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Review

Icing and aufeis in cold regions I: the origin of overflow

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Abstract

The process of icing involves the freezing of overflow layers, on ground or within streams, and results in ice bodies called "aufeis" that are common in most northern landscapes. Knowledge about aufeis is still limited despite the cold region engineering challenge they represent. Understanding the causes of overflow events leading to aufeis development represents a key for the prediction, mitigation, and management of this geohazard and can also support the planning and design of infrastructure in the North. This paper introduces a practical classification for the diverse range of overflow processes that generate aufeis, including under-represented processes, such as the instability of winter streamflow. Importantly, it distinguishes flow conveyance from water supply overflow processes and describes the temporal aspect of icing intensity. Finally, research topics are proposed to improve our understanding of aufeis, including their predictability, the impact of climate change on their occurrence and extent, and stream morphology–aufeis interaction.

Key words: icing, aufeis, overflow, cold region hydrology, stream ice processes

1. Introduction

Icing can be described as a cold region hydrological process that involves the freezing of successive overflow layers to form a sheet-like ice accumulation and is synonymous with "Aufeis" in German, "Naled" or "Taryn" in Russian, and "Kjøving" in Norwegian. The term "glaciation" is also commonly used to refer to the icing process in northern Canada. Seminal papers on the topic of aufeis in North America include the pioneer work of (Carey 1973; icing processes description), (Sloan et al. 1975; icing observations), (Kane 1981; aufeis formation mechanism), and (Wankiewicz 1984*a*, 1984*b*; hydrothermal aspects of stream aufeis). Key research was also presented by (Schohl and Ettema 1990; laboratory simulation of aufeis formation), (Clark and Lauriol 1997; hydrogeological and geochemistry aspects of aufeis), (Yoshikawa et al. 2007; comprehensive study of aufeis, including remote sensing), and (Morse and Wolfe 2015; environmental factors controlling aufeis). Daly (2013*a*) summarized knowledge about stream aufeis, including several case studies from Alaska. Recent aufeis assessments have also been completed in Yukon and Northwest Territories (e.g., Brasseur et al. 2016). Multiple aspects of aufeis have been recently presented in a review paper by Ensom et al. (2020), including valuable Russian literature.

Several studies (e.g., Kane 1981; Clark and Lauriol 1997; Morse and Wolf 2015) largely associate subarctic icing with groundwater sources (below or above permafrost) and with a rise in hydrostatic head. Icing is also often described as a post-freeze-up process during which frost penetrates through either the ground, or an ice cover, resulting in pressurized conditions in the underlying water column, causing overflow (e.g., Hu and Pollard 1997). Kane (1981) added a thickness component to the description of a river aufeis, suggesting that it could be several times greater than the normal water depth during open water conditions and greater than the thickness of a surface (i.e., floating) ice cover generated under equivalent weather conditions. Although this description translates the extreme rate of heat extraction associated with aufeis formation, it is not necessarily inclusive of all aufeis, especially those that are supply limited. Even the formation of white ice at the surface of a free-floating ice cover in rivers and lakes may be compatible with the definition of icing. For river ice scientists, aufeis is a type of ice cover that thickens from its surface upward and that is largely grounded (as opposed to floating). For engineers, icing is often considered as a geohazard that may reduce the performance or safety of infrastructure.

Icing typically occurs under consistently cold temperatures and is commonly found in permafrost regions of North America and Asia. Some of the largest aufeis fields (several tens of km^2, Clark and Lauriol 1997) result from the progressive winter drainage of deep (karst) groundwater in permafrost regions, but suprapermafrost groundwater can also generate large aufeis (e.g., Terry et al. 2020). Despite the prominence of icing in subarctic and Arctic regions, Grayson (2010), among others, have reported it outside permafrost areas. Indeed, unfrozen water sources and subzero temperatures do not exclusively exist in subarctic and Arctic regions, hence the process of overflow and freezing can occur during winter in relatively temperate regions.

In this paper, a broad definition of icing is considered. It includes underground and surface water sources, icing on any cold surface (not only existing ice), aufeis of any size and surface gradient, as well as overflow from both pressurized and free-flowing origins. It recognizes the existence of aufeis outside permafrost regions but generally imposes the presence of a confined (bankfast) or grounded (bedfast) ice state to the definition, which means that it excludes overflow from a lake or river on its own free-floating ice cover. This paper adopts the terminology and classification proposed by Ensom et al. (2020), namely, that icing refers to the overflow and freezing process, whereas aufeis is the resulting, layered ice accumulation.

Three physical conditions control aufeis initiation and development in cold regions:

- a water supply, which mostly depends on long- and short-term precipitation (annual totals and autumn rain, respectively),
- a net heat loss, supported by cold air and a low sun angle (or no sun at all), and
- the mechanical and thermal properties of ice.

Some aspects of the first two conditions may be dominant enough to sustain aufeis formation at the same location from year to year (e.g., Grey and McKay 1979; Hu and Pollard 1997), whereas other aufeis are less predictable and associated with a multiyear return period (e.g., Morse and Wolfe 2015). The third condition is what makes water–ice interaction unique among other fluids and solids.

Each ice layer within an aufeis body is the result of a two-stage process, overflow and then freezing. With the exception of groundwater springs that have relatively constant outflow, quantifying the occurrence and rate of overflow is often challenging; it requires a spatial understanding of multiple geophysical processes, from hydrogeological fluxes to weather-driven cold region hydrology and ice processes. The conditions leading to overflow are not fully understood, and by extension, predicting the thickness and extent of the resulting aufeis remains a challenge, especially in streams (Daly 2013*a*). For instance, Kane (1981) reported groundwater head fluctuations in phase but lagging behind air temperature variations, a process associated with the occurrence of overflow in an Alaskan creek that remains unexplained roughly 50 years after it was documented. The second stage of aufeis formation, freezing of the overflow, may seem straightforward water flowing over a cold surface, while exposed to cold air, will simply freeze. However, this does not directly explain why some overflow layers spread over great distances, whereas others freeze and accumulate close to the water source, nor does it encompass different freezing patterns of water, ice, and slush, which may coincide at the same time on top of each other. Through laboratory experiments involving a controlled water supply, Schohl and Ettema (1990) modeled this surprisingly complex process by varying different parameters, including local terrain gradient, lateral confinement, rate of heat loss to the air, and the characteristics of the cold surface on which aufeis forms.

The objectives of this paper are (1) to identify, explain, and classify the specific conditions and processes leading to overflow and icing and (2) to propose research avenues that will improve our understanding of aufeis of any size forming in a wide range of environments. A companion paper (Turcotte et al. 2023) addresses the engineering consequences of aufeis and describes 50 aufeis mitigation and management options.

2. Conditions leading to icing

Occasional observations, measurements, interventions, and most importantly, ambitious and targeted research programs have greatly contributed to the existing knowledge of icing and aufeis. For instance, Morse and Wolfe (2015) extensively used remote sensing to identify locations where large (more than one 30 m × 30 m Landsat pixel) aufeis occur. Even though several factors that influence icing have been documented, many of the discrete processes that trigger overflow events, including those feeding small aufeis, have only been partially described.

2.1. Altered flow conveyance processes

2.1.1. Formation of grounded stream ice

One of the early stages of ice formation in steep channels involves the formation of anchor ice (e.g., Turcotte and Morse 2013). This process generally begins with the production and adhesion of active frazil particles (e.g., Daly 2013*b*) to the channel bed substrate in a supercooled environment (e.g., Boyd et al. 2022), and it may continue through a combination of frazil interception and in situ crystal growth (e.g., Malenchak and Clark 2013). Snowfall on open water, a common occurrence in early winter, can also generate what Turcotte et al. (2012*a*) refer to as anchor snow slush, a type of anchor ice that is not driven by heat loss to the same extent as conventional anchor ice.

As the grounded anchor ice thickens upward, it obstructs the channel and progressively raises the water level. The preferential development of anchor ice in shallow areas or cross-sections, such as riffles or steps made of large rocks or woody debris, often leads to the emergence of anchor ice above the water surface and to the formation of a thermal ice cap. Then, further anchor ice growth (combined with flow turbulence) causes overflow, which generates aufeis islands and bankfast aufeis (Fig. 1). This process can eventually lead to the formation of a series of ice dams extending from bank to bank, creating a common stair-like freeze-up pattern in streams with a longitudinal gradient above 0.3% (Turcotte and Morse 2013). The bottom part of each ice dam may remain porous, while the upper part acquires structural strength through the icing process (Dubé et al. 2014; Rødtang et al. 2023). The rate of water level rise, and corresponding aufeis thickening during the formation of ice dams, has been reported to vary between 0.5 and 2.0 cm per hour during prolonged, consistently cold periods (Dubé et al. 2015).

Fig. 1. (*a*) Aufeis island (growing on emerging anchor ice, length of about 0.5 m) and (*b*) bankfast aufeis in small rivers of the Montmorency River, Québec (photo credit: BT, 1 February 2013).

The occurrence of widespread overbank flooding and the formation of thick aufeis during the early-winter period is often limited by transient air temperature warming or by the formation of a thin surface ice cover. In cold–temperate regions, the resulting partial ice cover offers enough insulation to reverse the heat flux (from net water column loss to net gain), and this causes porous anchor ice to be thermally eroded (melting may preferentially occur at the channel bed surface), deep flow paths to reopen, the water level to drop, and a free-spanning ice cover to develop (e.g., Turcotte et al. 2014). Therefore, the early-winter period represents a unique opportunity to observe icing far away from Arctic regions. In most steep subarctic and Arctic streams (or in some high-altitude mountain streams), the limited supply of (relatively cold) groundwater and (or) heat contained in the channel bed (e.g., Wankiewicz 1984*b*), combined with the potential for prolonged, intense cold spells may promote the occurrence of an uninterrupted transition between anchor ice formation and widespread icing events.

2.1.2. Thickening of bankfast stream ice

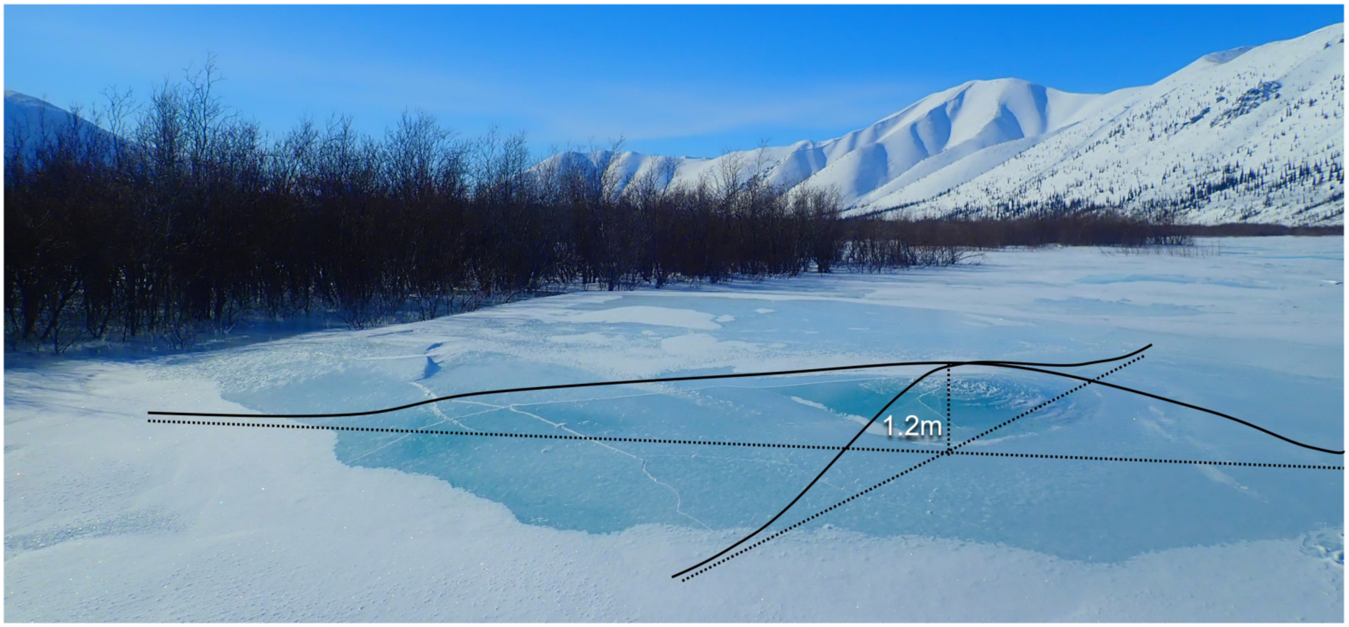
The most common type of river ice cover described in the literature is free-floating. The thickening of free-floating ice relies on two processes, columnar (transparent) ice formation downward at the ice–water interface and snow (white) ice formation upward at the snow–ice interface (Ashton and Beltaos 2013). When a floating ice cover thickens, the stage simply rises and the flow conveyance is maintained, since the hydraulic head corresponds to the water column added to the water-equivalent weight of the ice and snow.

In narrow channels, a surface ice cover can become sufficiently thick and strong to lose its capacity to float freely when hydraulic conditions change. The development of a confined (bankfast) ice cover depends on the cover thickness relative to the channel width (Beltaos 2008) and is likely to occur as winter progresses due to cumulative heat loss. In turn, the formation of a grounded ice cover (bedfast, often involving anchor ice formation), where the ice cover fuses with the channel bed over a large portion of the channel cross-section, mostly occurs in shallow water areas (e.g., less than 0.5 m deep). Bankfast and (or) bedfast conditions imply the presence of a flow restriction that may eventually take the form of a conduit beneath or within the ice cover and that can withstand pressurized conditions (Wankiewicz 1984*b*). Downward, thermal thickening of the ice cover reduces the flow conveyance capacity and may initiate and sustain the pressurized flow state. This process represents one of the main, if not the only, icing process reported in a number of stream aufeis studies. Hu and Pollard (1997) presented a list of channel and overbank features that act as flow pathways between the pressurized flow conduit and upwelling location, the most common being cracks in the ice.

The following processes may naturally control the amount or duration of pressure-driven overflow events that are associated with stream ice cover thickening:

- Ice expands as it warms. When overflow is initiated through an ice cover (or aufeis), it warms the underlying and surrounding ice, which expands and potentially seals cracks (at least uniform, longitudinal ones). The presence of dry tension cracks (deeper than hydrostatic elevation) in the ice cover of lakes may be explained by the warmer ice at the bottom of the cover (Metge 1976).
- For low discharge outflows in frigid conditions, the overflow may simply freeze and seal the pathway, therefore limiting the duration of the icing event.
- The formation of ice blisters (formed by injected water, Fig. 2) and ice mounds (concentration of icing layers) have been described by Pollard (1988) but are still not fully understood (Daly 2013*a*). They can be interpreted as phenomena that exploit the properties of ice (e.g., its capacity to sustain plastic deformation without breaking) to prevent overflow through an ice deformation response to a local

Fig. 2. Ice blister in the Tth“oh zraii njik (Gwich”in) or Ttth’oh zray (Hän for Blackstone River) at Km 145 of the Dempster Highway in late March 2022. This blister shape is depicted. Its internal pressure head corresponded to the blister elevation (it still contained liquid water). (Photo credit: BT, 24 March 2022).



overpressure. There is one rare instance of an ice mound explosion in Russia as reported in Carey (1973). However, in most instances, the pressure build-up and its variation over time are limited enough to prevent a dynamic conclusion to the phenomenon.

- When overflow begins, the ice cover surface gains heat from the relatively warm overlying water as well as from the release of latent heat during the freezing process (e.g., Hu et al. 1999). Therefore, the downward thickening of the ice cover is eventually interrupted by the overflow (Schohl and Ettema 1990), which stabilizes the pressure in the underlying water column. While this does not directly contribute to a decline of the overflow rate, it may prevent a further reduction of the under-ice flow conveyance capacity.

2.1.3. Freezing front migration through the ground

Groundwater outflow may cause ground icing at the beginning of the cold season (see subsection 2.2.1). However, in some instances, this process initiates later during winter, generally during or following a mid-winter or late-winter cold spell. This phenomenon is counterintuitive, since groundwater reservoirs generally diminish over winter. However, these conditions can be explained by a gradual, downward migration of the freezing front through a water-bearing layer, talik, or active layer, until it reaches an impermeable layer, such as bedrock, clay, or more commonly, permafrost (e.g., Carey 1973). This frozen barrier reduces the ground conveyance capacity, causing pressure to build up, eventually forcing water to the ground (snow) surface, and resulting in a seepage (diffuse overflow) type of aufeis. If the groundwater content is significant, the resulting aufeis may thicken or extend until snowmelt. This process is most commonly associated with cold winters in permafrost regions. Terry et al. (2020) recently explored the occurrence of this process within the bed of an Arctic braided river.

2.1.4. Collapsing of free-spanning stream aufeis slabs

At the end of winter, and prior to spring snowmelt, in-stream aufeis bodies become isothermal (at 0 °C). By doing so, the ice loses its structural strength and becomes prone to plastic deformation under its own weight (as well as the weight of any overlying snowpack). This transition is not discernible when the aufeis is supported by the channel bed and (or) banks (or in the case of a floating ice cover section, the underlying water) but it becomes apparent when the ice is in a free-spanning state. The loss of structural integrity may result in the formation of a single or multiple (in braided streams) longitudinal depressions at the aufeis surface, indicating the location of under-ice flow conduits. It may even be possible to hear the sound of free-flowing water in an air conduit under the ice surface.

As temperatures continue to warm in the spring, free-spanning ice eventually bends and cracks, with potential for ice slabs to collapse gradually or suddenly into the flow beneath. The hydraulic interference caused by large ice pieces in the flow may cause the water level to rise and overtop the surface of the surrounding aufeis or bankfast ice. When cold temperatures return (generally every night in early spring), this overflow can freeze on the existing aufeis. Later in the spring, when warm temperatures persist and as solar radiation intensifies, the overflow may thermally erode narrow channels on the grounded aufeis surface.

The phenomenon of ice bending and collapsing into the flow at the end of winter is typical of steep (gradient > 0.3%), single, and multichannel streams (e.g., Turcotte et al. 2014). This process may amplify the hydrological signature of daily runoff cycles in water level time series (Turcotte 2022) until the main channel is completely ice-free. In very narrow or incised creeks, even deteriorated aufeis may remain strong enough to maintain its free-spanning state and channel insulation well into spring.

2.1.5. The influence of winter precipitation

An early-winter thermal aspect of snow is its cooling effect when it falls (or is wind-blown) directly onto open water (e.g., Ashton 2013). This can also occur throughout winter in open leads found downstream of warm water sources. This snow would theoretically encourage downstream ice formation through sensible and latent heat loss. Subsequently, when snow directly falls in water at 0 °C (in rapids or downstream of freeze-up jam locations; Turcotte 2020), it will be carried downstream in the form of slush. In aufeis-prone streams, this slush may be entrained under the ice cover, and the water–slush mixture may be sufficiently viscous (or the slush may simply accumulate) to reduce the flow conveyance capacity and to initiate pressurized conditions.

Winter precipitation and the resulting snowpack is generally reported to affect flow conveyance indirectly through thermal insulation (e.g., Ensom et al. 2020). Indeed, in subarctic and Arctic regions, winters with (or areas characterized by) significant snowfall should theoretically see reduced frost penetration and associated ground icing activity. Snowfall events are also associated with overcast conditions, which increases long wave radiation gains and reduces heat loss (e.g., Ashton 2013). According to an experienced highway maintenance foreperson working in Yukon, early season snowfalls generally attenuate icing problems along roads during winter (Hoogland, pers. com., 2021). The link between a thin winter snowpack and the occurrence of aufeis is also reported by Vinson and Lofgren (2003). The occurrence of early winter ground icing, or ground icing that occurs outside permafrost areas (subsection 2.2.1), should be independent of the amount and density of snow on the ground because overflow is not triggered by reduced groundwater conveyance.

In specific contexts, wind-blown snow may also provide thermal insulation. In a cold–temperate, low-gradient headwater stream, wind-blown snow was even reported to suppress ice cover formation altogether (Turcotte et al. 2012*a*). However, snowdrifts have been observed to generate the opposite effect by directly promoting aufeis formation by impeding (under-ice or over-ice) flow. Thick and dense snow accumulations shaped by the wind could trigger overflow at locations where the ice cover is not fully grounded (either floating- or free-spanning) by depressing it into the water column. Regardless of the role of snowdrifts in initiating overflow events, when overflow does happen, local snow dams on the aufeis surface represents an opportunity for much thicker overflow events than those would otherwise occur.

It is relatively challenging to add another factor to already complex experiments and equations presented by Schohl and Ettema (1990), but wind-blown snow may represent a largely under-rated factor in stream aufeis formation that deserves further investigation. Based on measured snow accumulations at a nearby meteorological station, Hu and Pollard (1997) stated that the snowpack was unlikely a significant contributor to the aufeis volume (or mass) in the East Blackstone River, Yukon. However, they did not consider snow that may have been redistributed by wind from across the open landscape of Tombstone Territorial Park. It was recently observed, through a telemetry-enabled camera, that snow in the same area is continually redistributed, with sections of the East Blackstone River intercepting a large amount of wind-blown snow that becomes part of the local aufeis body following overflow events.

Snowmelt or rain events in mid-winter are relatively rare in most high-latitude regions where icing results from frost penetration (e.g., Janowicz 2010). When they occur, it should be assumed that ice formation is temporarily reduced or halted because of the landscape-wide heat gain. In addition, snowmelt or rain events increase the snow density and reduce the insulating properties of the snowpack (e.g., Sturm et al. 1997), or simply saturate or melt the snowpack entirely (especially in barren terrain or in wide, braided channels where the snowpack may be thin or patchy). Once cold temperatures return, the reduced insulation over the ground or aufeis could promote frost penetration, reduce ground or stream flow conveyance, and result in more intense icing activity than would be the case if temperatures had remained cold. In turn, late-winter snowfalls can delay aufeis deterioration by protecting the ice surface against short-wave radiation and warm air temperatures (as is the case for any river ice cover, e.g., Hicks et al. 2008). These events also increase the potential for significant spring snowmelt runoff (subsection 2.2.5), thereby compounding the conditions that promote spring flooding.

2.2. Water supply-driven processes

2.2.1. Groundwater free draining

Groundwater can surface year round in the form of diffuse or concentrated (spring) flow, regardless of ground characteristics and temperature. Unless this groundwater promptly enters a large waterbody (e.g., river or lake) or infiltrates back into the ground, it is susceptible to freezing under cold conditions. The downslope location, timing, extent, and thickness of the resultant aufeis depends on the groundwater temperature (warm water delays freezing), its outflow rate (high rates delay freezing), and the rate of heat loss (channelization, a thick snowpack, and moderately cold weather all delay freezing).

Shallow groundwater outflow rates typically decline through winter unless snowmelt and (or) rainfall replenish the groundwater reservoir. For deep water sources (e.g., fractured bedrock or subpermafrost aquifers), however, the outflow rate may remain steady during the entire cold season, resulting in some of the largest documented aufeis (e.g., Kane 1981; Ensom et al. 2020).

2.2.2. Upstream ice formation and downstream flow depression

During the early-winter phase of river ice formation, baseflow in streams and rivers (i.e., the relatively consistent supply of water originating from upstream ground, wetlands, and lakes) is affected by interdependent processes. First, a significant portion of the baseflow freezes to form stationary ice in the drainage network. Second, the formation of stationary ice increases flow resistance and slows water velocities. Third, the in-channel, ice-induced stage rise may block or even temporarily reverse groundwater inflow from the banks and bed. The combination of ice, hydraulic, and groundwater storage processes may significantly reduce downstream flow. At a watershed scale, this generates the well-documented, early-winter discharge depression (e.g., Prowse and Carter 2002), a process strongly influenced by freeze-up patterns (e.g., Turcotte 2020), by the general drainage network morphology as well as by weather conditions (e.g., Turcotte and Rainville 2022).

Once the formation of an ice cover is complete in most upstream reaches/tributaries, or if air temperatures rise, the freeze-up flow depression ends, and the channel discharge rises back to baseflow rates. If air temperatures rise to a point where a portion of the stream ice melts or becomes dislodged (or in the case of ice dam thermal erosion, subsection 2.1.1), a portion of the stored water may be released, and the discharge may temporarily exceed the expected baseflow rate. The flow rise under warming (but still freezing) conditions is counterintuitive and is commonly misinterpreted as a backwater response caused by the formation of stationary ice (e.g., Turcotte and Rainville 2022).

Ensom et al. (2020) noted that the exact physicomechanical relationship between documented winter fluctuations in air temperatures, hydrostatic head, and overflow events (as reported by Kane (1981)) remain unknown. In parallel, Turcotte et al. (2013) and Turcotte and Nafziger (2021) proposed that some streams continue to be affected by detectable discharge depressions well into winter months (an observation also reported further north by Wankiewicz (1984*b*) and Hamilton and Moore (1996)) and presented data sets that show a time lag between changes in air temperature and estimated discharge fluctuations. Even in permafrost regions where upstream heat is limited, alternating cold and mild (though still <0 °C) periods can generate distinct storage events or at least varying watershed-scale storage rates. Therefore, unstable winter flow conditions can occur (e.g., far downstream from large water bodies) as a result of weather-induced upstream water storage variations (Turcotte and Rainville 2022). This hydrological behaviour, interpreted from stage measurements at locations where ice conditions are stable, can be subtle in a floating ice cover setting, but a slight mid-winter flow variation (estimated to be less than 10% by Hamilton and Moore (1996)) may result in a significant head change in a confined or grounded ice setting with limited conveyance capacity (i.e., a stream aufeis). The resulting pressurized condition can force water to surface, causing overflow and icing.

Interestingly, even though studies have emphasized the water storage aspect of aufeis, most of them have neglected to consider that analogous processes are also likely occurring upstream. For example, Hu and pollard (1997) simulated the reduced (depressed or even depleted) outflow downstream of an aufeis but used a monotonic flow recession as an input to the model. Here, the authors propose that weather-induced flow variations during the winter period represent an important, if not a dominant, driving factor for the occurrence of overflow and icing events. The time lag identified by Kane (1981) between air temperature and piezometric variations may not be linked directly to the local aufeis thickness, as originally proposed, but more generally to the increasingly frozen and snow-insulated upstream landscape, which contributes to delaying the hydrological response to weather forcing.

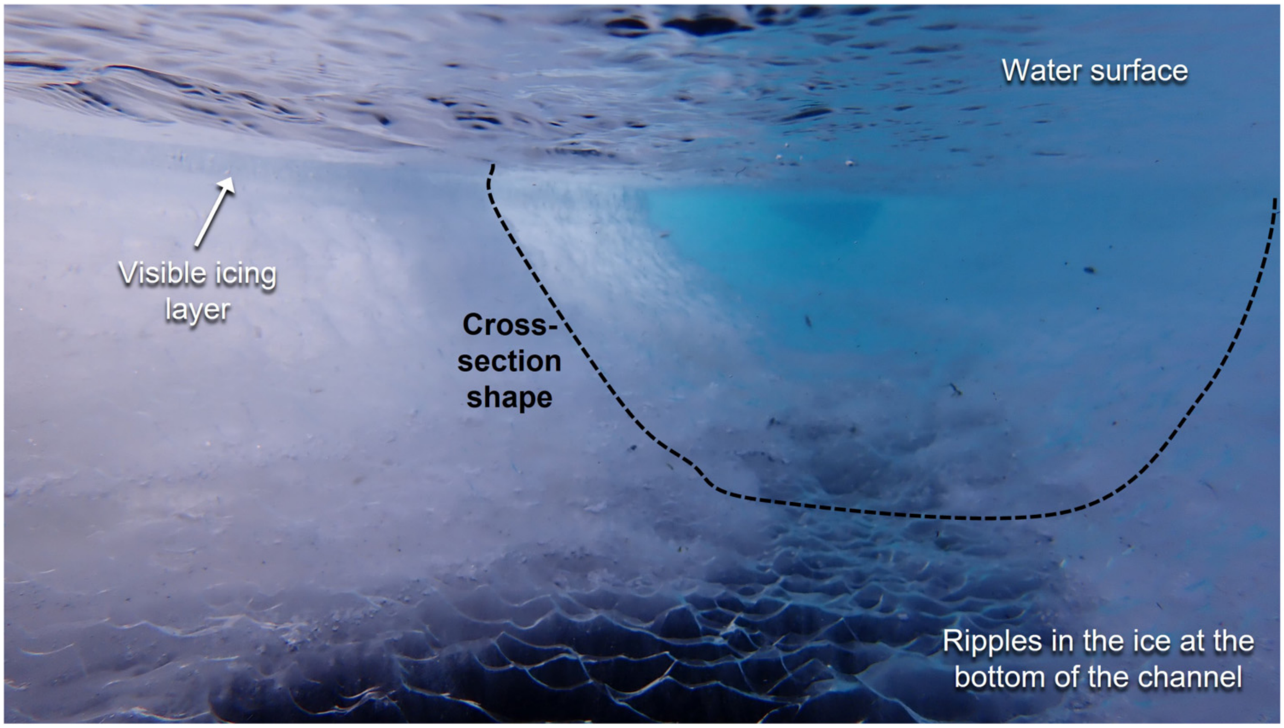
2.2.3. Flow diversion in multichannel reaches

Zufelt et al. (2009) reported the occurrence of both (transient) sheet flow (less than 1 cm deep) and active flow channels on the surface of aufeis in the braided Jarvis Creek, Alaska. The concentration of overflow in a defined channel on the ice surface (which in the case of Jarvis Creek, caused overbank flooding) is most likely to occur in the presence of a substantial overflow rate in a relatively steep channel. High overflow rates may be caused by variations in upstream storage (subsection 2.2.2; air temperatures were rising during the observed phenomenon at Fairbanks, located some 120 km away from Jarvis Creek). However, based on this specific case study, Daly (2013*a*) proposed that flow redirection between conduits within the braided channel unit may explain episodic active flow conditions at the aufeis surface. It is unclear whether this flow redirection phenomenon is the result of a reduced flow conveyance capacity at a nearby upstream location within the aufeis, and if so, whether it originated from (1) ice cover thickening (subsection 2.1.2), (2) the collapse of a fragile ice sheet in a conduit within the aufeis (subsection 2.1.4), (3) unstable near-surface (or hyporheic) conditions, or (4) another local or upstream ice process.

2.2.4. Mid-winter rain-on-snow runoff

A winter rain event that has the capacity to generate detectable runoff, despite the cold snowpack and largely frozen ground, is often associated with mid-winter (dynamic) breakup events in streams and rivers in cold-temperate regions (Beltaos 2008). In environments where stream aufeis are common, mid-winter runoff events are less common, and if they do happen, stream-scale breakup events are unlikely to occur for hydromechanical reasons (i.e., the ice cover is usually too thick and (or) overflow alleviates the pressure on the ice cover). However, the combination of warm air temperatures and rain may quickly bring a mid-winter flow

Fig. 3. Underwater photograph of an overflow channel in an aufeis on the North Klondike River, Yukon on 8 May 2022. The channel has a trapezoidal shape and is roughly 0.6 m deep and 1.0 m wide. (Photo credit: BT, 8 May 2022).



recession to an end (increase water supply) and cause small accumulations of broken border and surface ice floes (and a lower flow conveyance capacity), resulting in overflow. The reduced snowpack insulation (subsection 2.1.5) at the aufeis surface can also promote subsequent ice thickening once cold temperatures return.

If a runoff event occurs during the winter period, it is likely accompanied by shallow groundwater recharge if an unfrozen active layer still exists. In this case, ground icing activity should be expected to temporarily intensify once cold temperatures resume. This, however, does not apply to aufeis fed by subpermafrost or deep groundwater sources.

2.2.5. Spring snowmelt runoff

The rise in flow from spring snowmelt runoff (or rain-on-snow runoff) is likely to overwhelm the under-ice flow conveyance capacity in aufeis-affected stream reaches, especially when thawing conditions arrive rather suddenly. The collapse of aufeis slabs into the flowing water (section 2.1.4) may exacerbate the resulting overflow process. Long, thick aufeis may have stored a significant heat deficit during the preceding months, enough to freeze runoff from the first snowmelt cycles. Subsequently, thaw–freeze cycles may generate daytime snowmelt overflow followed by a night-time icing and additional aufeis thickening.

Warmer weather eventually causes overflow to melt narrow canals or galleries within the aufeis that minimize heat loss and refreezing at night (see example in Fig. 3). Once consistently warm temperatures are maintained, regardless of the latitude and snowmelt rates, ice thickening ceases and a single or multiple open channels may form longitudinally within the aufeis. Thick (often grounded) aufeis slabs are unlikely to be entrained downstream by the (shallow) freshet flow or to generate a dynamic ice run; therefore, breakup in aufeis affected streams is generally thermal (as opposed to mechanical, Beltaos (2008)). Residual grounded aufeis segments slowly melt during the warmer months, but the short subarctic and Arctic summer may enable portions of aufeis to persist into the next winter (e.g., Alekseev et al. 2011; Terry et al. 2020).

A similar phenomenon can occur downstream of spring aufeis. Depending on the groundwater temperature, a channel may start to melt its way through the upstream portion of the aufeis well before snowmelt begins. Eventually, the aufeis is thermally breached (from the top-down) or perforated (from underneath) by the spring flow and most of the aufeis remains in place once the local snow has melted (e.g., Morse and Wolfe 2015). For diffuse ground aufeis associated with a surficial (e.g., active layer) source, thaw–freeze cycles may cause further thickening before the water finds its way through, around, or under the ice (or back underground).

2.2.6. The role of autumn precipitation

Rainfall during the autumn season has a significant effect on suprapermafrost water sources available for growing aufeis (Ensom et al. 2020) and is also important for determining winter water supply outside permafrost regions, including downstream of wetlands and lakes. Generally, the relationship between wet conditions and subsequent aufeis volumes is direct and statistically supported (e.g., Morse and Wolfe 2015). Discharges in several streams of central Yukon were well above historical records during the month of October 2022, which indicates that the groundwater had been recently recharged. Ground icing was severe along roads in the area during the following month (Turcotte et al. 2023). The thermal aspect of autumn precipitation may be more subtle, with warm rainfalls or cold rain-on-snow events affecting the shallow ground temperature, which later influences aufeis development. Aufeis that are formed from springs are less impacted by anomalies in seasonal weather, but consecutive seasons or years of above-average precipitation and temperature may generate larger aufeis volumes (depending on the aquifer characteristics).

The formation of an ice cover in streams is also impacted by late-autumn flows. In steep channels, high flow conditions may prolong the period of ice dam formation and generate thicker ice features (refer to the process described in subsection 2.1.1). However, once fully covered, the under-ice flow conveyance capacity of the channel may be greater than what would have occurred at low flow, with an ice cover that efficiently insulates the channel. A thicker floating ice cover may also result from high autumn flows in lower gradient, narrow streams, mostly through a more dynamic frazil congestion process (e.g., Beltaos 2013). It is uncertain whether a higher than average baseflow ultimately results in thicker stream aufeis during the following winter, and the continuation of high precipitation into early winter may also produce contrasting effects on aufeis growth (as described in subsection 2.1.5). A dramatic stream icing event occurred along the Klutina River, Alaska, during a very cold period of December 1964, as reported by Carey (1973). This event was initiated by the ice cover freezing down to the bed and forcing subsequent overflow (an extreme example of the process described in subsection 2.1.2). In this case, both the pre-event water level (therefore the baseflow) and the snowpack were reported to be lower than normal. The opposite scenario was observed along the Dezadeash River, Yukon, during the first half of winter 2022–2023, with unusual overflow and icing following a record wet October.

3. Physical environments

This section explains the physical contexts that initiate and support the development of stream and ground aufeis. This includes geologic, hydrologic, hydrogeologic, geomorphologic, climatic, and anthropic aspects.

3.1. Morphological conditions

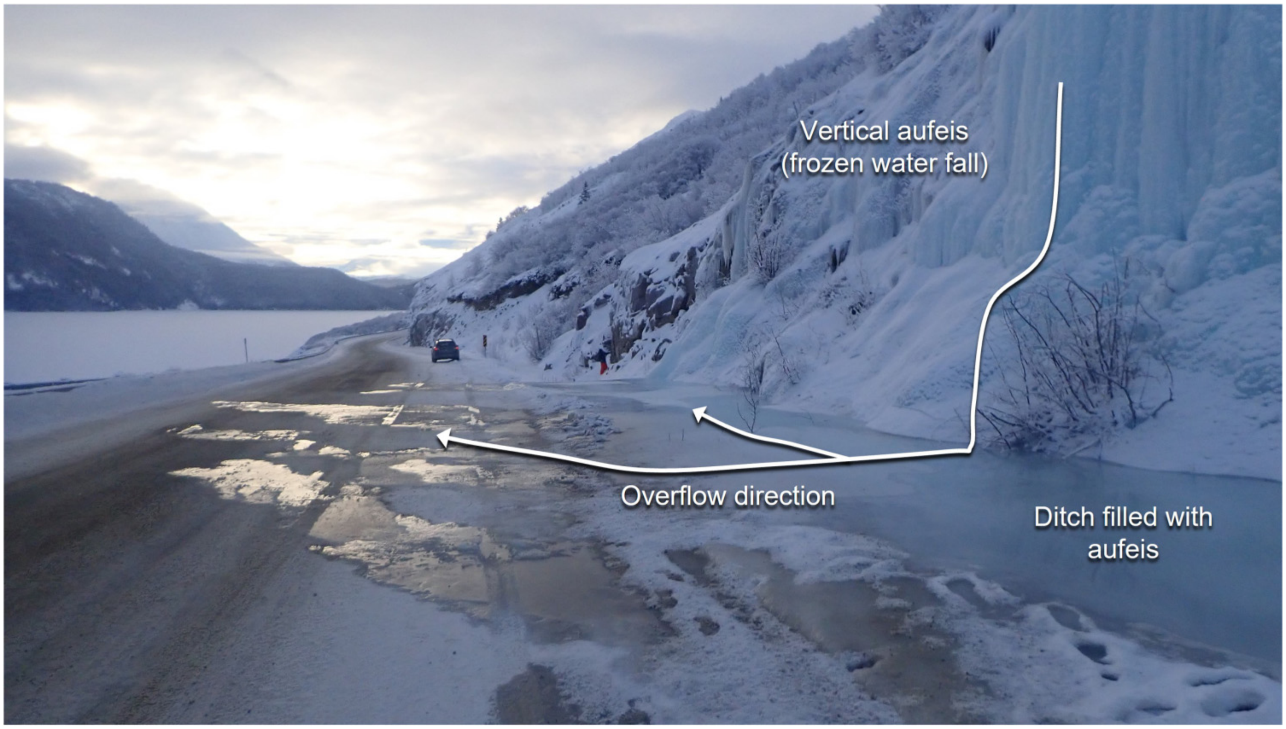
Various geomorphological and topographic characteristics are known to play a role in icing occurrence and aufeis distribution in areas with (e.g., Carey 1973; Vinson and Lofgren 2003) and without permafrost. In permafrost areas, for example, a thicker active layer on south-facing slopes than on north-facing slopes can store more suprapermafrost groundwater, which provides a more consistent and prolonged discharge that supplies valley bottom or stream aufeis. In turn, on north-facing slopes, smaller aufeis, most of which are caused by the spatially heterogeneous freezing of the active layer (subsection 2.1.3), are expected earlier during the winter season. In hilly to mountainous areas of discontinuous permafrost, abrupt concave upslope breaks are commonly associated with ground icing. Groundwater is forced to surface at locations where it meets permafrost or a thinner active layer at the slope toe or valley bottom. Other factors that directly or indirectly affect water supply and conveyance, thereby controlling the occurrence, intensity, and duration of icing events, include the distribution, thickness, permeability and hydraulic connectivity of different surficial materials and (or) bedrock (Clark and Lauriol 1997; Morse and Wolfe 2015), wind direction (e.g., snow redistribution and insulation), and vegetation type and distribution (e.g., Nicholls and Carey 2021).

Anchor ice-induced stream icing in early winter is often associated with steeper channels and can occur in virtually any region (e.g., Turcotte and Morse 2013) during cold spells when air temperature-driven heat loss at the water–air interface is greater than heat gain from the sun, channel bed, and groundwater. In turn, post-freeze-up stream icing can occur in channels of any gradient (e.g., Carey et al. 1975) and is often associated with a bedfast or bankfast type of ice cover, a condition associated with narrow, mid-size channels, shallow or intermittent creeks, or wide, braided streams located in subarctic and Arctic regions (Turcotte and Morse 2013). Within a watershed, deep rapid and stream segments located downstream of large lakes (in which deep water remains at up to 4 °C) may generate episodic frazil production events that reduce the conveyance capacity of downstream reaches where the ice accumulates, therefore potentially resulting in overflow and icing.

Braided streams and multichannel alluvial fans are especially prone to aufeis formation (Harden et al. 1977; Zufelt et al. 2009; Grayson 2010; Wohl and Scamardo 2022). Indeed, the significant cumulative width and low flow depth associated with these morphologies tend to maximize heat loss, therefore promoting the formation of bedfast ice and the occurrence of overflow. From an energy dissipation perspective, Clark and Lauriol (1997) explain that braided channel segments can be associated with lower gradients compared to laterally confined upstream and downstream reaches, and Hu and Pollard (1997) suggested that channel locations with relatively low water velocity (i.e., lower slope or greater width) are conducive to icing initiation.

Icing may also occur at the location of small tributaries where streamflow does not find its way under the ice cover of the downstream river or lake. For example, Jasek (1997) reports the formation of a large aufeis where the small Bluefish River (Sriinjìk) feeds into the larger Porcupine River (Ch'oodeenjìk) in Yukon. Ground heat and groundwater sources may also affect the location of stream aufeis. For example, an ice-free reach of the East Blackstone River, Yukon, exists downstream of a major aufeis. The aufeis toe is located near a perched pond that may be connected to the channel through a groundwater pathway, and the groundwater heat may be sufficient to offset heat loss from cold air. Icing may also occur in "losing" stream reaches, where a portion of in-

Fig. 4. Aufeis caused by the free draining of groundwater on the South Klondike Highway, Yukon, in January 2023. Water emerges from the ground at a cut slope, forms a frozen waterfall (vertical aufeis, upper right corner), fills up the ditch (lower right corner), and generates overflow on the road (on the left). (Photo credit: BT, 7 January 2023).



channel water is lost to groundwater, because of the absence of heat contribution from the surrounding groundwater (e.g., Daly et al. 2019; Kempema et al. 2019).

3.2. Altered flow paths

Human activity can significantly alter thermal and hydrological aspects of groundwater and surface water flow, impacting the occurrence and intensity of icing. Examples of anthropic terrain include

- ditches, which intercept and collect groundwater flow,
- linear infrastructure, such as roads, railways, or pipelines, which alter the permeability of the ground and create hydraulic barriers, sometimes forcing upslope upwelling,
- cut slopes, such as alongside highways, which impose a surface flow to groundwater (e.g., Lu et al. 2017), and
- mining exploration and extraction areas, where cutting or drilling through aquifers and opening new flow pathways to the surface promote icing at specific locations (and may reduce icing intensity elsewhere).

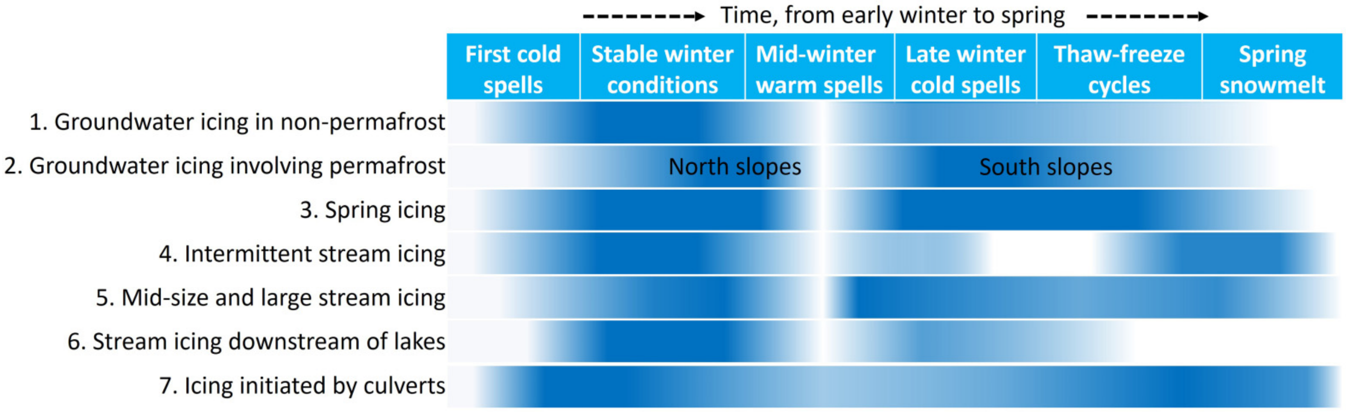
Figure 4 presents all four examples in a single photograph; the formation of aufeis on a cut slope, downslope of a decommissioned mine site, that is filling a drainage ditch and affecting road conditions. Linear structures found in urban environments, such sidewalks and streets, also promote anthropic aufeis development. After mid-winter rain events, or during winter or spring thaw–freeze cycles, runoff from property-scale watersheds may cause icing that translate into hazardous conditions for pedestrians and drivers, just like freezing rain.

In general, throughout subarctic or Arctic regions, any activity or infrastructure that reduces ground insulation (e.g., snow or organic layer removal or compaction), or modifies the ground permeability, provides an opportunity for frost penetration and ground icing to occur at unusual locations. In turn, this process may affect the human activity that triggered it (e.g., overflow and icing on winter roads, snowmobile trails, and cross-country ski trails) or reduce the integrity or safety of infrastructure.

3.3. Culverts and bridges

Several reasons explain why stream icing can be initiated or exacerbated by culverts as well as by low, short bridges (Carey 1973), including in temperate regions (Strasser et al. 2017). First, these hydraulic structures may prevent snow accumulation, so heat loss from the ice is more pronounced. Second, culvert material (typically corrugated metal) may have a high thermal conductivity and efficiently draw heat from the water, especially along the segment projecting from the embankment where it is directly exposed to cold air. Third, stream channels under roads or railroads may have a structurally imposed shape that confines the ice cover, and therefore promotes overflow and aufeis development. Fourth, vegetation along stream segments located in the road right-of-way is often removed to facilitate maintenance. A lack of vegetation may reduce the potential for snow insula-

Fig. 5. Conceptual summary of potential icing intensity over the winter period for seven different physical and hydrological contexts. Darker shades mean greater intensity.



tion and favors cold penetration. Fifth, snowplowing on the road can create dense and heavy snowbanks at the stream surface, potentially breaking the early-season ice cover, if any, and blocking the flow. Finally, in the spring, culverts and bridges prevent solar radiation from warming and deteriorating aufeis. As a result, ice may persist well after the local snowpack starts to melt, and if the ice remains cold, the ensuing runoff may contribute to further aufeis thickening. Given their characteristics, even culverts that have remained dry and open during previous months may become entirely blocked by aufeis during spring thaw–freeze cycles.

3.4. Flow regulation

Flow regulation, which is most commonly associated with the production of hydroelectricity, also generates unique downstream river ice conditions. The early-winter flow from a reservoir is usually relatively warm (just like in large lakes as described in subsection 3.1) and initially prevents ice formation over a relatively long distance downstream (e.g., from a few kilometers in small streams to hundreds of kilometers in larger rivers). However, under frigid air temperatures, high, turbulent flows generate a massive quantity of anchor and frazil ice, causing local and downstream in-channel or overbank flooding (e.g., Huokuna et al. 2022). Aufeis along such rivers have been reported (e.g., McParland et al. 2021) and are known to affect public and private properties, especially in a hydropeaking context when and where flow is correlated with daily energy demand fluctuations. Regulated rivers are generally affected by a thermal breakup scenario despite the presence of a potentially thick ice cover or aufeis. In some instances, though, late-season cold spells impose higher power generation that translates into elevated flow rates, which may cause ice jams, overbank flooding, and late-season aufeis thickening.

Beyond hydropower production, streamflow withdrawal (at constant or variable rate) for consumption or industrial use may be sufficient to promote ice cover grounding (or water supply variations), pressurized flow conditions, overflow, and aufeis development at locations where this type of ice process would rarely occur naturally. From a thermal perspective, industrial heat, or its removal (e.g., Daly et al. 2019), may also affect the occurrence and location of stream aufeis.

4. Temporal aspect of icing processes

Figure 5 presents a conceptual overview of potential icing intensity over a winter period in various physical contexts. The following list, corresponding to the environmental contexts presented in Fig. 5, provides complementary information:

1. Diffuse groundwater icing in cold–temperate regions is likely to be more intense during the first cold spells. In the absence of rain-on-snow events, the water supply should gradually decline, therefore attenuating ice formation.
2. Conversely, groundwater icing induced by frost penetration into the ground should occur first on north-facing slopes, and then later during the winter and extending into spring thaw–freeze cycles on south-facing slopes.
3. Spring sources generate aufeis thickening and spreading during the entire cold period, excluding warm spells. For very cold conditions (e.g., $-30\,^{\circ}\mathrm{C}$), the resulting aufeis is likely to build vertically rather than spread horizontally.
4. Intermittent streams could run out of water supply during the mid-winter period, but icing may resume during spring thaw–freeze cycles.
5. In larger streams (with flow throughout winter), including in braided channels, aufeis development generally initiates after freeze-up (e.g., Hu and Pollard 1997) and icing events are mainly driven by very cold conditions, snowdrifts, and by transient “milder” temperature conditions. Some studies have attempted to identify air temperature variation thresholds associated with overflow events (refer to subsection 2.2.2) at a regional scale, but this is difficult to achieve with meaningful accuracy at a local scale (e.g., it is highly site- and year-specific) unless the exact process initiating overflow is clearly identified and local and upstream heat fluxes are accurately measured.
6. Downstream of lakes and other surface water reservoirs, icing generally occurs during and soon after freeze-up

(some distance from the reservoir where an ice cover forms), and the potential intensity of icing, driven by frigid temperatures, would attenuate with the flow recession (if any, in the case of regulation).

7. Finally, icing initiated or exacerbated by culverts is likely to begin early in the season. If the culvert is not fully blocked by aufeis by mid-winter, this state may be achieved later, often during spring thaw–freeze cycles. What distinguishes this process from icing in intermittent streams (see point 4 above) is that the heat deficit of the aufeis in the culvert may generate icing, even when the local air temperature is above 0 °C (see subsection 3.3).

5. Discussion and research needs

Through the previous sections of this paper, areas of uncertainty related to the process of icing, the resulting aufeis, and their interactions with the environment have been identified. This section reviews these opportunities and expresses them in terms of research priorities, with direct and indirect benefits to cold region civil, hydrotechnical, and environmental engineering.

5.1. Towards predicting icing

Morse and Wolfe (2015) investigated the influence of autumn rainfall, early-winter snow and air temperature, total winter snowfall, and winter warming events on the interannual variation of aufeis. It is valuable to identify these relationships as they contribute to our understanding of relatively large aufeis, making them more predictable while also orientating process-based research in natural environments. However, questions remain about whether these relationships apply to small aufeis (e.g., those smaller than 1000 m^2), which cause the greatest cumulative impact on infrastructure in terms of maintenance and repair, and which have been overlooked as hazards in past decades of development in cold regions (e.g., Carey 1973; Vinson and Lofgren 2003).

Our limited understanding of aufeis likely reflects observations and correlations reported in the literature, some of which have produced contradictory findings, being specific to a site, a region (geology or hydrological regime), or a year. Developing a capacity to predict the timing and intensity of icing that may affect infrastructure and property depends on our understanding of the mechanisms that cause overflow (Section 2). Previous research has approached these questions from a spatial but static perspective (i.e., using satellite products or geophysical techniques) or from a time-dependent but single location perspective. For example, based on observations during a short summer period, Clark and Lauriol (1997) proposed that alluvial material may not be frozen to the bottom of aufeis. If this thermomechanical state had been investigated throughout winter, conclusions could have been different (as found by Terry et al. (2020)). Another example is the piezometric time series presented by Kane (1981) from a single channel location. These results may correspond to in-channel water head variations, but comparable data obtained from another nearby site could have informed the potential hydraulic (changes in conveyance capacity) or hydrological (water supply fluctuations) source to these variations.

Research involving both spatial (upstream, local, and downstream) and temporal (from autumn to spring) monitoring of aufeis, including hydrological and thermal parameters (what Turcotte et al. 2012*b* and 2014 refer to as a "continuum"), remains challenging, both from a technological and safety point of view, but is nonetheless needed. Recent research on the Kuparuk River, Alaska, used a combination of spatial and temporal monitoring strategies to investigate the presence of hyporheic (near-surface talik) flow that would feed aufeis throughout winter (Terry et al. 2020). Spatial and temporal monitoring of aufeis was also completed by Yoshikawa et al. (2007) in the same region. Although stage in aufeis-affected streams is rarely monitored during winter (Daly 2013*a*), researchers could take advantage of hydrometric stations operated by other agencies, such as the Water Survey of Canada, upstream or downstream of aufeis-affected reaches, to initiate a spatio-temporal monitoring program. The verification and analysis of stage signals at various sites would help clarify the hydro-cryologic continuum of stream aufeis.

In addition to identifying the sequence of processes that generate overflow and icing, documenting overflow events, their freezing patterns, and their water source(s) would help advance our understanding of the phenomenon. Examining variations in crystal structure or chemistry (e.g., water isotope ratios or major ion content, e.g., Clark and Lauriol 1997) could help distinguish freshwater, groundwater and snow contributions, the rate of freezing, and the rate of aufeis thickening. Remote cameras documenting overflow events would certainly provide valuable complementary data sets. A re-analysis of historical water level data to produce sub-daily time series of winter discharge estimates (Turcotte and Rainville 2022) could also inform how specific weather conditions affect upstream and local stream ice formation over time. Ground-penetrating radar (GPR) surveys offer a possible non-invasive alternative or complementary tool to directly measure aufeis thickness across a spatial grid of small-diameter holes drilled through aufeis. GPR, among other geophysical or remote sensing approaches, can be used to create three-dimensional maps of aufeis, in addition to supporting the detection of active and inactive flow pathways within and under the ice (e.g., Terry et al. 2020).

Quantifying the links between the conditions that drive aufeis development will enable the development of empirical or physics-based predictive numerical tools. Successful icing forecasts will not only lead to interventions that more effectively reduce the annual flood risk (Turcotte et al. 2023), but will also inform the sustainable design of current and future infrastructure as well as maintenance activities in the long term.

5.2. Impact of climate change on icing and aufeis

Weather patterns are changing, and the frequency of extreme events is increasing in northern Canada (Bush and Lemmen 2019). This makes the potential impact on aufeis of particular interest to northern communities, and more specifically, to Indigenous Peoples. The impact of climate

Table 1. Known and expected impacts of changing weather parameters on overflow processes that control aufeis formation.

			Autumn precipitation	Winter precipitation	Annual precipitation	Winter temperature	Winter and spring air temp. variability	Net expected impact on icing process
Expected trends in most of northern Canada (Bush and Lemmen 2019)			↗	↗	↗	↗	?	
Altered flow conveyance processes	Formation of grounded stream ice (2.1.1)		↗	?	↗	↘	?	?
	Thickening of non-floating stream ice (2.1.2)		↘	↘	↘	↘	?	↘
	Freezing front migration through the ground (2.1.3)		↘	↘	↘	↘	?	↘
	Collapse of free-spanning stream aufeis sections (2.1.4)		↗	?	?	↗	?	?
Water supply-driven processes	Groundwater free draining (2.2.1)	Subarctic	↗	↗	↗	↗	?	↗
		Temperate	↗	↗	↗	↘	?	?
	Upstream ice formation and downstream flow depression (2.2.2)		?	↘	?	↘	?	?
	Flow diversion in multichannel reaches (2.2.3)		↗	↘	↗	↘	?	?
	Mid-winter rain-on-snow runoff (2.2.4)		↗		↗	?	↗	
	Spring snowmelt runoff (2.2.5)		↗		↘	?	?	

↗: Increasing intensity/frequency, ↘: decreasing intensity/frequency, and ?: unknown/uncertain.

change must also be considered in engineering projects to support adaptation, or the strategic mitigation of geohazard risks.

Several studies have recently analyzed changes to aufeis, either based on the known causes of icing (e.g., Morse and Wolfe 2015) or historical trends (e.g., Pavelsky and Zarnetske 2017). Results summarized in Ensom et al. (2020) are diverse and include large aufeis that are becoming smaller, small aufeis that may become more numerous in specific areas, no observed changes to aufeis because of consistent groundwater supply, and no reported trend in aufeis development. Based on Section 2 and considering the confirmed and anticipated impact of climate change in northern Canada (Bush and Lemmen 2019; Hancock et al. 2022), Table 1 lists known and expected trends in aufeis resulting from evolving weather scenarios. The impact of some climatic conditions could result in a complex interplay of effects on icing processes, with some effects possibly offsetting each other with uncertain net consequences (as proposed by Morse and Wolfe 2015). For example, Yoshikawa et al. (2007) found no obvious trend in the extent of large aufeis in the Brooks Range, Alaska, over several decades despite a significantly warming climate.

One factor that seems to play an important role in the occurrence of stream icing is the frequency and intensity of air temperature fluctuations, probably through the stability of water supply (subsection 2.2.2). If these fluctuations were to increase in northern Canada in terms of frequency and magnitude, more water storage events would occur each winter and more thaw–freeze cycles would occur each spring, resulting in more overflow and icing episodes on an annual basis. There is no consensus about what to expect from climate change regarding the variability of winter weather conditions in the North in decades to come (e.g., Cohen et al. 2020; Blackport et al. 2021), and this significantly affects our ability to make meaningful projections about aufeis trends (Table 1).

Based on the tendencies identified in Table 1, the net impact of climate change on aufeis can only be confidently described for a few physical environments:

1. Some large ground or stream aufeis that depend on a relatively constant baseflow fed by subpermafrost groundwater could become larger due to the higher annual precipitation until warmer winters limit their development.
2. Icing that occurs in more temperate regions could be limited by warmer winters and warmer groundwater, regardless of the water supply and snow insulation.
3. Aufeis that result from the freezing of the active layer (subsection 2.1.3) are likely to either occur later in winter (thicker active layer freezes later), develop further downslope (new groundwater pathways), or not develop at all (presence of a spatially consistent, thick active layer).

Further research is needed to clarify how aufeis will continue to evolve in cold regions. Studies should take advantage of historical weather data and aufeis reports, including small aufeis (some of which may become detectable by new, high-resolution satellite missions) and should eventually include the development of models that use representative future weather scenarios to generate aufeis projections.

5.3. Morphological implications of stream aufeis

Beyond hydrological and engineering aspects of stream aufeis, it seems that their morphological implications and their impact on channel stability are still poorly explained in the existing scientific literature. This needs to be addressed because it may strongly influence our understanding of aufeis and support sustainable infrastructure development and maintenance.

Aufeis are often reported in braided streams due to the specific thermal and hydrogeomorphological dynamics of their channel (Section 3). The link between aufeis presence and a high braided channel mobility has recently been statistically demonstrated by Wohl and Scamardo (2022). However, it is unclear whether aufeis initiate, promote, or are a consequence of, this morphology. Braided channels are by definition unstable (e.g., Buffington and Montgomery 2013), regardless of the presence of ice. Clark and Lauriol (1997) provided insight into this topic by stating that the presence of a large aufeis in a braided section of the Firth River, Yukon, contributed to deflecting spring flows towards a valley wall. A similar observation is reported by Wohl and Scamardo (2022) for the Hula Hula River in Alaska. Both studies concluded that this form of ice exerts a strong control on the local channel morphology (or channel avulsion), an observation that may be applicable to other cold region morphological contexts.

Investigating the spatio-temporal aspect of aufeis formation/decay (i.e., their hydromorphological continuum) may also help improve our understanding of their evolution over time. At the beginning of winter, ice first forms at the downstream end of discrete aufeis-prone areas (i.e., a few hundred meters to several kilometers long) because a significant amount of heat first needs to be lost. Ice formation will migrate upstream when air temperatures drop and vice versa. During winter, when the discharge is lower and heat loss rates are high, ice formation is more likely to consistently occur at the upstream end of aufeis fields, leaving reduced (or no) water supply for the downstream portion. Pressurized flow conditions may mobilize unfrozen sediment, but the lack of fine sediment found in aufeis bodies (at least in unregulated streams) indicates that this may not be a common process. As the flow increases in early spring, it may concentrate in one or multiple narrow channels (Fig. 3) in the upstream portion of the aufeis, eventually thermally breaching the ice body and increasing the sediment transport capacity. Meanwhile, the heat from upstream is consistently lost to icemelt in the mid-reach, leaving the highly reflective (i.e., high albedo) downstream portion of the aufeis relatively intact. This spatial sequence supports overflow and ice-induced deflection towards the downstream banks. Depending on a number of factors, including dominant wind direction (i.e., the location of snowdrifts) and channel alignment (relative to sun location), a large proportion of the spring snowmelt may flow against the downstream banks. Under these conditions, another set of geological factors will determine whether significant erosion can occur, with potential to change the shape and extent of the braided stream segment.

This suggests that aufeis can promote an upstream incision and a downstream widening of braided stream segments. Observations from the North Klondike River, Yukon, reveal islands of young vegetation at the upstream end of a braided section (i.e., up to a location where the aufeis may not extend every winter, especially in a warming climate) and islands of taller bushes with exposed roots (i.e., a result of erosion) at the downstream end of the aufeis location. It would be of interest to use the approach applied by Wohl and Scamardo (2022) and to consider riparian vegetation evolution to confirm whether a downstream migration or an extent reduction of aufeis-affected braided stream reaches can be associated with a warming climate.

5.4. Ecological aspects of stream aufeis

The ecological aspect of stream aufeis is also important. Specific river ice formation processes (e.g., ice dams) are known to cause mortality among fish populations, including their eggs (Bergeron and Enders 2013). However, there is not much research specifically addressing the question of overwintering habitats in aufeis-affected streams, including the impact of stream aufeis on water temperature, dissolved oxygen, and nutrient fluxes. Fish and larvae are found in aufeis-affected streams during summer, but it is uncertain if and how they survive upstream, downstream, or beneath aufeis during winter. Stream aufeis can have thermomechanical impacts on the underlying channel bed and can cause downstream flow depletion events during winter, both of which could jeopardize fish spawning habitat. The presence or absence of life under aufeis is of engineering interest as it can, for example, provide valuable information to regulatory agencies that review applications for invasive icing remediation approaches, such as excavation (Turcotte et al. 2023).

5.5. Traditional knowledge about icing and aufeis

Most papers about icing and aufeis from North America entirely exclude observations from, and consultations with, Indigenous Peoples. Interestingly, unlike most researchers, Indigenous People constantly travel on the land and ice-covered streams. They know about overflow and icing areas to avoid, and they witness changing water paths that occur over time. From a perspective of decolonizing research and supporting reconciliation, involving northern communities at an early stage of a research project is essential in designing effective monitoring programs and yields stronger results. Generating knowledge about the land is a goal shared with Indigenous Peoples and knowledge co-production is immeasurably valued (Wong et al. 2020).

6. Conclusion

The processes of icing and resulting aufeis are generally poorly understood (Daly 2013*a*) because they require an understanding of several cold region scientific fields: geology, geochemistry, hydrogeology, fluvial geomorphology, permafrost, surface hydrology, thermodynamics, river ice, climatology, and statistics. It is difficult to train scientists and engineers to become experts in all these fields. Learning about aufeis must therefore engage diverse research communities and deliberate cross-disciplinary collaborative efforts. Field research on this topic involves working in very cold environments, which affects the performance of researchers and automated sensors deployed at aufeis locations. Novel and creative field solutions are needed to improve our ability to collect meaningful and robust data from these sites. Processes that are likely to play an important role in aufeis development, but have been previously overlooked, require specific attention, including the potential role of upstream water storage fluctuations and snowdrift-induced overflow backwater. A more systematic understanding of aufeis will contribute to the development of icing predictive models, climate change-resilient northern infrastructure, and effective glaciation and aufeis-induced flood mitigation techniques.

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Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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