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Review

Icing and aufeis in cold regions II: consequences and mitigation

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Abstract

The process of icing and the resulting layered ice masses, called aufeis, are caused by the freezing of overflow originating from groundwater or surface water. Aufeis can directly impact infrastructure and property, most commonly through winter ice formation and spring flooding within, against, and on the surface of hydraulic structures and transportation infrastructure. They also represent a safety concern for drivers. This geohazard often needs to be managed proactively and efficiently to mitigate associated risks. This paper provides an overview of the consequences of aufeis in northwestern Canada. A total of 50 existing and novel icing and aufeis mitigation approaches are described and classified. The context of applicability for each approach is identified, considering the source of water, the type of infrastructure, and its role in the formation of aufeis. Finally, future research avenues to support the development or improvement of aufeis risk reduction techniques are presented.

Key words: aufeis, winter floods, icing mitigation, cold region hydrology

1. Introduction

Icing is a common hydrogeological and hydrological process that occurs in cold regions between late autumn and early spring. The National Standard for a Risk-based Approach for Community Planning in Northern Regions (CAN/BNQ 9701–500/2023; Bureau de normalisation du Québec 2023) defines the resulting aufeis as a sheet-like mass of layered ice formed on the ground surface, or on river or lake ice, by the freezing of successive flows of water that may seep up from the ground, flow from a spring, or emerge from below river ice through fractures. Aufeis have been widely documented in North America and Asia since the middle of the 20th century (e.g., Carey 1973). They can range in extent from a few square meters (e.g., in ditches along roads) to several square kilometers (e.g., in subarctic braided rivers; e.g., Morse and Wolfe 2015) and they can vary in thickness from a few centimeters (before water supply depletion) to many meters (e.g., Sloan et al. 1975).

Beyond their many interesting aspects, aufeis often interact negatively with human-built features, particularly as winter ends when they act as major barriers to the spring freshet and thus significantly increase the probability of flooding (Prowse 1995). In turn, roads, railways, and pipelines also obstruct floodplains and interfere with drainage pathways, therefore influencing the frequency of overflow and extent of aufeis. Moreover, other cold-region assets located close to transportation infrastructure are often exposed to overflow and icing. The sizing of drainage structures (e.g., culverts, small bridges, and ditches) along linear infrastructure is often informed by an estimated design flow corresponding to a specific return period (e.g., 50 years). A factor of safety is generally added to this design to account for the uncertainty associated with a lack of local data or other factors such as beaver activity, sediment transport, woody debris, and climate change. In cold regions, however, a large portion of stream channel and ditch cross-sectional area is commonly filled with ice and unavailable for the conveyance of spring runoff. Some of this ice, especially inside a culvert, is not likely to melt entirely before high flows (or even annual peak flows) occur. Year after year in northern Canada, millions of dollars (CAD) are spent on icing mitigation and management (including more than one million dollars annually for Yukon alone; Burn (personal communication, 2023)), and some of the applied techniques are only partially effective, energy inefficient, and costly.

Icing mitigation and management are often necessary along linear infrastructure simply because aufeis interfere with multiple surface water and groundwater pathways. Carey (1973) reported that anti-icing techniques evolved slowly through the ingenuity of field maintenance personnel, rather than by systematic applied research. Interestingly, this remains accurate five decades later, with the creativity of highway maintenance crews significantly informing expenditures and procedures. There is an obvious need to further understand and better predict icing in Canada and other cold regions because that knowledge can ultimately reveal why specific icing remediation measures are ineffective and, by extension, which mitigation or management approaches can efficiently reduce aufeis-induced nuisance or damage. Based on a review of the aufeis literature as well as on observations of icing events, Turcotte et al. (2023) identified nine overflow processes leading to aufeis formation and regrouped in two categories: water may reach the ground or ice surface due to (i) a change in upstream water supply or (ii) an alteration of the local water conveyance capacity (of a stream or ground), all of which are ultimately driven by air temperature.

The objectives of this review paper are to (1) describe common consequences of aufeis occurring in different climate and geographic settings (Sections 2 and 3); (2) present and classify 50 known and novel icing and aufeis mitigation approaches (Section 4); (3) provide insight about the expected applicability of each mitigation approach in different hydrogeological or hydrological contexts (Section 4); and (4) propose immediate research avenues to design and test novel, or to improve existing, mitigation approaches (Section 5).

2. Observed consequences of aufeis in northwestern Canada

Icing is an unexpected process for those unfamiliar with northern hydrology. For engineers and maintenance crews in the cold region, it represents a persistent challenge at several locations from late autumn to spring. This section presents several icing-related issues, most of which have been observed by the authors in the Yukon in recent years as well as by research collaborators in the adjacent Northwest Territories, Canada. The listed events and their consequences, presented in chronological order, are illustrative and by no means represent an exhaustive list of all the potential impacts of aufeis on property and infrastructure in cold regions. Other aufeis-related issues reported in the literature are presented in Section 3.

2.1. Autumn

Ground icing occurs on the upslope side of the Dempster Highway at km 29 every early winter. In October 2022, however, the overflow (Fig. 1*a*) was more severe and widespread than usual, taking place at several locations between km 17 and km 32 as soon as air temperatures consistently dropped below freezing. Active icing extended well into the winter months, and machinery had to be deployed to excavate a flow path in the ditch beside the highway (Fig. 1*b*) over a cumulative distance of 1.8 km. The intensity of the icing process (i.e., the amount of ice formed over time) following a wet autumn and the color of the ice (Fig. 1*a*) revealed that the overflow originated from shallow groundwater. The formation of aufeis on the upslope side of this road segment is directly related to the cut slope and the ditch that intercept and force shallow groundwater to surface.

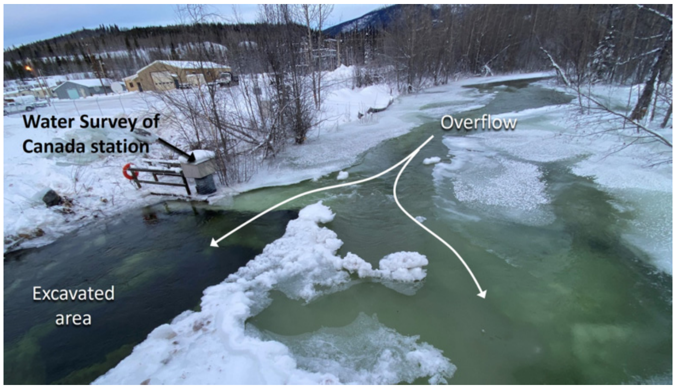
Aufeis also form at multiple small stream crossings along transportation corridors such as the Dempster Highway during the months of October and November. In this context, small streams can be described as those carrying enough water to maintain a baseflow during at least some winter months but less than about 0.5 m^3/s. At specific crossings, a frozen culvert outfall (e.g., Fig. 1*c*) indicates that the metal material contributes to the freezing process. Once more than half of the culvert's cross section is blocked by ice, the aufeis is structurally confined and cannot detach and float. The observed variability in aufeis thickness through culverts probably depends on the inflow, heat loss rate, snow accumulation, as well as culvert gradient and outlet hydraulic conditions.

Fig. 1. (*a*) Ground aufeis in October 2022 near km 27 on the Dempster Highway, Yukon (looking south; Photo credit: Benoit Turcotte). (*b*) Roadside and road surface aufeis mitigation in November 2022 near km 27 on the Dempster Highway (looking north; Photo credit: Louis-Philippe Roy, Yukon University). (*c*) Aufeis formation at a culvert outlet (diameter of 1.5 m) near km 100 of the Dempster Highway in October 2021 (Photo credit: Benoit Turcotte).

2.2. Early winter

Ground icing may occur at any time during the winter. When it does not originate from the free draining of suprapermafrost or subpermafrost groundwater, it may begin as soon as frost penetrates through the active layer, forcing suprapermafrost groundwater to surface and then to freeze (Turcotte et al. 2023).

Fig. 2. Overflow on Drury Creek, Yukon, at the Water Survey of Canada station 09AH005 in December 2020. Note how the ice cover was excavated immediately downstream of the station in an attempt to improve flow conveyance, but overflow kept occurring towards the right (Photo credit: Yukon Government).



A distinct icing process may take place in larger streams during the freeze-up period, especially those fed by relatively large lakes (whose outlet hydraulic control imposes a relatively high and stable flow). Drury Creek, crossing the Robert Campbell Highway (Yukon) at km 468, represents one of many Yukon sites where this phenomenon takes place. Its annual average flow is 6 m^3/s and it drains a watershed of 550 km^2, including Drury Lake, a large water body (25.5 km^2) located 12 km upstream of the highway bridge. A set of rapids (gradient of 2%) in the lower 4 kilometers of the creek promotes sustained frazil production. When flow rates are high (i.e., after a wet autumn), frazil accumulates under the ice cover already formed in the lower gradient reach located immediately downstream, which reduces the channel conveyance capacity and causes overflow. In December 2020 and December 2022, the resulting icing and stage rise threatened the newly constructed bridge as well as surrounding government properties (Fig. 2). Excavating the ice cover (to increase the flow conveyance capacity of the channel) using heavy machinery was only partially successful at stabilizing water levels.

Cold-region streams are often affected by overflow and aufeis thickening events once most of their channels are ice-covered. The main condition that enables the occurrence of overflow is a strong link between the ice cover and the channel bed and banks. This condition is achieved at several wide and shallow (i.e., less than 0.2 m-deep, approximately) stream sites located far downstream from groundwater heat sources for thermomechanical reasons (e.g., maximized heat loss rate and solid freezing of shallow stream areas). Overflow events in such streams have been reported in the literature and observed by the authors during cold periods (e.g., air temperatures below −30 °C), during warming periods (e.g., air temperatures rising back to −10 °C or above), and following snowfalls. This means that different hydrological mechanisms can result in overflow, icing, and flooding under a wide range of winter weather patterns (Turcotte et al. 2023).

2.3. Late winter

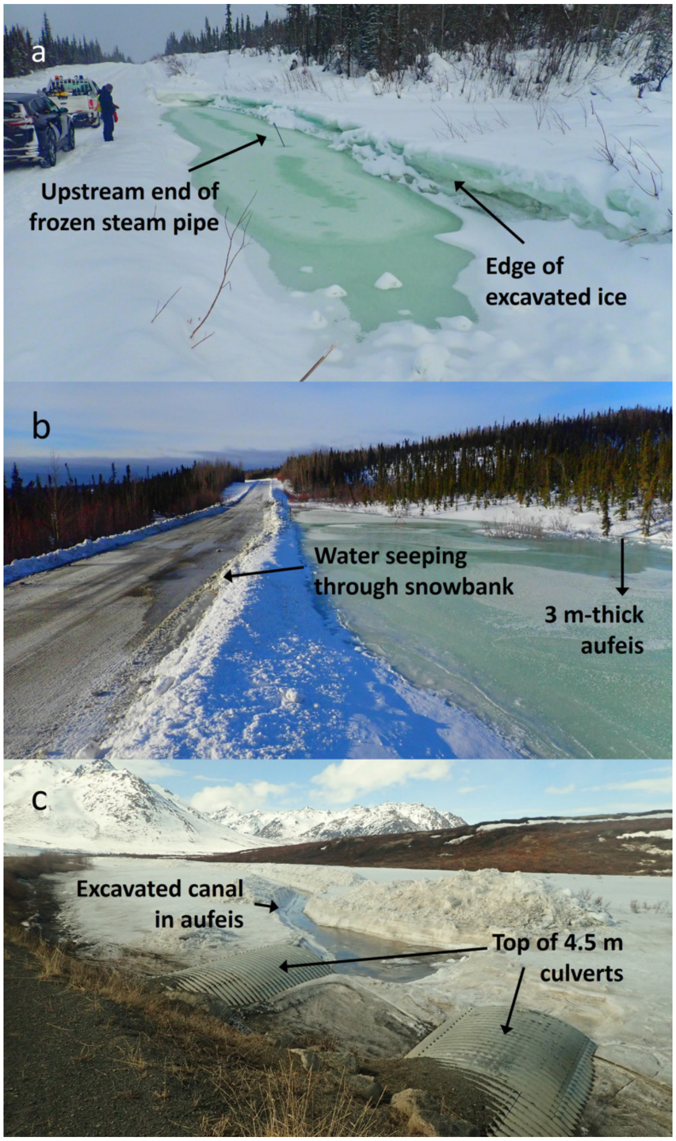
Active icing is common at several sites along Yukon highways during the months of March and April, before snowmelt begins. It is uncertain whether the ground overflow is triggered by the freezing of the active layer caused by cumulated heat loss (e.g., a late-season cold period may force groundwater to surface) or by the development of a flow path under the snowpack resulting from warm sunshine (e.g., an isothermal snow cover can carry water further downslope from its source). In streams, overflow may be the result of ground heat making its way downstream or it can be caused by the collapse (i.e., creeping) of the ice cover (or aufeis) under its own weight (Turcotte et al. 2023).

Figure 3*a* presents a partially frozen overflow accumulation at km 81 of the Silver Trail (part of the Yukon highway network). An excavator had been deployed a few days before the photograph was taken to remove the aufeis that had thickened to the top of the snowbank, above the road surface. The storage area created by the ice removal and the recent water accumulation indicate that the inflow rate was probably modest (e.g., less than 0.005 m^3/s). Near km 33 of the Dempster Highway, the aufeis shown in Fig. 3*b* had thickened (up to 3 m) to a point where the late winter overflow was seeping from the snowbank on the road surface. The mechanical removal of recently formed ice layers with a grader was observed to break the frozen lower portion of the snowbank, releasing the water that had been stored overnight on the aufeis surface (on the right), therefore making this management technique counterproductive. Heated lines (a permanent, handcrafted setup at that site) were connected to diesel generators on the following day, and the flow was successfully redirected to the other side of the road through a thawed gallery in the aufeis-affected culvert.

Figure 3*c* shows the top portion of two 4.5 m-diameter culverts located at km 86 of the Dempster Highway at the East Blackstone River (upstream of the aufeis research site documented by Hu and Pollard 1997). The thickening process of this aufeis corresponds to a combination of three processes: grounded ice thickening driven by frost penetration, overflow induced by upstream water storage variations, and overflow ponding upstream of snowdrifts. Before the photograph was taken (in early May 2022), an excavator had been deployed preventively, digging a trench (or canal) in the aufeis that was about 2 m wide, 1.5 m deep, and 1.3 km long. It is uncertain whether this mitigation approach is efficient in the context of a thick stream aufeis under which water flows during most of the winter period.

In the Ttth'oh zray (Blackstone River), ice blisters are often observed at the surface of a thick (more than 2 m) aufeis located next to the Dempster Highway (km 144). Ice blisters are three-dimensional features that form at the aufeis surface (e.g., Pollard 1988) and their presence can reveal the grounded (bedfast) nature of a river ice cover. In March 2022, the highest blister in the area stood about 1.2 m above the surrounding ice cover (Fig. 2 in Turcotte et al. 2023). A vertical buffer of about 1 m remained between the aufeis surface and the nearby road, but this is not always the case. Overflow events at that location seem to be mainly controlled by

Fig. 3. (*a*) Overflow at km 81 on the Silver Trail, Yukon, in late March 2022 (the aufeis was excavated, but overflow persisted). (*b*) Stream aufeis formation near km 33 on the Dempster Highway, Yukon, in late March 2022 (note the wet road surface next to the snowbank). (*c*) Looking downstream at the East Blackstone River from the Dempster Highway (km 86), Yukon, in early May 2022 (the aufeis thickness was about 4 m) (Photo credit: Benoit Turcotte).



variations in winter flow conditions (driven by air temperature fluctuations) but are also influenced by the presence of snow on the ice surface. Aufeis-related winter flooding that does not involve culverts and bridges has also been documented at other northern locations, often near wide (i.e., braided) channels. For instance, this phenomenon has affected other types of linear infrastructure (e.g., pipelines; Sloan et al. 1975) and facilities (e.g., Zufelt et al. 2009) in Alaska.

Aufeis also impacts the transportation of goods and people away from permanent linear infrastructure. For example, the winter road connecting Eagle Plains to Old Crow (Yukon) is often affected by overflow and icing, especially near wetlands and streams. During the winter of 2022, freight traffic on that winter road was significantly delayed by overflow, including on the ice surface of the Old Crow River just outside Old Crow. It is unclear if overflow resulted from natural processes, road preparation (involving snow compaction), or heavy freight loads (involving further snow compaction, ground compaction, and potential river ice fracturing).

2.4. Spring

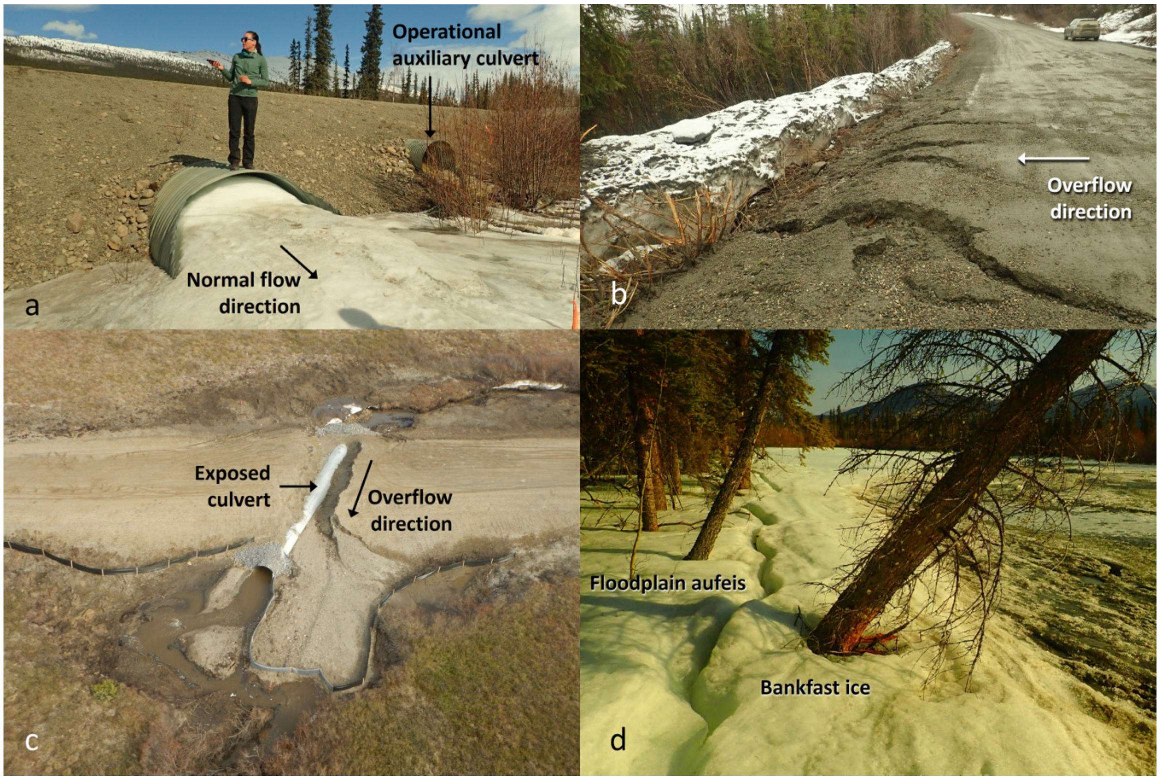
As stated above, aufeis are non-floating ice accumulations. In streams, they can hardly accommodate a runoff rise without causing overflow. In the spring, the slow melt of a thin snowpack may generate sufficiently low runoff rates that meltwater remains contained within natural channels and hydraulic structures. However, the sudden melt of a thick snowpack usually leads to overflow at several locations, resulting in expensive road maintenance.

A culvert that is mostly or entirely blocked by an aufeis at the onset of snowmelt represents a concern for highway maintenance personnel. Figure 4*a* presents a 2.3 m-diameter culvert blocked by ice with a smaller auxiliary culvert (in the background) draining the entire spring runoff in early May 2022 at km 33 of the Dempster Highway. A similar situation was observed during the preceding spring at this location. In 2021, however, the main culvert was only blocked at its inlet, whereas in Fig. 4*a*, it was blocked over its entire length. This visual assessment is important because it can inform the selection of the most efficient mitigation option. Figure 4*b* shows how even a small overflow resulting from an overwhelmed culvert can damage the surface of gravel roads and compromise driving conditions. Since aufeis may continue to restrict the conveyance capacity of culverts well into spring conditions, upslope ponding, overflow, and washouts remain possible in a largely snow-free landscape. In June 2017, the Inuvik–Tuktoyaktuk Highway (Northwest Territories) was affected by a washout resulting from an aufeis-blocked culvert (Fig. 4*c*).

Mechanical aspects of aufeis can also affect river channels and hydraulic structures. The collapse of thick (bankfast) border aufeis in regulated rivers is known to break bushes and large trees (e.g., Fig. 4*d*) soon after local breakup, a phenomenon that contributes to destabilizing the banks and channel morphology (McParland et al. 2021). This process may be amplified by the winter formation and spring melt of ice lenses within the banks (Kane 1981). This process also occurs in an urban context in the regulated Yukon River at Whitehorse, Yukon, where the collapse of thick border ice slabs has been observed to damage an erosion control structure, lifting and flipping over rocks with diameters meant to resist local flow shear stresses.

Aufeis may also interfere with the spring breakup of the ice cover in large rivers. For example, the aufeis that forms every winter at the outlet of the Sriinjìk (Bluefish River) in northern Yukon may be thick and extensive enough to impede breakup in the larger Ch’oodeenjìk (Porcupine River). This represents a concern for the community of Old Crow located roughly 40 km upstream of the Sriinjìk confluence.

Fig. 4. (*a*) Culvert (diameter of 2.3 m) entirely blocked by aufeis in the spring of 2022 near km 33 on the Dempster Highway, Yukon (note the auxiliary culvert [1.2 m] draining the spring flow (Photo credit: Benoit Turcotte). (*b*) Surficial road erosion near km 100 of the Silver Trail, Yukon, in May 2022 (Photo credit: Benoit Turcotte). (*c*) Washout at a stream crossing (2.4 m-diameter culvert) on the Inuvik–Tuktoyaktuk Highway (Northwest Territories) in June 2017 (Photo credit: Government of Northwest Territories). (*d*) Thick bankfast ice (aufeis) collapsing and breaking mature vegetation along the Äshèyi Chù (Aishihik River), Yukon (Photo credit: Yukon Government).



In 1991, the Sriinjìk aufeis initiated an ice jam that eventually caused a major flood in Old Crow (e.g., Jasek 1997). Massive aufeis that form on the ice cover of large rivers may have been neglected in studies that rely on the analysis of post-snowmelt (and therefore post-river ice breakup) satellite imagery.

3. Other known consequences of icing

Several additional consequences of aufeis are known to occur. In addition to what is described in the previous section, it is worth mentioning that aufeis can cause significant problems to road subgrade and embankment, railroads, and air strips, and even the winter lifting and spring loading of bridge structures (e.g., Carey 1973). Snowmobile trails, cross-country ski trails, and hiking trails may also be impacted by icing (which may represent a response to snow compaction). Urban drainage infrastructure can also be blocked by aufeis, resulting in water and ice accumulations in streets and around buildings, either during the winter or spring. In urban environments, thaw–freeze cycles cause the diurnal snowmelt water to freeze at night on sidewalks and roads. Mining infrastructure (e.g., ditches, culverts, and ponds) and activities that alter the terrain surface or subsurface may not always be adapted to cold region hydrogeological and hydrological processes. Beyond potential access road challenges, on-site overflow resulting from an aufeis blockage might be of particular concern if it involves contaminated water.

In addition to what is presented in Fig. 4*d*, icing affects riparian vegetation along rivers through ice push and by prolonging frozen ground conditions and delaying growth in the spring (e.g., McParland et al. 2021). It has also been known to benefit wildlife (e.g., moose) that use it as a solid walkway from which they browse the tops of riparian vegetation (e.g., willows). At the same time, the presence of widespread and slippery aufeis potentially discourages wildlife crossings, therefore impacting herbivorous–carnivorous contacts. Ground aufeis can also indicate the location of groundwater springs (e.g., Carey 1973), and large ground or stream aufeis fields can provide a precious water supply for pasture and human consumption during the following summer (Grayson 2010), in addition to serving ecological purposes.

4. Icing and aufeis mitigation

Table 1 lists 50 icing and aufeis mitigation approaches. Some of these approaches were first identified, tested, and implemented several decades ago (e.g., Carey 1973; Carey et al. 1975; Vinson and Lofgren 2003), whereas other mitigation strategies (those shaded in gray) are new or involve modifica-

Table 1. List of icing/aufeis mitigation approaches or techniques categorized by altered physical process(es), including their applicability, or chances of success, in different physical contexts.

Legend	
🟩	Should be considered, could be the best approach
🟨	Could be considered, context dependent, probable negative impacts
🟥	To avoid, could be counter-productive, will cause negative impacts, or not applicable
▨	Novel approaches / research needed
i	Only apply at multi-culvert sites
ii	May bring thermal and environmental issues
iii	Consider complementary approaches
iv	Should involve green energy sources
v	Only apply in emergency situations

Approaches or techniques		Contexts where aufeis form												
		Local, diffused ground icing or remote spring icing / very low inflow (Figure 3a)	Widespread ground icing / low to moderate inflow (Figures 1a-b)	Local spring icing / low to moderate inflow	Small stream, free falling culverts / low flow (Figure 1c)	Small stream, culvert initiating icing or completely blocked by ice (Figures 4a-b)	Intermittent stream, partially blocked culvert (Figure 1c)	Small stream, partially or entirely blocked culvert (Figure 4c)	Multi-culvert sites / small to moderate flow (Figures 3b-4a)	Braided streams and low-gradient alluvial fans / moderate flow (Figure 5)	Stream fed by a large lake / small to large flow (Figure 2)	Large stream icing / moderate winter flow (Figure 3c)	Large stream icing / high winter flow	Regulated stream (Figures 4d)
Hydraulic approaches														
H1	**Oversizing of culverts**	🟥	🟥	🟨	🟨	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟥	🟩
H2	**Auxiliary (or staggered) culverts**	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨
H3	**Bridge or bridge modification**	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩
H4	**Filtration dike**	🟥 Never recommended for efficiency reasons	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
H5	▨ **Blockage of the upstream end of a culvert**	🟩 *i*	🟨 *i*	🟥	🟥	🟨 *i*	🟨	🟨	🟩 *i*	🟨 *i*	🟥	🟥	🟥	🟥
H6	**Upstream extension of the culvert past a berm**	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥
H7	**Small dams**	🟨 *ii*	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥
H8	**Ground depressions**	🟨 *ii*	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
H9	**Flexible, traffic resistant pipes**	🟨 *iii*	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥
H10	▨ **Overflow resistant road segment**	🟨	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
H11	▨ **Temporary overflow road covers**	🟩	🟨	🟩	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥
H12	**Berms**	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨
H13	**Flow management in regulated streams**	🟥 Only for regulated streams	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩
Active thermal approaches														
AT1	**Fuel barrels**	🟥 Never recommended for efficiency and environmental reasons	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
AT2	**Steaming**	🟨 Effective, but moderate energy efficiency	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥
AT3	**Electric heating**	🟩 *iv*	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨 *iv*	🟥	🟥	🟥	🟥
AT4	▨ **Heat pumps**	🟩 *iv*	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨 *iv*	🟥	🟥	🟥	🟥
AT5	**In-stream injection of warm groundwater**	🟥	🟥	🟨 *ii*	🟩 *ii*	🟨 *ii*	🟨	🟩 *ii*	🟨 *ii*	🟨	🟨	🟥	🟥	🟥
Passive thermal approaches														
PT1	**Snow making**	🟨 *iv*	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥
PT2	▨ **Snow fences**	🟩	🟨	🟩	🟩	🟩	🟨	🟩	🟥	🟥	🟥	🟥	🟥	🟥
PT3	**Covering streams in the road right-of-way**	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟥	🟥	🟥
PT4	**Stream revegetation in the road right-of-way**	🟥	🟥	🟨	🟨	🟨	🟩	🟩	🟨	🟥	🟨	🟥	🟥	🟥
PT5	▨ **Seasonal frost belt**	🟩	🟩	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥
PT6	▨ **Thermosyphons**	🟩	🟨	🟥	🟨	🟨	🟨	🟥	🟨	🟥	🟥	🟥	🟥	🟥
PT7	▨ **Non-metal culverts**	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥
PT8	**Culvert insulation**	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥
PT9	▨ **Dusting (spring)**	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟥	🟩	🟩	🟥
Hydro-thermal approaches														
HT1	▨ **Temporary fences**	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
HT2	**Permanent fences and walls**	🟨 *ii*	🟨	🟨	🟥	🟨 *ii*	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥
HT3	▨ **Buried drains**	🟥	🟨	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
HT4	**Interceptor drains**	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
HT5	**Dams with a metal grid outlet**	🟨 *ii*	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥
HT6	**Diversion ditches**	🟥	🟨 *ii*	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥
HT7	**Permanent frost belts**	🟨 *ii*	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
HT8	▨ **Morphological alteration of a stream channel**	🟥	🟥	🟨 *ii*	🟨	🟨	🟨	🟩 *ii*	🟩	🟥	🟨 *ii*	🟥	🟥	🟨 *ii*
HT9	▨ **Vertical adjustment of culvert alignment**	🟨 *ii*	🟨	🟩 *ii*	🟩	🟩	🟩	🟩	🟩	🟨 *ii*	🟨	🟨	🟨	🟨
HT10	▨ **Partial blockage of a culvert outlet**	🟥	🟥	🟨	🟥	🟥	🟨	🟩	🟥	🟨	🟨	🟨	🟥	🟨
HT11	**Submerged secondary culverts**	🟥	🟥	🟥	🟥	🟨 *ii*	🟥	🟨 *ii*	🟨	🟨	🟨	🟥	🟥	🟨 *ii*
Mechanical approaches														
M1	**Grading of the road surface**	🟨 *iii*	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
M2	**Restoration of aufeis storage capacity**	🟩 *iv*	🟨 *iii, iv*	🟨	🟨	🟨	🟩 *iv*	🟥	🟥	🟥	🟥	🟥	🟥	🟥
M3	**Restoration of low flow conveyance capacity**	🟨 *ii, iii, v*	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥
M4	**Restoration of high flow conveyance capacity**	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨 *ii, v*	🟨	🟨	🟨	🟨
M5	**Mechanical digging of a canal in a thick aufeis**	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨 *iii*	🟨	🟨	🟨	🟨	🟨
M6	▨ **Double-angled-blade ice cutting machine**	🟨 *iv*	🟩 *iv*	🟩	🟥	🟥	🟥	🟥	🟨 *iv*	🟩 *iv*	🟨 *iv*	🟩 *iv*	🟥	🟥
M7	▨ **Rail or wire-guided drilling**	🟨 *iv*	🟨	🟨	🟩 *iv*	🟩	🟨 *iv*	🟨	🟨	🟥	🟥	🟥	🟥	🟥
M8	**Explosives**	🟥 Never recommended for efficiency and environmental reasons	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Chemical approach														
C	**De-icing salt**	🟥 Never recommended for efficiency and environmental reasons	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Planning approaches														
P1	**Avoidance**	🟨 *iii*	🟩	🟨 *iii*	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩
P2	**Relocation**	🟨 *iii*	🟩	🟨 *iii*	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩
P3	▨ **Diagnostic**	🟩 Should occur before any active or permanent intervention is implemented	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

tions to old techniques. The listed approaches are classified based on the dominant physical process involved in the intervention: hydraulic (H), thermal (active [AT] or passive [PT]), hydrothermal (HT), mechanical (M), and chemical (C). The last category includes planning (P) approaches.

The "applicability" of each approach is defined for a range of hydrological and geographic contexts (e.g., diffuse groundwater sources, intermittent streams) and is ranked (green, yellow, and red) based on the known or expected chances of success (reducing water levels and/or preventing flooding or structural damage), energy efficiency, cost efficiency, as well as the anticipated direct and indirect environmental consequences. For some approaches, especially those that are novel, their applicability should be tested through research and development. Therefore, Table 1 represents an index that is meant to advise readers about mitigation options that could be considered for different aufeis scenarios impacting infrastructure or property. It is not meant to replace geoscience/engineering expertise and local (including traditional) knowledge, nor does it include enough detail to inform design or decisions.

The following subsections provide a description and some detail about the 50 icing and aufeis mitigation approaches.

4.1. Hydraulic approaches

Hydraulic approaches are those that alter flow conditions. An approach that has been applied at multiple locations to reduce the impact of aufeis at stream crossings is the (H1) oversizing of culverts. Increasing the diameter of a culvert may preserve some hydraulic capacity to carry spring snowmelt runoff. This approach was recommended by Strasser et al. (2017) for a more temperate climate where heat loss is not significant. However, it may not offer any remediation against aufeis originating from small inflow and overflow rates in Arctic and subarctic regions or when the culvert itself initiates the icing process.

A comparable approach is the implementation of (H2) auxiliary (or staggered) culverts: culverts, commonly of smaller diameter, installed at a higher elevation within an embankment (e.g., Fig. 4*a*). However, at sites where the main culvert becomes entirely blocked by an aufeis, the icing process may continue and also affect the auxiliary culvert (this culvert is initially dry and therefore subject to significant heat loss prior to the initiation of overflow). Moreover, there may not always be enough space within the embankment for such a stream crossing design.

Generally, replacing one or multiple culverts by a (H3) bridge (or increasing the size of an existing bridge) is an appropriate solution, although it is costly. Bridges may restore the channel's conveyance capacity, its morphological identity, and part of its ecological role. Adapting culverts by creating hydraulic features that mimic natural flow conditions (e.g., substrate, baffles) represents an approach that may not be compatible with ice processes (e.g., Ladouceur and Ghobrial 2022).

Another method developed in Russia and described in Carey (1973) is the implementation of a (H4) filtration dike. These features are comprised of large rocks to create a porous road foundation that is meant to complement or replace the role of a culvert. This form of mitigation is unlikely to be applicable in most physical contexts because cold rocks effectively extract heat from the seeping water, not to mention that they may become clogged by sediment and organic debris over time.

The voluntary, early-winter (H5) blockage of the upstream end of a culvert at sites of two or multiple parallel culverts can be appropriate if no major runoff event is expected until the spring (i.e., in subarctic and Arctic regions) and where the downstream channel gradient is high or where the downstream end of culverts is perched (free surface). For this novel approach to be effective, the blocked culvert(s) would remain dry for the entire winter, and the removal of the blockage prior to snowmelt would restore this drainage route. Carey (1973) proposed a comparable idea for single culvert sites where there is essentially no winter flow or where windblown snow would otherwise fill the culvert.

Another approach for mitigating ground and stream icing where there is limited water supply is the (H6) upstream extension of the culvert past a berm, or small earth dam. This approach is being tested in Yukon and aims at transferring the aufeis development upslope, away from the road. Its effectiveness either depends on the early depletion of the winter flow or on the existence of water carrying some heat content through the winter. Comparably, (H7) small dams built in a channel or a floodplain can act as aufeis storage areas away from a vulnerable site (or against the site if the road embankment is raised). Their construction depends on the availability of suitable material. (H8) Ground depressions could also be considered for storage in the case of a low water supply. Both H7 and H8 designs must consider thermal (heat loss, presence of permafrost), hydrological (inflow relative to storage volume), and ecological (i.e., aquatic habitat) consequences, and this may affect their acceptability by environmental regulators.

Another set of purely hydraulic approaches can be applied in the spring to limit road surface erosion caused by snowmelt ponding (Figs. 4*b* and 4*c*). When inflow rates are relatively low, (H9) flexible, traffic-resistant pipes can be temporarily installed on the road surface. When the transverse terrain slope is adequate, a pump may only be needed to fill the pipes to initiate gravity drainage, which saves energy while not requiring continuous supervision by a foreperson.

A preventive hydraulic approach to reduce the consequence of uncontrolled spring overflow at aufeis-affected streams is to design an (H10) overflow-resistant road segment. This novel method involves establishing a permanent depression (i.e., a spillway) in the road surface at or near a crossing with an unerodable armor, geomembrane, or pavement extending from the upstream side of the road to the bottom of the downstream embankment or beyond. The width and depth of the depression would need to reflect the desired overflow capacity while ensuring acceptable driving conditions for traffic year-round. Using this technique, a road could be reopened immediately after an overflow event, as opposed to following a long delay associated with a washout event (Fig. 4*c*). For sites where only a small, local overflow can be expected on a gravel road, the emergency deployment of (H11) temporary overflow road covers could be considered to avoid the type of road surface damage presented in Fig. 4*b*.

For transportation corridors or infrastructure built next to aufeis-affected channels (e.g., braided channels, where aufeis often generate the annual maximum water level, e.g., Turcotte et al. 2017), dikes or (H12) berms represent a hydraulic approach that may limit the lateral extent of aufeis. These berms should be designed to be erosion-resistant to both high flows and overtopping, and they should not simply be made of gravel from the local channel bed.

Finally, (H13) flow management in regulated streams may represent a solution against massive ice production and overbank icing (e.g., Morrissette et al. 2017). This is not always possible for small streams, as it depends on access to potentially frozen gates. It may also not be possible for larger streams that are regulated for power generation. Hydropower is often used to compensate for more intermittent forms of energy production (e.g., wind and solar), so power output and therefore streamflow rates are often dictated by power demand.

4.2. Active thermal approaches

Active thermal approaches are those that require an external source of energy. Back in the early to mid-1900s, (AT1) fuel barrels (i.e., oil drums or firepots) were used to heat stream water and prevent icing in Alaska and northern Canada. These drums would be positioned directly in the channel upstream of a culvert or a bridge and would burn fossil fuel continuously (e.g., about 100 L of oil per day; Carey 1973) to maintain drainage in areas subject to icing. In addition to being highly energy inefficient, they are neither cost-effective nor compatible with environmental protection standards.

The description of culvert (AT2) steaming provided by Carey (1973) is still accurate: truck-mounted boilers that produce steam are either connected to portable lances or, more commonly, to permanent pipes installed close to the top and across the full length of culverts. Steampipes are operated at the majority of aufeis-affected culverts in Yukon as well as in some areas of northern British Columbia. The energy efficiency and safety of manipulating portable lances are relatively low compared with permanent steampipes. The latter used to contain an antifreeze solution, but this has been replaced by air and the steam is not recirculated back to the boiler. Though this technique requires that pipes be regularly inspected and maintained, it is especially adapted to small or mid-size culverts that are mostly or entirely blocked by aufeis. While winter interventions often need to be repeated because the pipe itself promotes ice formation through heat loss, spring interventions can produce lasting results.

(AT3) Electric heating was first tested in North America in the 1960s (Carey 1973). Carey et al. (1975) presented a case study at several creek crossings in Alaska and suggested a continuous but low-intensity heating strategy. This type of equipment is widely used in Yukon in a similar context to that of permanent steampipes. Typically, 170 m-long (550 ft) cables with a maximum capacity of 2300 Watts are tied to trees or poles on either side of the culvert. The objective is to melt a gallery at the bottom of the aufeis, with the overlying ice providing insulation. Wheel-mounted diesel generators are connected to these cables for short periods during the winter or in advance of spring snowmelt. From a purely theoretical calculation that assumes optimal system efficiency, operating the generator for 24 h at an aufeis-affected culvert with a double cable (circuit) would melt a 10 cm-diameter gallery through the ice. Although simpler to operate than steampipes, electric heating could be even more energy efficient (and environmentally respectful) if it could be turned on and off remotely (or on a predefined schedule) and if cables were shorter (about 60 m long).

Heated cables (AT3) and steampipes (AT2) can be damaged during spring or summer runoff events, especially when high flows carry a significant amount of sediment and woody debris. However, at most stream crossings, aufeis-induced flooding represents a greater risk than open-water floods. Damaged systems can be repaired or replaced prior to the cold season, which generally proves more efficient than relying on a portable hose type of steaming.

Other sources of heat exist beyond fire, steam, or electricity (all of which are fossil fuel-driven). The partial melt of aufeis in culverts or ditches could be performed by high-efficiency (AT4) heat pumps that extract energy from the air, ice, or ground. Where significant groundwater heat exists (either because of high ground temperatures or permeability), standard pumping and (AT5) in-stream injection of warm groundwater may prevent aufeis formation over a targeted channel segment, especially if applied once a surface ice cover has formed. In turn, pumping groundwater may disturb the hydrothermal regime over an increasingly extensive area over time. The context of the applicability of AT4 and AT5 would probably be limited to specific physical settings, including small streams.

4.3. Passive thermal approaches

The following category of approaches aims to reduce the risk posed by aufeis by tweaking naturally occurring heat fluxes. Many studies have found a link between a significant snowpack and reduced icing activity (e.g., Morse and Wolfe 2015). Fresh, dry snow certainly provides significant insulation. (PT1) snow-making machines (similar to those used in ski resorts) can be deployed and operated at the beginning of winter to insulate small streams near culverts. This solution had been suggested by Vinson and Lofgren (2003) to attenuate aufeis problems along the Denali Park access road, Alaska. Although this snow is much denser (>300 kg/m^3) than what naturally occurs (~100 kg/m^3), it can still prove effective, especially where the icing process is initiated a short distance downstream from the culvert. The source of water used to produce snow could represent a challenge because, in the case of small creeks, insufficient flows of water would be available. Water would likely need to be imported to each site by tanker truck. Additionally, the cost of the operation could become prohibitive since it could require the presence of workers during snow production to reduce the probability of equipment (e.g., nozzle) freezing (and leaking with consequential icing).

Installing adequately oriented (relatively to the site and dominant wind) (PT2) snow fences could yield comparable insulating results to snowmaking at a much lower cost, given that snow commonly begins to fall before air temperatures cool down to a point where icing occurs. However, Turcotte et al. (2023) reported that snowdrifts could promote thick overflow events, so approaches PT1 and PT2 are not recommended in fragile or partially floating ice cover contexts (the cover may break under, or be depressed by, the weight of snow). These approaches would be most effective where the heat content of the water is significant; otherwise, the aufeis problems could be exacerbated. At locations of known groundwater pathways in a relatively steep terrain, insulating the ground with snow could successfully transfer icing problems to sites of reduced vulnerability.

(PT3) Covering streams in the road right-of-way to reduce heat loss was tested by Carey et al. (1975), with generally unsatisfactory results. Regardless of the cover type (e.g., aluminum sheets or hay), this approach is labor-intensive and may negatively impact flow patterns in the spring. If it fails and aufeis development does occur, it may also affect the application of alternate mitigation measures. A preferable approach consists of (PT4) stream revegetation in the road right-of-way to improve insulation by snow interception. The branches of adapted native bush species are known to bend over small stream channels under the weight of newly fallen snow to create an insulating ceiling. Revegetating the right-of-way at streams or simply stopping the regular clearance (maintenance) of vegetation near stream channels may also save some costs immediately and into the future.

The reduction of ground insulation, either through vegetation removal or snow removal or compaction (Vinson and Lofgren 2003), can also be considered for aufeis management. This practice may fall under the category of a (PT5) seasonal frost belt. It represents a relatively affordable means of passively encouraging frost penetration and, therefore, mid- to late-winter ground icing upslope and away from a vulnerable asset. In Yukon, highway maintenance crews encourage snowmobiles to create compacted snow paths upslope of, and some distance away from, roads to promote ground freezing where it does not represent a concern (Hoogland (personal communication, 2023)). A systematic documentation of the performance of this approach under varying hydrometeorological and permafrost conditions has not been completed to date, but snow compaction is known to lower ground temperature and reduce the thaw of sensitive permafrost (e.g., O'Neill and Burn 2017).

(PT6) Thermosyphons (generally classified as active cooling approaches but considered here to be passive because they require no energy source) are devices meant to prevent sensitive permafrost from thawing. They consist of a sealed, fluid-filled tube with an upper part above the ground working as a condenser and a buried part in the ground functioning as an evaporator (Calmels et al. 2016). They have apparently not yet been used to promote icing at a desired location. Heat drains or cooling pipes relying on gravity-driven air circulation (open conduits) could also be used to cool the ground. Underground pipes can be connected to a pump to force the circulation of cold air into the ground. In this case, although the heat extraction can be considered passive, air circulation relies on a source of energy, and such a system cannot be considered fully passive.

Metal culverts are suspected to act as radiators that extract heat from the water (e.g., Turcotte et al. 2023). This explains why icing often begins to form in culverts (e.g., Fig. 1*c*), generating backwater and upstream aufeis development. (PT7) Non-metal culverts (e.g., made of high-density polyethylene (HDPE)) have been used instead of conventional metal culverts and have not been associated with icing problems over several years (Nyland (personal communication, 2023)). However, it is unclear if the water repellence property of HDPE plays a direct role in the success of the approach. Ice overpressure (when it warms up) is known to cause the failure of metal culverts (Jeffrey (personal communication, 2023)), so exploring the properties of other materials may also yield structural benefits.

Similarly, (PT8) culvert insulation could reduce heat loss during the winter and may help maintain flow through the culvert during the winter season. Several practical aspects would need to be considered beyond local icing dynamics. For example, the insulating layer (if made of material with a high air content) would need to remain dry and not interfere with the hydraulic capacity or structural resistance of the culvert. Combining culvert insulation with snow insulation on each side of stream crossings may yield optimal results.

(PT9) Dusting is a technique aimed at promoting the spring deterioration of an ice cover by lowering the albedo of its surface and absorbing more solar heat. It is meant to mimic a process that naturally occurs in streams when wind-blown sand or organic material settles on the ice surface. Reports about the performance of albedo alteration to accelerate ice degradation are not common. In the 1910s, lamp black and old crankcase oil were used to darken the ice surface on Lake Laberge, Yukon (Parks Canada 2021), but more environmentally adapted options exist. As a novel aufeis mitigation approach, local sediment or organic material could be scattered on the ice surface in a relatively narrow, straight line (just like the trench excavated in a stream aufeis presented in Fig. 3*c*) or following the channel thalweg. The dark material would be temporarily ineffective following a post-application snowfall, but in several parts of northern Canada, spring conditions are dry and the sun shines for several hours every day, which represent ideal conditions for testing this technique. Dusting is not compatible with culverts but may be effective for river aufeis problems downstream or beside a vulnerable site or linear infrastructure.

4.4. Hydro-thermal approaches

The following aufeis mitigation approaches involve the alteration of both flow conditions and the heat budget. (HT1) Temporary fences and vertical geomembranes can be installed downslope of ground icing initiation locations to deflect the flow either away from, or parallel to, a vulnerable zone or infrastructure boundary. They are meant to control the shape and extent of the aufeis, but observations reveal that this technique remains partially effective, in part because the thermal influence of the membrane is poorly understood. (HT2) Permanent fences and walls can also be built at ground aufeis locations and may be designed to provide significant upslope storage areas. The thermal function of these approaches depends on the heat extraction or attraction potential of the material, and they can be designed to support upslope icing during the winter or to accelerate the spring melting process. The detailed wall design provided by Lu et al. (2017) suggests that the success of this design relies on accurate knowledge about the possible range of site-specific thermal and hydrological conditions.

Where icing originates from a defined groundwater source that seems to persist all winter, (HT3) buried drains could be tested to dewater the ground and guide the flow from its source, under and past the vulnerable infrastructure, to an area where icing would not be a concern. If the required drain length is relatively short and if the drain is adequately insulated (e.g., buried under an organic layer or under snow), this would probably prove cost-effective, especially from a maintenance perspective. On the other hand, (HT4) interceptor drains meant to capture diffused or intermittent types of groundwater flows do not seem to represent a viable solution for icing control in subarctic environments (Livingston and Johnson 1978), especially if the groundwater temperature is close to its point of freezing.

For ground, spring, or small (seasonal) stream aufeis with a low or irregular inflow rate, (HT5) dams with a metal grid outlet can be built to store ice during the winter period while allowing drainage through the metal grid in the spring. This technique has essentially no operational costs other than the removal of organic matter intercepted by the grid during the open-water season. The metal grid outlet would promote freezing early in the winter by extracting heat from the water or ice, and the inverse process would occur in the spring, when water naturally melts its way through the aufeis (Carey 1973). Like H7 (small dams), this approach may be associated with undesirable environmental and upstream thermal impacts.

Another technique to maintain a safe distance between very small streams or ground aufeis and vulnerable assets involves constructing (HT6) diversion ditches. Narrow ditches could be designed to carry water and concentrate the little heat available to maintain liquid flow toward a convenient ice storage area or hydraulic structure. Insulating the ditch with material other than snow would be challenging for logistical, hydraulic, sustainability, and ecological reasons (e.g., Carey 1973). In contrast to ditches, (HT7) permanent frost belts would involve excavating wide, horizontal canals to store ice and encourage ground freezing at a preferable location. In Yukon, permanent ditches (or frost belts) have been excavated parallel to, and ∼80 m upslope of, the Dempster Highway between km 100 and 102. Although they seem to remain dry year-round, they appear to effectively protect downslope permafrost, potentially because they prevent water from ponding against the embankment or because they function as frost belts.

Carey (1973) described a pilot project at Crooked Creek, Alaska, that involved (HT8) morphological alteration of a stream channel to reduce heat loss and increase flow depth. This drastic modification to a stream environment is probably unsustainable from a channel stability and sediment transport point of view, and it is problematic from an ecological perspective. In addition, using metal mesh gabions for stability could promote ice formation and overflow during the first cold spells. However, straightening a creek (thereby increasing its gradient) and adding stabilization features (large rocks or woody debris that form steps) may promote the formation of a free-spanning ice cover that offers more insulation than a surface ice cover (Turcotte et al. 2014). This needs to be further explored.

At certain stream crossings, it is possible to adjust the gradient and relative depth of a culvert to optimize hydraulic conditions that reduce the potential for aufeis blockage. The (HT9) vertical adjustment of culvert alignment would need to consider hydrological, thermal, ecological, and structural aspects of the crossing. For example, increasing the flow depth may be beneficial in naturally low-gradient environments with continuous winter flow, whereas increasing the water velocity in intermittent streams could reduce the aufeis blockage ratio upon winter flow depletion.

A prototype to reduce heat loss through an alteration of stream hydraulic conditions would involve the (HT10) partial blockage of a culvert outlet and the insertion of a series of wood piers in the channel or ditch upstream of the culvert. The partial blockage would increase the water level in the culvert and some distance upstream (in low-gradient environments), reducing flow velocities and allowing a surface ice cover to rapidly develop. Once the ice cover is sufficiently thick (relative to the culvert width and pier spacing), the blockage could be removed, draining excess water and leaving a free-spanning ice cover that preserves heat and prevents further ice development. The piers would provide structural support to the ice cover upstream of the culvert. Where very little heat is carried by the water, insulating the downstream end of the culvert with snow or building a temporary, in-channel weir (made of local sediment) further downstream could generate a similar ice cover condition. These interventions would limit heat loss from the culvert and reduce cold air penetration under the ice cover.

The last approach presented in this subsection has been applied at some stream crossings in Yukon with moderate success (it solved the aufeis issue at three out of eight sites where it was applied; Jeffrey, 2023, Pers. Com.). Instead of staggered culverts at higher elevations (H2), (HT11) submerged secondary culverts were installed below the freezing level (under the ice cover at both ends of the main culvert), under an insulation layer. These secondary pipes were meant to carry the low winter flow while leaving the main culvert aufeis-free. Sediment accumulation in the upstream and downstream pools was identified as the main limitation of the approach, which is in turn probably not adapted to high-gradient settings and permafrost areas. This multi-culvert setup may also generate ecological issues.

4.5. Mechanical approaches

Mechanical approaches to reduce the impact of aufeis on infrastructure and property involve breaking the ice with machinery. (M1) Grading of the road surface (or using a crawler tractor equipped with a ripper, Vinson and Lofgren 2003) to remove a newly formed layer of ice may temporarily restore safe driving conditions. However, as presented in Fig. 3*b*, grading must be done carefully to avoid initiating a new road surface overflow and icing cycle. This maintenance operation should be complemented with another remediation approach that effectively reduces water levels upslope of the affected area.

Using heavy machinery to manage aufeis near infrastructure may give the impression of a temporary and poorly adapted solution to combat icing and flooding, especially under consistently cold conditions. The machinery does not restore the evacuation capacity of culverts (it can only damage them, which frequently occurs) and cannot reduce the water supply. However, from an energy point of view, ice represents a significant heat deficit (100 kWh per m^3 of solid ice plus 1.3 kWh per °C below freezing), hence it is far more efficient to break and remove ice mechanically than it is to melt it (e.g., Simard-Robitaille 2021). Therefore, it is necessary to explore the different contexts where heavy equipment can and should be deployed to reduce the impact of aufeis:

- The (M2) restoration of aufeis storage capacity upslope of a culvert that is entirely blocked by removing the entire ice accumulation may be effective in a situation where the inflow is small compared with the excavated ice volume (Fig. 3*a*). However, other approaches should eventually be applied to re-establish the drainage capacity of the culvert.
- The (M3) restoration of low flow conveyance capacity along a ditch or small stream blocked by grounded aufeis by excavating most of the ice accumulation is generally not effective, simply because it maximizes heat loss and promotes further icing. This approach should only be used in emergency situations (i.e., road icing, Fig. 1*b*) while other remediation or management approaches are identified and implemented.
- In larger streams, the (M4) restoration of a high flow conveyance capacity by deploying heavy machinery from the bank, from a bridge (Fig. 2), or directly in the channel (Fig. 5; also refer to Kempema et al. 2019) represents a conventional intervention at freeze-up. Removing a surface ice cover (or series of ice dams), however, can only reduce water levels effectively if the ice is stored at a location that does not impact flow conveyance. Ice rubble and slush entrained in the flow during the intervention often cause downstream channel blockage (which probably occurred at Drury Creek; Fig. 2), and the removal of the insulating ice cover layer promotes subsequent ice production, both processes potentially resulting in higher water levels than in a *status quo* situation. Environmental regulation may represent a limitation to the application of this approach unless an emergency amendment is granted.
- Fig. 3*c* presents the result of the (M 5) mechanical digging of a canal in a thick aufeis with an excavator at the end of winter. The canal was initially dry (the late-winter discharge was still flowing under the aufeis), which is convenient to delay or prevent spring icing during thaw–freeze cycles (Turcotte et al. 2023). This approach may be effective downstream of culverts or bridges or where the road is near a thick stream aufeis. Its application should extend downstream to a hydraulic control, which often means the downstream end of the aufeis; otherwise, the canal may fill up with stagnant water and freeze solid.

Fig. 5. Bulldozer deployed in the shallow Ship Creek affected by early-season ice formation near Anchorage, Alaska (Photo credit: Steven Daly, December 2016).

Another ice cover weakening technique applied in floating ice cover contexts involves cutting the ice with adapted machinery (Burrell 1995) to promote its mobilization upon increasing discharge. Unfortunately, performing vertical cuts in an aufeis, even to a significant depth (but not down to the bed), is not expected to promote its mobilization because of its grounded state and its significant thickness compared to the flow depth. However, if a machine was adapted to cut ice at an angle, two parallel cuts facing each other could free a continuous triangular ice prism that could be easily removed to create a canal at a much faster rate than what is achieved with a standard excavator (M5). This (M6) double-angled-blade ice cutting machine would need to be designed and built, an investment that would prove affordable if it was adapted to various aufeis contexts (e.g., including ditches).

When deploying heavy equipment close to or directly in a stream (this applies to techniques M2–M6), it is important to pre-emptively locate the edge of the channel bank, the grounded ice cover, and the floating or free-spanning ice cover, and to measure the under-ice water depth to assess and reduce the risk of injuries or equipment damage. Heavy machinery cannot be supported by free-spanning ice or unconsolidated ice pieces, and machinery that is not adapted to float should not be deployed on a floating ice cover (almost independently of its thickness). Accidents involving machinery falling through an ice cover are regularly reported in the North.

The efficiency of removing ice rather than melting it has been mentioned, but the above-described approaches are not compatible with aufeis confined in a culvert. Increasing the hydraulic capacity of a stream blocked by aufeis is of limited pertinence if the nearby culvert remains clogged. The potential application of (M7) horizontal directional drilling, as used in the mining industry, glacier research, or when installing utilities below large watercourses, may be worth exploring to address the issue of culverts entirely filled with ice. In a context where culverts are rarely straight (e.g., because of icing loading, permafrost thaw, or heavy traffic-induced deformation), auger blades can be damaged by the metal edge and vice versa. Rail or wire-guided (attached to the celling of the culvert) drilling should be explored as a means to generate a gallery through a culvert aufeis, from downstream to upstream, with results that would compare to those delivered by steaming or electric heating but with much less energy and time required.

(M8) Explosives have been used to break a floating ice cover, mostly to reduce the probability of ice jam formation or to break an existing ice jam that is causing flooding (e.g., Burrell 1995). In the context of a thick, grounded, intact aufeis with a limited flow relative to the size of the accumulation, explosives may not be the most suitable approach since a safety distance from any infrastructure would need to be maintained (including from roads and culverts). Furthermore, the shape of the resulting hole or canal would be irregular, some ice pieces would still need to be removed mechanically, and safety measures would be required. Environmental concerns surrounding the use of explosives in/near waterways may also hinder the use of this method. There is a lack of understanding about aquatic life under stream aufeis, and this represents a challenging topic for research (Turcotte et al. 2023).

4.6. Chemical approach

The most common chemical approach to preventing ice formation or promoting ice melt is generally known as (C) de-icing salt or simply de-icers (most often chloride-based products). The role of such chemicals is to depress the freezing point of water, and they are still widely applied on sidewalks and roads in northern urban settings. In natural, freshwater environments, the amount of de-icing salt required to partially melt an aufeis can negatively impact the ecosystem (Amrhein et al. 1992; Backstrom et al. 2004) and salt could become persistent in the environment if regularly employed. De-icing salt also promotes corrosion of metal surfaces (e.g., culverts), and its use is therefore not recommended for most aufeis situations. When icing occurs on low-traffic roads, which is typically the case in northern Canada, grading (M1) or the spreading of small gravel to improve tire adherence should be preferred over de-icers.

4.7. Planning approaches

Many roads in northern Canada were built with limited knowledge about, or consideration for, cold-region geohazards or ice-related technical challenges. Nowadays, the existence of detailed geological and geographical information, including historical satellite imagery, permafrost maps, and aquifer maps, can contribute to a better planning and predesign phase. The (P1) avoidance of areas with expected icing activity may represent a strategic decision for new infrastructure projects as it significantly reduces their vulnerability and maintenance cost. Infrastructure development in the North should also consider the anticipated impacts of climate change on icing and aufeis, a topic explored in Turcotte et al. (2023).

At some sites or along specific portions of existing infrastructure, annual icing remediation operations can be costly and/or largely ineffective. When taking other geohazards into account (e.g., permafrost thaw, channel erosion, open-water floods), and for reasons similar to those mentioned in the preceding paragraph, the entire (P2) relocation of the infrastructure may represent a cost-effective solution.

In some situations involving icing-related challenges, the source of overflow is known, and the physical characteristics of the aufeis are obvious enough to identify optimal mitigation decisions. This is not always the case, however, sometimes because of the complexity of the physical context and the various processes governing distinct overflow events (e.g., Turcotte et al. 2023). Figures 1–4 include several examples where mitigation is partially or entirely ineffective. The extent and distribution of aufeis in culverts and the state of a stream ice cover (e.g., grounded or floating), for example, may be unknown, which affects the applicability and efficiency of potential mitigation measures. Moreover, aufeis conditions may vary at a given site from year to year, which can be misleading for personnel responsible for maintaining infrastructure safety and preventing damage. A (P3) diagnostic is therefore needed in several aufeis situations ahead of initiating an intervention, especially when a significant cost is involved. A diagnostic could comprise the development of an aufeis mitigation protocol to justify interventions as well as a database of the techniques that prove effective under specific conditions.

5. Discussion and research avenues

Several areas of uncertainty remain about the processes leading to overflow and freezing, the resulting aufeis, and the interactions between water or ice and the environment or infrastructure. Turcotte et al. (2023) proposed different research avenues to bridge this knowledge gap, including the spatio-temporal monitoring of aufeis-related parameters (e.g., water pressure) and the analysis of water quality parameters (e.g., major ion content). Improving our understanding of icing and aufeis represents an obvious first step towards selecting, testing, and adopting mitigation measures that are adapted to specific contexts, including the challenges of infrastructure maintenance in the North and those associated with a changing climate. Nonetheless, research directly addressing aufeis mitigation may occur simultaneously to improve the performance and reduce the cost of some approaches listed in Table 1.

Some mitigation measures described in the literature are rejected in any aufeis context (H4, AT1, M8, and C) for efficiency, environmental, or safety reasons (red rows in Table 1). Several approaches are not preferred (yellow rows in Table 1) for similar reasons, but also considering thermal and morphological aspects and the lack of knowledge regarding their feasibility. For example, some slightly intrusive approaches may alter surface and ground hydrothermal fluxes with net impacts beyond the zone of application and with effects that could only become detectable several years after implementation. Finally, some approaches (H1, H3, H13, AT3, AT5, PT4, M2, P1, and P2; containing green boxes in Table 1) are known to generate positive results with low to no adverse impacts in specific contexts. Most of them take advantage of natural processes, rather than attempting to combat them, and are highly energy efficient.

There is a need to confirm the context and conditions of applicability as well as the potential efficiency of various new and underrated approaches listed in Table 1 (identified by gray cells). Research and development projects may be inspired by the following suggestions:

- H5: Blockage of the upstream end of a culvert: Snowmelt (or rain-on-snow) runoff can occur in the absence of any ice melt. Therefore, it is important to be able to remove the culvert blockage before it becomes submerged and inaccessible. Using a metal grid (refer to HT5 in Section 4.4) as a blockage could prove effective if the grid is heated and debris can be easily removed. A temporary, inflatable device could also be designed and inserted in the culvert before winter.
- H10: Overflow-resistant road segments: Innovative road surface materials could be designed and tested. Their color and permeability would be important considerations in a permafrost environment.
- H11: Temporary overflow geomembrane: These covers should be resistant to abrasion by traffic and debris while being light enough to be easily deployed and removed.
- AT4: Heat pumps: This technology should be adapted to icing environments where a significant heat transfer (to compensate for the latent heat of fusion of ice) should be prioritized over a high temperature gradient. The approach could serve a double purpose of maintaining a frozen environment near an aufeis-affected site while melting a flow path at a desired location. Quick-deploy types of pumps could be designed and connected to an existing pipe system, just like steaming setups.
- PT2: Snow fences: There is a need to clearly distinguish settings and weather conditions leading to snow saturation and inclusion into aufeis bodies from those where snow effectively insulates a surface and prevents further overflow. This type of knowledge can be achieved through monitoring heat exchanges and snow characteristics (e.g., using multiple temperature sensors) at different test sites where unsuccessful snow management would be of no consequence.
- PT5: Seasonal frost belts: The performance of this approach could be documented using piezometers or thermistor lines upstream and downstream of a path where snow removal or compaction occurs.
- PT6: Thermosyphons: This approach may be cost-effective at sites where ground or small stream icing represents a recurrent (i.e., annual) hazard. A zone suitable for aufeis development should be designed (potentially including fences) in the vicinity of the thermosyphons area. A list of hydrothermal factors supporting the success of the approach should be developed.
- PT7: Non-metal culverts: A comparative performance test in a controlled (or monitored) environment should provide further insight into the real impact of alternate culvert material on icing intensity. In the spring, heat exchanges around and within a black HDPE culvert, for example, could be compared with those of a standard metal culvert. The durability and lifespan of the alternate culvert material should also be considered.
- PT9: Dusting: In addition to exploring materials (either solid or liquid, organic or inorganic) that effectively reduce albedo, the dispersion mechanism for this material should also be considered. The performance of the approach could be documented through regular drone flights and the use of upward and downward-facing pyranometers. The impact on downstream water quality should be minimized (e.g., turbidity or water quality should remain within natural ranges).
- HT1: Temporary fences: Vinson and Lofgren (2003) reported that fences are more efficient for aufeis management when arranged in the form of steps. The color and the type of material (permeability and resistance) also play an important role in the efficiency of the approach. For example, a black impermeable material may promote premature aufeis melting at the end of winter, with water draining downslope and freezing beyond the fenced area. Reusable fences are preferred, and a detailed protocol for their deployment and retrieval should be developed.
- HT3: Buried drains: The main consideration for this type of permanent installation is the stability of the spring outflow location. Attempts could be made to combine this approach with a heat pump (AT4) that would support the stability of the flow path through the ground by extracting nearby heat. Different insulation strategies could also be tested.
- HT8: Morphological alteration of a stream channel: The feasibility of this approach should rely on the knowledge of experts from different fields, especially fluvial geomorphology, environmental engineering, and aquatic and riparian ecology. The challenge would be to slightly alter the stream's hydraulic conditions and heat budget in a sustainable way (i.e., mimicking natural processes) without negatively impacting life (e.g., some species may depend on seasonally high water levels). This could be achieved through stream restoration techniques that account for river ice processes (e.g., Tuthill 2008) while allowing sediment transport. Specific techniques can be developed based on observations from natural channels where aufeis never form despite consistently cold conditions.
- HT9: Vertical adjustment of culvert alignment: Hydraulic tests in a cold laboratory involving multiple culvert alignments and a wide range of flow and temperature conditions could help develop curves or equations that would reveal optimal designs to minimize aufeis blockage. These curves could subsequently be tested through the investigation of multiple existing stream crossings affected, or not, by aufeis.
- HT10: Partial blockage of the downstream end of a culvert: This innovative approach has been described in enough detail in Section 4.4 to be tested. Different types of downstream blockage techniques could be considered, but they would represent less of a challenge compared with what

is described for H5. This approach could be complemented with the techniques described for HT8.

- M6: Double-angled-blade ice cutting machine: A mechanical engineering feasibility study could consider a design option with two rotating blades of varying diameters and power. Laser technology may eventually be considered to cut ice with high precision and negligible energy waste. The cost-effectiveness of a prototype could be compared to that of a standard excavator, just like the analysis performed by Simard-Robitaille (2021) for several ice cover weakening techniques.
- M7: Horizontal directional drilling: Considering the number of culverts that become clogged by aufeis every spring in northern Canada and abroad, the design and development of a light (portable) auger (e.g., 5–10 cm in diameter) could represent a strategic investment for those who maintain transportation infrastructure. Horizontal ice drilling would be needed over lengths varying from 10 to 30 m (enough to surface at the upstream end of a culvert), and the crushed ice would need to be extracted from the gallery and disposed. This approach would be easier to apply at the downstream end of a free-falling culvert.
- P3: Diagnostic: Tools or instruments should be used to support accurate and quick diagnostics of aufeis. For example, a pole (e.g., staff gauge) could be fixed at the head and exit of culverts to identify their locations when buried under ice and snow, especially prior to a mechanical intervention (e.g., M2). Small-diameter drilling could confirm the thickness of the aufeis over a defined area as well as detect the presence of liquid water. High-resolution infrared drone imagery could also reveal the location of flow galleries within an aufeis. Carey et al. (1975) mentioned the use of a conductivity (or resistivity) cable to evaluate the distribution of aufeis within a culvert, a permanent installation that could be combined with a wire used to guide aufeis drilling (M7). Eventually, non-contact types of instruments (e.g., sonic or radar) could be developed for the three-dimensional mapping of aufeis.

In Table 1, "*iv*" stands for the consideration of green or sustainable energy sources for novel or existing thermal (AT3–4) and mechanical (M2, M6–7) approaches. The use of fossil fuel as a source of energy (also as a hydraulic fluid and for parts lubrication) should be avoided, if possible, for environmental reasons (humans have burned enough fossil fuel that results in undesired ice melt at a global scale). Heating systems that would be directly connected to the grid are not an option at most stream crossings in the North, but they do exist, including along the Silver Trail in Yukon, where the grid is powered predominantly by hydropower. For remote aufeis-affected sites, wheel-mounted solar panels (as opposed to diesel generators) or permanent solar panel setups could be considered, especially at locations where overflow tends to become problematic in the spring.

6. Summary

This paper has provided an overview of the impacts of aufeis, with an emphasis on infrastructure and properties. Icing represents a hydrological and hydrogeological process that naturally occurs and that can be initiated, exacerbated, attenuated, or inhibited by modifications to hydrothermal processes. The second part of the paper focused on mitigation in situations where ground and stream overflow, icing, and aufeis produce negative impacts. Beyond the 50 (known and novel) mitigation approaches listed and described in Section 4, an effort was made to identify their respective contexts of applicability (Table 1), considering multiple environmental and efficiency aspects. It is recommended to prioritize risk reduction strategies that take advantage of natural processes. The last part of this paper focused on practical research needs and development avenues that will improve icing and aufeis mitigation strategies.

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

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