat from the water to the atmosphere, slowing the formation of ice.

It is often of interest to estimate or predict the thickness of ice at a given location. The change in ice thickness as a function of time can be calculated by assuming the ice cover is a simple slab of ice floating on water at the freezing point. The model of ice growth is defined using a partial differential equation describing the nonlinear heat transfer (Michel 1971; USACE 2002) but practically a simplified solution is what is most useful (Equation 1):

$$t_i = \alpha(\boldsymbol{AFDD})^{1/2,} \tag{1}$$

where

t_i = ice thickness,
α = prediction coefficient, and
$\boldsymbol{AFFD}$ = accumulated freezing degree days.

Accumulated freezing degree days (AFDD) is defined as the sum of average daily degrees below freezing for a specified time period between the onset of freeze-up and day *j*. The value is calculated according to the following Equation (2):

$$\boldsymbol{AFDD} = \sum_{i=1}^{j}(\boldsymbol{T_f} - \boldsymbol{T_{aj}}), \tag{2}$$

where

T_f = freezing temperature 0°C (32°F) and
T_{ai} = average daily temperature on day *j*.

Typical values for the prediction coefficient, α, are presented in Table 1.

Table 1. Typical values of α. (Reproduced from Michel 1971. Public domain.)

Ice Cover Condition	α *	α †
Windy lake w/no snow	2.7	0.80
Average lake with snow	1.7–2.4	0.50–0.70
Average river with snow	1.4–1.7	0.40–0.50
Sheltered small river	0.7–1.4	0.20–0.40

* AFDD calculated using degrees Celsius. The ice thickness is in centimeters.
† AFDD calculated using degrees Fahrenheit. The ice thickness is in inches.

Using Equations 1 and 2 to estimate ice thickness are effective, especially if there is the opportunity to calibrate the prediction coefficient to measured ice thicknesses (Giovando et al. 2018). The method is best used to calculate continuously thickening ice, as the heat transfer involved in ice thinning from either surface melt or heat flux from the water are not considered in the simplified solution. This method assumes the ice cover is formed statically, and thus it is not suitable for estimating the thickness of river ice cover that is formed dynamically through the mechanical accumulation of ice. The heat transfer model can be adapted to estimate thermally driven ice thickening that occurs once a dynamically formed ice cover is present, but the adaption of the method to that case is outside the scope of this report. See Michel (1971) and Beltaos (2013) publications for a more in-depth discussion.

2.2.5 Aufeis

Another type of ice formation is called aufeis—a German word, meaning *top ice*. Aufeis can be defined as a “sheet-like mass of layered ice formed on the ground surface, or on river or lake ice, by freezing of successive flows of water that may seep from the ground, flow from a spring or emerge from below river ice through fractures” (Harris et al. 1988). Aufeis is strongly associated with the Arctic and near Arctic regions of the world but can be found anywhere there is a source of water and subfreezing air temperatures. The flooding of an ice cover surface requires two conditions: an increase in the water surface elevation (stage), and that the ice cover does not respond to the increase in stage by floating higher (Daly et al. 2011). When these conditions exist, aufeis can extend well into the stream overbanks inducing extensive flooding across the floodplain. Additionally, air temperature trends, local hydrology and geohydrology, geology and permafrost characteristics, snow cover thickness, and the presence of infrastructure can all influence aufeis extent (Ensom et al. 2020). Aufeis extents can proceed onto the overbanks, flooding vegetation and surroundings. In such cases, trapped under-ice flows can discharge along larger vegetation stems producing additional aufeis events around that vegetation. Aufeis research conducted along Jarvis Creek, Alaska (located near Delta Junction, Alaska) demonstrated such icing occurrences (Figure 5) (Daly et al. 2011). The Jarvis Creek research also provides an example of a geohydrologic phenomenon common to alpine regions of Alaska. The Jarvis Creek streambed is comprised of outwash gravels with higher porosity than the surrounding compacted glacial moraines, which coupled with a regionally low water table, result in losing stream reach thus reducing the total discharge to near zero during the winter months.

(Daly et al. 2011). This effect is also known as the disappearing stream effect and is common to streams in glacial outwash plains across Alaska. Because the water stages get very low in Jarvis Creek, the ice thickens to the point where it is attached to the streambed material. When flowing water underneath the ice reaches these locations with the ice adhered to the bed material, the ice does not become buoyant therefore creating increased pressure upstream. The flows then relieve this pressure by seeping or flowing out on top of the ice.

Figure 5. Jarvis Creek, Central Alaska. Discharge along the stems of larger plants in overbank, which are encased in aufeis.

Often, ice mounds or ice blisters, are found in conjunction with aufeis events in Alaskan streams. They can vary in size and location along a channel and are characterized by an increase in elevation along the ice surface; a centered, longitudinal crack frequently paralleling flow direction, and aufeis surroundings that may indicate its presence. Internal ice blister conditions can be hollow (air-filled), solid ice, or pressurized fluid filled (Chacho et al. 1993). In the latter, downstream blockage along a flow conduit likely contributes to ice mounds containing pressurized water such that when the mound is punctured, overflow and subsequent icing may result (Kovacs 1992; and Daly et al. 2011).

Aufeis events pose threats to engineered infrastructure such as bridge crossings, culverts, and road embankments proximal to runoff areas (Ensom et al. 2020). In the case of bridge crossings, the bridge cover may provide protection from snowfall accumulation which would otherwise insulate the ice cover reducing total thickness. The relatively greater ice cover thickness under the bridge crossing may impede flow inducing an aufeis event at that point. Subsequent buildup could induce roadway flooding and threaten infrastructure stability. In some cases, culverts with insufficient diameters can fill almost completely causing roadway flooding (Figure 6). Where road embankments are close to natural runoff areas, the disturbed ground may change natural flow paths such that potential overflow could occur in an aufeis event.

Figure 6. Road culverts obstructed by aufeis, Alberta, Canada. (Image reproduced with permission from F. Hicks.)

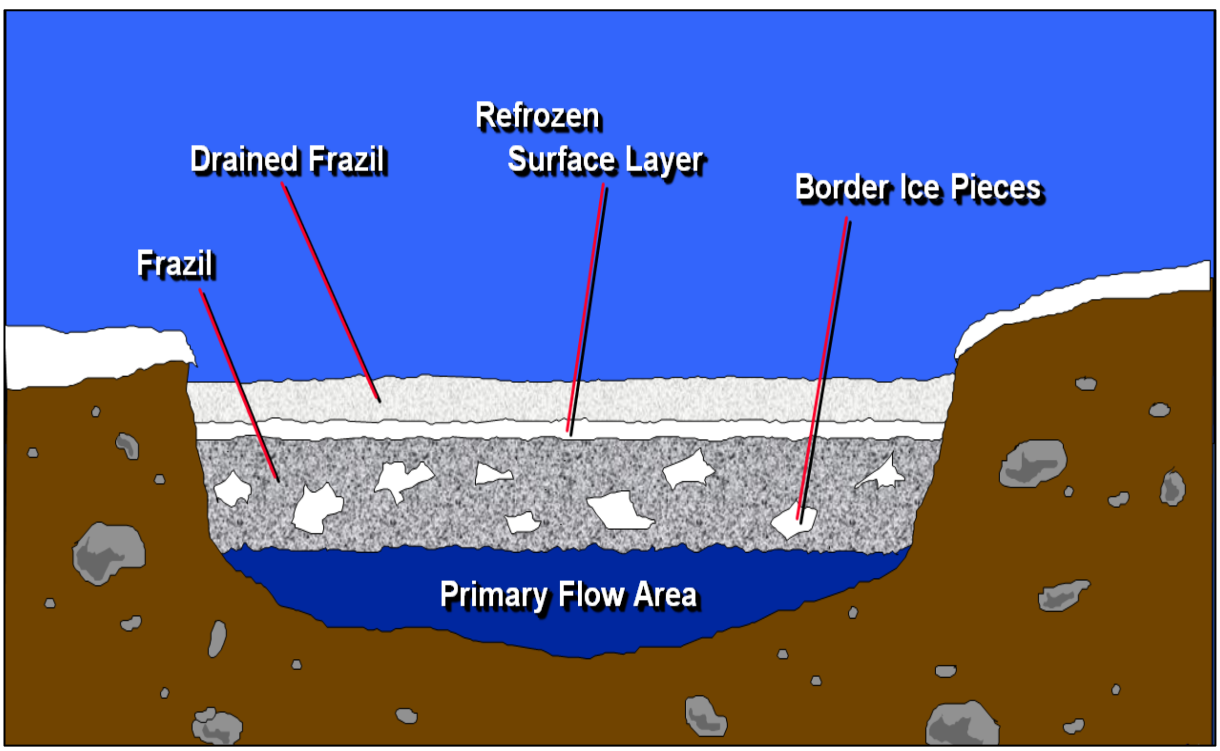
2.3 Types of ice jams and their formation

A stationary accumulation of ice that restricts flow is defined as an ice jam (USACE 2002). As ice accumulates and the flow restriction increases, water levels upstream of the jam location will rise and may result in flooding of areas outside the river channel. The accumulated ice can occur during both freeze-up and breakup conditions depending on meteorologic and hydrologic conditions. Freeze-up jams will generally be associated with cold periods during the winter season. Conversely, breakup jams are usually a result of changes to both meteorologic and hydrologic conditions which fragment surface ice cover and transport the ice volume to a jam prone reach of the river. For the continuous US (CONUS), breakup jams can occur midwinter through spring snowmelt runoff; however, in Alaska, breakup jams are most common only during spring snowmelt runoff periods. Additional details for each of these jam types is provided in subsequent sections.

2.3.1 Freeze-up

Freeze-up ice jams are most often a result of frazil ice accumulation associated with supercooling water temperatures. During the winter season, open water areas are susceptible to large amounts of frazil generation. As the frazil ice is transported downstream ice flocs and eventually floes are developed (see Figure 1). When an obstruction (e.g., bridge, ice boom, and ice sheet) is reached, significant frazil ice accumulation can occur resulting in a freeze-up jam. Freeze-up jams can also initiate at locations where the river channel geometry changes (e.g., bend and slope from steep to mild). Figure 7 shows an example of a typical freeze-up jam cross section.

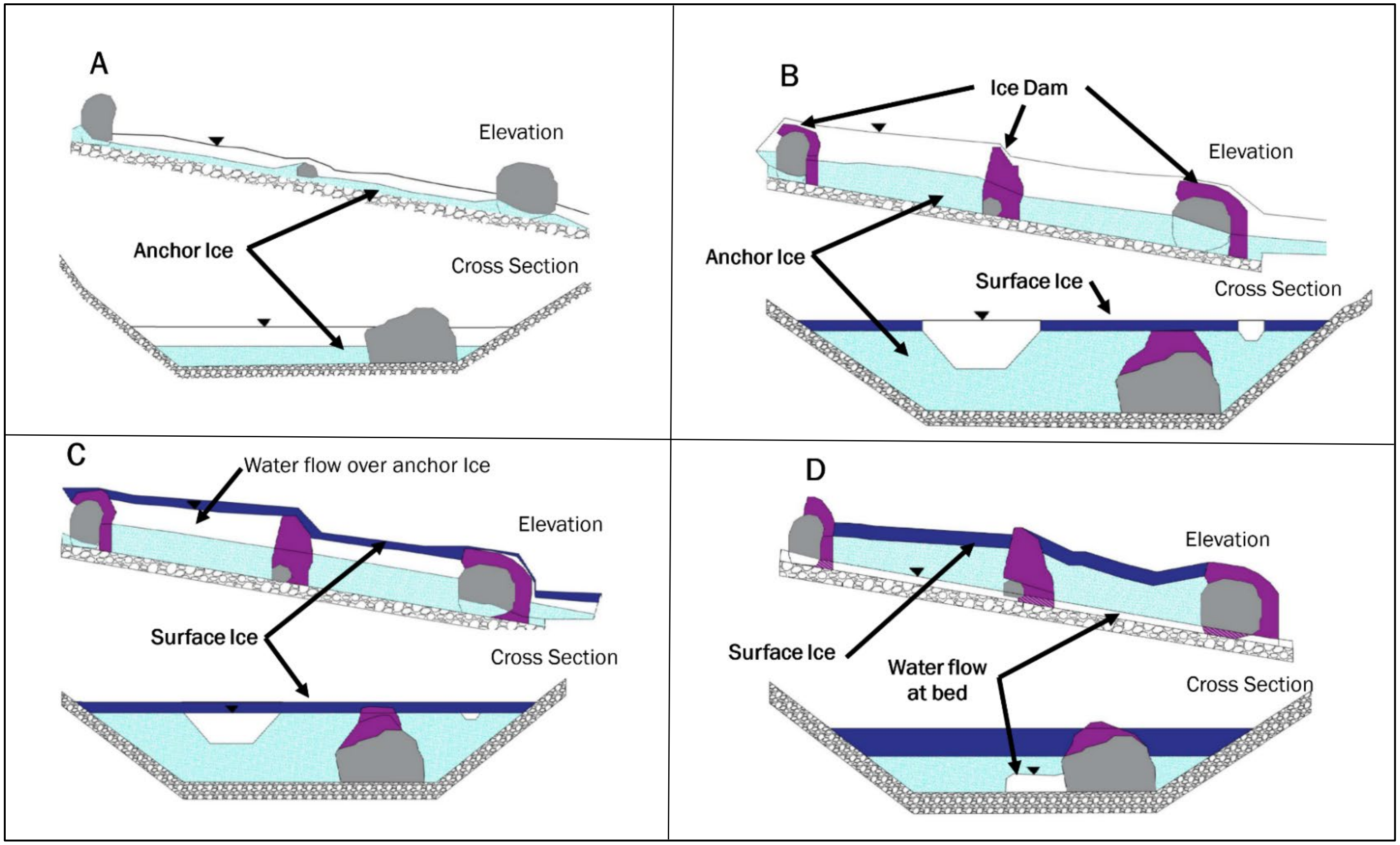
Figure 7. Diagram of freeze-up jam cross section.



Frazil ice can also result in freeze-up jams which are formed when frazil ice deposits on the channel bottom as anchor ice to form *anchor ice dams* (Figure 8) (Kempema and Ettema 2011). Anchor ice dams are relatively rare and usually occur in steep, shallow rivers and streams (Rødtang et al. 2021). In Alaska, a case study on Ship Creek near Anchorage, Alaska was completed in 2019 (Daly et al. 2019) which analyzed the formation processes of anchor ice and anchor ice dams. Schematics in Figure 9 (*A*–*D*) show a systematic development of the typical ice dam process beginning with anchor ice formation along the bed (*A*) and progressing through increasingly greater ice accumulation on cobbles and boulders (*B*–*C*) until only a small subanchor ice channel is available for flow (*D*). Anchor ice dams can result in significant upstream stage rise but are relatively short in duration since continued exposure to supercooled water is needed for the anchor ice to remain attached to the bottom of the river channel (Daly et al. 2019; Kempema and Ettema 2011).

Figure 8. Frazil ice dam on Willow Creek in Willow, Alaska.

Figure 9. Anchor ice dam progression concept. (Image reproduced from Daly et al. 2019. Public domain.) Early-stage anchor ice formation along stream bed (*A*). Ice dam formation around large cobbles or boulders with subsequent rise in water level and some surface ice development (*B*). Full ice-cover formation across the channel (*C*). Ice dam breaching and anchor ice detachment. Note flow along stream bed at this stage (*D*).

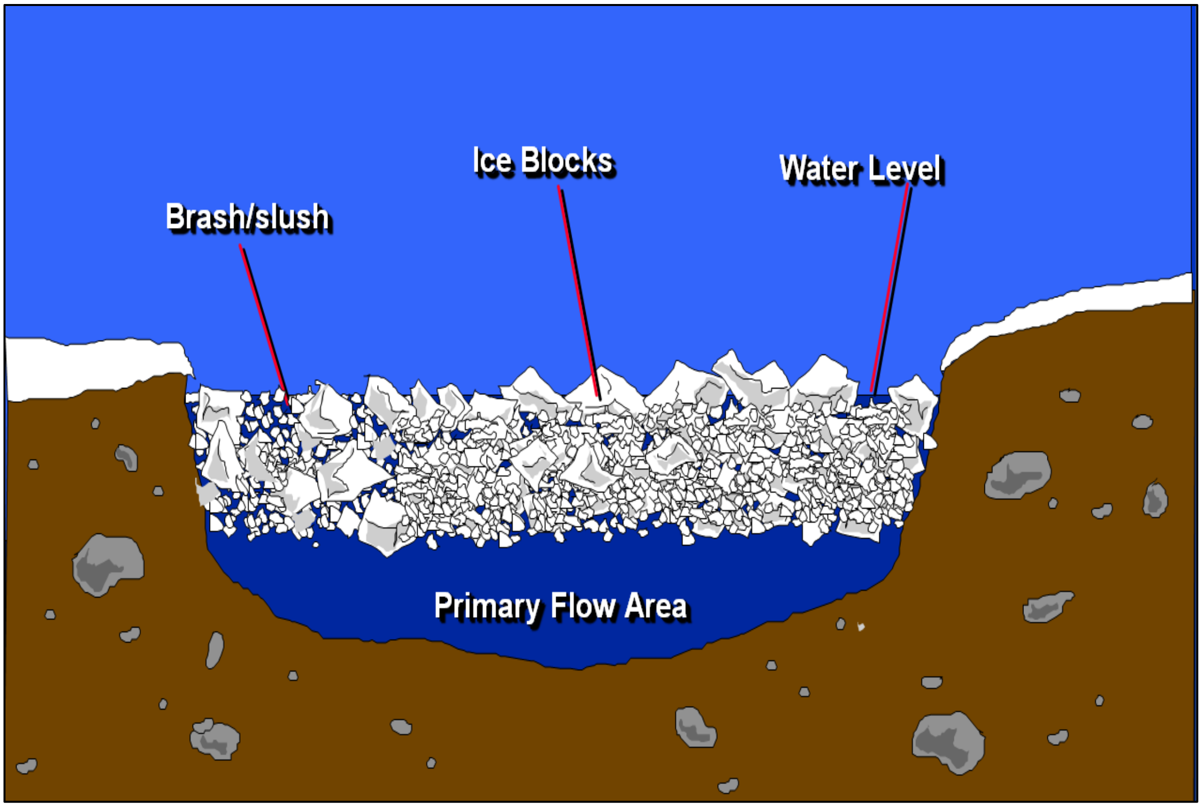


Water intakes can experience significant problems with frazil ice if they are operated when the water is supercooled. The crystals in the supercooled water will be growing in size and will stick to any object they contact—including intake trash racks—as long as these objects are at a temperature below freezing (Daly 1991; Daly and Ettema 2006; Richard and Morse 2008). Given the effective heat transfer rates provided by flowing water, any object in the water that is not heated will quickly be at the temperature of the supercooled water and will accumulate frazil. Sufficient frazil can accumulate on the trash rack to effectively block it and completely stop the flow of water into the intake, often with severe consequences (Daly 1991).

2.3.2 Breakup

Breakup ice jams (Figure 10) are usually formed when fragmented ice (e.g., blocks or brash) from a previously intact ice cover or freeze-up jam is broken up by changes in hydrologic conditions. Rapid rises in river discharge from rainfall or snowmelt runoff can result in hydrologic conditions sufficient to cause ice breakup. A breakup jam will occur when the ice fragments being transported downstream exceed the ice carrying capacity for the river flow in that specific location. Obstructions can alter the ice carrying capacity over a relatively short reach. The obstruction can be an intact ice cover, bridge, or channel geometry or channel slope change. The jam thickness and subsequent upstream water level impacts will depend on several factors including ice supply, ice strength, and shear strength of the channel banks (USACE 2002).

Figure 10. Diagram of break-up jam cross section.



2.4 Ice cover breakup

The seasonal disappearance of ice (commonly known as breakup) across North America can generally be described by two processes, either thermal melt-out or mechanical breakup. Thermal melt-out consists of the river ice cover deteriorating through warming and the absorption of solar radiation. This process melts the ice in place, with no increase in flow and little or no ice movement. Mechanical breakup results from the increase of flow entering the river and uses the hydrodynamic forces to break the ice into fragments. Actual breakup is usually a combination of both processes and often takes place during warming periods, when the ice cover strength deteriorates to some degree and the flow entering the river increases because of snowmelt or precipitation. When breakup trends more toward a mechanical breakup process, large volumes of fragmented ice can result in jams which produce potentially dramatic and dangerous increases in river stage (Beltaos 1995; USACE 2002).

2.4.1 Thermal melt-out

Across North America thermal melt-out will ultimately be the breakup mechanism if mechanical breakup does not occur. Thermal melt-outs vary spatially depending on the latitude, local climate, and ice exposure. Thermal melt-outs are a result of heat transfer primarily through convection from the water underneath the ice, by convection from the warm air passing over the top of the ice surface, and radiation, both longwave (infrared) and shortwave (sunlight) (USACE 2002). As the hours of daylight increase areas of open water can absorb substantial energy from solar radiation. This results in relatively warmer water passing beneath the ice cover and transferring energy to the ice, thus melting the ice from underneath. Additionally, as meltwater pools on the ice surface, the albedo (proportion of solar energy reflected) will significantly decrease and therefore result in increased energy absorption in the top of the ice from sunlight. Internal deterioration of the ice can occur without significant loss of thickness if solar radiation is able to penetrate into the ice cover. However, fine-grained ice covers, composed of snow ice or frazil ice, are less likely to deteriorate through penetration of solar radiation because of increased opacity (USACE 2002).

2.4.2 Mechanical ice cover breakup

In most rivers, breakup occurs first on smaller tributaries, and then proceeds to the main stem rivers (USACE 2002). This process can result in several ice jams forming as ice fragments are transported downstream and collide with intact ice cover. Mechanical breakup initiation, progress, and ice jam severity will be dependent on the ice conditions, river morphology, meteorologic and hydrologic conditions. The precise mechanical breakup conditions will be unique each year, but overall breakup sequences may have specific patterns for each river system.

3 Ice Jam Flooding in Alaska

3.1 History of ice jam flooding in Alaska

Ice jams have been occurring in Alaska for as long as it has undergone freeze–thaw cycles, but the first documented ice jam was at the mouth of the Porcupine River near Fort Yukon in June of 1889. Since then, hundreds more have taken place throughout Alaska waterways contributing major impacts to local ecosystems as well as damages to human establishments. A total of 1,435 ice jams have been recorded in Alaska between 1889 and 2022 (Figure 11), and over 73% of the recorded jams happened in May—85% if April is included (White and Eames 1997) (Figure 12). In more recent years (2000 through 2022) the distribution of ice jams between April and May has shifted slightly to 61% of jams occurring in May and 18% in April. Since most ice jams happen in the spring, that suggests most of the ice jams in Alaska are break-up jams. Intuitively, the vast region of Alaska imposes natural limitations on the amount of ice jams actually documented compared to other high ice-jam frequency states like Minnesota or Wisconsin. Population densities in Alaska are isolated to municipalities like Anchorage, Fairbanks, Juneau, and communities in the Matanuska-Susitna Borough; and, despite much of the remaining villages and settlements being located on or near river systems, most of the land space in Alaska remains unoccupied. As White and Eames (1997) note,

> The number of ice jams reported in the database in certain years largely depends on the jam location and availability of jam records. For example, in 1991, one of the more populated areas, Fairbanks, experienced extensive ice jam flooding. As a result, news stories and other publications emphasized ice jam occurrences everywhere in Alaska more than usual that year, and 55 ice jams are recorded in the database for 1991.

Ice jams as a function of geographic location, quantitative magnitude, and stream order or depicted in Figure 13. Many of the jams are proximal to higher population densities such as Anchorage or Fairbanks. Rivers under more frequent observation may be biased in their indication of greater quantities of ice jams. An example is the National Weather Service Alaska-Pacific River Forecast Center's (NWS-APRFC) Riverwatch program which monitors ice conditions for the Yukon and Kuskokwim rivers.[2] Notably, higher order streams do not necessarily indicate higher presence of ice jams strictly based on their size. The Kobuk and Kuskokwim rivers demonstrate comparable numbers of ice jams to the Yukon River though it is a higher order (Figure 14). Generally, stream order is the measure of the position of a stream in the sequential series of streams that combine to form the river network, and it is usually indicated with a positive integer (Wohl 2019). Lower stream order values indicate smaller waterbodies.

Figure 11. Ice jams reported in the Cold Regions Research and Engineering Laboratory (CRREL) Ice Jam Database (IJDB) for Alaska (1889–2022).

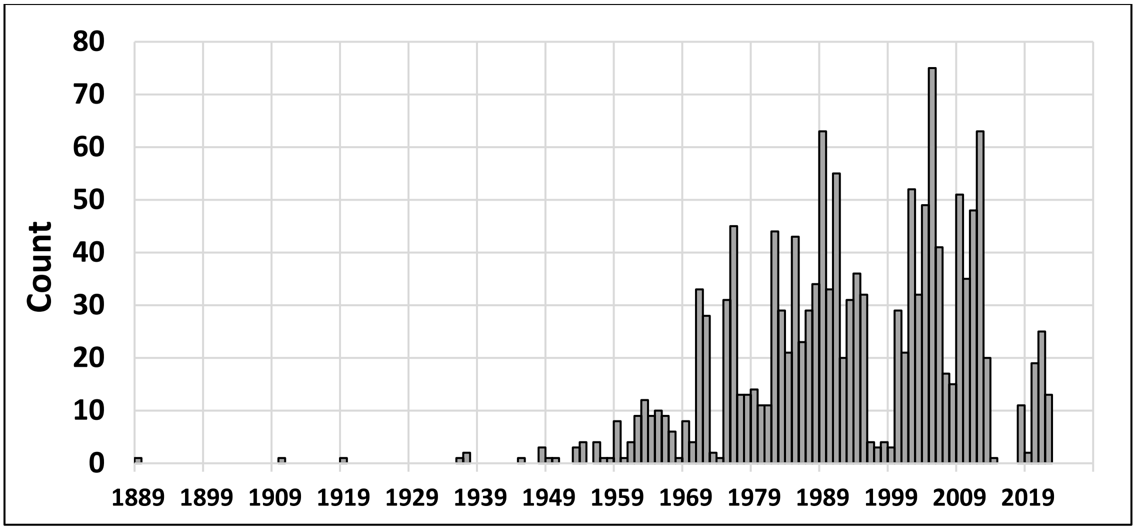
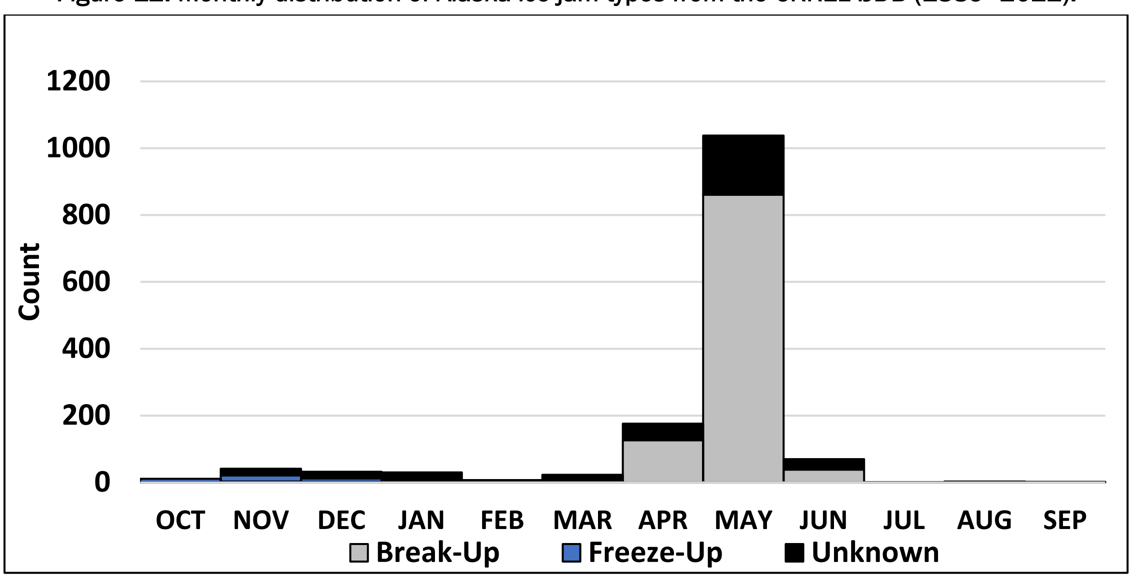


Figure 12. Monthly distribution of Alaska ice jam types from the CRREL IJDB (1889–2022).



2 https://www.weather.gov/aprfc/.

Figure 13. Ice jam count intensity based on events in CRREL IJDB. The three Alaskan Rivers with the highest ice jam counts are highlighted (1889–2022).

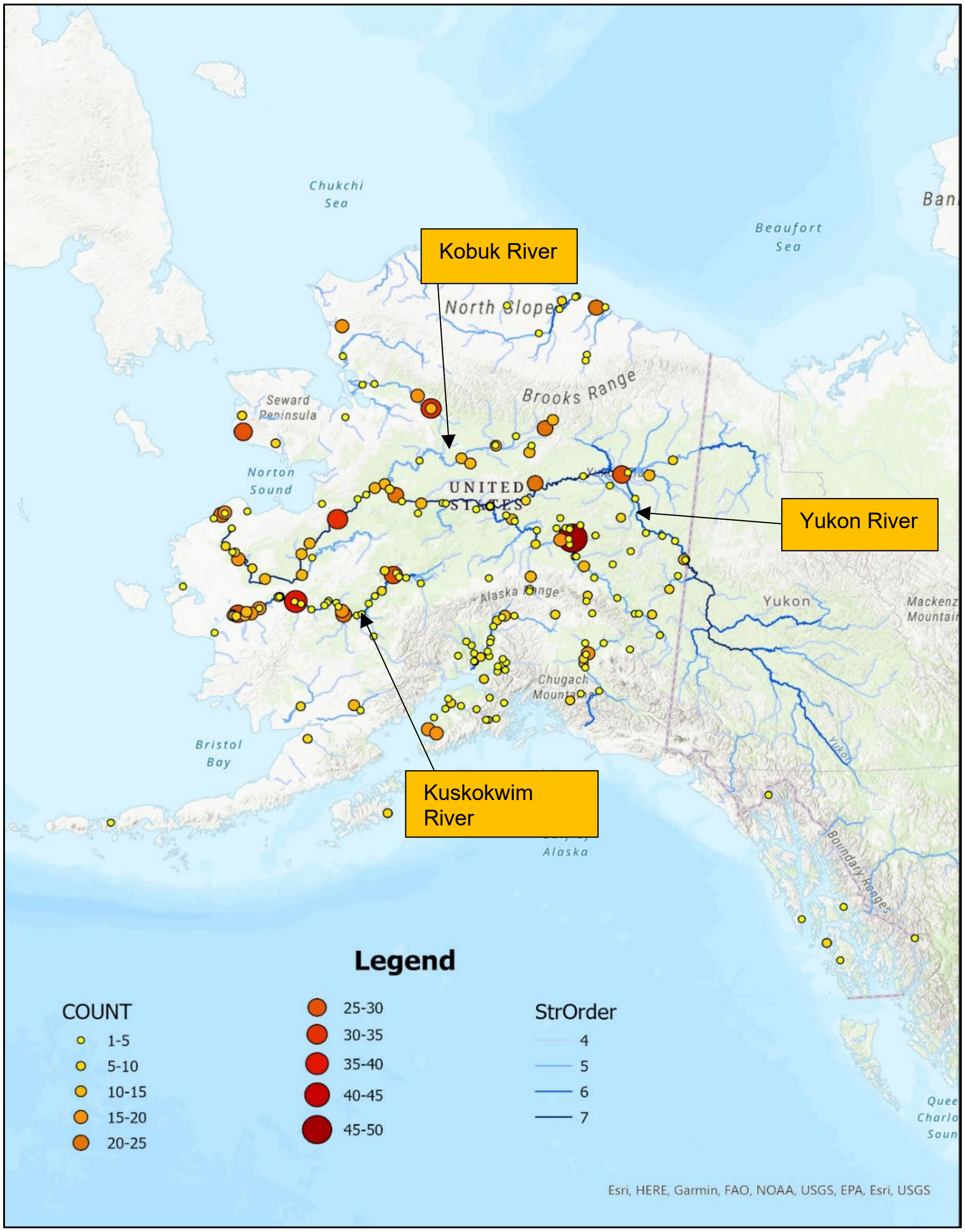
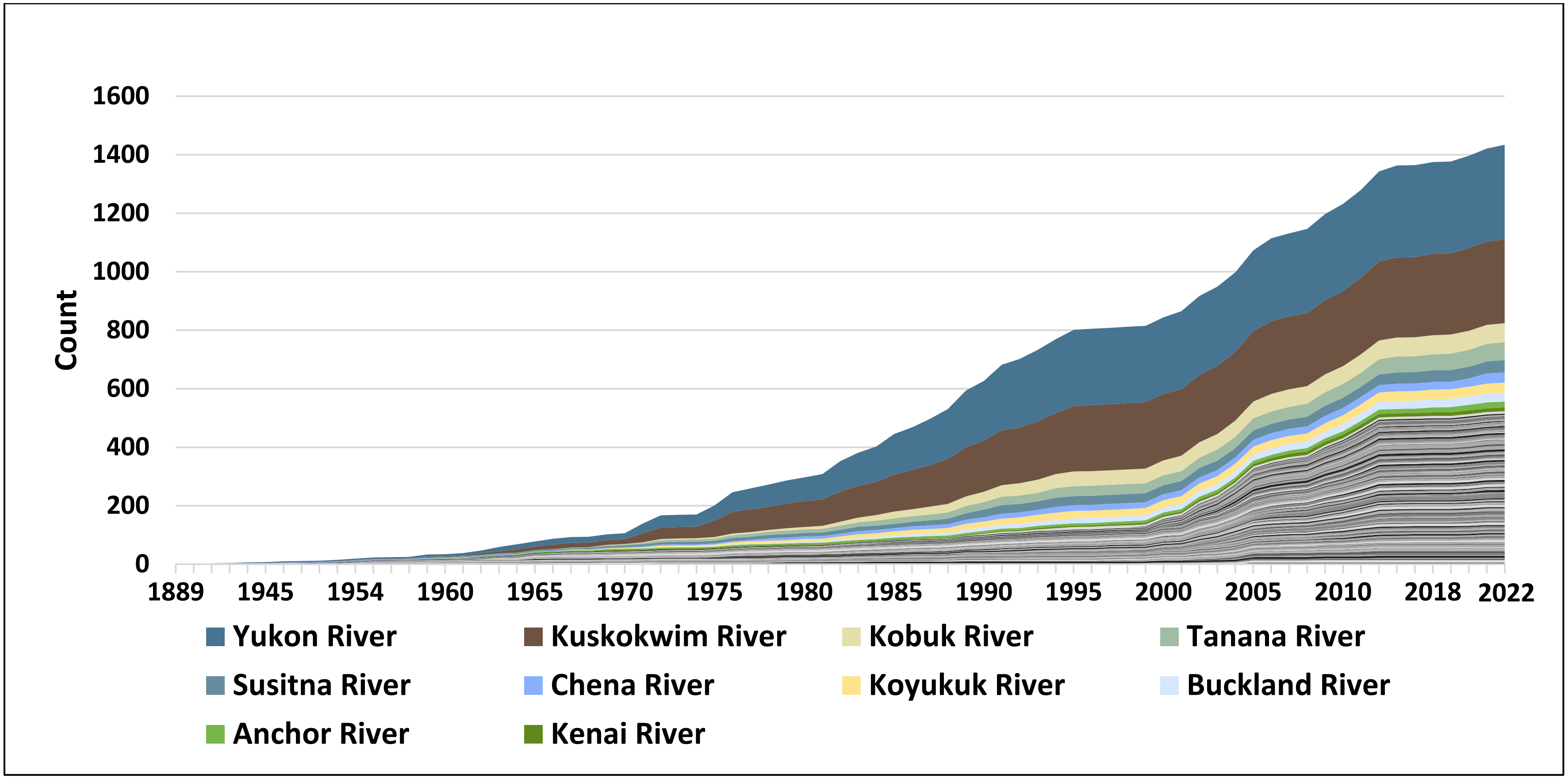


Figure 14. Cumulative breakdown of jams by river in Alaska from the IJDB (1889–2022).



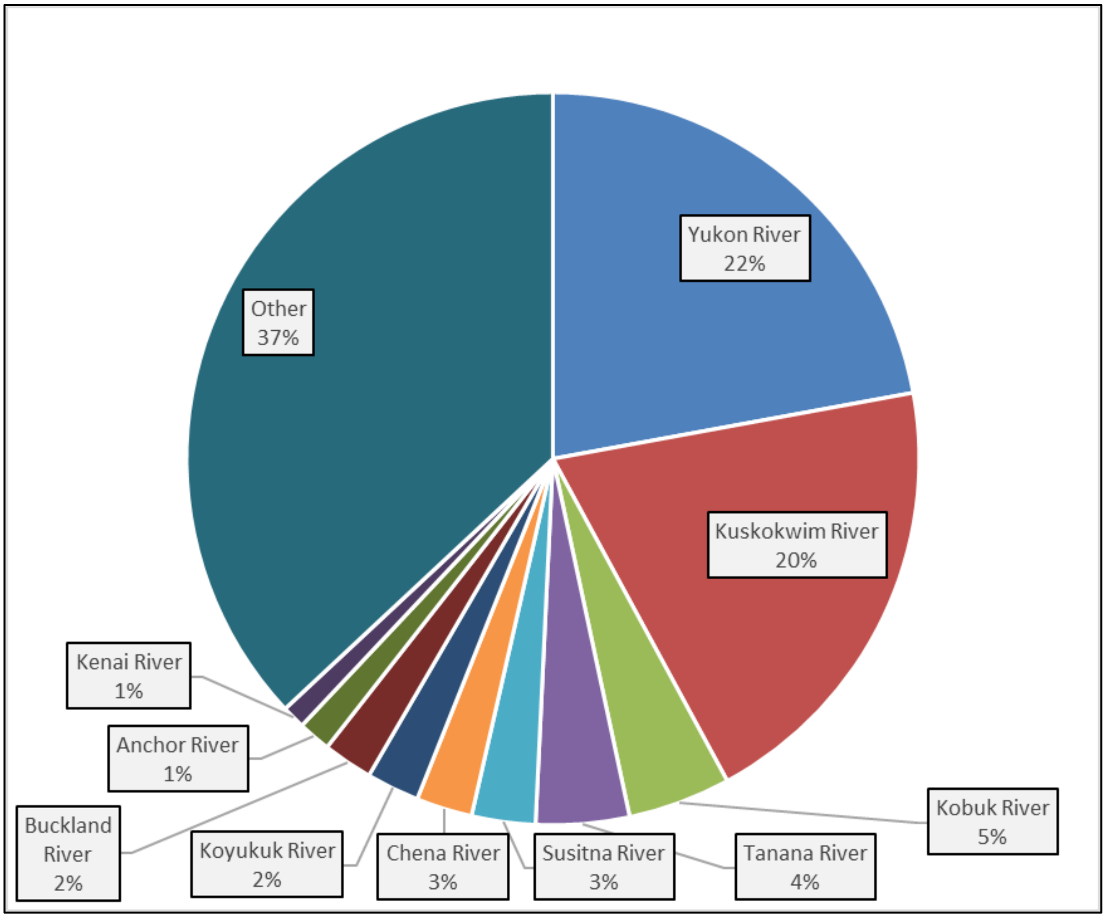
3.2 Cold Regions Research and Engineering Laboratory (CRREL) Ice Jam Database (IJDB): Alaska Records

The CRREL IJDB[3] is an online repository developed to record national ice jam events for use by officials, researchers, and emergency managers. The IJDB currently contains records of over 23,000 reported ice jams in the United States. A typical ice jam record includes the affected water body, the location of the event (city, state, and coordinates), the date of the event, the type of ice event (breakup, freeze-up, or unknown), a description of the damage, and the source of the jam information (Carr et al. 2015). Ice jam events are added to the IJDB based on reports from many sources, including National Weather Service reports, newspaper, television, social media, observer reports, and USGS gage records. This results in a natural bias toward developed areas and infrastructure, and events that do not cause social or economic impacts are more likely to go unreported and unlogged in the IJDB. The database should be viewed as a collection of identified ice jams rather than a complete record of all ice-impacted high water events (White and Eames 1999).

As of the end of water year 2022, IJDB contained records from 224 different locations on 167 rivers in Alaska. About 65% of the recorded jams occurred on 10 rivers with the remaining jams dispersed across smaller rivers throughout the state. The top 2 rivers with the most recorded ice events are the Yukon with 383 jams, and the Kuskokwim with 301 (Figure 15). These rivers have significantly higher recorded ice jams than any other river; the Kobuk is the closest to them with 66 recorded jams (Figure 15).

[3] https://icejam.sec.usace.army.mil/

Figure 15. Ice Jam distribution by river based on IJDB records (1889–2022).



3.2.1 Yukon and Kuskokwim ice jam distributions by community

In part because the rivers' sizes and in part because of the number of communities along each, the Yukon and Kuskokwim Rivers claim the most ice jams of all the rivers in Alaska. Figure 16 and Figure 17 breakdown the distribution of ice jams by community along these two rivers. For the Kuskokwim (Figure 16), Aniak Village holds a significant lead at 35 ice jams—between 1953 and 2022—which is notably greater than most other communities along both the Kuskokwim and Yukon. Along the latter, the community of Circle holds the most ice jams at 24 followed closely by communities of Fort Yukon and Emmonak with 22 ice jams each (Figure 17).

Figure 16. Location and frequency of jams along the Kuskokwim River from 1953 to 2022.

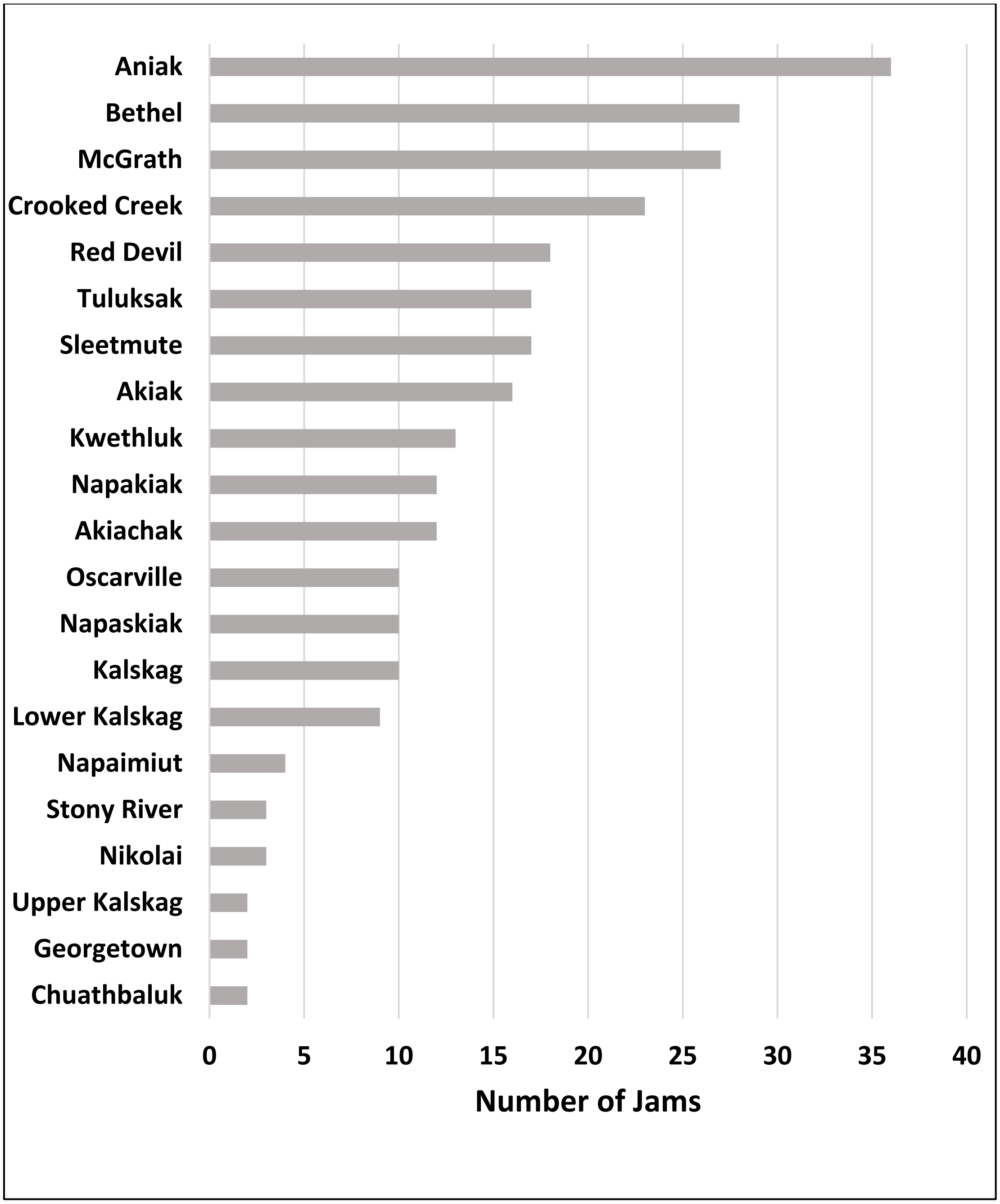
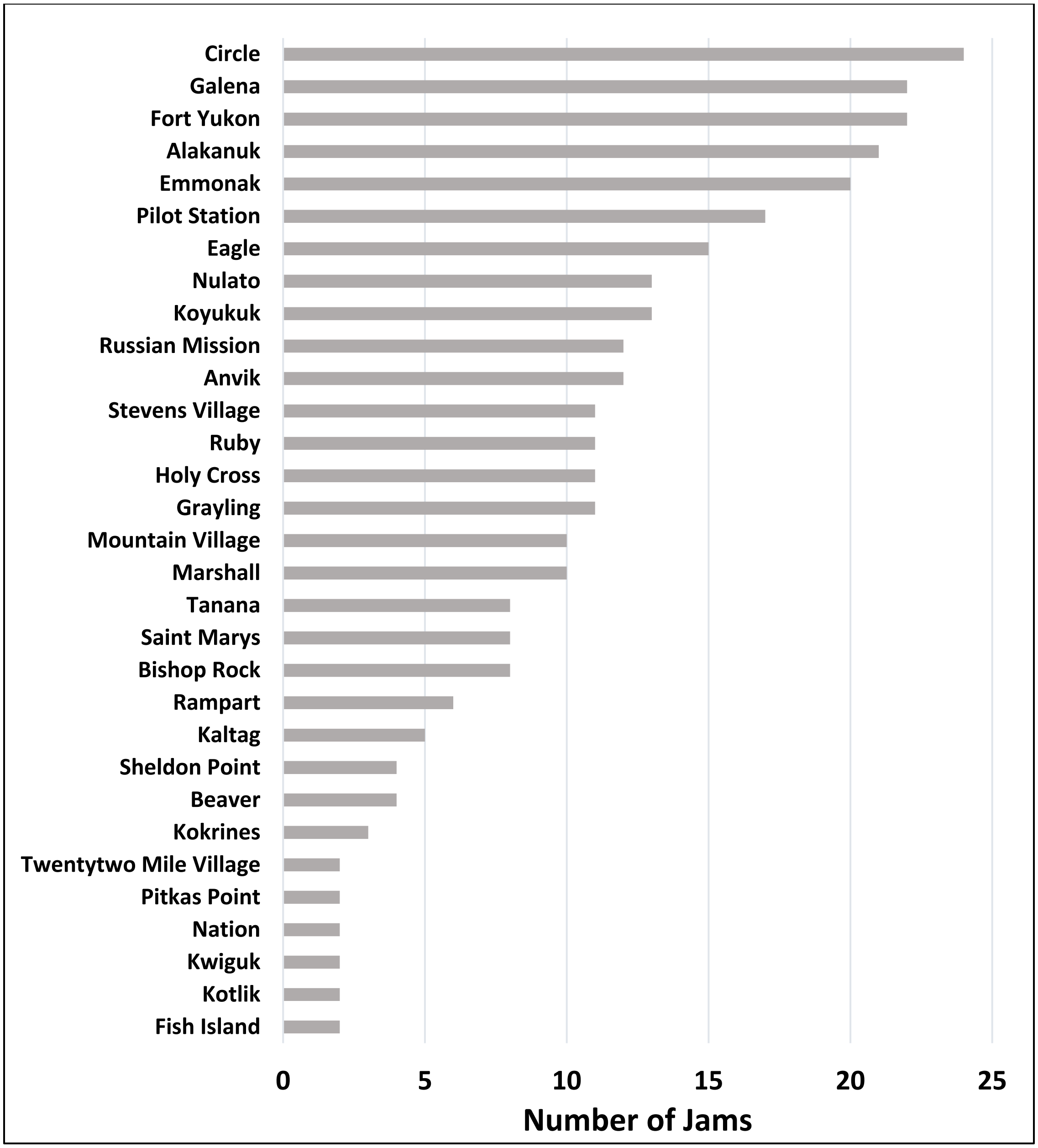


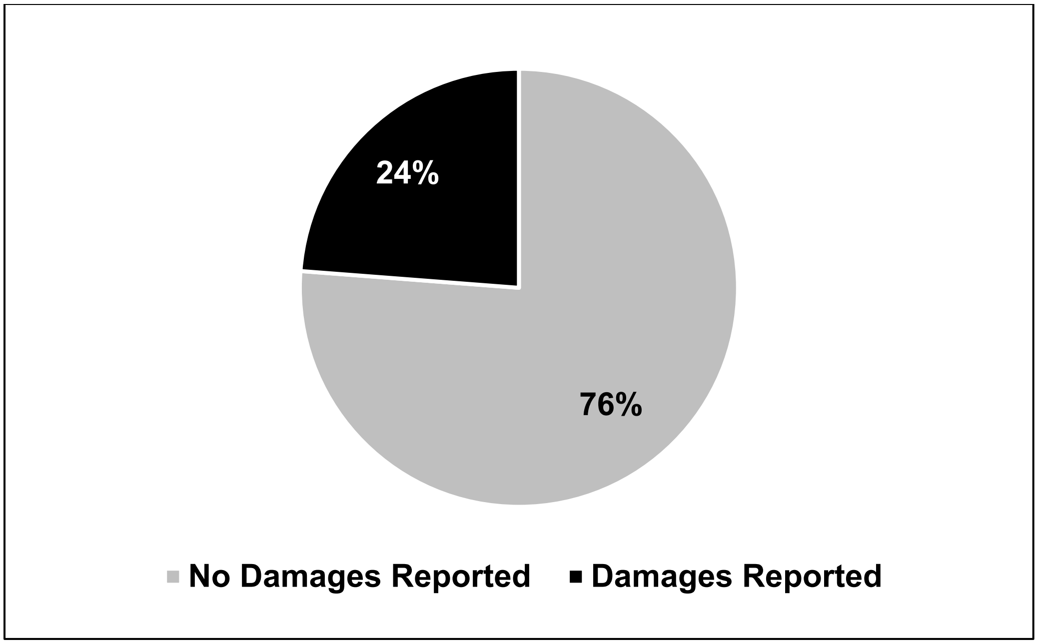
Figure 17. Location and frequency of jams along the Yukon River from 1936 to 2022.



3.2.2 Ice jam flooding damages

One of the main ways ice jams affect communities is flooding which can cause a variety of damages that impact people, resources, and infrastructure. Of the 1,435 ice jams recorded in Alaska, 351 have information on damages. Jams that have reported damages are mostly house or road related damages. Other damages reported include evacuations and airport related infrastructure (Figure 18).

Figure 18. Percentage of jams that have damages reported for Alaska in the IJDB from 1889–2022.



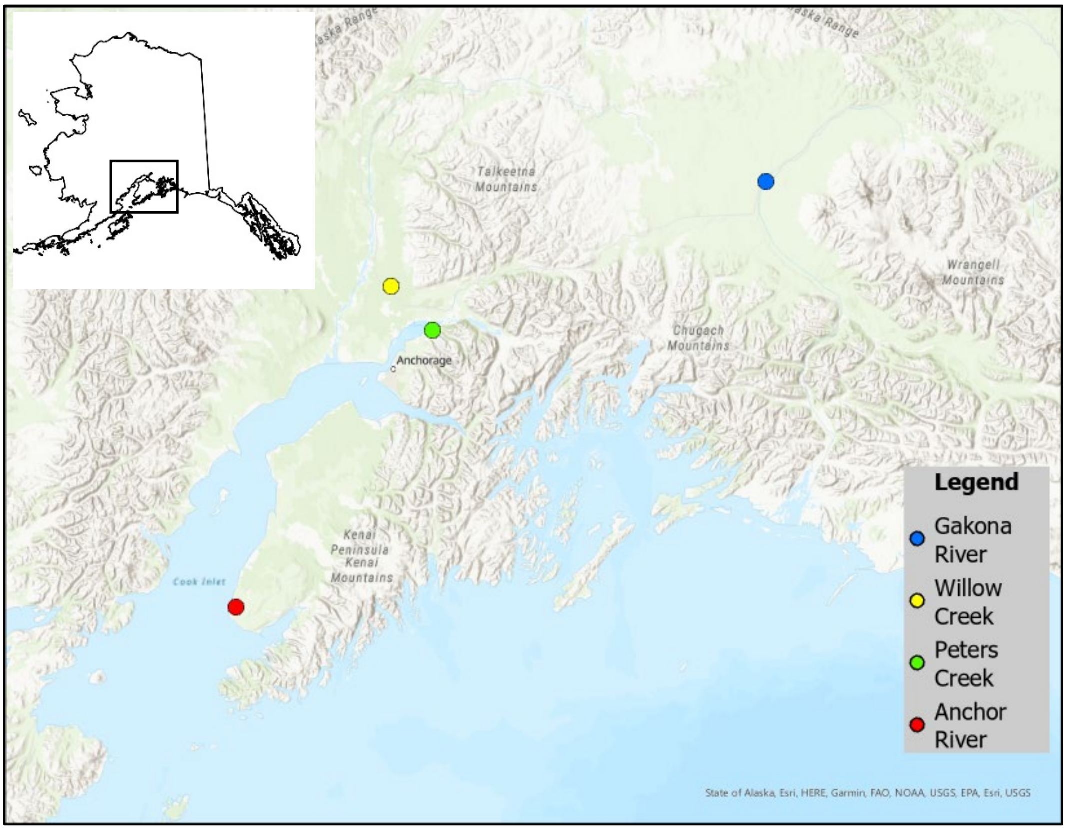
A unique case in the subsequent effects of ice jam buildup occurred during 1963 in Fairbanks, Alaska when the USACE used dynamite to blast apart an ice jam which threated facilities and grounds of then Ladd Army Airfield. The result of the blasting caused the release of a large volume of water and ice flows which damaged several vessels moored downstream (Peterson versus United States 1963). The owners of the vessels sought to recover money damages, but the case was not ruled in their favor. The case highlights the potential challenges caused by blasting an ice jam in a densely populated area. Along with vessels the large mass ice can also damage near-shore property. Finally, the effectiveness of blasting is highly dependent on downstream conditions (USACE 2002) and subsequent ice jams forming downstream can still be possible.

More recently, in May 2022 an ice jam along the Tanana River near the remote town of Manley Hot Springs, Alaska caused major flooding which partially submerged at least half of the homes in that community. Residents were forced to evacuate, and when flood waters began to recede, were left with damages to fuel and food supplies (Rockey 2022). In this case, no intervention occurred.

3.3 Case studies

The following case studies highlight areas of interest in Alaska that have been subject to various ice jam events. The cases selected highlight both major ice jam types—freeze-up and breakup—as well as unique mitigation techniques in the historic cases of Gakona River and Peters Creek. The geographic location of each river system is shown in Figure 19.

Figure 19. Ice Jam events across south-central Alaska.



3.3.1 Willow Creek

Data obtained from the CRREL IJDB for Willow Creek between 1986 and 2022 found that the creek experienced 6 ice jams with 2 being freeze-up jams, 2 breakup jams, and the other 2 being of unknown type. For the 2 unknown and the 2 freeze-up events, backwater because of river ice was reported which suggests that, despite 2 events being labeled as unknown, they behaved as freeze-up jams. In a recent case of a Willow Creek ice jam in 2019 (Figure 20), emergency officials evacuated some residents from their homes, and indicated that the ice jam was because of a rapid dip in regional air temperature (Matanuska-Susitna Borough 2019). Starting on 20 December 2019 air temperatures plunged to −24.4°C

(−12°F) by 21 December 2019 at the Point Mac weather stations (NOAA 2022). The extreme cold resulting in rapid ice accumulation was followed by a relatively fast warm-up starting on 27 December 2019. The air temperature climbed from −20.5°C (−5°F) to over 7.2°C (45°F) by 31 December 2019 (NOAA 2022).

Figure 20. Willow Creek ice jam event, 2019. (Image reproduced with permission from Stefan Hinman/Matanuska-Susitna Burrough.)

3.3.2 Anchor River

Data obtained from the CRREL IJDB for the Anchor River between 1959 and 2022 found that the river experienced 22 ice jams 12 of which were breakup jams, 1 freeze-up jam, and the remaining types not recorded or unknown. During the final days of 2015 and the first days of 2016, the Anchor River experienced a breakup ice jam inducing flooding which caused minor damages to some residences, flooded a nearby campground, and flooded parts of a nearby road (Figure 21) (Eaton 2015). It was attributed to warm temperatures and an overnight rain, abnormal occurrences for that time of year.

Figure 21. Aerial view of Anchor River ice jam, 2016. (Image reproduced with permission from Casey Fetterhoff.)

3.3.3 Gakona River

Data obtained from the CRREL IJDB for the Gakona River between 1953 and 2022 shows that the river experienced 17 ice jam events over that period, all of which were break-up jam events. In all these occurrences accept the earliest which occurred during late March of 1953, the breakup jams fell within the expected time frame of April and May. More recently, a large ice jam was recorded by the owners of a local lodge during which there was some flooding. During the breakup the owners reported that ice blocks shook the bridge when they collided with the concrete pillars (Figure 22) (Gakona Lodge Owners, pers. comm.). Figure *A* shows the broad view of the ice jam event, and *B* shows a sizeable ice block lodged against a bridge pier.

Figure 22. Gakona River ice jam, 2017 (*A*); ice blocks lodged against bridge piling during the aftermath of the 2017 Gakona River ice jam (*B*). (Images reproduced with permission from Gakona River Lodge.)

3.3.4 Peters Creek

Data obtained from the CRREL IJDB for Peters Creek found a total of two recorded ice jam events of unknown type which occurred during November in both 2006 and 2017. According to discussions with individuals familiar with the area, the reach experiences freeze up conditions regularly with accumulations of anchor ice significantly reducing the flow area of the natural channel, causing routine shallow out of bank flooding (Jeff Urbanus, Anchorage Borough, pers. comm., 2023). Given the frequent nature of the ice accumulation, locals have become accustomed to the issues and freeze-up jams are likely underreported here. Figure 23 shows the accumulation of anchor ice the channel and frazil accumulation on the banks, restricting flow, and causing it to flow at a stage higher than normal.

Figure 23. Peters Creek anchor ice formation, December 2022.

4 Ice Process Monitoring

4.1 Remote sensing of ice coverage

4.1.1 Satellite remote sensing technologies

Remote sensing of river ice behavior using satellite constellations is becoming more feasible because of decreased space access cost, as well as advancements in the observational technology available for satellite payloads (Vitug 2020). Satellite remote sensing can also classify ice covers, determine breakup time, characterize breakup progression, and determine breakup initiation points (Altena and Kääb 2021). These features of satellite remote sensing could aid response agencies in implementing mitigation and response plans to ice jams in Alaska. Select satellite systems and their products and benefits are discussed here, and links to each systems data is in Table 2. The revisit interval for higher latitudes like Alaska for these systems is generally higher (less time) compared to CONUS (Li and Chen 2020).

Table 2. Data access links for satellite systems that have been used in previous studies to monitor river ice.

Satellite System	Data Access
RADARSAT-1	https://www.asc-csa.gc.ca/eng/satellites/radarsat1/
Sentinel-1 and Sentinel-2	https://scihub.copernicus.eu
PROBA-V	http://proba-v.vgt.vito.be/en/product-access
MODIS Snow cover products	https://modis-snow-ice.gsfc.nasa.gov/
MODIS Sea Ice Extent and IST	https://modis-snow-ice.gsfc.nasa.gov/?c=MOD29
VIIRS	https://realearth.ssec.wisc.edu/

Several studies using satellite or satellite constellations to characterize river ice behavior have been conducted. One such study concentrated on the collaboration between two satellite constellations—Sentinel 2 and PROBA-V—to quantify river ice movement in near real time and demonstrated the "potential of extracting river ice movement from a combination of low and medium resolution satellite sensors in sun-synchronous orbit" (Altena and Kääb 2021). In this case, the orbital path similarities, and the onboard instrumentation of both systems, when united, provided an optimal sensing arrangement for detection and monitoring of river ice. The Copernicus Sentinel-2 mission focuses on land cover and change classification, atmospheric correction, and cloud and snow separation and caries a Multispectral Instrument payload

(SUHET 2015). The PROBA-V is ideal for monitoring plant and forest growth as well as inland water bodies and carries a multispectral push-broom spectrometer with four spectral bands (Sterckx et al. 2014).

Another relevant remote sensing system is the Moderate Resolution Imaging Spectroradiometer (MODIS) which is the primary element on board two satellites—the Aqua and the Terra—collecting cryosphere data related to snow and ice. (Hall et al. 2015). It has been used in at least two cryosphere studies producing usable products identifying snow covered land and snow-covered inland ice (Hall et al. 2006) as well as sea ice extent and ice surface temperature (Hall and Riggs 2015), and these products are available daily (Table 2).

The Visible Infrared Imaging Radiometer Suite (VIIRS) system has been used to successfully generate near real-time flood detection products that have been used by forecasters in many regions around the world (including Alaska) to forewarn of ice-jam flooding events (Li et al. 2018). The interactive animation and forecast tool is maintained by NOAA at the University of Wisconsin (Table 2).

Two studies have been conducted with Sentinel-1 SAR (Synthetic Aperture Radar) data (Stonevicius et al. 2022) and RADARSAT data (Lindenschmidt et al. 2010) which demonstrated the applicability of both systems to monitoring river ice behavior. In the former study, Sentinel 1 SAR data was used to determine ice presence of river ice in narrow sections of Lithuanian rivers under cloudy conditions, and in the latter, RADARSAT imagery was used to evaluate ice thickness along sections of the Red River in Canada and the US. In general, SAR techniques perform well for monitoring river ice behavior in cloudy environments because of its ability to penetrate cloud layers. This has also been shown in studies such as Jasek et al. (2003) and Mermoz et al. (2014) which also show how SAR techniques can be used to determine river ice thickness. In both studies, satellite imagery was used to determine ice thicknesses (and subsequent ice thickening rate in the former) at multiple Canadian rivers. In addition, cloudy conditions did not prevent the collection of meaningful data.

4.1.2 UAVs

At least two studies have used UAV systems to observe river ice behavior in Manitoba, Canada (Clark and Wall 2016) and in Alaska (Cherry 2021).

From an observational standpoint, UAVs (also known as drones) can provide imagery perspectives on river ice behavior (Figure 24) otherwise unavailable from other observational platforms such as satellites or crewed aircraft. Operational range and logistical access issues prevent drone systems from being used along most rivers' full extents or in remote areas; however, locations easier to access may be associated with more populated areas subsequently of higher interest from a disaster management perspective. Additionally, Cherry (2021) noted that UAV performance was limited by temperature and wind factors that would not otherwise limit crewed aircraft.

Figure 24. UAV-sourced orthomosaic of Peters Creek, Alaska, November 2020. (Image reproduced from Cherry 2021. Used with permission.)

4.2 Detection of ice movement

4.2.1 Time lapse photography

From a mitigation standpoint, time lapse photography can be an effective tool for predicting ice jam extent. Game cameras can be used for such monitoring, and number of rivers are currently being monitored in Alaska. The Fresh Eyes on Ice program operated by the University of Alaska

Fairbanks has 12 cameras on 9 rivers in Alaska. The cameras are configured to update multiple times daily.[4]

Monitoring every area of interest along numerous rivers across Alaska is logistically challenging; however, where a river's reach approaches populated areas, strategic placement of monitoring cameras could provide rapid, high-quality information about ice jam behavior in that area.

4.2.2 Automated image processing

Automated image classification is an extension to other forms of image collection. Traditionally, images collected by shore-based cameras used operationally require regular review from a human to interpret the image, note, and potentially document any useful observations such as advancing ice cover or presence of open water. Image archives are also used to assemble time series of useful data such as ice presence for model validation (Giovando et al. 2019). Both use-cases require somewhat tedious review of the media.

Hamill et al. (2019) demonstrated the utility of machine learning to automatically classify images of ice monitoring cameras located on the Pend Oreille River in Idaho. A portion of the images were used to train a deep neural network to identify ice, snow, water, terrain, and vegetation. The model could then be applied to future images to automatically detect changes in ice coverage. The results from Hamill et al. (2019) indicated over 80% accuracy for ice classification using machine learning methods. Kalke and Loewen (2018) also used machine learning (support vector machines) to effectively extract ice concentrations from a bridge mounted camera during the freeze-up period.

Automated algorithms to classify river ice have also been applied to satellite collected products including optical MODIS (Chaouch et al. 2014) and SAR (Palomaki and Sproles 2022). These methods are useful for larger river systems but are somewhat limited in application to smaller rivers because of the current spatial and temporal resolution of satellite-based products.

[4] To view the live feed, visit http://fresheyesonice.org/view-data/realtime-data/river-ice-camera/.

4.2.3 Ground based lidar and single beam

The CRREL Ice Engineering Group has recently experimented with a single beam rangefinder (SBRF) based system for ice monitoring (Figure 25*A*). The system was originally developed to make offset water level measurements using a rangefinder mounted on the shore and aimed downward at the river at an angle (Pitcher et al. 2019). The vertical distance of the stationary SBRF above the water surface is calculated using the angle of the beam, which the system measures with an internal inclinometer, and the SBRF's line-of-sight distance to the water surface. The stage of the water body is calculated as the vertical elevation of the SBRF's laser origin minus the calculated vertical distance it is above the water surface.

Figure 25. Example of single beam rangefinder (SBRF) installation position: SBRF instrument housing (*A*) and the SBRF placement next to the river with river ice present (*B*).

This system allows a stage measurement system to be installed at an accessible location that is not likely to be impacted by flood waters or ice movement, as in Figure 25*B*. A built-in telemetry system using either cellular or satellite communication transmits the stage at intervals that are defined by the user and that can be modified remotely. Since the SBRF uses a laser pulse to make measurements, it works in daylight and darkness.

The system collected quality returns from ice- and snow-covered river surfaces when tested on the White River in Vermont during the winter of 2020–2021 (C. Engel, CRREL, pers.comm. 2022). The main limitation of this system for use in ice run monitoring is that it measures single point on the ice cover. During an ice breakup event the ice cover is expected to rise as a water wave moves downstream, and the SBRF would be able to measure this and potentially issue an alert based on a user defined threshold of rise or rate-of-rise which would likely trigger breakup. During an ice run, as broken ice moves through the SBRF beam, the returns would likely become noisy though confidently relating this to an ice run event may be challenging.

Low-cost lidar sensors are emerging as another potential tool for ice monitoring. The mass-production of solid state lidar systems for autonomous vehicle applications has dramatically lowered the cost of lidar systems (Rapp et al. 2020). The CRREL Ice Engineering Group is planning to test prototype systems built around low-cost lidar sensors for ice monitoring and potentially early warning applications. In principle, the lidar-based systems will be deployed similarly to the SBRF described above, but will have the advantage of a wide field-of-view collecting distance data in a point cloud spanning a swath of the river. This will hopefully allow for detection of varying ice surface textures such as a transition from relatively smooth intact ice or snow-covered ice to broken and jumbled ice typical of an ice run. A major benefit of this type of system is that it can operate in darkness and collect 3D scenes of the river ice surface nearly continuously.

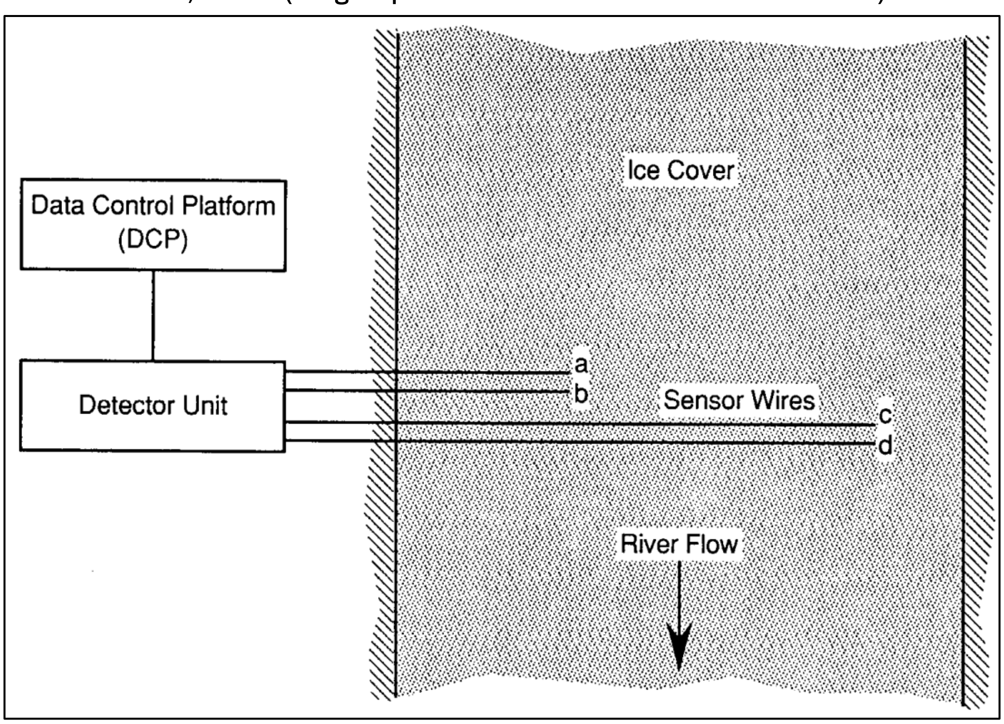
4.2.4 Trip wire ice motion detectors

Trip wire type ice motion detectors have been successfully used by CRREL on several ice prone rivers (Furman and White 2001; Zufelt 1993). These systems consist of a physical wire circuit which is installed in an ice cover during midwinter. The circuit is connected to a datalogger or telemetry system and is in a closed state until the wires are disturbed, and the circuit is broken. When ice begins to run, the wires will be either broken in the ice cover or torn from break-away connections on the bank. The datalogger records the date and time that the circuit was broken, and this can be relayed as an early warning signal. Multiple circuits could be connected to a single logger allowing for more than one specific location of a river to be monitored, limited by wire length and voltage considerations.

Figure 26 shows a schematic layout of this type of system, with a detector system connected to a data control platform that would serve as the communication node in an early warning system. Older versions would auto-dial a predefined phone number over a telephone line when the circuit was opened, but with the more widespread coverage of cellular networks, and availability of satellite communications these systems can be installed in more remote locations.

These systems are relatively simple, consisting mainly of the trip wires, and the logger and telemetry system in a weatherproof housing. If local power is not available, a battery or solar charging system would be required, and unless the trip wires are exceptionally long, the power demands should be quite modest.

Figure 26. CRREL ice jam motion detector using a trip wire; installed on the Kennebec River, Maine. (Image reproduced from Zufelt 1993. Public domain.)



4.3 Measurement of ice thickness

Ice thickness is one of the most important defining factors of an ice jam (Beltaos 1995), and a variety of methods exists to determine it. Manual measurements have been used the most extensively, but emerging technologies such as sonar are providing more options for greater spatial characterization. In Alaska, the National Weather Service maintains an interactive ice thickness webpage, which records thicknesses for select rivers and lakes across the state.[5]

4.3.1 Manual ice thickness measurements

Manual measurements of ice thickness may be a simple matter on small frozen lakes with static water surfaces but may be a more complex undertaking on medium or large rivers with constant flow throughout the year. In addition to the potential for more variable thickness, ice covers on such rivers may be jagged and uneven preventing general thickness quantification. One common toolkit for measuring ice thicknesses is the ice thickness kit. It is essentially comprised of an auger (which can be fabricated to desired length, but a typical length is 1 m), tape measure equipped with folding T-anchor at the zero mark, and extension rods (Ueda et al. 1975). Such kits are commercially available and have many variations to fit the user's needs. The auger can be driven manually with a hand crank or with gas or electric powerheads. Some modern power drills are powerful enough and have sufficient battery life to last up to 50 m of drilling depending on temperature conditions. Procedures for taking manual ice thickness measurements are comparatively simple in themselves but accompanying safety procedures can be more involved and may require a small crew of people to safely proceed. When operating the auger, it is recommended to extract the flight every 30 cm—keeping consistent clockwise rotation—to remove cuttings that could otherwise clog the hole. Cuttings should be swept away from the hole to reduce likelihood of falling into it. For greater thicknesses of ice (>1 m), a flashlight may be helpful when examining depth. When a power drill that uses a chuck, rather than a connector pin, is used for auger operation, it is recommended to have a flexible rubber ring greater than the diameter of the auger to be affixed to the top of the auger, below the drill connection point to prevent loss of the auger should detachment from the drill occur while the auger is downhole. Typical ice thickness kits included a tape

[5] https://www.weather.gov/aprfc/IceThickness.

measure affixed with a weighted T-anchor at the zero mark. To measure ice thickness, unfold the T-anchor and insert it parallel to the long axis of the hole. Once the T-anchor is under the ice, retract the tape until the T-anchor contacts the underside of the ice and record the thickness indicated on the tape. To extract the tape, apply tension force such that the T-anchor folds and can be removed through the hole. The safety aspect of taking manual ice thickness measurements can vary widely based on conditions. The University of Alaska Fairbanks has compiled an ice safety and resources webpage wherein instructional guides for manual ice thickness measurements can be found in video format.[6]

4.3.2 Ice thickness using sonar or ground penetrating radar

Acoustic imaging techniques (sonar) have been extensively used to model the ocean floor (Wille 2005), have been validated for their ability to measure ice thickness (Killen and Gulliver 1991), and have been used more recently to measure a number of freshwater ice characteristics including river (Ghobrial et al. 2012) and lake (Hawley et al. 2018) ice drafts—essentially, floating ice thickness below the water level. The latter two studies used the shallow water ice profiling sonar which was developed specifically to measure ice drafts in rivers. The instrument is positioned on the bottom of the river and faces upward, and Ghobriel et al. (2012) reported that both high (546 kHz) and low frequency sonar (235 kHz) were "suitable for monitoring surface ice conditions."

Ground-penetrating radar (GPR) has also been used to successfully determine ice thicknesses in freshwater, sea, and even glacial ice (Blindow et al. 2007). Commercial technologies are readily available with a variety of configurations and antenna frequencies customizable for the user.

4.3.3 Estimating ice thickness

While measuring ice thickness directly is preferrable, there are many instances which measurement is not feasible because of safety, access, or environmental conditions. If ice thickness is needed for analysis or modeling, the alternative is to use Equation 1 and meteorological information from a nearby ground station. In very remote areas, meteorological data that is representative of the project location may not be available. We recommend using reanalysis air temperature grids

[6] http://fresheyesonice.org/all-about-ice/.

instead. Datasets that maybe useful for this application are summarized by the USACE Hydrologic Engineering Center (https://www.hec.usace.army.mil/confluence/hmsdocs/hmsguides/working-with-gridded-boundary-condition-data/gridded-data-sources).

4.4 Predicting ice jams

Predicting ice jams is important because accurate predictions facilitate improved emergency response, increase flood prevention abilities, and more timely communication procedures around the event. However, accurate and repeatable prediction techniques are difficult to develop, and no ubiquitous technique exists to date. Some areas of rivers may be more prone to ice jams than others. Reaches with a decrease in river slope, natural or artificial channel constriction, decreased depth allowing ice to ground, and sharp bends are known to be more susceptible to ice jams (Beltaos et al. 2006).

Some forecasting and modelling techniques have shown promise for ice jam prediction. Ideally, generalized, site-transferable methods which can address all known ice-jam issues would be developed; however, the reality is that current prediction techniques are almost entirely site-specific and include variables of direct relevance to specific sites only. Additionally, a wide variety of forecasting and modeling techniques are available today, but many require enhancement for more generalized use. Madaeni et al. concisely summarize two types of modeling processes: numerical ice-jam prediction models and data-driven machine learning models, which show promise for predicting ice jams with better confidence (2020). They conclude that, though data-driven models can perform better than numerical models, both require observational data (either for calibration in the case of numerical models or for training in the case of the machine learning models), and both require more research to become operationally effective which emphasizes the importance of frequent and comprehensive data collection for ice-jam issues (Madaeni et al. 2020).

Numerical models can predict ice thickness, jam geometry, and backwater surfaces based on physical processes, and they can be adapted to inputs outside the historical record (i.e., to evaluate the effects of climate change); however, they need calibration to perform well at a given site, rely on accuracy of sometimes hard to measure input parameters, and show significant variability when used in a prediction mode. Some examples of these models include HEC-RAS (Daly and Vuyovich 2003), RIVJAM (Beltaos 1993), River1D (Blackburn and She 2019), DynaRice (Shen 2002), and RIVICE (Lindenschmidt 2017).

Three types of data-driven models have found popularity in hydrologic applications: artificial neural networks (ANNs), fuzzy logic systems (FL), and genetic programming (GP). The former two have demonstrated cost-effectiveness and flexibility in some areas of river ice processes, but GP has yet to be used for ice-related river problems (Madaeni et al. 2020). Some advantages of data-driven models over empirical and statistical methods include nonlinear solution boundaries, the absence of the need for normally distributed data (typically rare for environmental data), and the fact that there is no need to know the effects and trends of seasonal variation (Madaeni et al. 2020). However, sufficient generalization has not been achieved with data-driven models to produce skillful forecasts in locations with no historical information related to ice. For those locations that do have historical ice infomation, some data-driven models have demostrated promising forecasting abilities. For example, in Fort McMurray, Alberta, Canada along the Athabasca River, two types of FL systems qualitatively and quantitatively predict the maximum breakup water level under four "candidate indicators"—independent variables calculated ahead of river ice breakup having—with good prediction accuracy (Sun and Trevor 2015). In another example, an ANN developed for the confluence of Oil Creek and the Allegheny River near Oil City, Pensylvania predicted ice jam occurance with 94.1% accuracy and predicted no occurance with 92.6% accuracy (Massie et al. 2002). In both examples, historical data up to six decades prior were available.

5 Ice Jam Mitigation Techniques

5.1 Background

Ice jam mitigation measures are categorized as either structural or nonstructural. Structural solutions are generally reserved for reaches with chronic or serious flood risk issues related to ice jams. Because the planning, design, and cost of the structural measures is often substantial. Structural measures are implemented prior to an ice jam flood event. Conversely, nonstructural measures are intended to reduce vulnerabilities to flooding or the severity of the ice jam. These measures can be used in advance of flooding or during an active ice jam flood event (USACE 2002).

Alaska poses unique challenges to implementation of mitigation techniques. Mobilization and travel time to and from event sites may be greater than those in other US states. Weather and temperature conditions can often be extreme or change quickly and without warning, and access to some communities that may be affected by ice jam events are limited as many Alaskan villages are located off the established road system.

Table 3 contains categories of mitigation measures by their applicability to different jam types (i.e., breakup or freeze-up ice jams) and the type of measure (i.e., permanent, advanced, and emergency). Additional details of these measures are discussed in the USACE *Ice Engineering* manual (2002).

Table 3. Mitigation categories (reproduced from USACE 2002).

Technique	Jam Type	Type of Mitigation
Structural		
Dikes, levees, floodwalls	F, B	P
Dams and weirs	F, B	P
Ice booms	F, B	P, A
Retention structures	B	P
Channel modifications	F, B	P
Ice storage zones	B	P, A
Nonstructural		
Forecasting	F, B	A, P
Monitoring and detection	F, B	E, A, P
Thermal control	F, B	E, A, P
Land management	F, B	P
Ice cutting	B	A
Operational procedures	F, B	A, P
Dusting	F, B	E, A
Ice breaking	F, B	E, A
Mechanical removal	F, B	E, A
Blasting	F, B	E, A
Traditional Techniques		
Floodproofing	F, B	P
Sandbagging	F, B	A, E
Evacuation	F, B	A, E
Levee closing	F, B	A, E
Key:	**B = Breakup jam** **F = Freeze-up jam**	**P = Permanent measure A = Advance measure** **E = Emergency measure**

5.2 Advance Measures

Advance measures are typically non-structural interventions employed weeks or months in advance of expected ice jam occurrences. The objectives of advance mitigation measures include flood risk reduction, reduction of the ice supply, control of the breakup sequence, and an increase of the ice conveyance in the channel.

Forecasting and monitoring are widely used measures to inform the public and provide information to local officials of conditions that could be problematic during freeze-up or breakup periods. The monitoring also allows for early warning systems to be used immediately prior to or during the early stages of an ice jam flood event. Additional advanced measures including mechanical weakening (e.g., chainsaw, backhoe, or trenching machine) and thermal weakening through increasing the amount of solar energy absorbed by the ice (i.e., decreasing the ice albedo).

5.2.1 Monitoring, detection, and forecasting

Monitoring and forecasting of ice and ice jams was discussed in Section 4. An example of this technique is information provided by the NWS-APRFC related to ice jam and flooding potential. Information is available for select rivers such as the Yukon and Kuskokwim during ice season through the NWS-APRFC River Watch program.[7]

5.2.2 Early warning system

Early warning systems could include such techniques as tripwires or motion detectors discussed in Section 4.2.4. Prediction and detection technologies in general may be applied in such a way as to sound an alarm based on certain parameters. Simple remote gages to collect data on river ice movement and breakup could be useful. Water level gages can detect any rapid increase in river stage, which often precedes ice breakup. Automated temperature sensors help to verify whether conditions are conducive to ice jam formation or breakup (USACE 2002).

5.2.3 Mechanical weakening

Walk-behind cutting saws, larger machinery, or watercraft can and have been used to mechanically weaken ice sheets in advance of an anticipated jam event to alleviate potential clogs. Cutting cracks or trenches in the ice cover along the thalweg could allow for more ice movement or more water flow through that area. Cuts do not necessarily have to be full depth. Cutting a flow path could reduce potential for a jam event without actual breaking apart of the whole ice cover. However, in the event complete fracturing of the ice cover is needed, heavy equipment or large watercraft can be used to weaken or fracture the ice cover (Figure 27–Figure 29). Excavators can be a useful option especially when equipment is available and a working platform can be established (Figure 27*A*). Some unique equipment such as the Amphibex (Figure 27*B*) have been specifically designed to breakup floating ice covers. In this case, it is effective but can be slower than some other techniques. For larger rivers or coastal ice jam events, large ice cutter vessels known as icebreakers (Figure 28) can be an effective and

[7] https://www.weather.gov/aprfc/riverWatchProgram

comparatively faster technique but are limited by bathymetry. Uniquely, air cushioned vehicles (ACVs; a.k.a. hovercraft) (Figure 29) have been used to break up ice sheets by creating a wave that propagates through and subsequently breaks the ice cover (Nakonechny 2019).

Figure 27. Excavator used to remove ice jam (*A*) (image reproduced from USACE 2002) and Amphibex specialized equipment (*B*). (Image reproduced with permission from Normrock Industries Inc.)

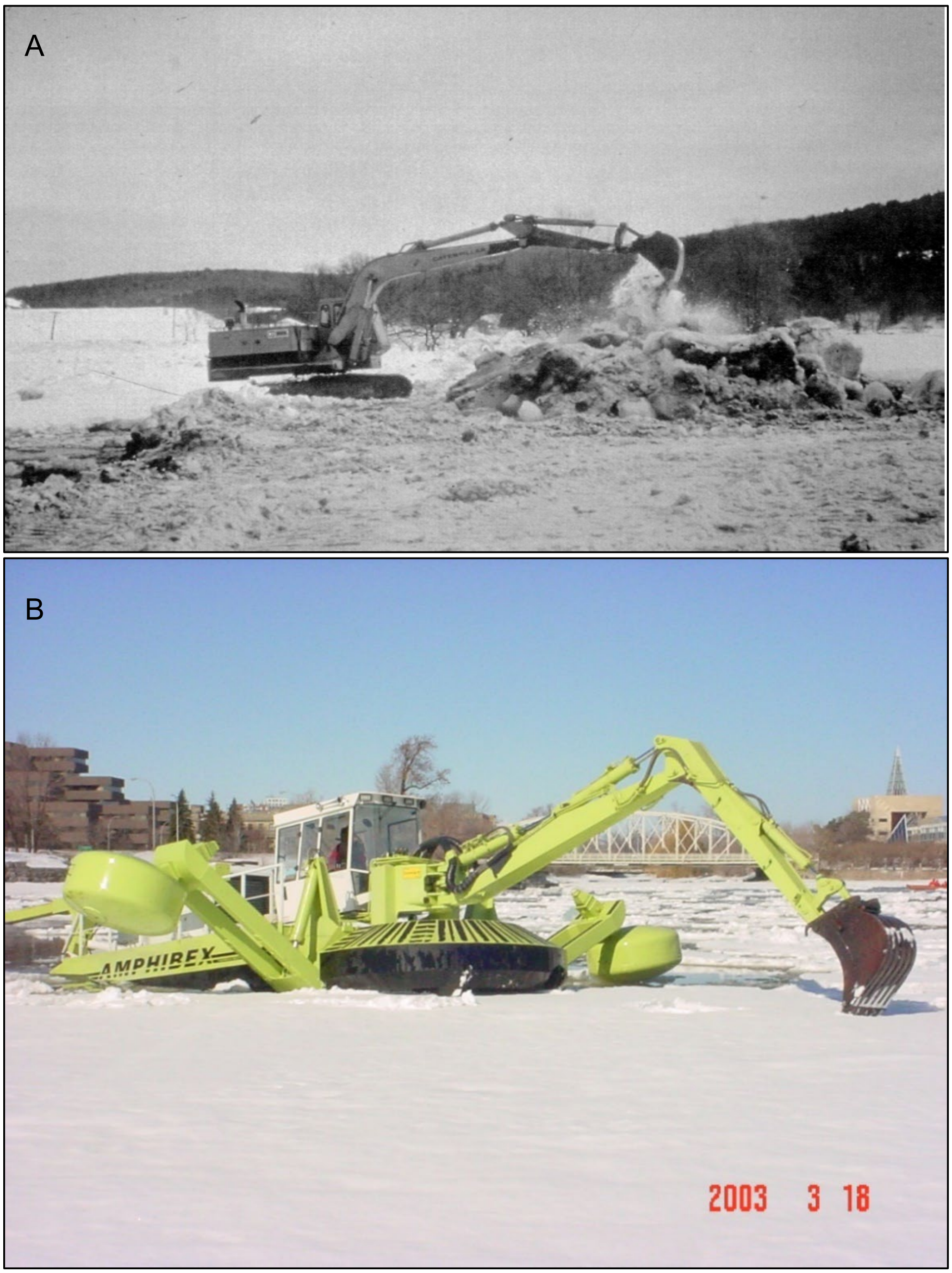


Figure 28. Canadian Cutter Risley, January 2022, working the lower St. Clair River. (Image reproduced from US Army Corp of Engineers [USACE] Detroit District. Public domain.)

Figure 29. Hovercraft as an ice-breaking tool. (Image reproduced from Eric Bégin, *Canadian Coast Guard WABAN-AKI*, https://www.flickr.com/ Public domain.)

5.2.4 Thermal weakening

One primary method of thermal weakening is dusting (Figure 30). In this method, covering the ice surface with any dark substance that can be evenly spread induces faster melting and ice weakening because of the increased solar radiation absorption from the dark substance. Commonly used substances include coal dust, fly ash, topsoil, sand, and riverbed material (USACE 2002; White and Kay 1997). Other local materials have been used such as leaves (Haehnel et al. 1996). Shadows created by rough ice jam surfaces, wind, and additional snow layers can hinder the effects of dusting. Subsequently, it is ideal to apply the dust layer as early as possible, but after the last snowfall. The application procedure is sufficiently described in *Ice Engineering* (USACE 2002) as follows:

> The dusting operation should spread the material layer as evenly as possible. A surface concentration of about 50 percent should be the goal; too much dusting material insulates the ice rather than acting to promote deterioration. Important factors are time, the higher sun angles in the late spring, and good luck in avoiding snowstorms that would cover the dust.

This technique has been successfully used on a reach of the Yukon River downstream of Galena, Alaska, where dust was applied 2 to 3 weeks before breakup significantly reducing ice jam frequency (Moor and Watson 1971). Increasing the amount of solar radiation absorbed the ice by using dusting is still used. In 2022, severe cold weather led to an ice jam in a supply canal that feeds an electric generating facility in Nebraska. Dusting was used to help promote breakup so flows in the supply canal would not be impeded (Edward Dekleva, Nebraska Public Power District, pers. comm., 2022). While aerial dusting has been the most common application method (USACE 2002), pumping fine material from the channel bottom and application via hydroseeder have also been used with the latter proving more cost effective for rivers with nearby roads or bridge crossings (Haehnel et al. 1996). From Table 4, it is clear aerial dusting operational costs can vary by a factor of 2 or more.

Table 4. Cost of dusting operations in 2022 US dollars (adapted from USACE 2002).

Method	2022 Cost ($/m²)	2022 Cost ($/ft²)	Application rate (m²/hr)	Application rate (ft²/hr)	Location	Reference
Pumping	0.40 (0.75[a])	0.04 (0.075[a])	2,400	25,833	Alaska	Moor and Watson 1971
Aerial Dusting	0.82 (1.55[a])	0.08 (0.15[a])	14,000	150,696	Galena, AK	Haehnel et al. 1996
Aerial Dusting	2.10 (3.95[a])	(0.20 (0.39[a])	8,000	86,112	Platte River, NE	Haehnel et al. 1996
Hydroseeder (cannon)	0.88 (1.65[a])	0.08 (0.16[a])	8,000	86,112	Montpelier and White River, VT	Haehnel et al. 1996
Hydroseeder (extension hose)	1.20 (2.25[a])	0.11 (0.22[a])	4,000	43,056	Montpelier, VT	Haehnel et al. 1996

[a] Cost brought forward from 1996 using the Consumer Price Index.

Figure 30. Dusting using agricultural aircraft. (Image reproduced from USACE 2002. Public domain.)

5.3 Emergency measures

Emergency measures are those techniques employed while an ice jam is imminent or has recently occurred. The objectives of emergency mitigation measures include flood protection, to increase conveyance in the channel, and to remove or partially remove an ice jam that is in place. The cost and effectiveness of emergency measures depends on the timing of their use relative to the formation of the ice jam. Some emergency techniques include icebreaking, mechanical removal, ice blasting, evacuation, levee closing, and flood fighting techniques. Effective implementation of these techniques also depends on the clear execution of the emergency action plan (Drabek and Hoetmer 1991). Several issues need to be considered before implementing emergency measures. These issues include the short-term (7 to 10-day) meteorologic and hydrologic forecast. For example, during a severe cold weather event resulting in a freeze-up jam, removing ice through mechanical excavation may not be effective. Another issue is consideration of downstream locations that may jam if an ice run is created from upstream emergency measures.

5.3.1 Ice breaking and mechanical removal

Vehicles such as icebreaker vessels (see Figure 28) or ACVs (see Figure 29) can be used to break ice sheets in emergency situations according to the limitations of the vehicles. In the case of icebreaker vessels, water depth must be sufficient for the vessel draft, and waterway must be navigably wide enough. Icebreaker operations can be expensive, and icebreakers cannot be used in small rivers of limited depth. The availability of an icebreaker on short notice and the difficulty of access to the ice in upstream reaches can also limit this method (USACE 2002). For ACVs, the ice cover surface must not be too jagged such that it punctures the air skirts, and air temperatures must not be so extreme as to cause icing of the propulsion system; however, an advantage of ACVs is their maneuverability and shallow water compatibility (USACE 2002).

Heavy equipment, such as long-reach excavators (Figure 31 and Figure 32), have the advantage of not only being able to break the ice, but also to remove it. This can be advantageous in flooding situations where floating ice blocks or other debris have been deposited on the surrounding riverbanks. Given the right conditions, sufficient ice thickness, and relatively smooth ice cover surface, heavy equipment can also be used from the ice itself to break up the jam. In some cases, water depth may be shallow enough such that machinery can be used in the riverbed itself to break up and remove the jam. In such cases, environmental considerations play a role in the implementation of this technique. In general, it is best to begin at the downstream end of the ice cover and work upstream, so the broken ice will be carried away by the flow (USACE 2002). In areas where ice jams occur regularly equipment can be staged to provide quick responses as ice effected water levels reach flood stage. An example of this situation is on Chester Creek which flows through Anchorage, Alaska where equipment is staged throughout the winter season (Jeff Urbanus, Municipality of Anchorage, pers. comm., 2022).

Figure 31. Excavator removing jammed ice from underneath a bridge near Nome, Alaska (Photo: Alaska Department of Transportation, used with permission).

Figure 32. Example of long boom excavator removing jammed ice, weakening the toe of an intact jam in Johnson, Vermont (Photo: Eric Osgood, used with permission).

5.3.2 Blasting

As an emergency measure, blasting of ice jams often provides the fastest result, but requires careful planning and, in some populated areas, may not be a safe option. Subsequently, time until execution may be longer than for other techniques. USACE *Ice Engineering* (2002) lists two “absolute prerequisites” for blasting,

1. enough flow passing down the river to transport the ice away from the site
2. and sufficient open water area downstream to receive the ice.

The ideal time for blasting a jam is immediately after it has formed; however, the approval process for such an operation usually eliminates the possibility of this occurring. The effectiveness of a blasting operation on ice jams depends on the charge placement. Ideally, the charge will be placed below the ice surface through holes drilled at regular intervals. To the degree possible, the blasting line should be placed along the thalweg of the river (USACE 2002). The relationship between charge weight, ice thickness, and the resulting hole diameter are shown in USACE *Ice Engineering* (2002), Figures 12–15.

In large river systems which typically breakup from upstream to downstream, blasting may not be a feasible option because the prerequisite condition of sufficient open water downstream may not be met. Therefore, when planning to use this method as an emergency measure, an understanding of the river breakup sequence and timing for the river that has the ice jam is also needed.

5.3.3 Flood fighting

Evacuation, closing levees (if they exist on the river at risk), and using sandbags to protect structures (Figure 33) are common flood fighting techniques also applicable to floods induced by ice jams. Winter weather conditions are a determining factor for implementing evacuation and levee closing, and the availability of large quantities of sandbags may be a limiting factor for floodproofing. Material for sandbagging operations can be positioned in locations where ice jams commonly occur. The challenge is often that ice jam floods will occur without sufficient warning to allow for sandbagging operations to be effective. For rural Alaskan communities, flood fighting is a significant challenge. The materials (e.g., sandbags) may not be readily available nor enough people available to mount a flood fight response. Additionally, mobilizing materials, equipment, and additional personnel may be expensive and risky because of the lack of available housing for volunteers and food and water may also be threatened by the flood event.

Figure 33. Using sandbags to fight ice-jam induced flooding. (Photo: J. McGuire. https://www.flickr.com/)

In recent years alternatives to sandbags such as inflatable dams, flood fences, and storm bags which expand when wetted, are all available through several national suppliers. The continued challenge with these alternatives is their effectiveness during freezing temperatures and resistance to ice forces. Field testing of sandbag alternatives may be useful and provide innovative solutions that can be deployed quickly for relatively low costs.

5.3.4 No action

Depending on the location and river system, no emergency actions may be possible. In certain locations ice jams may form and release relatively quickly (<1 day) and mobilization of other emergency measures may not be feasible. Effective monitoring and assessment of ice jam prone locations throughout the state may inform whether action is needed or not.

5.4 Permanent measures

Permanent measures are techniques that often employ structural solutions. The objectives of permanent measures include flood protection, a reduction of ice supply, an increase in conveyance of the channel, to control the breakup sequence of an ice cover, or to displace an ice jam initiation location.

There are two general categories of structural measures. The first are those designs which prevent water from reaching specific areas during a flood (i.e., dikes, levees, and floodwalls). These structures can be relatively small (floodwalls) if limited land areas are prone to ice jam flooding. Conversely, dikes and levees can be several miles in length to reduce flood risk for large land areas adjacent to the river. The second category are structures that directly control ice formation and movement. This category is broad and includes ice sheet retention, breakup ice control and ice diversion (Tuthill 1995).

These measures involve intensive study and design, which typically means lead times measured in years. For example, the Cazenovia Creek, New York, ice control structure was constructed in 2006, but studies and conceptual design of the project were started in the 1980s (Lever et al. 2000). Project costs are typically high making it challenging to achieve favorable cost-benefit ratios, but this level of mitigation measure can come with high benefits and reliability.

5.4.1 Dykes, levees, and floodwalls

The use of levees and dikes is a very common and long-standing practice for managing open water flooding. Levees and other barriers along a river channel can provide reduced flood risk and damages for both open water and ice affected flood events. However, the initial planning and design should account for the distinct differences in hydrology, hydraulics, environmental conditions, and structural loading between flood event types. Levees set near the river channel to prevent ice jam flooding can concentrate ice and prevent it from accessing floodplains where historically it could be stranded.

Beltaos and Doyle (1996) investigated the use of setback *dykes* which involves construction of levees offset into the floodplain. Where property is available to build these structures, the combined benefit of flood protection of structures is balanced with maintaining flood plain storage for ice and floodwaters. Dyke construction was a presented as a potential mitigation option for aufeis related flooding on Jarvis Creek (Daly et al. 2011).

5.4.2 Dams and weirs

Large dams can provide significant mitigation benefits for ice jam related problems, but they are capital intensive projects with significant environmental impacts. The reservoirs behind dams can create a solid ice cover which can arrest ice runs and collect frazil ice during freeze-up.

The use of low-head dams can help mitigate ice related flooding issues, primarily by encouraging the growth of stable thermally grown ice covers which collect frazil ice and limit additional ice production through the formation of an insulative cap of ice over the river. The Cherryfield Dam in Maine is a low-head structure that forms a long shallow pool upstream of a river reach which historically saw major frazil ice jams. The pool formed by the dam typically forms a thermally grown ice cover that prevents frazil ice formation in the pool and collects and stores frazil generated upstream. The structure has been effective in preventing frazil ice jams since its construction in the 1960s (Tuthill 1995).

5.4.3 Ice booms

Ice booms are often used for ice mitigation. Foltyn and Tuthill (1996) is a quintessential source of design guidance for these structures. However, significant innovations in materials and connection details were made and currently chained steel tube systems (Abdelnour et al. 2019) are state of the art. Timber systems used in the past for cost effectiveness are generally obsolete with the availability of cost effective steel and high density polyethylene booms.

These widely used structures can vary in design, but the key elements are pontoons which are tethered together and anchored in a manner usually perpendicular to the ice movement direction (Figure 34). Booms are not suited for high velocity reaches and should be considered for use when surface velocities are 0.69 m/s (2.25 ft/s) or less and relatively steady (USACE 2002). Ice booms can be used for both temporary ice retention during breakup events or to promote ice cover formation as a freeze-up jam mitigation measure.

Figure 34. Example of ice boom arrangement, St. Marys River, Michigan. (Image reproduced from USACE Soo Project Office. Public domain.)

Ice booms have several advantages including relatively low cost, seasonally deployment capability (i.e., removed during open water seasons), relatively low maintenance, and the ecological impacts are minimized when compared to other in-channel structural alternatives. Disadvantages of ice booms are that they only temporarily hold ice back, can eventually release ice downstream if overloaded, and they impede vessel traffic. In addition, anchors may need to be constructed in locations within the channel depending on the width of the river and direction which is most desirable for ice to be moved. In general, ice booms should be considered as a first option for ice mitigation structures; however, analysis of the ice conditions for the specific waterbody should be performed prior to installation. Estimation of forces and anchor locations requires thorough investigation for the boom to be effective.

5.4.4 Pier structures

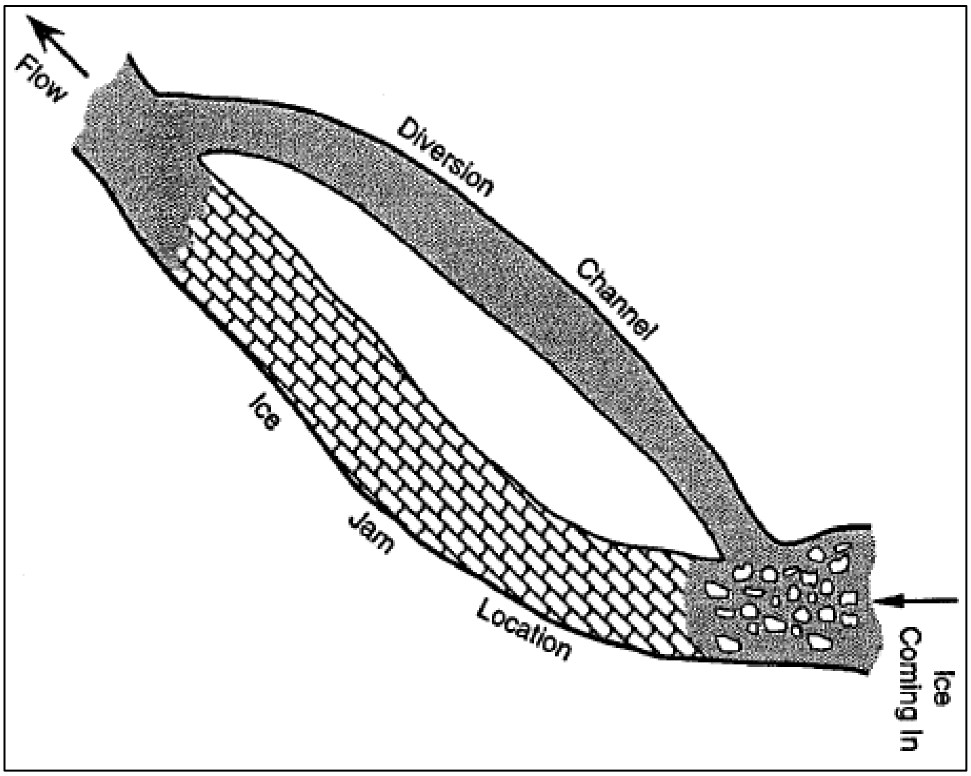
Pier structures are designed to intentionally induce an ice jam by hindering the flow of ice blocks sized greater than the gap between the piers (Figure 35). They can be used to create ice storage zones in reaches that do not have vulnerable infrastructure (Figure 36*A*). Generally, ice control structures may be effective barriers to ice blocks, but they may also detain other types of debris such as floating wood and vegetation which may, when melt occurs, need to be removed (Figure 36*B*). The piers are often concrete or steel columns, but other materials can be used so long as they can resist the anticipated forces during both ice and open water flooding conditions.

Figure 35. Ice control pier structures, Cazenovia Creek, New York (Image reproduced from USACE Buffalo District. Public domain.)

Figure 36. Ice control using concrete pier structures Salmon River, Connecticut. Prior to melt out (*A*) (Google Earth) and after (*B*). Note debris buildup upstream of pier structures (*B*).

Ice jams created by ice control structures are likely to cause a rise in river stages upstream of the structure. In rural areas this may be perfectly acceptable and flood flows may inundate undeveloped areas. In areas with greater levels of development, diversion channels, ice storage zones, and general channel modification are important compliments to ice control structures (ICS). Structures like the Cazenovia Creek ICS required the construction of a diversion channel as in Figure 37 to allow continuous flow to bypass the intentionally created ice jam in the main channel.

Figure 37. Diversion channel schematic for ice jam flood control. (Image reproduced from USACE 2002. Public domain.)



Pier or boom structures supporting steel nets were also evaluated for efficacy, and it was found that they could potentially be a very effective solution even for rivers reaches with slopes exceeding 1%—so long as the net was not frozen to the river bottom (Morse et al. 2003). The study further identified economic benefits, finding the capital cost for a pier-net ICS in a 60 m wide river for flow rates of up to 200 m^3/s to be $1.2 M (including 20% contingency) (Morse et al. 2003).

There are several advantages to pier-type ICS structures including effectiveness, reduced need for construction materials, and limited ecological impacts, since fish passage is generally not affected. Pier structures do have some disadvantages. Because these projects require in-channel construction, the planning, design, and construction can be a lengthy process. Also, land acquisition may be needed depending on the total project footprint and expected ice volume retention.

Pier type ICS structures have been combined with weirs which can be effective at limiting the effects of ice runs (Carr et al. 2017). Overall weir-type ICS structures should be used in very specific situations following a thorough analysis.

With all ICS projects, data collection of existing ice conditions can be a significant help during the planning and design processes. For areas where a structural measure is being considered, the collection of ice information including extent, thickness, and duration for several winter seasons is very valuable for design purposes. In areas where direct measurement of the ice is not feasible, we recommend contacting CRREL to determine an alternative monitoring plan that will be useful for any ICS development.

5.4.5 Flow control

Flow control can reduce the potential for ice jams by preventing rapid changes in flow and stage which can cause ice cover break up and ice jams (Tuthill 1999). This method is applicable to regulated river systems where discharge can be limited through temporary storage of river flows. Usually this approach is considered on rivers with projects that have large storage capacities.

5.4.6 Thermal control

Ice forms when water cools to the freezing point and goes through a phase change to a solid state. Both processes results in a reduction of energy, first from heat leaving the water, typically to the atmosphere as the water approaches the freezing point, and then during the phase change, latent heat is lost to the surrounding water. The rate of water cooling and phase change can be suppressed through the addition of heat from an external source. The phase change from water to ice can also be reversed if sufficient heat is added to cause the ice to melt.

A common source of external heat is warm water, including discharges from industrial facilities, power plant cooling systems removing waste heat, and from groundwater wells. Another source of warm water that many communities have access to is wastewater effluent (USACE 2002). The City of Montpelier, Vermont has used effluent discharges from its wastewater treatment plant to suppress ice growth and thin ice cover in an ice jam prone reach of the Winooski River (Figure 38). Industrial discharge has been used in Oil City, Pennsylvania for similar purposes (Deck and Gooch 1981). Thinner ice is more likely to run and less likely to jam during a breakup event. The effectiveness of this measure depends on quantity and temperature of available water, the discharge in the river and the meteorological conditions in the location of interest. Ashton (1979) describes a predictive method to calculate the effects of thermal effluents on ice formation using a simple Lagrangian approach. In general, if water above the freezing point is added to a river system, ice formation will be suppressed, but the degree of suppression increases with both discharge volume and water temperature. If the lateral mixing across the width of the river is limited, ice thinning may be spatially limited to the footprint of the discharge plume.

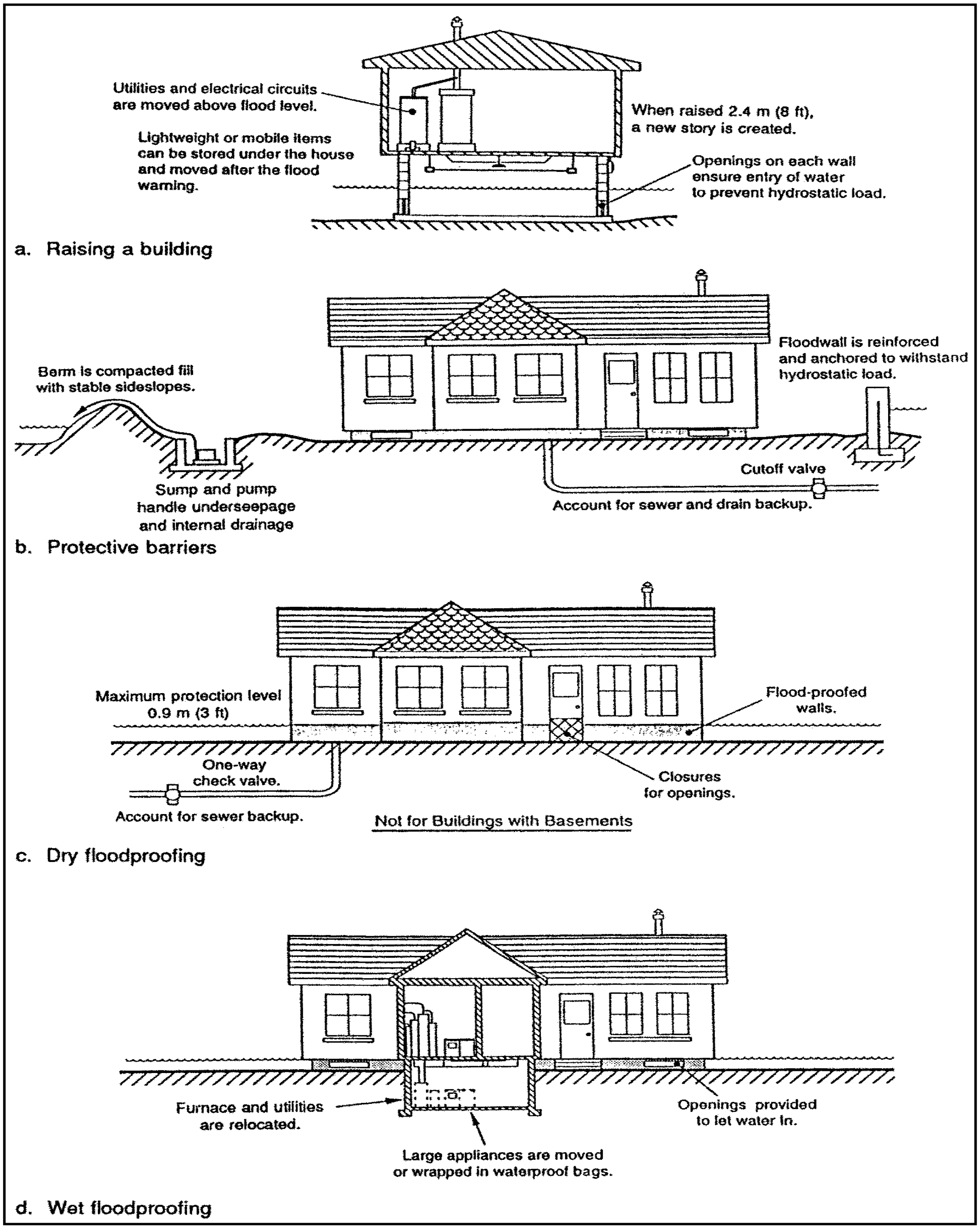
Figure 38. Effect of effluent discharge in river ice pack. (Image courtesy of Montpelier Public Works, Vermont.)

5.4.7 Floodproofing

There are four floodproofing techniques applicable to floods induced by ice jams (Figure 39). Raising the building is a common practice in regions prone to recurring flooding. Piles or raised load-bearing walls support the structure and allow water to pass underneath the structure. Critical utilities are relocated above the flood level and typical height increases are 2.4 m (8 ft) (USACE 2002). Protective barriers are another technique that can be equally as effective as raising the structure. Such examples include compacted berms and reinforced walls with sumps and pumps as potential supplements in both cases. Dry floodproofing involves sealing walls, doors, and other openings, and, when necessary, reinforcing the structure to prevent damage from ice blocks. For some structures wet floodproofing may be an appropriate option. This includes creating the structure to allow water to enter lower levels and removing critical utilities to higher levels or individually sealing them with waterproofs wraps. Additional information about floodproofing is provided by the USACE National Nonstructural Committee.[8]

[8] https://www.usace.army.mil/Missions/Civil-Works/Project-Planning/nnc/.

Figure 39. Floodproofing techniques. (Image reproduced from USACE 2002. Public domain.)



5.4.8 Land management

For those floods induced by ice jams, analysis of the magnitude of ice jams and their effects on surroundings, can inform land-use planning strategies. Hydrologic and hydraulic modeling can help determine at risk areas and make recommendations that could prevent unwanted flooding damages. It is important to consider ice affected stage in any modeling used within a risk analysis. Often the open water stage frequency underestimates the probable maximum stage during ice jam events (FEMA 2018; USACE 2002).

5.5 Aufeis mitigation case study

In Alaska, two mitigation techniques for aufeis-induced floods that were evaluated are trenching and berm construction. Both techniques were evaluated along the lower reaches of Jarvis Creek—located near Delta Junction, Alaska (Daly et al. 2011). With trenching, heavy equipment was used to excavate a trench through the built-up aufeis thereby providing a flow path for spring melt-out flows, and in berm construction, two different berm sizes were modeled for flood prevention efficacy. During winter seasons where trenching was used, aufeis buildup was observed, but no flooding occurred which suggested trenching was an effective mitigation technique. Since heavy equipment is involved mobilization and planning may be difficult because of spatial and temporal aufeis prediction limitations (Daly et al. 2011). On a year-by-year basis, it is difficult to predict aufeis locations and extents along the creek length, though improving records of aufeis events can inform predictions. Additionally, flow accumulation through the trenched zone may increase the melt-out volume by virtue of greater solar energy absorption and distribution (Daly et al. 2011).

Earthen berm construction as an aufeis-induced flood mitigation technique along Jarvis Creek was also evaluated by computer modeling (Daly et al. 2011). An 800 m long and 3,100 m long berm were evaluated for flood-mitigation efficacy. According to the hydraulic model used in the study, both berms would intercept and return flood waters to the main channel, but the 3,100 m long berm would provide greater protection for an increased aufeis extent (Daly et al. 2011). As with trenching, geometry and local aufeis extent and flood history are major informers of berm construction parameters. Difficulty in predicting recurring aufeis event locations is a limiting factor in berm construction as well.

6 Design Considerations for Culverts and Bridges in Ice Prone Environments

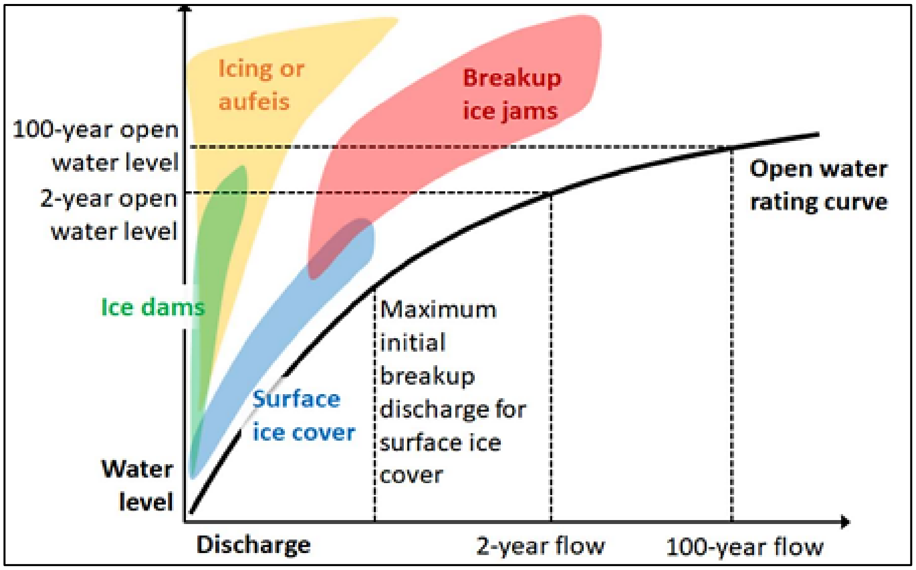
Infrastructure placement across a natural flow path of any sized system may change its hydraulic behavior. In regions where ice conditions develop, transriver infrastructure could also affect the behavior of river ice leading to potential detriments to the surroundings and to the infrastructure itself. Bridges and culverts are some of the most common transriver structures and this section briefly describes some of their design considerations and lists related resources. From an ice jam mitigation standpoint, knowledge of design considerations for bridges and culverts may inform expectations as to the locations and consequential magnitudes of ice jams.

6.1 Bridges

Ice can affect bridges in several ways: via ice loads directly applied to a bridge pier or on the structure from ice floe impacts, static ice loads, ice jamming, ice-related water level rise and flooding, and ice-induced hydraulic scour (Burrell et al. 2021). Ice floes impacting a structure such as a bridge pier can exert a force equal to the crushing force of ice, found to be between 1 and 3 MPa for large aspect ratios (Sodhi and Haehnel 2003).

Absent of direct impacts, the presence of ice can affect the hydraulic environment around a bridge and should be considered in design aspects which depend on water level frequency curves. A number of ice processes such as aufeis events, ice dams, breakup ice jams, and surface ice can increase water levels above an open water rating curve (Figure 40). Often ice affected stages are not the most extreme when compared to open water, but the relative frequency of ice affected events can change the shape of stage-frequency curves used to estimate risk and expected damages at projects. On larger rivers in Alaska, breakup ice jam stage is often the most severe and is critical to use for design criteria. On smaller streams which typical have freeze up ice jamming, ice affected water levels will not be as high as the open water levels. Methods to include ice impacts to stage-frequency curve development should be employed in locations where ice processes are typical (White et al. 2000; FEMA 2018).

Figure 40. Concept of ice processes influence on water level above an open water rating curve. (Image reproduced with permission from Burrell et al. 2021.)



Bridges often have abutments which encroach on the natural river channel and bridge piers which physically obstruct the passage of ice. These results in bridges often being the site of an ice jam, which can cause flooding issues upstream and add significant forces to the bridge itself. Beltaos et al. (2006) provides some general guidance on considerations to reduce the potential for a bridge to cause an ice jam. The general principle suggests is to “maximize the driving force and minimize the resisting force of the structure” (Beltaos 2006)

Driving force pushes the ice through the structure and is maximized when the upstream and downstream reaches are long, straight and relatively steep. Sharp bends upstream will reduce the driving force, as will the presence of islands, bars and shallow or over widened sections. Where stream grades transition from steep to shallow, such as at the entrance to a lake or where a mountain stream flattens into a shallow graded delta, the driving force is reduced and these locations are susceptible to naturally forming jams that the presence of a bridge can tend to exacerbate.

Resisting forces are essentially the bridge’s ability to resist ice movement, which should be minimized, allowing ice to flow as freely as possible through the structure. Avoiding or minimizing the placement of support piers within the river is one way to prevent ice jamming. In locations where large ice loads are expected inclined pier noses can be used to reduce the resisting force of the structure. The inclined pier noses are designed to use the driving force to encourage ice to ride up on a wedge shaped ramp in front of the pier and fail in a flexural mode in which ice is quite weak. For simple piers where ice will tend to impact and fail because of crushing, and the installation of inclined piers in impractical, using slender columns will reduce the resisting force of the structure.

6.2 Culverts

Culverts can be affected by ice buildup and blockage, restricting flow and causing road washouts, and ice-related damages because of static or dynamic forces (Burrell et al. 2021). Over-sizing of a culvert or installing many culverts may prove effective during specific years, but it would not significantly improve water-level conditions in some problematic settings (e.g., Figure 41). Another option is replacing culverts with bridges to promote water movement downstream of constructed embankment. A third option is staggered culverts with conduits both at the base of the embankment fill and separate conduits at a higher elevation which will usually be dry except during runoff events in the spring when the lower culverts are blocked with ice (Carey 1984). Adaptation and mitigation need to be based on an understanding of the hydrological and thermal aspect of ice processes.

Many culverts or relevant roadway embankments across Alaska contain pipes (known as *thaw pipes*) crossing the embankment or passing through culverts that can be injected with steam to thaw ice buildup. This is an effective mitigation technique assuming consistent yearly aufeis extent. In locations were power is not available, other on-site generation may be feasible with wind or solar power. Tests using solar power to heat thaw pipes were conducted in the 1980s with some success given the right conditions (e.g., horizon is sufficiently low to allow exposure to sunlight) (Zarling and Murray 1983). Other solutions to ice-filled culverts have been explored, but require potentially higher ecological impact. Researchers tested an insulated drainage system in the Da Hinggangling forest region in China (Yu et al. 2005). This system pipes water underground past the embankment or structure of concern.

Figure 41. Culvert icing in oversized culverts. (Image reproduced with permission from Burrell et al. 2021.)

7 Effects of Climate Change on Ice Jams

A good summary of overall impacts of climate change on ice formation in Arctic regions, including Alaska, are provided by the Intergovernmental Panel on Climate Change's Special Report on the Ocean and Cryosphere in a Changing Climate (Meredith et al. 2019) and the US 4th National Climate Assessment (Markon et al. 2018). These reports both consistently state that air temperatures in Alaska have been warming at twice the rate of the global average for at least the last 20 years (Markon et al. 2018; Meredith et al. 2019). The statewide average increase is estimated to be 0.4 °C (0.7 °F) per decade since the 1970s (Markon et al. 2018). This has resulted in declines in sea ice extent and duration, snow cover, and permafrost. Markon et al. (2018) reports that annual average arctic sea ice extent has declined approximately 4.1% per decade since the 1980s. In addition, snow cover extent for May and June have been estimated to have decreased by 3.5% and 13.4%, respectively per decade between the late 1960s and 2018 (Meredith et al. 2019). Permafrost has similarly been impacted by the warmer temperatures since the 1970s. It is anticipated that up to a quarter of near-surface permafrost will disappear in Alaska by the end of the 21- century (Markon et al. 2018).

While these reports provide a good overview of impacts for both observed and projected climate change impacts in Alaska, there is almost no mention of river ice. Dynamic changes in river ice behavior can be expected from increasing warming trends. Exactly what those changes are with respect to the frequency, intensity and extent of ice jams remains an unanswered question. Many of the studies directly relating climate change impacts and river ice have been focused on Canada with only limited investigations for the US and even fewer directly evaluating river ice in Alaska. Therefore, we have selected several Canada focused studies to help describe the potential river ice changes in Alaska because of climate trends.

7.1 Studies in Canada

Several studies in Canadian watersheds seek to understand how the effects of climate change have impacted river ice processes, including ice jams, and how future climate scenarios will change ice phenology and ice jam frequencies (Andrishak and Hicks 2008; Beltaos 2021; Beltaos and Bonsal 2021; Beltaos and Prowse 2001; Beltaos and Prowse 2009; Burrell et al. 2021; Chen and She, 2020; Das et al. 2017; Gebre et al. 2014; Prowse et al.

2011; Rokaya et al. 2019; Turcotte et al. 2019; Turcotte 2021; Poulin et al. 2021; Timalsina et al. 2015; Beltaos and Burrell 2003). A review by Prowse et al. (2011) reports that measured ice cover duration for Arctic lakes has decreased between 12–17 days over per century and trends are for both later freeze-up and earlier breakup dates. The shorter ice cover season will have impacts potentially on many aspects of society for those living in the Arctic. For example, transportation and mobility during the winter could require additional infrastructure such as roads and bridges (Andrishak and Hicks 2008). Another substantial concern is the change in ice jam potential along with the associated flood risk. With continued warming reduced river ice thickness is expected (Beltaos and Bonsal 2021); however, increases in midwinter breakup events could result in increased flood damages (Turcotte et al. 2020). Midwinter breakup is currently more common in Atlantic Canada and Central Quebec, but the first of this type of event was recorded on the Klondike River in Yukon, Canada in 2002 through 2003 (Janowicz 2010).

On the Peace and Athabasca Rivers, several studies have evaluated how climate change will impact ice formation and ice jam flooding (Andrishak and Hicks 2008; Beltaos and Bonsal 2021; Das et al. 2017; Rokaya et al. 2019). Both Andrishak and Hicks (2008) and Beltaos and Bonsal (2021) project reduced ice cover duration and ice thickness for the Peace River. Andrishak and Hicks (2008) indicated a 60% reduction of ice cover days of for the 2040–2060 time horizon relative to the 1984–2003 historical period. Beltaos and Bonsal report an estimated decrease of 0.3 m of ice thickness for the Peace River by the 2080s relative to the 1980s historical period. These results suggest a future reduction in ice jam potential on the Peace River. Studies on the Athabasca River, also report shorter ice cover duration and likelihood of ice jams (Rokaya et al. 2019); in contrast, the Das et al. (2017) report a lengthening of the ice season by one to two weeks by the 2060s relative to the 1971–2000 historical period. Both Rokaya et al. (2019) and Das et al. (2017) report decreases in future ice jam potential based on modeling, but severe ice jams are still possible even with increased warming from climate change because of seasonal cold weather periods. As the Arctic continues to warm, the areas where midwinter breakup jams occur may expand. Summaries of climate change impacts on ice jams and future research needs in this topic area are summarized by Turcotte et al. (2019) and Burrel et al. (2021).

7.2 Studies in United States

In the US there were only a few studies that have evaluated historical trends in river ice (Hodgkins et al. 2005; Huntington et al. 2003; Newton and Mullan 2021; White et al. 2007; Yang and Zhang 2022). Ice phenology studies in Alaska have been performed (Arp et al. 2013), but not within the context of a statewide assessment of how climate change is impacting ice cover duration. Within CONUS similar studies to those focused in Canada, have been completed for the Northeastern US (Hodgkins et al. 2005; Huntington et al. 2003; Newton et al. 2021). For example, it was reported the ice cover duration in the Northeastern US has decreased by 0.63 days per decade for New Hampshire lakes and rivers (Newton et al. 2021). Huntington et al. (2003) found the average ice thickness in Maine has decreased by approximately 23 cm from 1912–2001. A recent study evaluating how climate change has impacted ice thickness in Alaska which reports the mean maximum river ice thickness has decreased at a rate of 0.26 cm per year between 1961 and 2015 (Yang and Zhang 2022). This results in over 14 cm of mean maximum river ice thickness during that 55-year period. Very limited studies have been performed to estimate changes in ice thickness using future climate projections. A study by Nalbant and Sharma (2022) estimated thickness to decrease between 13% to 35% in the first half of the 21st century and 30% to 57% in the second half. This was for locations across northern CONUS. Based on the references currently available, there is a significant gap in the both the breadth and depth of studies that have been performed for Alaskan watersheds that have evaluated climate change impacts on ice phenology and ice jam frequency.

8 Recommendations and Conclusions

8.1 Research recommendations

There are several areas of research that could advance our forecasting, monitoring, mitigation, and modeling of ice jams. We have divided these research needs into three categories and assigned a relative level of effort required—(1): *low* to (5): *high*—for getting the information needed to meet the knowledge gap.

- Forecasting and Monitoring:
    - Testing of established ice movement technologies (1)
        - This research would involve identification of sites on rivers which have annual ice formation. Ice monitoring technologies that have been developed could be tested and evaluated simultaneously. The purpose of this setup is to compare technologies in the same environmental and river ice conditions.
    - Testing of ice movement technologies still in research (3)
        - This research would use similar locations that are used for the testing of established technologies. The primary difference is that untested or experimental methods could also be deployed and compared with existing technologies.
    - Projecting ice jam changes with future climate scenarios (3)
        - This research would use downscaled climate temperature and precipitation datasets and the degree-day method for estimating ice thickness. A comparison of relative ice thickness differences can be made between historical and future climate conditions. This analysis would allow for identification of rivers that are most susceptible to climate change impacts on river ice.

- Ice Mitigation

    - Field documentation and evaluation of ice forces on different structural components (4)
        - This research would involve coordination with several partners including the Alaska Department of Transportation. Monitoring of ice forces on different type structures would be performed. In addition, the ice thickness and compression strength would be measured to correlate that with the forces on structures.
    - Ice strength using coring samples (3)
        - This research would take core samples from locations where critical infrastructure is located and where ice jams commonly form. The strength of the ice for various conditions (e.g., freeze-up and breakup) would be measured. This would help with design of ice mitigation measures at those locations.
    - Establish aufeis mitigation field test site (5)
        - This research would monitor the evolution of aufeis at specific locations where aufeis formation is a common occurrence. The purpose of this research is to directly correlate environmental, weather and ice conditions which could then be used to design aufeis mitigation systems.

- Ice Modeling:

    - Development of stage frequency estimates for areas of chronic ice jam flooding (3)
        - This research would involve gathering of stage information for locations chronic ice jam flooding and performing a stage frequency analysis. To supplement the observational record (assuming one is available), modeled stages could be developed through using assumed ice jam locations and parameters. An ensemble of ice jam scenarios would be developed so the stage frequency and uncertainty could be fully defined at all probability levels.

- Develop dynamic ice jam model for locations with known jam issues (3)
  - This research would use a model which includes dynamic ice formation. The feedback between the ice formation and potential jam severity could be evaluated for a specific river and location. The purpose of this effort would be to associate ice cover conditions prior to breakup with jam severity potential.
- Development of Alaska specific prediction coefficients (α) for ice thickness estimation (4)

This research would require gathering all published ice thickness measurements available in Alaska through literature review along with potentially collecting additional measurements in locations which have no ice thickness information. Using the thickness values, prediction coefficients can be determined through model calibration with the site specific AFDD inputs.

8.2 Conclusions

The objectives of this report were to provide an overview of ice formation processes, summarize the historical ice jam record for Alaska, and provide a summary of commonly used ice mitigation measures. Whenever possible examples from Alaska specific studies were included to provide enhanced relevance for that region.

The processes and seasonality of ice formation are critical for understanding the type of ice jam that could form (i.e., freeze-up or breakup). Freeze-up jams are most common when cold weather events result in supercooling of river water temperatures which create frazil ice. The accumulation of frazil ice can be substantial at locations of obstacles in the river or dramatic changes in channel geometry. Breakup jams are most common in Alaska during the spring snowmelt runoff season. These jams are a result of fragmented ice collecting on obstacles in the river or locations of channel geometry changes.

Ice jams are common in Alaska, especially during the ice breakup season. The large river systems, including the Yukon, Kobuk, and Kuskokwim, have several locations which have historical ice jams in the CRREL IJDB. The first recorded ice jams in the IJDB for Alaska extends back to the latter part of the 19th century. Based on the records in the IJDB, it appears there is an increasing trend for ice jams over the last several decades. This is simply an artifact of the two key limitations of the IJDB, which are (1) only reported ice jams are put into the database and (2) the systematic records (e.g., stream gage records) only extend back a few decades. Even with the known bias in the IJDB, the information can still be used to identify locations of continued ice jam flood risk in Alaska.

There are several mitigation techniques applicable for Alaska. The advanced measures of monitoring and forecasting ice jams is already occurring through the efforts provided by the NWS-APRFC. Site specific measures for local monitoring can include stationary lidar units for ice motion detection. Additional advanced measures can include floodproofing of homes and staging of equipment to remove ice during jam events. Options for structural measures may be more limited in Alaska because of ecosystem concerns. However, in specific locations ice control structures maybe an effective solution. Because of the annual ice jam risk in Alaska, continual testing of mitigation techniques is recommended.

Bibliography

Abdelnour, E., R. Abdelnour, and L. Pelletier. 2019. "Ice Management of the Beauharnois Canal with Redesigned Ice Booms." *Committee on River Ice Processes and the Environment*. http://www.cripe.ca/docs/proceedings/20/Abdelnour-et-al-2019.pdf.

Altena, B., and A. Kääb. 2021. "Quantifying River Ice Movement Through a Combination of European Satellite Monitoring Services." *International Journal of Applied Earth Observations and Geoinformation* 98. https://doi.org/10.1016/j.jag.2021.102315.

Andrishak, R., and F. Hicks. 2008. "Simulating the Effects of Climate Change on the Ice Regime of the Peace River." *Canadian Journal of Civil Engineering* 35 (5): 461–472. https://doi.org/10.1139/L07-129.

Arp, C. D., Jones, B. M., and Grosse, G. 2013. "Recent Lake Ice-out Phenology Within and Among Lake Districts of Alaska, U.S.A." *Limnology and Oceanography* 58 (6): 2013–2028. https://doi.org/10.4319/lo.2013.58.6.2013.

Ashton, G. D. 1979. "River Ice: The Presence of Ice on Rivers Changes Their Behavior, Interferes with Their Use, and Causes Severe Economic Disruption." *American Scientist* 67 (1): 38–45. http://www.jstor.org/stable/27849059.

Beltaos, S. 1993. "Numerical Computation of River Ice Jams." *Canadian Journal of Civil Engineering* 20 (1): 88–99. https://doi.org/10.1139/l93-010.

Beltaos, S., ed. 1995. "River Ice Jams." Highlands Ranch, CO: Water Resources Publications, LLC. https://www.wrpllc.com/books/rij.html.

Beltaos, S, ed. 2013. "River Ice Formation." Alberta, Canada: Committee on River Ice Processes and the Environment, Canadian Geophysical Union Hydrology Section. https://www.researchgate.net/profile/Spyros-Beltaos/publication/308517799_River_Ice_Formation/links/5d701e50a6fdcc9961af8b91/River-Ice-Formation.pdf.

Beltaos, S. 2021. "Assessing the Frequency of Floods in Ice-Covered Rivers Under a Changing Climate: Review of Methodology". *Geosciences* 11 (514): 1–19. https://doi.org/10.3390/geosciences11120514.

Beltaos, S., and B. Bonsal. 2021. "Climate change impacts on Peace River ice thickness and implications to ice-jam flooding of Peace-Athabasca Delta, Canada." Cold Regions Science and Technology 186.

Beltaos, S., and B. C. Burrell. 2003. "Climatic Change and River Ice Breakup." *Canadian Journal of Civil Engineering* 30 (1): 145–155. https://doi.org/10.1139/l02-042.

Beltaos, S., and P. F. Doyle. 1996. "Ice Jam Mitigation Using Setback Dykes: Coldwater River at Merritt, BC." *Journal of Cold Regions Engineering* 10 (4): 190–206. https://doi.org/10.1061/(ASCE)0887-381X(1996)10:4(190).

Beltaos, S., L. Miller, B. C. Burrell, and D. Sullivan. 2006. "Formation of Breakup Ice Jams at Bridges." *Journal of Hydraulic Engineering* 132 (11): 1229–1236. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:11(1229).

Beltaos, S., and T. D. Prowse. 2001. "Climate Impacts on Extreme Ice-jam Events in Canadian Rivers." *Hydrological Sciences Journal* 46 (1): 157–181. https://doi.org/10.1080/02626660109492807.

Beltaos, S., and T. D. Prowse. 2009. "River-ice Hydrology in a Shrinking Cryosphere." *Hydrological Processes* 23 (1): 122–144. https://doi.org/10.1002/hyp.7165.

Blackburn, J. and She, Y. 2019. "A Comprehensive Public-domain River Ice Process Model and Its Application to a Complex Natural River." *Cold Regions Science and Technology* 163:44–58. https://doi.org/10.1016/j.coldregions.2019.04.010.

Blindow, N., D. Eisenburger, B. Illich, H. Petzold, and T. Richter. 2007. "Ground Penetrating Radar." In *Environmental Geology*, 283–335. Berlin Heidelberg: Springer. https://doi.org/10.1007/978-3-540-74671-3_10.

Burrell, B. C., S. Beltaos, and B. Turcotte. 2022. "Effects of Climate Change on River-ice Processes and Ice Jams." *International Journal of River Basin Management* 1–21. https://doi.org/10.1080/15715124.2021.2007936.

Burrell, B. C., B. Turcotte, G. Comfort, and J. Groeneveld. 2021. "Infrastructure and River Ice: An Overview." *Committee on River Ice Processes and the Environment*. http://www.cripe.ca/docs/proceedings/21/Burrell-et-al-2021.pdf.

Carey, K. L. 1984. *Solving Problems of Ice-Blocked Drainage*. CRREL-TD-84-2. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/2686.

Carlson, R. F., J. P. Zarling, and L. E. Link. 1989. "Cold regions engineering research—Strategic Plan." *Journal of Cold Regions Engineering* 3 (4): 172–190. https://doi.org/10.1061/(ASCE)0887-381X(1989)3:4(172).

Carr, M. L., S. P. Gaughan, C. R. George, and J. G. Mason. 2015. "CRREL's Ice Jam Database: Improvements and Updates." *Committee on River Ice Processes and the Environment*. https://www.researchgate.net/profile/Meredith-Carr/publication/308794107_CRREL's_Ice_Jam_Database_Improvements_and_Updates/links/5c9a1a78299bf11169485e6a/CRRELs-Ice-Jam-Database-Improvements-and-Updates.pdf.

Carr, M., C. M. Vuyovich, and A. M. Tuthill. 2017. "Benefit Analysis of Ice Control Structures in Oil City, Pennsylvania." *Journal of Cold Regions Engineering* 31 (2): 1–21. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000120.

Chacho, E. F., S. A. Arcone, and A. J. Delaney. 1993. "Winter Stream Morphology on the North Slope of Alaska." Edited by T. D. Prowse. *Proceedings Workshop on Environmental Aspects of River Ice*. Saskatoon, Saskatchewan, Canada: National Hydrology Research Institute. Subcomittee on the Hydraulics of Ice Covered Rivers. NHRI Symposium, No 12. ERDC-CRREL. 1–2.

Chaouch, N., M. Temimi, P. Romanov, R. Cabrera, G. McKillop, and R. Khanbilvardi. 2014. "An Automated Algorithm for River Ice Monitoring Over the Susquehanna River Using MODIS Data." *Hydrological Processes* 28 (1): 62–73. https://doi.org/10.1002/hyp.9548.

Chen, Y., and She, Y. 2020. "Long-term Variations of River Ice Breakup Timing Across Canada and Its Response to Climate Change." *Cold Regions Science and Technology* 176:1–19. https://doi.org/10.1016/j.coldregions.2020.103091.

Cherry, J. 2021. *Testing of Novel Technologies for Monitoring Aufeis Under Bridges in Alaska*. FHWA-AK-RD-4000(182). Juneau, AK: Alaska Department of Transportation & Public Facilities.

Clark, S. P., and A. Wall. 2016. "Freeze-up Monitoring on the Dauphin River, Manitoba, Canada." *International Association for Hydro-Environment Engineering and Research*. https://www.researchgate.net/publication/303873496.

Daly, S. F. 1991. *Frazil Ice Blockage of Intake Trash Racks*. CR-TD-91-1. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/2677.

Daly, S. F. 1994. *International Association for Hydraulic Research Working Group on Thermal Regimes: Report on Frazil Ice*. ERDC/CRREL SR-94-23. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/12325.

Daly, S. F., and R. Ettema. 2006. "Frazil Ice Blockage of Water Intakes in the Great Lakes." *Journal of Hydraulic Engineering* 132 (8): 814–824. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:8(814).

Daly, S. F., J. S. Rocks, M. Reilly-Collette, and A. B. Gelvin. 2019. *Ice Control to Prevent Flooding in Ship Creek, Alaska*. ERDC/CRREL TR-19-11. Hanover, NH: ERDC-CRREL. https://hdl.handle.net/11681/33483.

Daly, S. F., and C. M. Vuyovich. 2003. "Modeling River Ice with HEC-RAS." *Committee on River Ice Processes and the Environment*. http://www.cripe.ca/docs/proceedings/12/Daly-Vuyovich-2003.pdf.

Daly, S. F., J. E. Zufelt, P. Fitzgerald, A. Gelvin, and S. Newman. 2011. *Aufeis Formation in Jarvis Creek and Flood Mitigation*. ERDC/CRREL TR 11-14. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/5468.

Das, A., P. Rokaya, and K. E. Lindenschmidt. 2017. "Assessing the Impacts of Climate Change On Ice Jams Along the Athabasca River at Fort McMurray, Alberta, Canada." *Committee on River Ice Processes and the Environment*. http://cripe.ca/docs/proceedings/19/Das-et-al-2017.pdf.

Deck, David, and Gordon Gooch. 1981. Ice Jams Problems at Oil City, Pennsylvania. Special Report 81-9, Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

Drabek, T. E., and G. J. Hoetmer. 1991. *Emergency Management: Principles and Practice for Local Governments*. Washington, DC: International City Management Association.

Eaton, D. 2015. “Flooding Closes Old Sterling Highway Near Anchor Point.” *KBBI News*, December 30, 2015. https://www.kbbi.org/local-news/2015-12-30/flooding-closes-old-sterling-highway-near-anchor-point.

Ensom, T. P., O. M. Makarieva, P. Morse, D. Kane, V. Alekseev, and P. Marsh. 2020. “The Distribution and Dynamics of Aufeis in Permafrost Regions.” *Permafrost and Periglacial Processes* 31 (3): 383–395. https://doi.org/10.1002/ppp.2051.

FEMA. 2018. *Guidance for Flood Risk Analysis and Mapping. Ice-Jam Analyses and Mapping*. Guidance Document 94. Washington, DC: DHS-FEMA. https://www.fema.gov/sites/default/files/2020-02/Ice_Jam_Guidance_Feb_2018.pdf.

Foltyn, E. P., and A. M. Tuthill. 1996. *Design of Ice Booms*. ERDC/CRREL TD-96-1. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/2688.

Furman, L., and K. White. 2001. *Ice Jams, Winter 2000–2001*. Ice Engineering No. 32. Hanover, NH: ERDC-CRREL. https://apps.dtic.mil/sti/pdfs/ADA407405.pdf.

Gebre, S., T. Boissy, and K. Alfredsen. 2014. “Sensitivity to Climate Change of the Thermal Structure and Ice Cover Regime of Three Hydropower Reservoirs.” *Journal of Hydrology* 510:208–227. https://doi.org/10.1016/j.jhydrol.2013.12.023.

Ghobrial, T. R., M. Loewen, and F. Hicks. 2012. “Continuous Monitoring of River Surface Ice During Freeze-up Using Upward Looking Sonar.” *Cold Regions Science and Technology* 86:69–85. https://doi.org/10.1016/j.coldregions.2012.10.009.

Giovando, J. J., C. Engel, J. Rocks, S. F. Daly, D. O'Connor, and D. Hamill. 2019. *Ice Management Operations at Albeni Falls Dam*. ERDC/CRREL TR 19-21. Hanover, NH: ERDC-CRREL. http://dx.doi.org/10.21079/11681/34364.

Giovando, J. J., R. B. Haehnel, T. B. Baldwin, and S. F. Daly. 2018. *Ice Forces along the Missouri River Shoreline of the Lower Brule Sioux Tribe Lands*. ERDC/CRREL TR-18-12. Hanover, NH: ERDC-CRREL. http://dx.doi.org/10.21079/11681/28005.

Haehnel, R. B., C. H. Clark, and S. Taylor. 1996. *Dusting River Ice With Leaf Mulch to Aid In Ice Deterioration*. ERDC/CRREL SR-96-7. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/12134.

Hall, D. K., and G. A. Riggs. 2015. MODIS/Aqua Sea Ice Extent 5-Min L2 Swath 1km. (Version 6): *NASA National Snow and Ice Data Center Distributed Active Archive Center*. http://dx.doi.org/10.5067/MODIS/MYD29.006.

Hall, D. K., G. A. Riggs, and V. V. Salomonson. 2006. MODIS/Terra Snow Cover 5-Min L2 Swath 500m (Version 5): *NASA National Snow and Ice Data Center Distributed Active Archive Center*. http://dx.doi.org/10.5067/ACYTYZB9BEOS.

Hamill, D., J. Giovando, C. Engel, J. Rocks, and S. Daly. 2019. “River Ice Classification from High-Angle Oblique Imagery Using Deep Neural Networks.” *Cold Regions Engineering* 271–279. https://doi.org/10.1061/9780784482599.032.

Hammar, L., and H. T. Shen. 1995. “Frazil Evolution in Channels.” *Journal of Hydraulic Research* 33 (3) 291–306. https://doi.org/10.1080/00221689509498572.

Harris, S. A., H. M. French, J. A. Heginbottom, G. H. Johnston, B. Ladanyi, D. C. Sego, and R. O. van Everdingen. 1988. Glossary of permafrost and related ground-ice terms. Technical Memorandum No. 142, Ottowa, Ontario, CA: National Research Council of Canada. doi:10.4224/20386561.

Hawley, N., D. Beletsky, and J. Wang. 2018. “Ice Thickness Measurements in Lake Erie During the Winter of 2010–2011.” *Journal of Great Lakes Research* 44 (3): 388–397. https://doi.org/10.1016/j.jglr.2018.04.004.

Hicks, F. 2009. “An Overview of River Ice Problems: CRIPE07 Guest Editorial.” *Cold Regions Science and Technology* 55 (2): 175–185. https://doi.org/10.1016/j.coldregions.2008.09.006.

Hodgkins, G., R. W. Dudley, and T. G. Huntington. 2005. "Changes in the Number and Timing of Days of Ice-Affected Flow on Northern New England Rivers, 1930–2000." Climatic Change (Springer) 71: 319–340.

Huntington, T. G., G. A. Hodgkins, and R. W. Dudley. 2003. "Historical trends in river ice thickness and coherence in hydroclimatological trends in Maine." Climatic Change (Kluwer Academic Publishers) 61: 217–236.

Hydrologic Engineering Center. n.d. (Gridded Data Sources; accessed November 2, 2022), https://www.hec.usace.army.mil/confluence/hmsdocs/hmsguides/working-with-gridded-boundary-condition-data/gridded-data-sources.

Janowicz, J. R. 2010. "Observed trends in the river ice regimes of northwest Canada." Hydrology Research 41 (6): 462–470. doi:https://doi.org/10.2166/nh.2010.145.

Jasek, M., F. Weber, and J. Hurley. 2003. “Ice Thickness and Roughness Analysis on the Peace River Using RADARSAT-1 SAR Imagery.” *Committee on River Ice Processes and the Environment*. http://cripe.ca/docs/proceedings/12/Jasek-Weber-Hurley-2003.pdf.

Kalke, H., and M. Loewen. 2018. “Support Vector Machine Learning Applied to Digital Images of River Ice Conditions.” *Cold Regions Science and Technology* 155:225–236. https://doi.org/10.1016/j.coldregions.2018.08.014.

Kempema, E. W., and R. Ettema. 2011. “Anchor Ice Rafting: Observations From the Laramie River.” *River Research and Applications* 27 (9), 1126–1135. https://doi.org/10.1002/rra.1450.

Kempema, E. W., K. Osada, B. Remlinger, and R. Ettema. 2019. "Anchor-ice-related Flooding along Flat Creek, Jackson, Wyoming: Insights from a Stream in Mountainous Terrain." *Committee on River Ice Processes and the Environment*. http://www.cripe.ca/docs/proceedings/20/Kempema-et-al-2019.pdf.

Killen, J. M., and J. S. Gulliver. 1991. *The Use of SONAR to Measure Ice Thickness*. Project Report No. 322. Minneapolis, MN: St. Anthony Falls Hydraulic Laboratory-University of Minnesota. https://conservancy.umn.edu/bitstream/handle/11299/108651/pr322.pdf.

Kontar, Y. Y., U. S. Bhatt, S. D. Lindsey, E. W. Plumb, and R. L. Thoman. 2015. "Interdisciplinary Approach to Hydrological Hazard Mitigation and Disaster Response and Effects of Climate Change on the Occurrence of Flood Severity in Central Alaska." *Proceedings of the IAHS* 369:13–17. https://doi.org/10.5194/piahs-369-13-2015.

Kovacs, A. 1992. *Glacier, River, and Sea Ice Blister Observations*. ERDC/CRREL SR-92-2. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/11648.

Leppäranta, Matti. 2015. *Freezing of Lakes and the Evolution of their Ice Cover*. 1st Edition. Berlin Heidelberg: Springer. https://link.springer.com/book/10.1007/978-3-642-29081-7.

Lever, J. H., G. E. Gooch, and S, F. Daly. 2000. *Cazenovia Creek Ice-Control Structure*. ERDC/CRREL TR-00-14. Hanover, NH: ERDC-CRREL. https://apps.dtic.mil/sti/pdfs/ADA382170.pdf.

Li, J., and B. Chen. 2020. "Global Revisit Interval Analysis of Landsat-8 -9 and Sentinel-2A -2B Data for Terrestrial Monitoring." *Sensors (Basel)* 20 (22): 1–15. https://doi.org/10.3390/s20226631.

Li, S., D. Sun, M. D. Goldberg, B. Sjoberg, D. Santek, J. P. Hoffman, M. DeWeese, P. Restrepo, S. Lindsey, and E. Holloway. 2018. "Automatic Near Real-time Flood Detection Using Suomi-NPP/VIIRS Data." *Remote Sensing of Environment* 204:672–689. https://doi.org/10.1016/j.rse.2017.09.032.

Lindenschmidt, K. E. 2017. "RIVICE—A Non-Proprietary, Open Source, One-Dimensional River-Ice Model." *Water* 9 (5): 314. https://doi.org/10.3390/w9050314.

Lindenschmidt, K. E., G. Syrenne, and R. Harrison. 2010. "Measuring Ice Thicknesses Along the Red River in Canada Using RADARSAT-2 Satellite Imagery." *Journal of Water Resource and Protection* 2 (11): 923–933. http://dx.doi.org/10.4236/jwarp.2010.211110.

Madaeni, F., R. Lhissou, K. Chokmani, S. Raymond, and Y. Gauthier. 2020. "Ice Jam Formation, Breakup and Prediction Methods Based on Hydroclimatic Data Using Artificial Intelligence: A Review." *Cold Regions Science and Technology* 174. https://doi.org/10.1016/j.coldregions.2020.103032.

Markon, C., S. Gray, M. Berman, L. Eerkes-Medrano, T. Hennessy, H. P. Huntington, J. Littell, M. McCammon, R. Thoman, and S. F. Trainor. 2018. “Alaska.” In *Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II*, edited by D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, 1185–1241. Washington, DC: US Global Change Research Program. https://doi.org/10.7930/NCA4.2018.CH26.

Massie, D. D., K. D. White, S. F. Daly, and A. Soofi. 2002. “Predicting Ice Jams With Neural Networks.” *Proceedings of the ASME 2002 21st International Conference on Offshore Mechanics and Arctic Engineering*. Oslo, Norway: ASME. 669–673. http://dx.doi.org/10.1115/OMAE2002-28551.

Matanuska-Susitna Borough. 2019. “Willow Creek Flooding 2019: December 26, 2019.” *Matanuska-Susitna Borough*. Accessed November 1, 2022. https://matsugov.us/24-communication/msb/20958-willow-creke-flooding-2019#.

McFarlane, V., and S. P. Clark. 2021. “A Detailed Energy Budget Analysis of River Supercooling and the Importance of Accurately Quantifying Net Radiation to Predict Ice Formation.” *Hydrological Processes* 35 (3): 1–15. https://doi.org/10.1002/hyp.14056.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, et al. 2019. “Polar Regions.” In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Edited by H.-O. Pörtner et al. Cambridge, UK: Cambridge University Press, 203–320. https://doi.org/10.1017/9781009157964.005.

Mermoz, S., S. Allain-Bailache, M. Bernier, E. Pottier, J. J. Van Der Sanden, and K. Chokmani. 2014. “Retrieval of River Ice Thickness From C-Band PolSAR Data.” *IEEE Transactions on Geoscience and Remote Sensing* 52 (6): 3052–3062. https://doi.org/10.1109/IGARSS.2012.6350734.

Michel, B. 1971. *Winter Regime of Rivers and Lakes*. ERDC/CRREL CRSE-3-B1a. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/2656.

Moor, J. H., and C. H. Watson. 1971. “Field Tests of Ice Jam Prevention Techniques.” *Journal of the Hydraulics Division* 97 (6): 777–789. https://doi.org/10.1061/JYCEAJ.0002993.

Morse, B., J. Francoeur, H. Delcourt, and M. Leclerc. 2003. “Ice Control Structures Using Steel Nets.” 12th Workshop on the Hydraulics of Ice Covered Rivers . Edmonton, AB, Canada: CGU HS *Committee on River Ice Processes and the Environment*.

Nakonechny, S. 2019.“How a Canadian Coast Guard Hovercraft Breaks Up Ice Without Touching It.” *CBC/Radio Canada*, March 18, 2019. https://www.cbc.ca/news/canada/montreal/coast-guard-hovercraft-flooding-1.5056869.

Nalbant, M. A., and S. Sharma. 2022. "Investigating the Impact of Climate Change on River Ice Thickness Across the Northern Belt of United States." *ISH Journal of Hydraulic Engineering*. https://doi.org/10.1080/09715010.2022.2050309.

NASA/MODIS (Moderate Resolution Imaging Spectroradiometer). n.d. "Specifications." MODIS (accessed November 8, 2022). https://modis.gsfc.nasa.gov/about/specifications.php.

National Park Service. 2010. "Episode 9: Frazil Ice." Produced by S. M. Bumgardner. *Yosemite Nature Notes*, May 1, 2010. https://www.nps.gov/media/video/view.htm?id=6F8B3C8C-EF6B-7E9E-A59DF5B55E60A27A.

National Weather Service. 2009. *Flood Damages Suffered in the United States During Water Year 2009*. WY09. Silver Spring, MD: NOAA-NWS. https://www.weather.gov/media/water/WY09%20Flood%20Loss%20Summary.pdf.

Newton, A. M., and D. J. Mullan. 2021. "Climate Change and Northern Hemisphere Lake and River Ice Phenology From 1931–2005." *The Cryosphere* 15 (5): 2211–2234. https://doi.org/10.5194/tc-15-2211-2021.

Niziol, T. 2020. "Ice Jams: A Winter and Spring Version of Flash Floods." *Weather Underground*, May 1, 2020. https://www.wunderground.com/cat6/ice-jams-a-winter-and-spring-version-of-flash-floods.

Palomaki, R. T., and E. A. Sproles. 2022. "Quantifying the Effect of River Ice Surface Roughness on Sentinel-1 SAR Backscatter." *Remote Sensing* 14 (5644): 1–20. https://doi.org/10.3390/rs14225644.

Peterson v. United States. 1963. 217 F. Supp. 867 (United States District Court D, Alaska, April 16). https://casetext.com/case/peterson-v-united-states-23.

Pitcher, L. H., L. C. Smith, A. LeWinter, B. T. Overstreet, P. J. Gadomski, D. C. Finnegan, A. K. Rennermalm, and L. C. Andrews. 2019. "Direct Measurements of Ice Sheet Meltwater Runoff in Inglefield Land, Northwest Greenland." Abstract. *American Geophysical Union* C13C:1331. https://ui.adsabs.harvard.edu/abs/2019AGUFM.C13C1331P/abstract.

Poulin, G., T. Ghobrial, and B. Turcotte. 2021. "Trends in Maximum Ice-induced Water Levels and Flooding Frequencies in Some Rivers of Quebec, Canada." *Committee on River Ice Processes and the Environment*. http://www.cripe.ca/docs/proceedings/21/Poulin-et-al-2021.pdf.

Prowse, T. D. 1995. "River Ice Processes." In *River Ice Jams*, edited by S. Beltaos, 37. Highland Ranch, CO: Water Resources Publications.

Prowse, T., K. Alfredsen, S. Beltaos, B. R. Bonsal, W. B. Bowden, C. R. Duguay, A. Korhola, et al. 2011. "Effects of Changes in Arctic Lake and River Ice." *AMBIO* 40:63–74. https://doi.org/10.1007/s13280-011-0217-6.

Rapp, J., J. Tachella, Y. Altmann, S. McLaughlin, and V. K. Goyal. 2020. "Advances in Single-Photon Lidar for Autonomous Vehicles: Working Principles, Challenges, and Recent Advances" *IEEE Signal Processing Magazine*, 37 (4): 62–71. https://doi.org/10.1109/MSP.2020.2983772.

Richard, M., and B. Morse. 2008. "Multiple Frazil Ice Blockages at a Water Intake in the St. Lawrence River." *Cold Regions Science and Technology* 53 (2), 131–149. https://doi.org/10.1016/j.coldregions.2007.10.003.

Richard, M., B. Morse, and S. F. Daly. 2015. "Modeling Frazil Ice Growth in the St. Lawrence River." *Canadian Journal of Civil Engineering* 42 (9): 592–608. https://doi.org/10.1139/cjce-2014-0082.

Rockey, T. 2022. "Manley Hot Springs Flooding From Ice Jam." *Alaska News Source*, May 7, 2022. https://www.alaskasnewssource.com/2022/05/07/manley-hot-springs-flooding-ice-jam/.

Rødtang, Einar, Janik John, and Knut Alfredsen. 2021. "Anchor Ice Dam Survey in Small Steep Rivers." 21st Workshop on the Hydraulics of Ice Covered Rivers. Saskatoon, Saskatchewan, Canada,: CGU HS Committee on River Ice Processes and the Environment .

Rokaya, P., L. Morales-Marín, B. Bonsal, H. Wheater, and K-E. Lindenschmidt. 2019. "Climatic Effects on Ice Phenology and Ice-jam Flooding of the Athabasca River in Western Canada." *Hydrological Sciences Journal* 64 (11): 1265–1278. https://doi.org/10.1080/02626667.2019.1638927.

Shen, H. T. 2002. "Development of a Comprehensive River Ice Simulation System." *Ice in the Environment, Proceedings of the 16th IAHR international symposium on ice*. https://www.researchgate.net/publication/268397715_Development_of_a_comprehensive_river_ice_simulation_system.

Shen, H. T., and D. S. Wang. 1995. "Under Cover Transport and Accumulation of Frazil Granules." *Journal of Hydraulic Engineering* 121 (2): 184–195. https://doi.org/10.1061/(ASCE)0733-9429(1995)121:2(184).

Sodhi, D. S., and R. B. Haehnel. 2003. "Crushing Ice Forces on Structures." *Cold Regions Engineering* 17 (4): 153–170. https://doi.org/10.1061/(ASCE)0887-381X(2003)17:4(153).

Sterckx, S., I. Benhadj, G. Duhoux, S. Livens, W. Dierckx, E. Goor, S. Adriaensen, et al. 2014. "The PROBA-V Mission: Image Processing and Calibration." *International Journal of Remote Sensing* 35 (7): 2565–2588. https://doi.org/10.1080/01431161.2014.883094.

Stonevicius, E., G. Uselis, and D. Grendaite. 2022. "Ice Detection with Sentinel-1 SAR Backscatter Threshold in Long Sections of Temperate Climate Rivers." *Remote Sensing* 14 (7): 1–20. https://doi.org/10.3390/rs14071627.

SUHET (Sentinel User Handbook and Exploitation Tools). 2015. *Sentinel-2 User Handbook*. Issue 1, Revision 2. Paris, France: European Space Agency. https://sentinel.esa.int/documents/247904/685211/sentinel-2_user_handbook.

Sun, W., and B. Trevor. 2015. "A Comparison of Fuzzy Logic Models for Breakup Forecasting of the Athabasca River." *Committee on River Ice Processes and the Environment*. http://cripe.ca/docs/proceedings/18/25_Sun_Trevor_2015.pdf.

Timalsina, N. P., K. T. Alfredsen, and Å. Killingtveit. 2015. "Impacts of Climate Change on Ice Regime in a River Regulated for Hydropower." *Canadian Journal of Civil Engineering* 42 (9): 634–644. https://doi.org/10.1139/cjce-2014-0261.

Tunseth, M. 2017. "Ice Causing Flooding on Peters Creek." *Chugiak Eagle River Star*, December 18, 2017. https://www.alaskastar.com/2017-11-28/ice-causing-flooding-peters-creek.

Turcotte, B. 2021. "Flooding Processes and Recent Trends in Ice-induced High-water Levels Along Rivers of Northwestern Canada." *Committee on River Ice Processes and the Environment*. http://www.cripe.ca/docs/proceedings/21/Turcotte-2021.pdf.

Turcotte, B., B. C. Burrell, and S. Beltaos. 2019. "Impact of Climate Change on Breakup Ice Jams in Canada: State of Knowledge and Research Approaches." *Committee on River Ice Processes and the Environment*. http://www.cripe.ca/docs/proceedings/20/Turcotte-et-al-2019.pdf.

Tuthill, A. M. 1995. *Structural Ice Control: Review of Existing Methods*. ERDC/CRREL SR-95-18. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/12098.

Tuthill, A. M. 1999. *Flow Control to Manage River Ice*. ERDC/CRREL SR-99-8. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/11809.

Ueda, H., P. Sellman, and G. Abele. 1975. *USA CRREL Snow and Ice Testing Equipment*. ERDC/CRREL SR-146. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/11945.

USACE. 1994. *Ice Jam Flooding: Causes and Possible Solutions*. CECW-EH EP 1110-2-11. Washington, DC: DA-USACE. https://www.publications.usace.army.mil/Portals/76/Publications/EngineerPamphlets/ep_1110-2-11.pdf.

USACE (US Army Corp of Engineers). 2002. *Ice Engineering*. CECW-EH EM 1110-2-1612. Washington, DC: Department of the Army–USACE. **Error! Hyperlink reference not valid.**.

Vitug, Eric. 2020. "Affordable Access to Space." NASA. Accessed November 2, 2022. https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/archived/Affordable-Access-to-Space.

White, K. D. 2004. *Ice Engineering: Method to Estimate River Ice Thickness Based on Meteorological Data*. ERDC/CRREL TN-04-3. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/2602.

White, K. D., and H. J. Eames. 1997. *Ice Jams in Alaska*. ERDC/CRREL Ice Engineering-16. Hanover, NH: ERDC-CRREL. https://apps.dtic.mil/sti/pdfs/ADA407543.pdf.

White, K. D., and H. J. Eames. 1999. *CRREL Ice Jams Database*. ERDC/CRREL CR-99-2. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/9250.

White, K. D. and R. L. Kay. 1997. “Dusting Procedures for Advance Ice-Jam Mitigation Measures.” *American Society of Civil Engineers*, 11 (2): 130–145. https://doi.org/10.1061/(ASCE)0887-381X(1997)11:2(130).

White, K. D., K. J. Pederson, and R. T. Pomerleau. 2000. *Ice Affected Flood Frequency*. ERDC/CRRE: MP-00-5482. Hanover, NH: ERDC-CRREL. https://www.coldregions.org/vufind/Record/222143.

White, K. D., A. M. Tuthill, C. M. Vuyovich, and P. B. Weyrick. 2007. "Observed Climate Variability Impacts and River Ice in the United States." *Committee on River Ice Processes and the Environment.*

Wille, P. C. 2005. *Sound Images of the Ocean: in Research and Monitoring*. Berlin, Germany: Springer.

Wohl, E. 2019. Rivers in the Landscape. 2nd. Hoboken, NJ: Wiley-Blackwell.

Yang, R-M., and T. Zhang. 2022. “Dramatic Thinning of Alaskan River Ice and Its Climatic Controls.” *Advances in Climate Change Research* 13 (5): 623–631. https://doi.org/10.1016/j.accre.2022.08.001.

Yu, W. B., Y. M. Lai, W. L. Bai, X. F. Zhang, D. Sh. Zhuang, Q. H. Li, and J. W. Wang. 2005. “Icing Problems on Road in Da Hinggangling Forest Region and Prevention Measures.” *Cold Regions Science and Technology* 42 (1): 79–88. https://doi.org/10.1016/j.coldregions.2005.02.004.

Zufelt, J. E. 1993. *Ice Motion Detector System*. ERDC/CRREL MP-3973. Hanover, NH: ERDC-CRREL. https://www.coldregions.org/vufind/Record/203205.

Abbreviations

ACV	Air cushioned vehicle
AFFD	Accumulated freezing degree days
ANN	Artificial neural network
CONUS	Continental United States
CRREL	Cold Regions Research and Engineering Laboratory
ERDC	Engineering Research and Development Center
FL	Fuzzy logic
GP	Genetic programming
GPR	Ground-penetrating radar
ICS	Ice control structures
IJDB	Ice Jam Database
MODIS	Moderate Resolution Imaging Spectroradiometer
NWS-APRFC	National Weather Service-Alaska-Pacific River Forecast Center
SAR	Synthetic Aperture Radar
SBRF	Single beam rangefinder
SUHET	Sentinel User Handbook and Exploitation Tools
USACE	Us Army Corp of Engineers
VIIRS	Visible Infrared Imaging Radiometer Suite

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14. ABSTRACT
Ice is an important part of the Alaska ecosystems and can form through dynamic (e.g., frazil) or static (e.g., thermal) processes. In Alaska, both freeze-up and breakup ice jams occur, however breakup jams during the spring snowmelt period are most common. Historically there have been many river systems in Alaska that have chronic ice jam issues. These ice jams have resulted in several significant ice jam floods. There are several ice jam mitigation techniques that can be used to either provide state and local emergency managers warnings of a potential ice jam or reduce the impacts of a jam. Common relatively low-cost mitigation methods that can be implemented prior to a jam forming are monitoring and detection of movement, mechanical or thermal weakening of the ice cover. Permanent measures are also effective and maybe the best option in specific locations. These measures include structures to keep flood waters from inundating areas (e.g., levee) or they can be designed to hold back ice fragments moving downstream (e.g., ice boom and pier structures). Climate change impacts to ice processes are important for Alaska and additional investigations will be needed to quantify the ecologic, hydrologic, and societal impacts.

15. SUBJECT TERMS
Alaska; Ice jam; Ice jam database; Ice jam mitigation

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