Hydrology Research

Hydrology Research Vol 54 No 6, 770 doi: 10.2166/nh.2023.008

Frazil ice events: Assessing what to expect in the future

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ABSTRACT

This article addresses the question: What is expected from frazil ice activity in rivers, taking into account the changing climate? It begins with an overview of what frazil ice is and what is required for the occurrence of frazil ice events, namely a supercooled water column. Methodologies to anticipate frazil ice events in the short term are based on air temperature and water discharge, underlining the significance of these two parameters for any predictive methods. Longer-term approaches, calibrated against past events (hindcasting), are used to anticipate frazil ice activity into the future, with indicators such as frazil ice risk, water temperature and frazil volume. Any of these approaches could conceivably be applied to frazil-prone river stretches. To assess climate impact, each location should be treated separately. River ice dynamics can lead to the formation of a hanging dam, a frequent outcome of frazil ice generation in the early winter, causing flow restriction. Flood modeling and forecasting capabilities have been developed and implemented for operational use. More frequent mid-winter breakups are expected to extend the occurrence of frazil ice events into the winter months – the prediction of these will require climate model output to adequately capture month-to-month variability.

Key words: breakup jam, climate change, flood, freeze-up jam, hanging dam, ice jam

HIGHLIGHTS

- Previous modeling endeavors aimed at foreseeing frazil ice generation in rivers are summarized.
- Frazil ice risk, water temperature and frazil ice volume are model outputs.
- Each frazil-prone location should be the subject of its own climate impact study.
- Mid-winter breakups (MWBs) will likely be more frequent in the future, which implies that clogging risks at water intakes will extend well into the winter months.

INTRODUCTION

Frazil ice consists of individual sub-mm to mm-sized particles which, under close inspection, most commonly form disks, but also needles, hexagons and a variety of other shapes. Frazil ice is difficult to observe in its natural environment because it develops below the surface and often at night, when the air is coldest. It has been studied in the field – Ghobrial & Loewen (2021) and Boyd *et al.* (2022) are two recent examples – but more extensively in a laboratory environment (see review in Barrette 2021). Frazil ice development, in combination with anchor ice (e.g., Pan *et al.* 2020), collectively alluded to as 'underwater ice' (Daly & Barrette 2022), is notorious for the challenges they pose to shoreline infrastructures. For instance, that material has a propensity to clog water intakes of facilities such as hydroelectric power stations (Figure 1) (Ettema *et al.* 2009; Gebre *et al.* 2013; Daly & Barrette 2022). Underwater ice may also promote ice jamming and consequent flooding, especially if it develops into hanging dams below a stable ice cover (Beltaos 1996; Asvall 1999; Grześ & Majewski 2000; Hicks 2009; Morissette *et al.* 2017). These features restrict the amount of flow, with a consequent rise in the upstream water level. A freeze-up ice jam is a common outcome of frazil ice events. Because these jams occur at the beginning of the winter, they represent a risk to shoreline infrastructures from flooding at that time of the year. This is in contrast with breakup jams, which typically occur at the end of the winter.

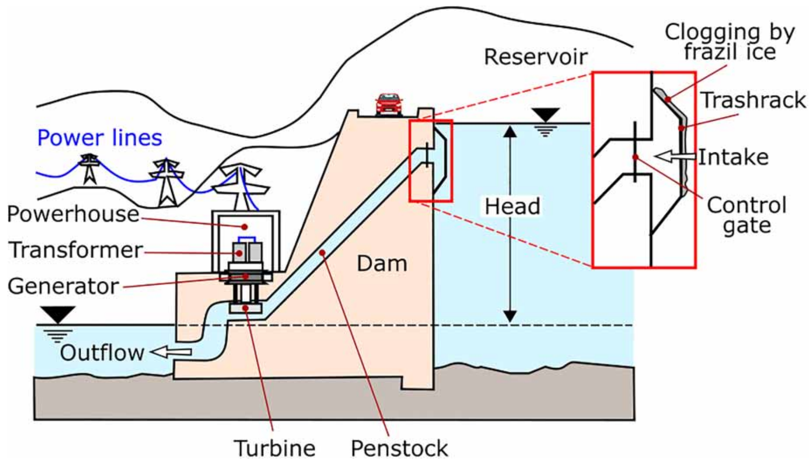

Figure 1 | Example of an asset (a hydroelectric dam) that is adversely affected by the development of underwater ice. This typically occurs on the trash rack and may cause a significant reduction in the discharge rate and consequent reduction in power generation (modified after Daly & Barrette (2022)).

OBJECTIVES

A question that is currently raised by stakeholders and decision makers concerned with the viability of shoreline infrastructures is: *What is expected from frazil ice activity in rivers, taking into account the changing climate?* The objectives of this article are, firstly, to present a brief overview of the circumstances under which frazil ice forms, namely nucleation mechanisms as well as the nature of a supercooling event. A basic understanding of these phenomena, which are highly dependent on air temperature, is deemed an informative initial step. Secondly, a brief description is presented of the main studies published so far that attempted to foresee frazil ice events and their contribution to ice jams. Lastly, it is to sum up the outcome of these studies.

RIVER ICE AND SUPERCOOLING

Freeze-up of a water body may be either static or dynamic (Devik 1942, 1949; Mason 1958; Michel 1978; Beltaos 2013). A static state is when the surface is relatively undisturbed, in areas with low flow velocity, which is dominated by thermal effects. Growth proceeds from the solid matter along the shoreline and at the water surface from pre-existing ice nuclei. Heat transmission is from conduction – as such, the very low thermal conductivity of water causes a considerable thermal gradient in the water column immediately below. Air temperature, wind and short- and long-wave radiations are the main controlling factors in growth. A dynamic state is when the water column is turbulent due to currents and wind. In that case, the heat transmission is through convection and there is a very small thermal gradient with depth. In both static and dynamic freeze-up scenarios, the water is supercooled, also called 'subcooling' or 'undercooling' in the material science literature (Cantrell & Heymsfield 2005; Shamseddine *et al.* 2022). Although the temperature is below freezing point (0 °C), it remains in the liquid state. The amount of supercooling is the difference between that phase change temperature and the lowest temperature reached by the liquid, i.e., just before it starts to form crystals (Cantrell & Heymsfield 2005; Shamseddine *et al.* 2022). However, while supercooling for static scenarios is at or near the ice–water interface, dynamic scenarios can give rise to the supercooling of the entire water column. This happens during periods of intense heat transfer from the water surface to the cold air above it.

There are thus two basic requirements for a supercooling 'event' (Daly & Barrette 2022): a turbulent water column and a period of intense heat transfer from the water surface that cools the water temperature to below 0 °C.

FRAZIL ICE

A frazil ice event has a distinct start and a distinct end, during which time the water column is supercooled. As crystals form, the latent heat released by this nucleation process causes the temperature to go up again. The resulting temperature change is known as supercooling history, during which the ice crystallizes, flocculates and rises to the water surface.

Nucleation

Under the right circumstances, water can exist in the liquid phase well below the phase change temperature (Cantrell & Heymsfield 2005; Hartmann *et al.* 2011; Zahir *et al.* 2019). For the crystallization of pure water, that can happen in the upper troposphere, 'where temperatures are consistently lower than −33 °C' (Cantrell & Heymsfield 2005, p. 798). It leads to crystal nucleation events of a stochastic nature, which is referred to as *homogeneous nucleation*. When it is supercooled, however, the material is in a metastable state, such that a number of factors can trigger solidification at higher temperatures. The main one is the presence of foreign particles, which can act as catalysts or 'seeds', a process known as *heterogeneous nucleation* (Cantrell & Heymsfield 2005; Fujikawa *et al.* 2018). It explains why the extent of supercooling is normally much lower than that occurring in pure water. Particles of foreign matter at the surface, inside a water column or the material along river shorelines can all act as nucleation sites.

A second dichotomy refers to *the nature* of the interface from which nucleation arises. If it is at the interface with a foreign substance, it is referred to as *primary nucleation* (border ice, formed from shoreline material or anchor ice, formed from the riverbed). If it arises at the interface with already existing ice particles (snow, crystals forming above the water surface), it is referred to as *secondary nucleation* (Evans *et al.* 1974; Botsaris 1976). Various mechanisms allow the multiplication of nuclei. These include the detachment of tiny dendrites growing from existing crystals with or without liquid-shearing action, as well as the collision of crystals against an external surface or between crystals.

Supercooling history

Figure 2 shows the classical temperature history for two cases: one where the energy that is released is enough to bring the water to the phase change temperature (0 °C) and the other where an equilibrium temperature is achieved. The latter, called *residual* temperature, is the balance between latent heat and heat removal. The supercooling history in that figure has been documented in many studies done in the laboratory as well as in the field. The nucleation temperature T_n may be down to about −0.1 °C (see Boyd *et al.* 2022 and enclosed references), though it is usually higher, i.e., several hundreds of a degree below zero. The residual temperature is typically a few hundred degrees higher than the nucleation temperature – that temperature does not always level off (e.g., Ghobrial *et al.* 2021; Boyd *et al.* 2022). The time t_n in the supercooling history is when the ice, which at that point may have grown into a full cover, adjusts to the colder air temperature above it. A frazil ice event in Figure 2 occurs when the water temperature decreases from T_m to when nucleation abates. It can lead to the massive generation of ice crystals inside the water column.

Frazil ice dynamics

Frazil ice events only occur in reaches of open water (Michel 1978; Daly 2008; Beltaos 2013; Burrell *et al.* 2022). This is summarized in Figure 3, a conceptual (and simplified) scheme, in which water flows from the left where it is faster due to a steeper riverbed. This prevents the water surface from freezing; it also promotes turbulence. Water temperature decreases during motion, typically during a spell of cold air temperatures at night when there are no short-wave radiations from the sun and long-wave radiations from the clouds. The water column becomes supercooled, inducing frazil ice generation throughout the water column. If the latent heat released is sufficient, the water temperature will rise to the freezing point (otherwise, the

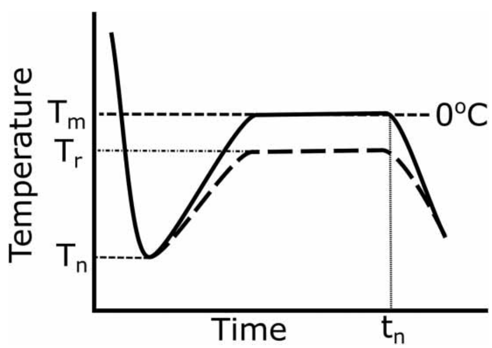

Figure 2 | Supercooling history. T_m: temperature of the phase change (0 °C in rivers); T_n: temperature at which nucleation begins; T_r: residual temperature; t_n: time after which the ice cover cools down once it has formed.

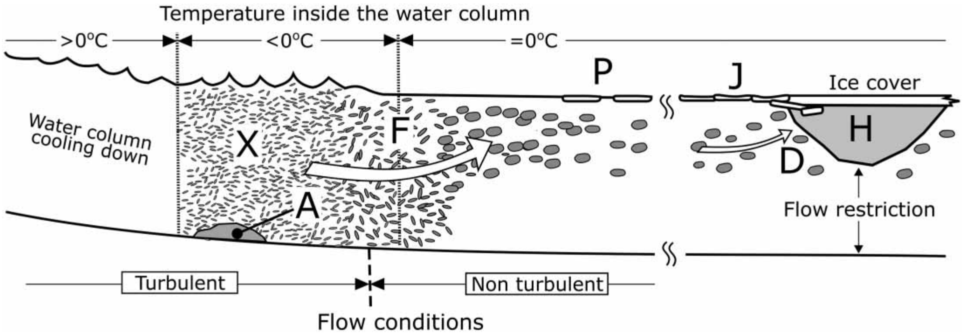

Figure 3 | Development of frazil ice in a river. A: anchor ice; D: deposition; F: flocs; H: hanging dam; J: juxtapositioning; P: ice pans/pancake ice; X: frazil ice crystals. Adapted from similar illustrations in Michel (1978), Beltaos (1996), Daly (2008) and Lindenschmidt (2020).

water will remain supercooled) (Figure 2). The frazil ice flocculates into clusters, which can then drift downstream for considerable distances. Flocs can also float to the surface and form slush pans or pancake ice (with raised rims due to the collision between them). Pans may then be juxtaposed against a stable ice cover downstream or driven below it. Depending on flow velocity, they may also be transported below the ice cover. A hanging dam is a localized accumulation of ice below the ice cover, which can restrict flow and induce a substantial rise in water level upstream. If anchor ice forms, it can be released from the river bed (e.g., due to the action of solar radiations), then rise to the surface and get incorporated into ice cover (Pan *et al.* 2020). Note that an ice jam can be made entirely of frazil ice (e.g., Beltaos 2013; Vergeynst *et al.* 2017).

FORESEEING FRAZIL ICE EVENTS

Foreseeing frazil ice events may be envisaged for two timescales. In the *short term*, i.e., within a few days to a few weeks, the relevance of these procedures would be at an operational level. That is, it benefits the management of facilities such as a hydroelectric dam, a run-of-the-river facility or municipal water plant, in preparing against these events. In the *long term*, i.e., within the next number of decades, it would provide an indication of the number of frazil ice events at a target location or along a given river reach. The emphasis in this article is in methods that aim at foreseeing frazil ice events at both timescales, with a focus on modeling endeavors. For the sake of conciseness, accounts addressing general river ice aspects and ice jams (e.g., Turcotte & Morse 2016; Beltaos 2021) are not considered in this article, even if they mention frazil ice. Other related matter, possibly of interest to the reader, includes means of quantifying the amount of frazil ice in a hanging dam (e.g., Vergeynst *et al.* 2017) and ways to mitigate frazil ice jams (e.g., Gholamreza-Kashi *et al.* 2011; Turcotte & Morse 2016).

Short-term assessments

The aim of short-term assessments is to increase confidence in being able to foresee frazil ice events within a timeframe of more than 1 day, i.e., for an operational perspective. These also help better understand longer-term approaches in the context of climate change. Among the many parameters that influence whether or not a frazil ice event will occur, air temperature and water discharge are those that matter most for both the short- and long-term perspectives.

Two examples of short-term analyses are given. Firstly, Beltaos *et al.* (2007) conducted some analyses on historical flooding events due to frazil ice over 140 years for Belleville River, in Ontario, Canada. Using an index for temperature – the lowest value of cumulative degree-days in January during 15 consecutive days – they showed that the majority of flooding events occurred below an approximate value of −7 °C (for that index). When plotted against a discharge index – the maximum discharge within the January 1–January 20 timeframe – approximate values −12 °C and 60 m^3/s were recommended as a tentative delineation for the likelihood of flooding events, for that particular location.

A second example, similar to the first one, was proposed by Gholamreza-Kashi (2016) for Spencer Creek in southern Ontario, Canada. Historical information on flooding events and associated temperature/flow conditions were gathered. Then, air temperature data and flow data were collected on a daily basis from stations at the site of interest. A 5-day rolling average was obtained on the number of freezing degree-days and the flow data. Based on the above information, and using appropriate threshold values, the probability of frazil ice occurrence leading to a flooding event was assessed on a qualitative basis. In their case, an upper-bound temperature value of –14 °C and a lower-bound discharge value of 11 m^3/s were used. For the purpose of the demonstration, that methodology was simplified, in the sense that it overlooks a number of other factors that play a role in frazil ice development. They provide an example of this, when a flooding event would have been expected but did not occur, possibly because of the presence of a thick ice cover. The methodology also relies on the availability of sufficient historical information, as well as current air temperature and flow data at the site of interest. It is meant to be updated on an ongoing basis with new flooding events.

The general principle behind these two studies is shown in Figure 4, a simplified version of the 'graphical method' used to foresee ice jams (Beltaos 2021). It basically considers that frazil ice events result from a favorable combination of low temperature and high flows. Threshold determination is location-based and requires an adequate amount of historical information.

Long-term assessments

To what extent can a changing climate affect frazil ice dynamics over the years? For a comprehensive overview of its impact on river ice dynamics and ice jams, the reader is referred to Burrell *et al.* (2022). In general terms, higher winter temperatures can promote the generation of frazil ice in rivers. Combined with an increase in the amount of rain, higher temperatures can induce a mid-winter succession of breakup and freeze-up, i.e., higher volumes of surface and underwater ice.

General approach

The procedures to foresee these events are generally divided into hindcast and forecast – Figure 5 captures the main aspects. For the hindcast exercise, a method is devised to produce the desired outcome validated against historical information of two types: climatological and hydrological. It relies on a number of parameters that are obtained from other studies – these can also be empirical or assumed. If that exercise is successful, it is then implemented in future climate scenarios, with an adjustment in parameter values. These future scenarios are produced from general climate models (GCMs), which are downscaled to higher-resolution regional climate models (RGMs).

Some examples of these procedures are provided below – they are divided into two types: *Thermal analysis* and *Temperature and precipitation*.

Thermal analysis

Andrishak & Hicks (2005, 2008) evaluated the thermal regime of the Peace River, in Alberta, Canada. To do so, they developed a model based on River1D, a one-dimensional finite element code, which solved the conservation of water mass and longitudinal momentum. For the hindcast exercise, the model was adapted so as to take into account additional considerations, such as water temperature, frazil ice dynamics and surface ice. The model did not address the more complex mechanical processes, such as ice jam formation or ice cover consolidation. The parameters required to conduct this exercise included water temperature, ice conditions and inflow information, such as water level and discharge. The calibration of model temperature against observations yielded a value of 15 W/m^2 for the heat exchange coefficient. The procedures incorporated the calibration of an empirical parameter meant to capture the effect of reduced ice velocity of the frazil ice pans as they approach the leading edge of the ice cover, and the effect of 'associated crushing, under-turning or consolidation of floes'. This was done against historical records of, namely, the ice front progression. Frazil floe porosity, frazil rise parameter, Manning's value and ice–water heat exchange coefficients were also obtained by these procedures.

Their forecast exercise relied on the Canadian CGCM2 climate model. Using parameter values produced in the hindcast exercise, a comparison was made between the migration of the ice front upstream historically and that into the future

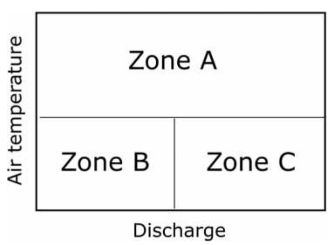

Figure 4 | Predictive approach used by Beltaos *et al.* (2007) and Gholamreza-Kashi (2016). Zone A: the air temperature is too high to generate frazil ice; Zone B: a low discharge promotes the development of a stable ice cover, not frazil ice; Zone C: highest likelihood for frazil ice development.

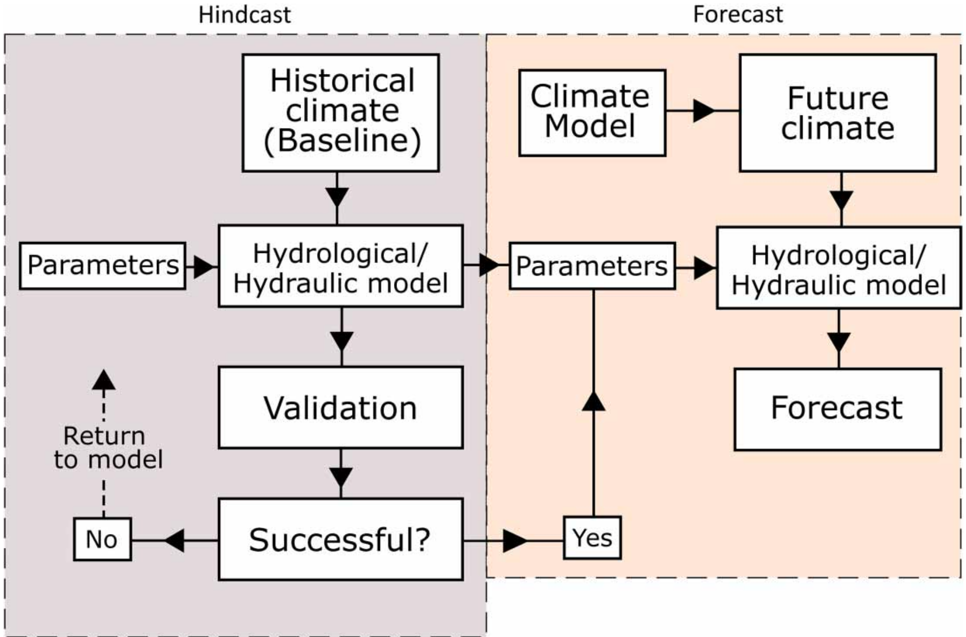

Figure 5 | General scheme used for assessing frazil ice activity in the long term – it comprises hindcasting (left) and forecasting (right) procedures.

(2040–2060). It was determined that the latter was reduced compared to the former. A similar comparison of the ice cover duration was made, with the future showing a reduction ranging from 41 to 63%. These studies are based on the assumption that the ice cover evolution at these locations is the outcome of frazil ice production. The downstream to upstream ice cover progression is attributed to the juxtaposition of frazil ice pans against the leading edge of the ice cover. The model does not factor in the amount of border ice, which can be considerable in natural rivers. This leads to an uncertainty in evaluating the relative proportion of frazil ice that contributes to the ice cover progression.

Temperature and precipitation

Huokuna *et al.* (2009) studied the impacts of climate change on frazil ice formation in the Kokemäenjoki River, Finland, a system well known for generating frazil and anchor ice. Temperature and precipitation data, obtained from four climate scenarios in the hindcast exercise, were fed into a hydrological model that simulated conditions such as 'snow accumulation and melt, soil moisture, evaporation, ground water, runoff and discharges and water levels of main rivers and lakes' (p. 120). A 30-year time span (1971–2000) was used as a reference, which is combined with the observed temperatures and precipitations. The latter, generated by the climate models – see Huokuna *et al.* (2009) for more information, were then used to produce future conditions in the forecast exercise. Noteworthy in that exercise is that it also took into account the regulation practices (i.e., the control of water discharge) of the dams upstream of the study area. These were incorporated into the simulation of future scenarios (2040–2069). An increase in discharge for the future scenarios (compared to the past scenarios) is shown, with a concurrent decrease in the summer. A procedure was then devised to determine the number of 'frazil ice risk days', which is defined as days when both the air temperature and discharge levels are considered favorable for the generation of frazil ice, i.e., -4 °C and 400 m^3/s, respectively. These numbers were obtained via a calibration procedure against observed ice conditions between 1971 and 2007. The number of frazil ice risk days increased for the future climate scenarios, more so for the warm climate than for the colder climate, particularly in January and February (Figure 6).

Aaltonen *et al.* (2010) followed up on Huokuna *et al.* (2009) with a study on the same river but with a refined approach where temporal and local temperature variations were accounted for. Several climate scenarios were used – see Aaltonen *et al.* (2010) for more information. Daily discharges for the 30-year periods 1971–2000 (the reference period), 2010–39 and 2040–69 were simulated with the same hydrological model, with flow regulation also factored in the modeling exercise. The number of frazil ice risk days increases in all climate scenarios, with December and January being the most frazil ice

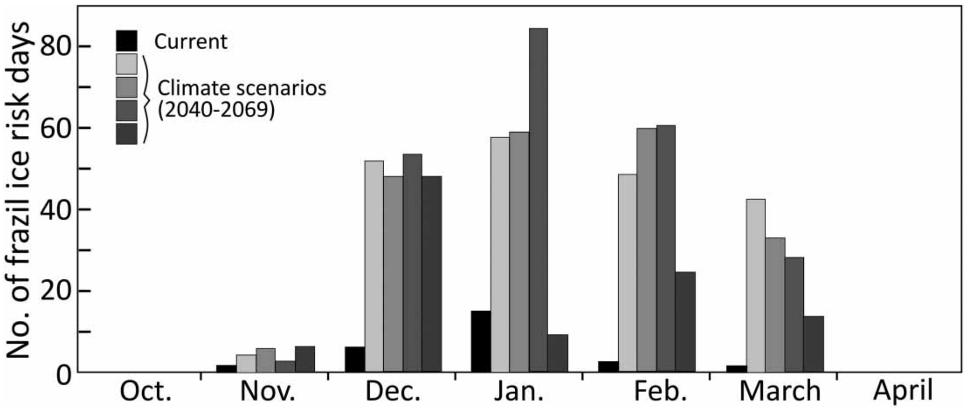

Figure 6 | Frazil ice risk days, as determined by the analyses of Huokuna *et al.* (2009), under four climate scenarios – adapted from Figure 5 in that paper.

prone. Compared to the reference period, an increase in monthly energy heat flux from water to air is observed for the frazil ice risk days, for the months of January, February and March.

Gebre *et al.* (2014) compared predictions of frazil ice volume for regulated (downstream of reservoir) and non-regulated (run-of-the-river) cases on the Okla River in Norway (see the source for more information on the climate scenarios). The baseline timespan was 2002–2009, and the future time span was in the 2080s. A one-dimensional hydraulic model, Mike11, with Mike-Ice, a plug-in 1D-based river ice module, was used to simulate parameters such as water temperature, ice cover formation and frazil ice generation. The outcome included changes in winter duration as well as mid-winter thaw frequency. It was also used to assess frazil ice production over both the regulated and non-regulated cases. In the former case, the modeling exercise showed lower volumes of frazil ice in the future (Figure 7); in the latter case, no significant changes were anticipated.

In Timalsina *et al.* (2015), ice generation in a regulated river was also investigated in the Orkla River. The segments included that studied by Gebre *et al.* (2014) but also extended further downstream. The climate baseline for the hindcast procedures was 1971–2000. The information was used as input into the Hydrologiska Byråns Vattenbalansavdelning (HBV) model, which is a conceptual rainfall-runoff hydrological model, the output of which was then fed into nMAG, a hydropower model that factors in elements such as reservoirs, hydropower dams and interbasin transfer. The output of nMAG was incorporated into the model. For the forecast procedures, frazil ice data were generated by Mike-Ice for the periods 2041–50 and 2071–2080 (Figure 8). For both future time periods, and for all climate models, the forecast indicated a decrease in the

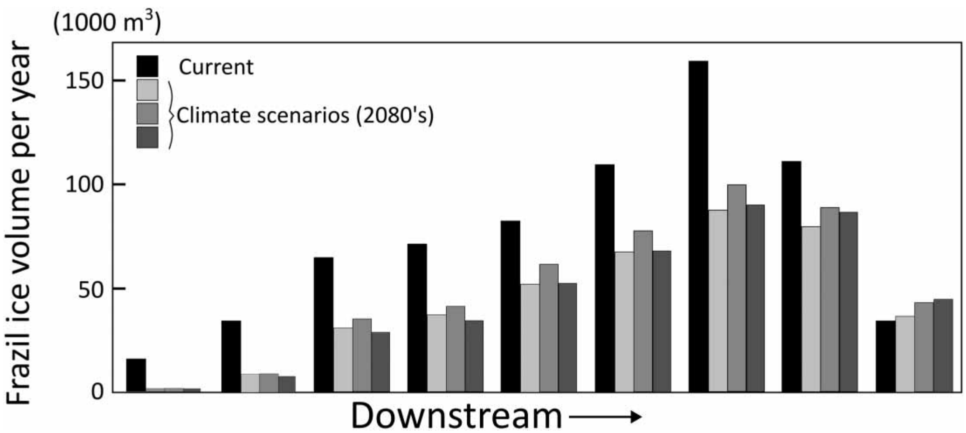

Figure 7 | Frazil ice volume at nine locations, as determined by the analyses of Gebre *et al.* (2014) for their non-regulated case, under three climate scenarios. Adapted from Figure 6 in that paper.

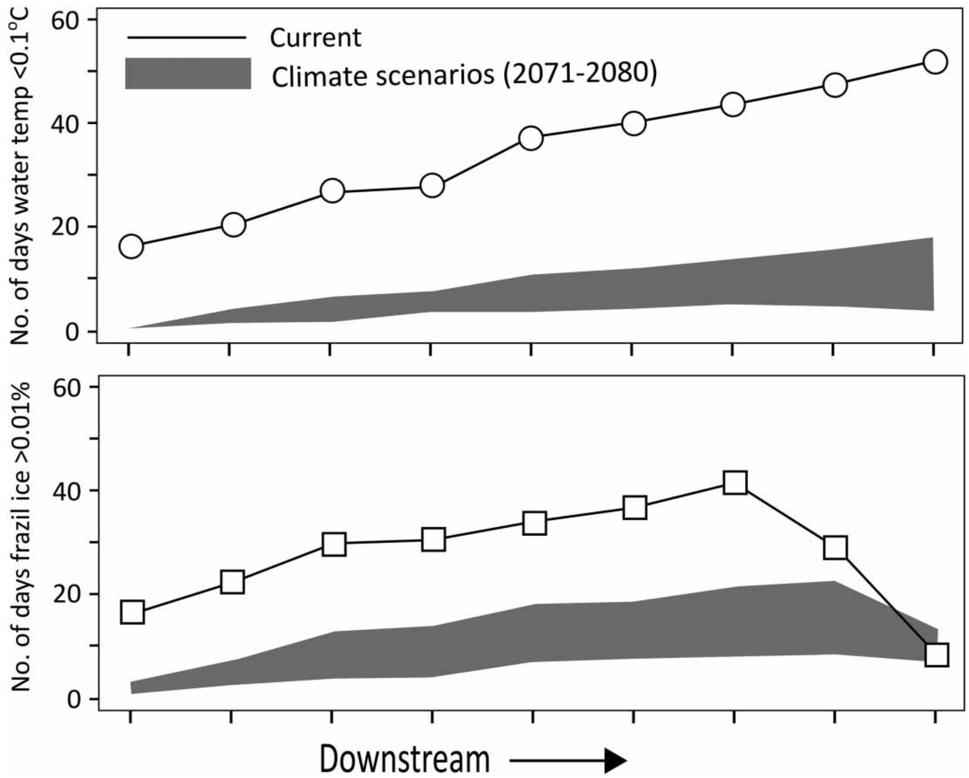

Figure 8 | Outcome of the analyses in Timalsina *et al.* (2015). On the horizontal axis, nine locations along the Orkla River are shown. On the vertical axis, (top) number of days with water temperature <0.1 °C and (bottom) number of days when the amount of frazil ice exceeds 0.01% of the ice volume are shown.

number of days where water temperatures would go below 0.1 °C and in the number of days during which frazil ice would be expected in the water column. Figure 8 illustrates these forecasted trends for the 2071–2080 time period; it also shows that this decrease in the number of frazil ice days (lower plot) is not uniform across all locations.

FREEZE-UP ICE JAMS

A freeze-up ice jam, defined as 'an unconsolidated cover that eventually becomes, fully or in part, a sheet of solid ice' (Beltaos 2013, p. 181), is an important part of river ice formation. It occurs at the beginning of the winter, thereby representing a risk to shoreline infrastructures from flooding at that time of the year (in contrast with breakup jams, which typically occur at the end of the winter). Along frazil-prone river reaches, extreme ice thicknesses can be achieved. Flood modeling and forecasting capabilities have been developed and implemented for operational use – these tools were used to foresee climate impact.

For instance, in the case of the Churchill River in Labrador (Lindenschmidt *et al.* 2021), freeze-up and freeze-up jamming are expected to be delayed in future fall seasons due to increased air temperatures (KGS Group 2020). However, increased flows due to increased precipitation could lead to freeze-up ice jamming events becoming more severe. A freeze-up ice jam flood forecasting system was also developed for the Exploits River in Newfoundland (Hatch 2021). It was determined that, with a warming climate, 'warmer fall temperatures will lead to a delay in the freeze-up date, and warmer spring temperatures will likely lead to earlier breakup dates and shorter winter seasons. These changes will affect the nature and character of the ice cover that forms on the river, and the processes that drive its formation' (Hatch 2021, p. 6–63). The warmer temperatures will lead to less production of frazil ice; hence, shorter freeze-up ice covers are expected, reducing the hazard of freeze-up ice jam flooding.

A workshop was held in October 2022 in Poznan, Poland, on ice jam flood hazard and risk assessment, with representation from Norway, Sweden, Finland, Germany and Poland (Lindenschmidt *et al.* 2023). Most ice jam flooding in these European countries occurs during freeze-up. An important question posed at the workshop was if ice jam flooding should be specifically addressed in the European Union (EU) Floods Directive. It was concluded that ice jam floods are already receiving attention in the directive since all types of floods need to be cataloged in the flood management plans, including pluvial and open-water fluvial floods. Special mention regarding ice jam floods is not required in the directive since most ice jam flooding events in these regions of the Baltic Sea have exceedance water level probabilities that are below those of open-water fluvial floods, probably because most ice jams occur during freeze-up. This does not mean that freeze-up ice jam floods are less severe than open-water floods.

A cold spell in February 2021 caused severe ice jamming and subsequent flooding on the Oder and Vistula rivers (Lindenschmidt *et al.* 2023). Such floods are of great concern and steps have been taken to develop and improve flood forecasting capabilities along these rivers (Lindenschmidt *et al.* 2019). The Torne River along the Swedish/Finnish border is also plagued by ice jam flooding (Lindenschmidt *et al.* 2018) and flood hazard maps have been developed by both countries to inform the public and water managers of the potential of flooding from freeze-up ice jam (examples of maps are provided in Lindenschmidt *et al.* (2023)). It is difficult to say how the frequency and severity of freeze-up ice jams will change in the future due to the changing climate. An interesting observation, though, is that 'projections for the future indicate a greater increase in land areas where river floods become more frequent, compared to the fraction of areas for which fluvial floods will decrease' (Lindenschmidt *et al.* 2023, p. 5).

MID-WINTER BREAKUPS

Mid-winter breakups (MWBs) are breakups that typically occur during January and February, i.e., they precede those in the spring (Beltaos *et al.* 2003; Huntington *et al.* 2003; Newton *et al.* 2016; Burrell *et al.* 2022; Das *et al.* 2022; De Coste *et al.* 2022). The analyses by Das *et al.* (2023) are a recent example specifically meant to foresee MWBs in the short term, including frazil ice generation. Factors favoring MWBs include higher-than-normal air temperatures, increased precipitations, increased water discharges and thinner ice. MWBs can promote the generation of frazil ice in the expanses of open water (i.e., the outcome of the breakup) with the return of the cold air temperatures prevailing at that time of the year. The frequency of MWBs has been increasing over time as an outcome of climate change. Consequently, risks of trash rack clogging are no longer limited to the fall but extend well into the winter season. From a climate change perspective, this will add to the challenge of foreseeing these events. The reason is that climate models cannot adequately assess variability *within* any given winter period. Instead, the usual practice is to conduct ensemble-type analyses based on these models but over a full winter. These scenarios are sometimes labeled according to the conditions, i.e., as 'warm', 'wet' or 'cold' scenarios (using Huokuna *et al.* (2009) as an example).

CONCLUSION

Frazil ice and anchor ice, collectively referred to as underwater ice, constitute a challenge for various engineered structures whose operations rely on water intakes; that ice is also known to promote flooding, particularly during the freeze-up period. Will a changing climate promote circumstances favoring the supercooling of the water column? From the brief review presented herein, we conclude there is no generic yes-or-no answer to this question. The climate seems to have an impact in most cases, but not in others, i.e., each case should be treated separately. The present study highlights several ways in which that has been done. One challenge is that, since frazil ice forms below the water surface, it is difficult to monitor. Predictive approaches mostly rely on what is observed near the surface or above it (including hydrological, hydraulic and climate data). Approaches are also empirical, i.e., parameters such as threshold values are only valid for specific locations. The methodologies summarized herein, be it to assess frazil ice risks or anticipate water temperature and frazil ice volume, could be envisaged for problematic areas (on a case-by-case basis). An expected increase in the frequency of MWBs due to warm spells implies that some shoreline communities will have to prepare for frazil ice events and their consequences not only in the fall but also well into the winter months. From a climate impact perspective, this means that, in addition to the already existing challenge of anticipating year-to-year variability, climate models would have to capture month-to-month variability with sufficient accuracy. Overall, it is the future of fixed ice coverage in rivers, frazil ice notwithstanding, that needs to be better understood.

ACKNOWLEDGEMENTS

Funding for this work was provided by Infrastructure Canada through NRC's Climate Resilient Built Environment initiative. The authors gratefully acknowledge comments on the manuscript from two anonymous reviewers.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 16 January 2023; accepted in revised form 20 May 2023. Available online 7 June 2023