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Hydrokinetic turbines in freezing rivers: challenges and mitigation measures

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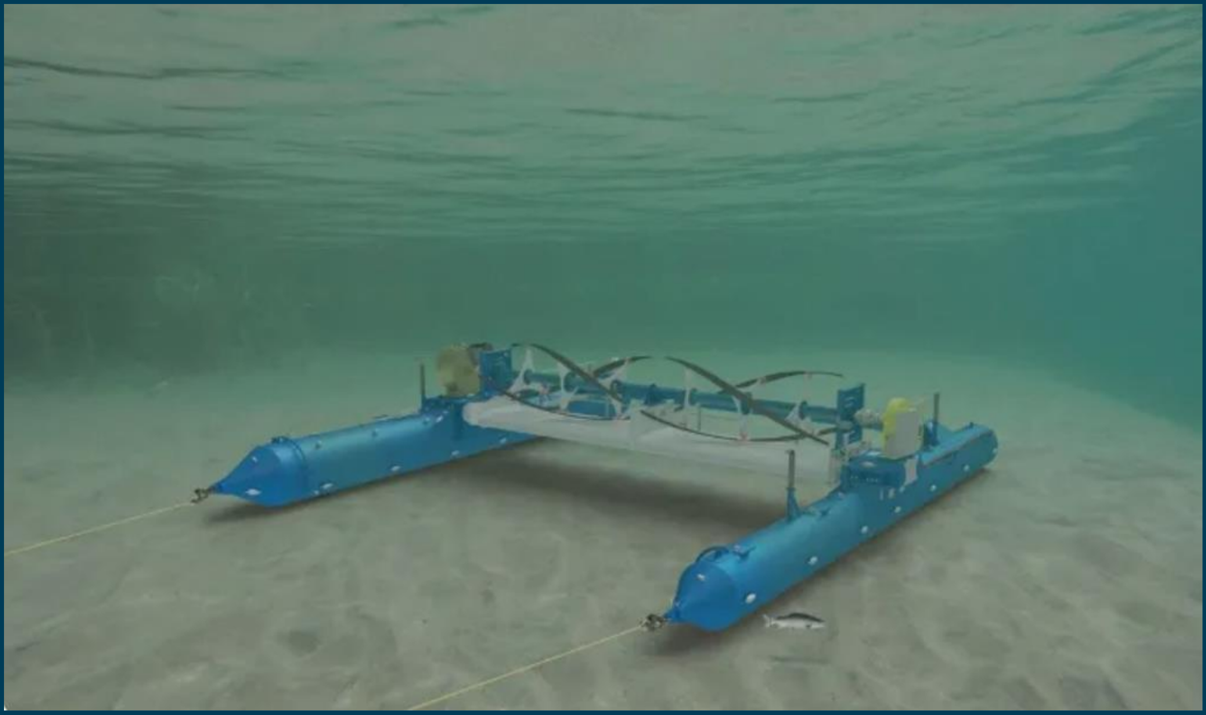
Hydrokinetic turbines in freezing rivers: Challenges and mitigation measures



NRC-OCRE-2025-TRQ-031
April 2026

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National Research Council Canada Conseil national de recherches Canada

Canada

<u>Frontispiece</u>: The RivGen power system is an example of a hydrokinetic turbine. This is a cross-flow turbine—a horizontal axis of the Darrieus type with helical blades. Image used with permission from Ocean Renewable Power Company (ORPC).[1]

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[1] https://orpc.co/

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Summary

In this document, high-level guidance is provided for the deployment of hydrokinetic turbines (HkTs) meant to operate in rivers during the winter. These devices are run-of-the-river systems that harness the kinetic energy of flowing water to generate electricity. Their deployment in rivers that experience seasonal ice cover presents unique technical challenges. These turbines must operate reliably in cold environments where ice formation, maintenance difficulties, and accessibility issues complicate operations. HkTs can nonetheless function effectively in harsh northern climates; a successful example of such deployment is the RivGen system in Igiugig, Alaska.

River ice processes are central to understanding the risks faced by HkTs. Ice in rivers forms both at the surface and below it, each with distinct implications for turbine operation. Border ice, skim ice, and a complete ice cover are all influenced by air temperature, current velocity, and local channel morphology. As an ice cover develops and with the formation of ice jams, the ice increases flow resistance and raises upstream water levels. Below the surface, frazil and anchor ice (collectively referred to as underwater ice) form under turbulent, supercooled conditions. Frazil ice adheres to submerged objects in its active state, eventually coalescing into flocs that rise toward the surface as frazil transitions to its passive state. Anchor ice develops when these frazil crystals adhere to the bottom or grow in place. Processes occurring below the surface are difficult to observe directly, yet they are critical to turbine performance, as frazil can adhere to blades, housings, and sensors, while anchor ice can modify local hydraulics.

Understanding site-specific ice conditions is essential. Historical records, local knowledge, and modern remote-sensing tools such as optical and synthetic aperture radar (SAR) imagery provide insight into freeze-up and break-up timing, open-water reaches, and ice jam locations. These data, complemented by field observations and hydrodynamic or data-driven modeling, help identify suitable deployment zones and anticipate seasonal variability.

Mitigation measures focus on careful siting, operational planning, and protective design. Ice booms can be used to encourage the formation of stable surface ice covers, reducing frazil production upstream. They can also help divert ice away from HkTs as it drifts downstream. Selecting materials less conducive to ice adhesion and shielding exposed components can also help limit frazil accumulation. Platform-mounted systems offer easier access but are more exposed to drifting surface ice, while bottom-founded designs are less affected by surface movement but remain vulnerable to underwater ice and thick surface ice released during ice break-up.

Because river ice behavior varies greatly from one location and year to another, implementing any mitigation strategy will require iterative testing and adaptive management. The integration of field data is a key element to inform and guide ice management practice.

1. Introduction

The principle behind energy generation from hydrokinetic turbines (hereafter also referred to as HkTs) is similar to that of wind turbines, but with the notable advantage that water is about 800 times denser than air. This greater density allows HkTs to produce substantial amounts of energy at lower flow velocities (1–3 m/s). These systems offer an attractive alternative to conventional hydroelectric dams for renewable power generation, in part due to their relatively low environmental impact and minimal disruption to aquatic ecosystems.

A turbine in these environments must withstand significant mechanical forces, and because such systems are often completely submerged, accessibility and maintenance can be more complex and demanding. This is especially the case when they are intended to operate in *freezing rivers*.

1.1. Hydrokinetic turbines in rivers

Hydrokinetic turbines in rivers (Figure 1) are a predictable source of electricity that can be fed directly into regional power grids, microgrids, or used as stand-alone units. While not as potent as a dam in terms of energy output, HkTs are less costly and far more flexible from a deployment perspective. These systems are well suited for remote and rural areas as an alternative to traditional fuel consumption (e.g., diesel or gas) in these communities, as well as for industrial applications. Riverine turbines are small enough to fit in relatively narrow channels. Because of their size, they do not depend on heavy lift equipment or access to large marine vessels. They can also be integrated with energy storage and intermittent sources of renewable energy such as wind and solar.

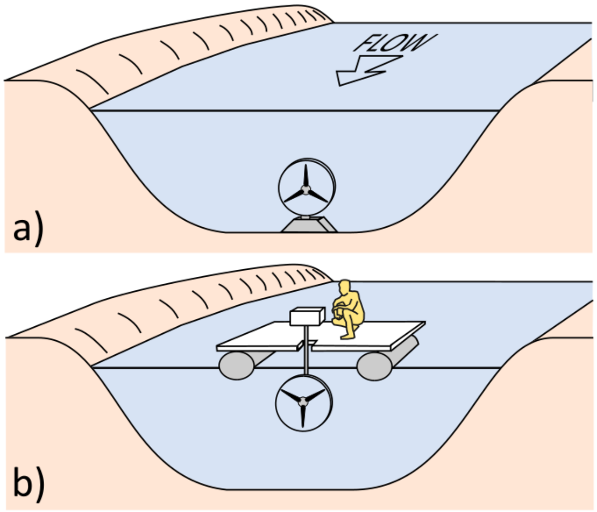

Figure 1: Two primary configurations for hydrokinetic turbines operating in ice-affected rivers: a) installed on the riverbed and b) suspended from the surface to an optimal depth. A single axial flow, propeller-type turbine is shown here as an example.

Hydrokinetic turbines operating in a river environment are known as *run-of-the-river* hydroelectric energy systems. This means that they do not rely on a large difference in height between their upstream and downstream sides (that difference is called the *head*), as is the case for a hydroelectric dam that stores water behind it. Instead, these turbines typically operate under less than one meter of head, and the turbine is driven by river flow.[2] Note that there are run-of-the-river hydroelectric dams as well—they do not impound water, but they remain large structures that generally span the full river width.

Key to the success of HkT systems, however, is the selection of an adequate site. Once that site is chosen, the turbine is introduced into the river. There are two common deployment modes (Figure 1):

- The turbine is installed directly on the riverbed.
- The turbine is suspended to a given depth from a floating platform or another surface structure (e.g., a bridge). In some designs, the platform itself can be immersed.

1.2. Riverine versus marine turbines

The deployment of HkTs in a marine environment differs from deployment in rivers in several ways, including the following:

- Marine HkTs typically rely on tides, which occur twice a day, and the flow is in two directions; they can also be activated by waves and ocean currents. They are designed with larger capacities. In contrast, flow in rivers is driven by currents only—these are unidirectional, continuous, and generally consistent on a day-to-day basis.
- Deployment along a coastline is in deeper water, which allows for larger devices.
- Deployment procedures face different challenges. In a marine environment, tidal flow strength reduces to zero for a few hours each day, a time that can be used for deployment or maintenance. In rivers, the flow is continuous, which is more challenging.
- While wind and wave regimes in coastal zones represent a liability when conditions become severe, access to large ships for installation, maintenance, and retrieval is advantageous.
- *Ice conditions are very different*. The development of *shorefast ice*, a thick and extensive ice cover along a coastline, along with deeper waters, typically affords a certain level of protection against winds and waves. Away from the shore, sea ice is dynamic, with its movement driven mainly by winds and water currents. In rivers, ice dynamics may be less predictable. The present document provides an overview of river ice processes and dynamics.

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[2] In this report, the term *flow* refers broadly to the movement of water, whereas *current* specifically denotes the measurable component of that motion, expressed in metres per second.

1.3. Objectives of this report

Ice is one of several challenges for operating hydrokinetic turbines in rivers. Over the past twenty years or so, several research teams have studied how ice dynamics affect these systems and identified important factors to consider when planning their installation and upkeep. One turbine in Alaska has been running successfully since 2019; its example will be briefly described herein.

The document has two objectives:

1) To provide a broad understanding of river ice dynamics. These processes are complex—although scientific knowledge continues to advance, significant gaps remain, particularly regarding phenomena occurring below the water surface. This understanding is critical for HkTs. Underwater ice is difficult to observe and quantify, and its effects are highly site-specific. Often, direct observation and operational experience remain the most reliable ways to determine its impact on turbine operations. Observations have shown ice formation at depths exceeding 50 meters in lakes, indicating that in riverine environments, *water depth alone does not provide protection from ice-related challenges*.
2) In light of these challenges, to outline various measures to reduce the risks faced by HkTs operating under freezing conditions.

1.4. Approach

The document includes:

- A brief description of a successful HkT deployment.
- A succinct explanation of river ice, including its formation, types, and dynamics.
- Information on how to assess a prospective deployment site for river ice conditions.
- How river ice affects the deployment and operation of hydrokinetic turbines in these environments.
- Mitigation measures.

This overview does *not* address the following topics in detail:

- The different types of turbines and deployment modes, anchoring methods, instrumentation, or data acquisition procedures.
- How ice directly affects power generation (though the report does provide context for exploring that topic as a follow-up).

The information provided herein is based on the authors' experience. We also consulted a range of reliable sources, including scientific studies, technical reports, books, and trusted websites.

1.5. Target audience

This document provides an introductory overview of river ice and its implications for hydrokinetic turbines. It is written for a wide audience, including community members, government representatives, and others interested in the subject. Technology developers may also find it useful.

2. Example of a successful deployment

Igiugig is a small community located in southern Alaska (Figure 2), home to members of the Yup'ik, Aleuts, and Athabascan Indigenous nations. It is on the Kvichak River near the mouth of Lake Iliamna. The area is well known for its large population of sockeye salmon, which the community depends on for subsistence and livelihood.

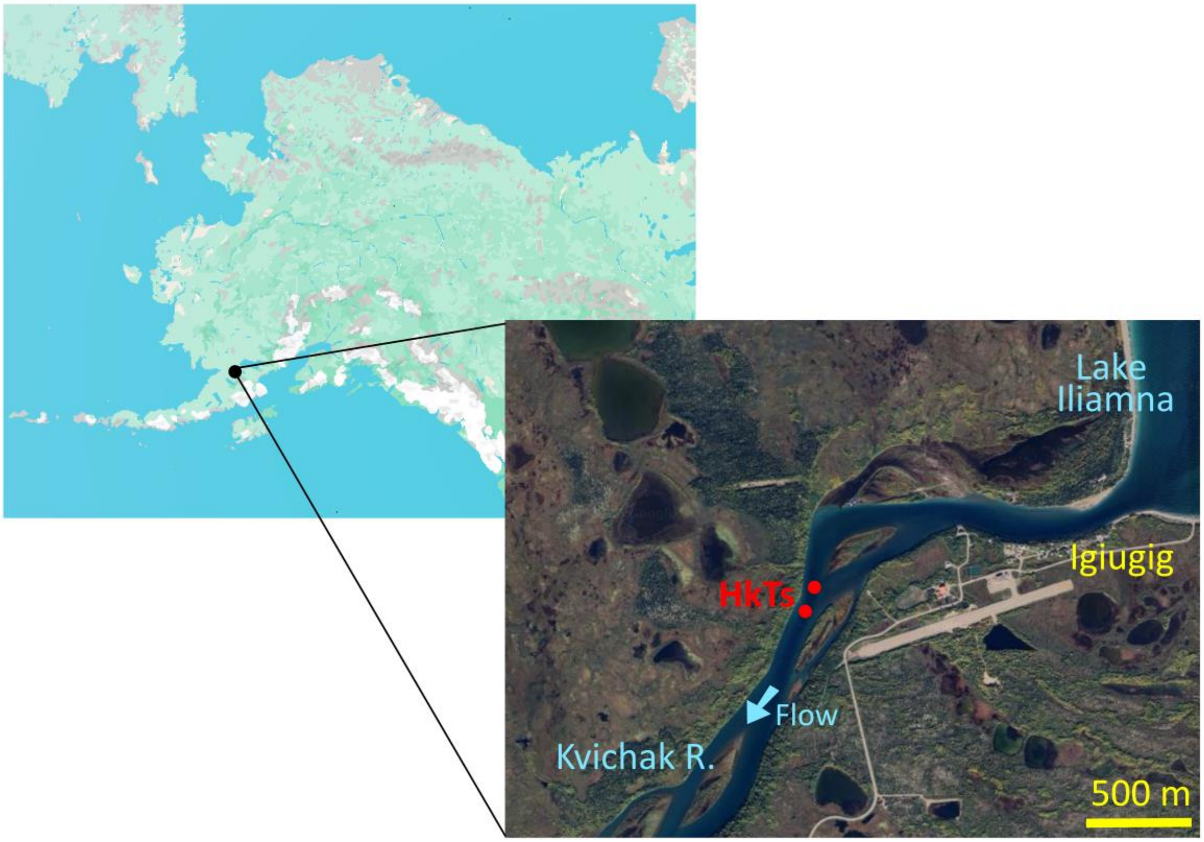

Figure 2: Location of Igiugig in Alaska and the two hydrokinetic turbines. Images © 2026 Google. Data: Maxar Technologies CNES / Airbus.

Since 2019, this community has been drawing electricity from the river using a hydrokinetic turbine. This system is referred to as a RivGen Power system, an ORPC product.[3]

Fish and ice were two of the community's main concerns regarding the deployment. Several reconnaissance studies were conducted in support of two trial deployments that took place in 2014 and 2015: a site characterization and hydrographic survey (2011) by TerraSound Ltd.; an

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[3] RivGen® Power System & Integrated Microgrid Solutions - ORPC

analysis of flow around the HkT (2014, 2015) by the University of Washington; observations of fish behavior around the HkT (2015) by LGL Alaska Research Associated, Inc., showing no significant impact on wildlife; and a more detailed study of impacts on juvenile salmon (2022) by the University of Alaska, showing some interaction with the turbine.

The turbine is 12 m wide and 1.5 m in diameter and is meant to rest on the riverbed. There are currently two units at the site, about 2 km downstream of Iliamna Lake, at a water depth of about 5 m, where the river width is 150 m. In cross-section, each turbine occupies about 10% of the channel's total cross-sectional area. Maximum current velocity is about 2.5 m/s, and total capacity is 70 kW. The first turbine was installed in 2019, the second one in 2023. Each system includes the device itself, a horizontal cross-flow hydrokinetic turbine, mooring lines, unburied transmission and data cables to shore, and an onshore station that houses system electronics.

The two HkTs have been performing well, with no observed injury or mortality to aquatic life and successful energy delivery despite temperatures down to -40°C. This achievement is based on the outcome and lessons learned from several studies that were conducted at that location in the years before formal deployment. Sources of information are included at the end of the present document.

3. Overview of river ice processes

River ice may be divided into two types:
- Ice that forms at the surface.
- Ice that forms below the surface (referred to herein as *underwater ice*).

Each presents its own challenges to hydrokinetic turbines.

Air temperature and river flow are the main factors controlling the formation of both ice types. Other important factors include snow cover, solar radiation, and wind speed and direction.

3.1. Ice forming at the water surface

Surface ice is what community members and the general population are familiar with because, unlike underwater ice, it can easily be observed from the shoreline, from a bridge, and from the air. The way it evolves can be complex and varies from site to site, but some generalizations can be made.

3.1.1. Formation of surface ice

Surface ice growth usually starts at the shoreline from objects, such as rocks and vegetation, that have been cooled down to below the freezing point from the ambient air. That is called *border ice*. It may extend toward the center of the river channel, and, if the current is low, it will merge with border ice growing from the opposite shoreline. Higher currents will prevent that from happening.

Ice can also nucleate within the river channel from drifting debris or from material seeded with snow or ice crystals above the water surface. That ice is often alluded to as *skim ice*.

3.1.1.1. Role of air temperature

As average air temperatures drop in the fall, water temperatures in the river also decline. Ice formation generally begins downstream because the water has been exposed to cold air for a longer distance as it flows. After the initial ice forms and a freezing front develops, it gradually moves upstream.

Cold air temperatures cause ice to thicken once an ice cover or sections of it start to form. The ice grows downward because heat is drawn away from the ice-water boundary at its base and transferred upward through the ice. This heat is then released from the surface of the ice. The lower the air temperature, the more efficiently this heat is removed.

If there is snow on the ice surface, it will act as an insulator, reducing the amount of heat leaving the ice-water system. The increase in ice thickness is thus also a function of snow depth. Depending on latitude (how far north the river is located), the maximum ice thickness in rivers generally does not exceed 1–1.5 meters, with the thickest ice closer to the shoreline, where it can reach the river bed.

There are ways to approximate the thickness of an ice cover. One common method is to add up the number of degrees below the freezing point (0°C) for each day starting at the beginning of the cold weather. This is called the cumulative degree days of freezing (CDDF)[4]. That number is then used as an input to Stefan's equation:

$$h = \alpha\sqrt{CDDF}$$

where α is a coefficient with a value *that depends on the site*. For example, it may be about 0.02, depending on factors such as snow thickness on the ice, sunlight, and wind at the location of interest. The parameter *h* is the ice thickness (in meters) expected from a given number of CDDF.

3.1.1.2. Role of current velocity

Current velocity is equal to the volume of water per unit time, also called the *discharge*, divided by the channel's cross-sectional area. It is usually measured in meters per second:

$$Current\ velocity\ (m/s) = \frac{Volume\ per\ unit\ time(m^3/s)}{Area(m^2)}$$

In *open water conditions* (summer), the discharge is mostly a function of the amount of rainfall.[5] The cross-sectional area varies over the length of the river as a function of width and depth. Current velocity is higher where the river is narrower (for the same depth) or shallower (for the same width).

The above also applies to *icy conditions* (winter), except that the influence of precipitation is not as influential, as most is in the form of snow. The amount of snow does matter at the end of the winter, because snowmelt is an additional input to the river. Liquid precipitations during mid-winter warm spells can also be a driver in river ice processes.

River flow may be divided into three regimes; these affect ice formation in different ways.

Weaker currents (Figure 3a)
Low current velocities are favorable to ice growth. This scenario is also representative of what happens in a lake. The surface ice grows from the shorelines outward (border ice) and may yield a uniform and regular ice cover, resulting in a smooth ice underside.

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[4] For example, say November 15 of a given year is chosen as the first day of the cold season. It has a daily average temperature of -2°C. November 16, 17 and 18 have averages of -1°C, 0°C and -3°C., respectively. The CDDF for those four days is 6°C (=2+1+0+3).

[5] How much of it makes its way into a river channel is determined from hydrological models, which take into consideration factors such as evaporation and soil percolation/retention. Hydraulic models, on the other hand, simulate water and ice processes in the river channel (this is discussed later).

Stronger currents (Figure 3b)

Current velocities may be high enough to prevent the formation of surface ice—this tends to occur in the center of the channel, away from the border ice. In those circumstances, open water conditions may prevail. These provide an indication that the hydrokinetic potential along that river reach may be favorable to deployment.

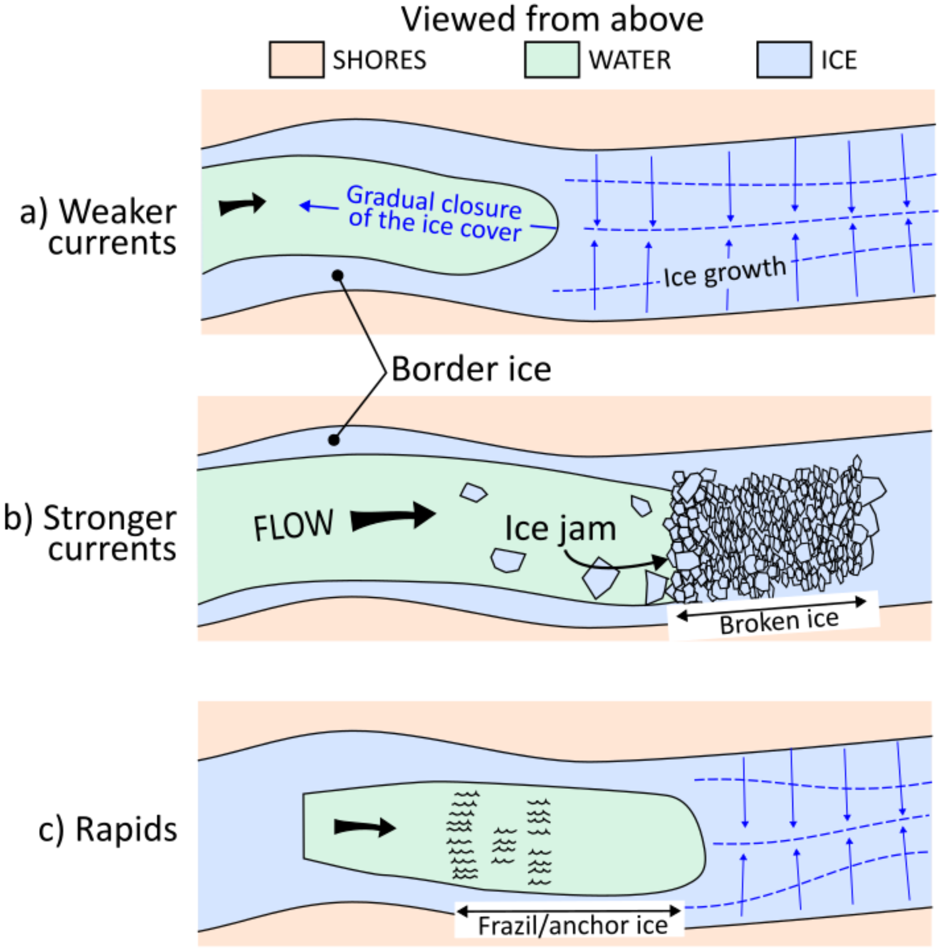

Figure 3: Three flow regimes are shown here as a simplification, each leading to particular ice conditions: a) Currents are too low to prevent the formation of an ice cover—growth will occur from the shoreline toward the center of the channel; b) Stronger currents can prevent ice cover formation or disrupt an already established one and turn it into a zone of broken ice that can form an ice jam. c) Rapids indicate either an increase in discharge or a decrease in water depth at that location, or both—these zones are often associated with the production of frazil and anchor ice.

There is no clear consensus on a threshold velocity above which surface ice will not form. A general range is often cited as 0.5 to 1.0 m/s.

In scenarios where river discharge is low initially and then increases (such as what commonly occurs in the spring or during mid-winter warm spells), current velocities may become high enough to break up a uniform ice cover. These fragments, or *floes*, then drift downstream and may accumulate and pile up at a given location (an existing ice cover, a river bend, a bridge…), in places leading to extensive (and sometimes thick) surfaces of broken ice that remain in place. This is called an *ice jam*.

Rapids (Figure 3c)
This flow regime is set apart *because of its propensity to generate underwater ice*. Rapids are areas where the interaction between the flow and the riverbed causes the water column to become turbulent (i.e., zones of white water). This often happens when the riverbed becomes steeper, thereby increasing discharge. It can also happen where the river is shallower, with a reduction in the channel's cross-sectional area. Open water in these areas may exist throughout the winter.

Photographs of the flow regimes described above are depicted in Figure 4.

Figure 4: Left) Ice conditions on the Rideau River at the Adàwe Bridge, Ottawa, where the river is shallower (and rapids develop). Upstream and downstream of that reach, the current is slower, favoring the development of a full ice cover. River width is about 120 m. Photo: NRC. Right) Small ice jam in the Ottawa River. Ice fragments were driven against each other and accreted at that location (at upper right is Gull Island, with a width of about 50 m). Photo: NRC.

3.1.2. Effects of surface ice on river flow

While river flow controls ice formation, *once that ice has formed*, it will, in turn, affect river flow. The dynamics of the currents are instrumental in that regard. Figure 5 shows an idealized 3D current profile across a river channel *in open water conditions*. Flow resistance along the shorelines and the riverbed contributes to slowing current velocity, with a maximum near the channel's center and at some depth below the water surface.

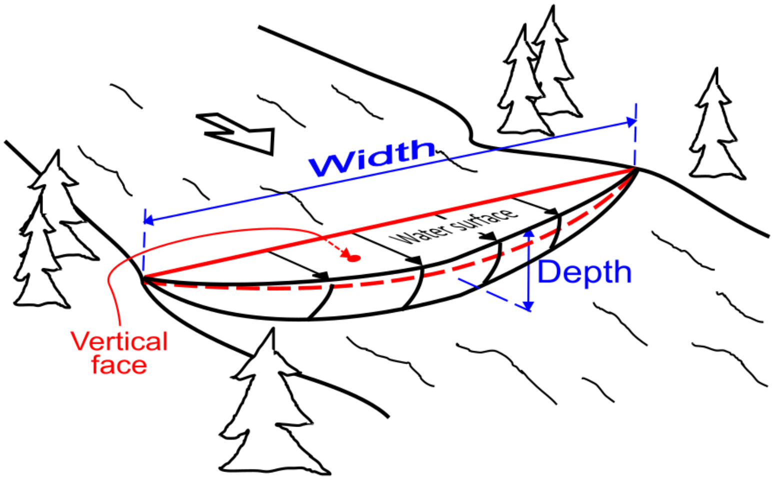

Figure 5: Idealized current velocity envelope across a river channel. The vertical cross-sectional area is shown in red.

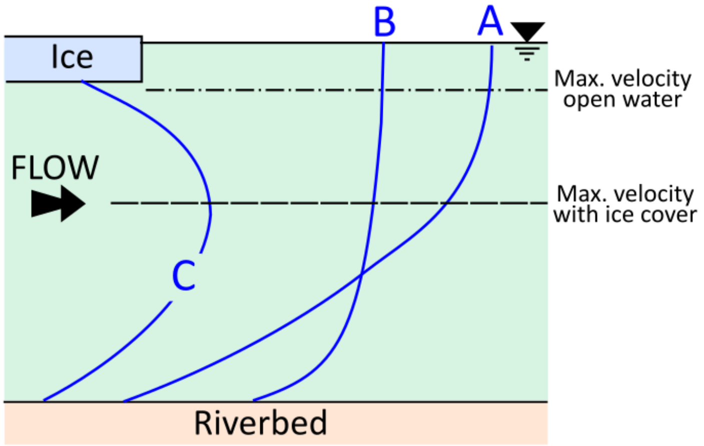

Figure 6: Idealized current profiles under laminar flow (A), turbulent flow (B), and under an ice cover (C).

Three such profiles are depicted in Figure 6. The *presence of an ice cover* lowers the channel's ability to circulate water. This occurs mainly in two ways:

1) *By increasing flow resistance*: Water flowing down a river does so because of gravity, which is counteracted by friction along the riverbed and shorelines.[6] In the winter, the ice cover is an *additional interface* that further slows down flow. This corresponds to current profile C in Figure 6. Less water flow translates into an increase in water levels upstream—this is known as *backwater*. The rougher the ice's underside, the more backwater.
2) *By decreasing the river's cross-sectional area*: In places, river ice may thicken to a significant depth below the water surface, thereby partly blocking off the channel (Figure 7).

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[6] Otherwise, the current velocity would increase to infinity (like an object dropped from a given altitude would without air friction)

The consequences of that activity are the generation of underwater ice and flooding along the shorelines. These will be discussed later. Note that *current velocity is highly site-dependent and also conditional on the morphology of the ice underside.* While friction at the ice/water interface will reduce current velocity, in places this may be counteracted by an increase in backwater levels. This can be assessed with hydraulic models (also discussed later).

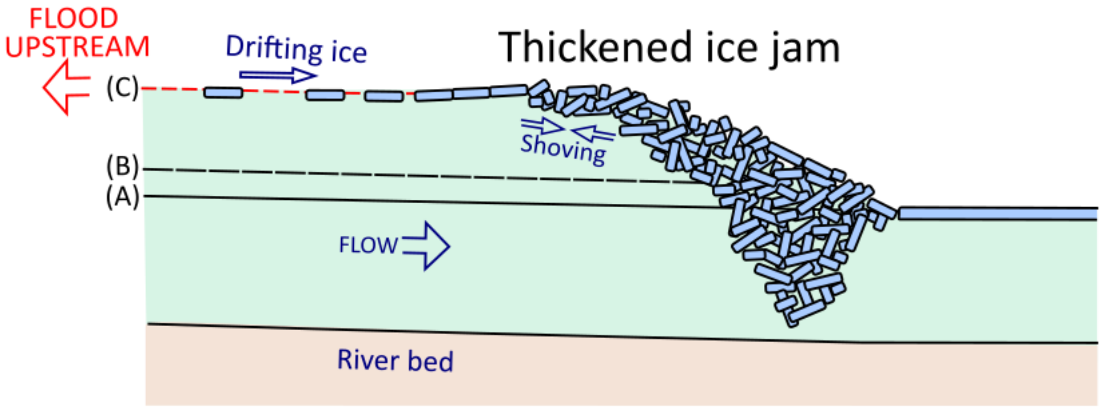

Figure 7: Schematic cross-section of an accumulation of river ice fragments (which may be representative of Figure 3b). This depicts a thick ice jam. Letters A, B, and C at left refer to Figure 17.

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3.1.3. Ice cover break-up

Ice cover break-up refers to the passage from icy to open water conditions, which occurs in the spring. In some places and in some years, this can also happen in mid-winter, e.g., following a warm spell and a significant rainfall, with refreezing afterward.

There are two types of break-ups: *thermal* and *dynamic* (the latter is also known as *mechanical*).

3.1.3.1. Thermal break-up

Thermal break-up is when the ice cover gradually melts in place, without involving a significant amount of fragmentation or drifting. This scenario is similar to what happens in a lake. It is more likely to happen at low current velocities.

3.1.3.2. Dynamic break-up

High current velocities will exert more stress on the ice cover, which is then more likely to break up. It may be accompanied by ice cover lifting and fracturing due to a higher discharge or backwater. When that happens, fragments of ice drift downstream and typically accumulate at a given location, where they may pile up into an ice jam with significant thicknesses. This reduction in the channel's cross-sectional area reduces the discharge, which in turn increases backwater.

If the pressure of the water upstream of the jam becomes high enough,[7] that ice may suddenly break up and release a large amount of ice, preceded by a precursor wave,[8] a feature known as a *jave* (Figure 8).[9] This is a potentially dangerous event for shoreline and in-channel facilities.

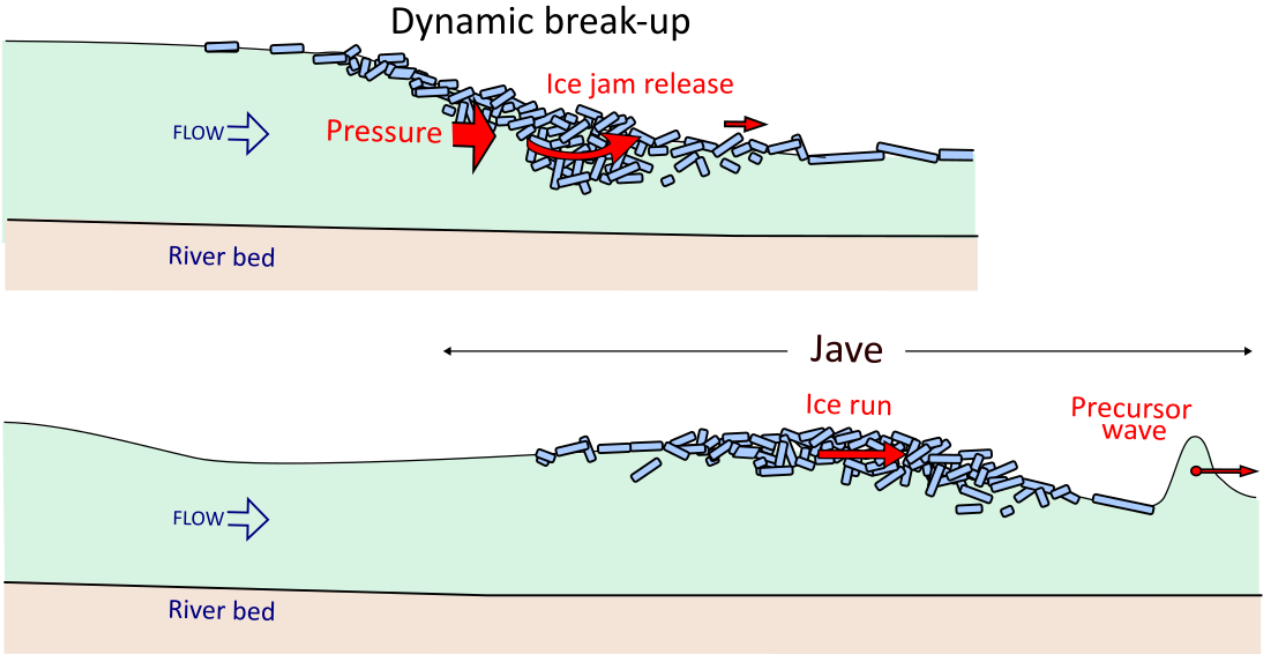

Figure 8: The dynamic break-up of an ice jam such as the one shown in Figure 7 and associated jave. The vertical scale is exaggerated for the purpose of the illustration.

3.2. Ice forming below the water surface

Underwater ice is ice that forms *beneath* the water surface (Figure 9). This is counterintuitive because ice, being less dense than water, would normally be expected to form and remain at the surface. What happens is that, in places where the water is turbulent—often where rapids are observed—an ice cover is unable to form. When the air temperature is low,[10] the water may become *colder* than its freezing point (0°C) by a minute amount—down to no more than about -0.1°C.

This state, called *supercooling*, can extend right down to the riverbed, being driven by the turbulence. It is thermodynamically out of balance and therefore cannot remain that way.

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[7] This pressure is due to a higher water level upstream of the jam compared to downstream. The weight of the ice also contributes to it (keeping in mind that the river surface is leaning toward downstream, however slightly).

[8] Referred to as *dynamic forerunner* in river ice engineering - it travels faster then the ice run, and the speed at which it travels is known as *celerity*.

[9] A combination of 'jam' and 'wave'—'jave' rhymes with 'wave'.

[10] Air temperature below -5°C—the colder, the more effective.

To return to an equilibrium state, crystals of ice will be generated at all depths within the supercooled layer—Figure 10 and Figure 11 show examples of what it can look like. This ice is known as *frazil ice*. Each frazil ice particle releases heat,[11] and the water temperature will gradually rise back up toward 0°C, then stabilize. Huge volumes of frazil ice can be generated that way.

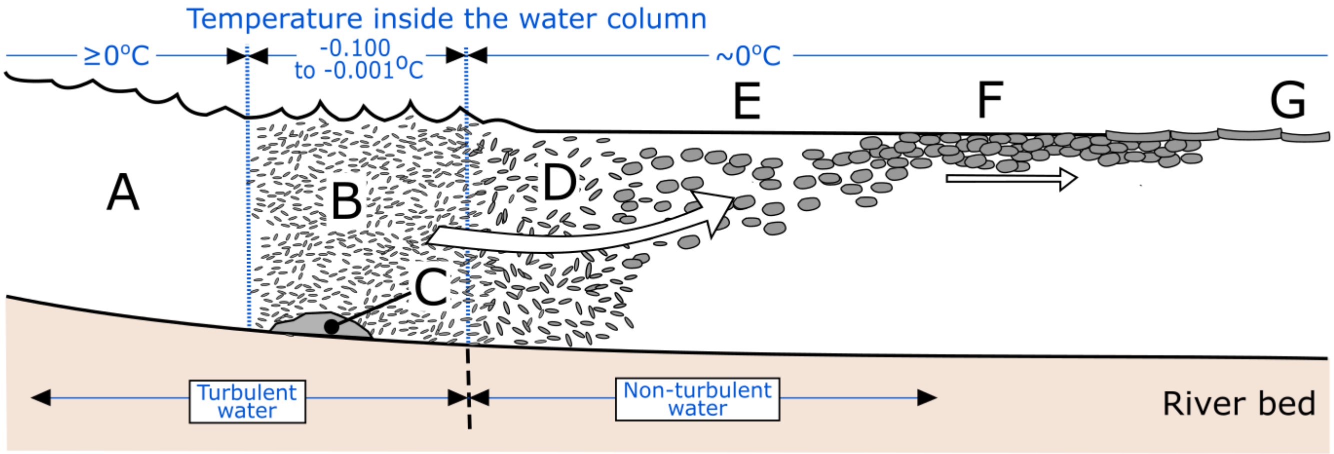

Figure 9: Frazil ice generation and related river ice processes. A: Ice-free; B: frazil ice crystals (active state); C: anchor ice (active state); D: flocs resulting from frazil crystals sticking to each other (active-passive state); E: flocs moving toward the surface (passive state); F: drifting slush layer; G: frazil ice pans forming a continuous ice cover. Not to scale.

This phenomenon is more common in the fall or early winter, while the river is in the process of building its ice cover, but it can also occur following a mid-winter break-up and a return to open water conditions at that location.

Cold air temperatures, combined with an open sky with no solar radiation (characteristic of cloudless nights), are typical conditions under which underwater ice forms, but other parameters also play a role, including winds, water temperature, and water regulation.[12] Conditions favorable to frazil ice formation usually diminish as the sun rises and heats the water (Figure 12).

In places and in some years, frazil ice has also been observed in mid-winter, typically following a warm spell. Higher air temperatures cause the ice cover to melt away where the current is higher, which favors ice break-up, thereby creating open water reaches. When the air temperature drops back to below freezing point, these reaches may once more become the source of frazil ice.

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[11] If heat is *required* to melt ice, it stands to reason that heat will be *released* when ice forms. That crystallization process warms up the water and re-establishes thermal equilibrium.

[12] Water regulation refers to the control of water levels, a standard procedure in hydroelectric dam operations.

Frazil ice is known to exist in two states: *active and passive.*

3.2.1. Active frazil

Active frazil alludes to the early phase of frazil formation when the ice *adheres to objects* in the water column or protruding into it from the riverbed—rocks, grass, even fish gills, as well as any artificial element, such as water intake trash racks and grids—an example is shown in Figure 13. It can then grow from these attachment sites. Frazil particles can also stick together, a process known as *flocculation*.

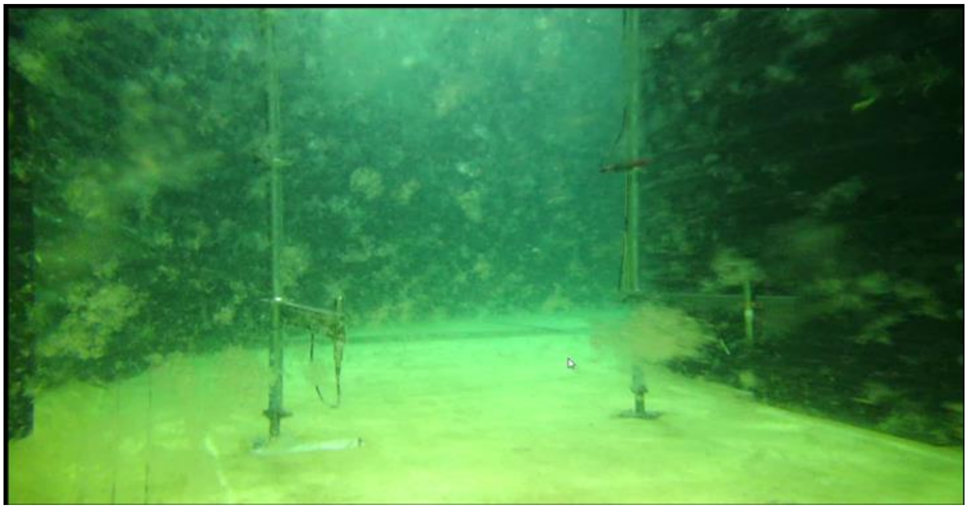

Figure 10: Frazil ice crystals and flocs below the water surface inside a laboratory setup. The visible parts of the rods are about 1 meter in height. Photo: NRC.

Figure 11: Frazil ice crystals also from a laboratory setup. Photo: NRC.

Figure 12: The Ottawa River, between the cities of Ottawa and Gatineau, looking upstream. Vapor is seen above the water surface, an indication it is losing heat. Frazil ice floes are drifting downstream (between the islands). Photo: NRC.

Figure 13: Frazil ice adhesion to two grids. Under the same flow conditions and with similar frazil concentrations, a difference was observed in how the rectangular (right) and foil-shaped (left) grids became clogged. The variation is attributed to differences in the local velocity fields around the bars. Scale: the grids are about one meter in height. Photo: NRC.

3.2.2. Anchor ice

Ice that grows on the riverbed is often called *anchor ice*. It begins by nucleating directly from riverbed material or from any object that is immersed in supercooled water (including equipment and instrumentation). It can also be the outcome of frazil ice adhesion during its active state. As anchor ice thickens, it can reduce water depth in places, thereby promoting turbulence—this may be seen in Figure 14 and Figure 15.

That ice may remain in place for a duration ranging from several hours to weeks. It may then be released by the action of buoyancy, currents, and solar radiation.

Figure 14: Looking downstream at the Ottawa River, between the cities of Gatineau (left) and Ottawa (right). This site displays the extensive development of anchor ice (light-brown zones), which remained in place for several weeks. Where they come close to the water surface, white water is present. Photo: NRC.

3.2.3. Passive frazil

As frazil ice within the water column drifts downstream, it transitions from an active to a passive state, *in which it loses its tendency to stick to objects* (Figure 9).

If no ice cover is present downstream, frazil crystals and flocs are driven toward the surface by buoyancy. At that point, that material builds into a layer of slush, then into sub-meter to meter-sized pans (Figure 16). These keep drifting downstream and may eventually accumulate at a given location downstream, where they turn into an ice cover.

Figure 15: Rideau River, Ottawa, looking upstream, where a zone of rapids can be discerned. The river width is about 120 m, and it is flowing toward the camera. Ice growth along the riverbed, known as anchor ice, is seen here through slightly more turbulent water. It shows up lighter-colored in that photograph. Photo: NRC.

Figure 16: Ottawa River, eight kilometers downstream of the location shown in Figure 14. Drifting frazil ice pans aggregated and got incorporated into the border ice (glove on the branch for scale)[13]*. Photo: NRC.*

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[13] The brownish-looking ice around the branch at the bottom of the picture is called *aufeis*, i.e., ice that forms on top of an already-established ice cover (here as a result of water seepage throught the ground).

3.3. Ice-induced floods along river shorelines

Every year, river ice is responsible for severe flooding events along river shorelines. This is a primary motivation for much of the research on river ice, which is conducted by universities, government institutions, and organizations from the private sector.

Ice-induced floods are caused by ice jams. They occur either upstream or downstream of the jam, under different mechanisms.

3.3.1. Floods occurring during the *formation* of an ice jam

It was shown earlier that the friction along the ice-water interface (at the base of the ice cover) slows down flow. A portion of the water then accumulates upstream—the backwater—instead of making its way downstream as it would without the ice cover. The nature of the ice-water interface is also important. The rougher the undersurface, the higher the friction and the more backwater. In addition, if the ice cover thickens, as ice jams often do, it reduces the channel's cross-sectional area, which further increases backwater levels. This is summarized in Figure 17.

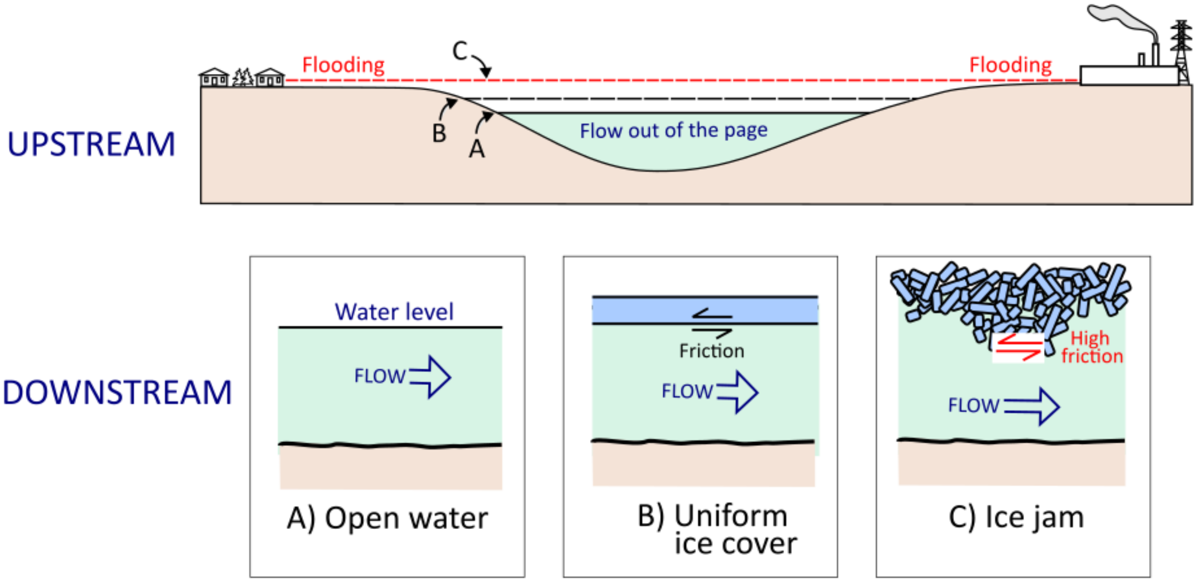

Figure 17: Comparison between the water levels in the following scenarios: A) without ice (open-water season), B) where there is a uniform, smooth ice cover downstream, and C) where broken ice downstream forms an ice jam, roughening the underside and thickening the ice cover.

Flooding events that are associated with the *formation* of ice jams occur *upstream* of the jam. Some salient characteristics are as follows:

- *Ice jams are difficult to anticipate.* While open water floods are mostly a function of precipitation, which can be forecast and quantified using hydrological models, those in icy rivers are mostly a function of the ice dynamics, which are complex.
- *Where* they occur is also difficult to foresee.

- *The rise in water level is relatively fast*—it may take several hours to days.
- *Cold conditions hamper operations*. Air temperatures below the freezing point can make the deployment of equipment and personnel more challenging.
- *Large, fast-moving ice fragments accompany flooding*. They exacerbate the damages in the flooded areas.

3.3.2. Flood occurring upon the *release* of an ice jam

Flooding events that are associated with the *release* of an ice jam occur *downstream* of the jam. Some salient characteristics are as follows:

- *The location of the jam is known*. Compared with the floods upstream of an ice jam, there is less uncertainty about where the flooding could occur downstream upon ice release.
- The *timing* of the release is difficult to anticipate.
- *The release can be extremely fast*. As a consequence, so is the water level rise downstream. This makes it much more difficult to prepare against these floods.
- Several factors influence the situation. One is the volume of water and ice retained by the jam—the total amount of material moved by it during the jave. Other factors include whether the river downstream is covered with ice or has open water, as well as the river's shape and variations in riverbed configuration.

3.3.3. Relationship between water level and discharge

Two of the most important variables in a river are water level (or *stage*) and discharge. The first is measured at about 2800 hydrometric stations in Canada, which are instrumented for that purpose. The second is derived from the first. This network is managed by the Water Survey of Canada (WSC), which is part of Environment and Climate Change Canada (ECCC), in partnership with several provinces and territories.[14]

In open water conditions, the discharge is the product of the channel cross-sectional area and the current velocity across that section. That value is then correlated with the water level. Once a relationship between discharge and water level—called the *rating curve*—is established, it can be used to derive discharge from a measured water level. The morphology of the riverbed and the shorelines is surveyed regularly or on an as-needed basis to keep track of changes in cross-sections and ensure that the relationship remains valid.

The presence of ice complicates the relationship between the two variables. This is shown in Figure 18 for four scenarios: open water conditions, uniform ice cover, a freeze-up jam (occurring in the fall), and a break-up jam (occurring in the spring). The three ice-induced water level responses are associated with a reduction in the channel's conveyance. Hence, for a given discharge, the water level is higher when ice is present.

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[14] https://wateroffice.ec.gc.ca/index_e.html

The pattern shown in Figure 18 and variations thereof are well documented across the river ice literature. What it shows is that, unlike in the open water season, the water level is *not* representative of the discharge.

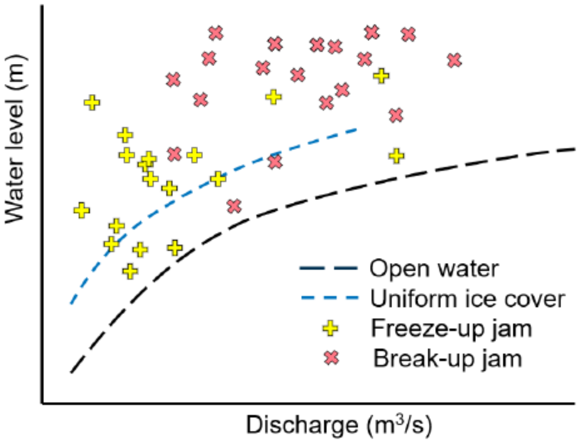

Figure 18: Generic relationship between the water level and the discharge in a given river reach. The chaotic nature of water levels when ice jams occur contrasts with those when there is no ice or when there is a uniform ice cover.

To account for the presence of ice and its effects on water level, a correction is applied by the WSC using specific standard operating procedures. The output of that procedure is a realistic value for discharge corresponding to each water level, irrespective of the state of the ice cover.

3.4. Summary of river ice evolution

A simplification of river ice evolution is shown in Figure 19—it summarizes much of what was described earlier. For the purpose of this summary, the various processes are divided into six groups (A-F):

A. *Freeze-up*: The outcome of freeze-up is greatly influenced by the amount of turbulence affecting the water column. Rapids (white water) are often an indication of a high turbulence level. Non-turbulent conditions can occur under slow- to fast-flowing waters.
B. *Input from the atmosphere:* Snow settling on a relatively calm water surface will promote the formation of an ice cover. If it accumulates onto an already existing ice cover, it will act as an insulator and slow down ice growth below it. From a hydrological standpoint, the melting of overland snow will contribute to increasing water levels in the spring. This group also comprises rainfalls during a mid-winter warm spell (not indicated).
C. *Surface ice*:
    - *Border ice:* Surface ice growth from the shoreline extending toward the center of the river channel. If the current is low, that ice from both shorelines will merge. Higher currents will prevent that from happening.
    - *Skim ice*: Skim ice forms inside the river channel.
    - *Ice cover formation*: This includes both vertical (thickening) and horizontal growth.
    - *Aufeis (not indicated)*: This is water seeping from the shorelines onto the existing ice cover and freezing in place.

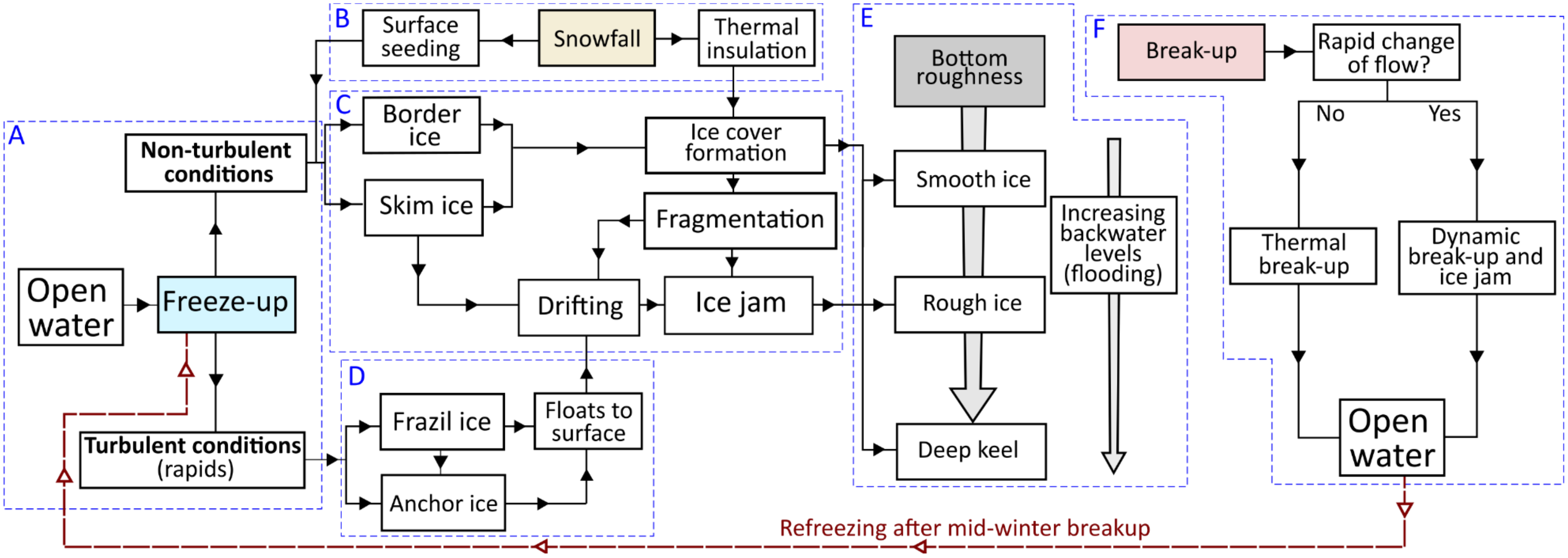

Figure 19: The evolution of river ice—it is here simplified by clustering the processes into six groups: A) Freeze-up; B) Input from the atmosphere; C) Surface ice; D) Underwater ice; E) Consequences on water levels; F) Break-up.

  - *Fragmentation*: This is the process by which an intact expanse of the ice cover, typically border ice but also in-channel ice, is broken up by currents. This depends on current strength but can also happen upon ice cover lifting due to higher water levels.
  - *Drifting*: Any ice that is not fastened to the shoreline will be conveyed downstream by the currents.
  - *Ice jam*: This is where drifting ice comes to a stop. If the current is strong enough, it will fragment the ice cover at that location.

D. *Underwater ice*: This is ice that forms below the water surface, often (though not always) where rapids exist. The water's turbulent state allows it to become supercooled and generate frazil ice inside the water column or growth from the riverbed (anchor ice).
E. *Bottom roughness*: This is the consequence of the processes in Group C: the rougher the underside, the higher the water level upstream of it (backwater).
F. *Break-up*: At the end of the winter, the ice cover may either melt in place (thermal break-up), or through complex fragmentation processes (dynamic break-up). When it does so in mid-winter, the resulting open water conditions can refreeze through processes similar to those that took place in the fall.

3.5. Relevance of a changing climate

River ice processes are very sensitive to climate. Air temperature is the most influential parameter; others include solid and liquid precipitation, wind, solar radiation, cloud cover, and humidity. These parameters interact in complex ways and affect the ice conditions and processes such as freeze-up and break-up timing, ice thickness and strength, the likelihood of mid-winter thaws, and the potential for ice jams at a given deployment site.

In the *short term* (from one year to another), fluctuations in individual variables are expected to occur, i.e., cold winters can follow a warmer winter and vice versa. These changes are highly site-dependent, which underscores the need to evaluate current or prospective deployment sites on a case-by-case basis, each against their historical records.

From a *climate change* perspective, i.e., in the medium to long term (~10–50 years), researchers generally agree on the following trends:

- There will be an overall increase in air temperature, albeit not uniform across Canada.
- Warmer summers and more rain in the fall will contribute to delaying freeze-up.
- There will be a reduction in the length of the ice season, with later freeze-ups and earlier break-ups.
- Warmer winters will result in thinner and weaker ice covers, which may translate into less severe ice jams.
- Milder winters accompanied by rainfalls will increase the number of mid-winter break-ups, with a consequent increase in frazil ice production at some locations.
- Less surface ice cover on water bodies could increase the potential for frazil production.

- Higher winds in lakes and in wide, low-gradient rivers, will feed wave regimes that prevent ice cover formation.
- More water vapor in the atmosphere would increase cloud coverage, thereby reducing frazil production (since cloudless skies favor heat removal from open water surfaces).
- In a regulated river, i.e., where the water discharge is controlled by a dam, how that flow will be altered in the context of a changing climate will add uncertainty to future river regimes.

To account for variability and uncertainty in projections, climate trends are derived from ensembles of large-scale models—that is, collections of different models or multiple simulations of the same model initialized with slightly varying starting conditions. Figure 20 displays the projected temperature changes along two time frames—2031-2050 and 2081-2100—for two scenarios: low emission, assuming efforts at reducing greenhouse gases are successful, and high emission, assuming nothing is done about it.

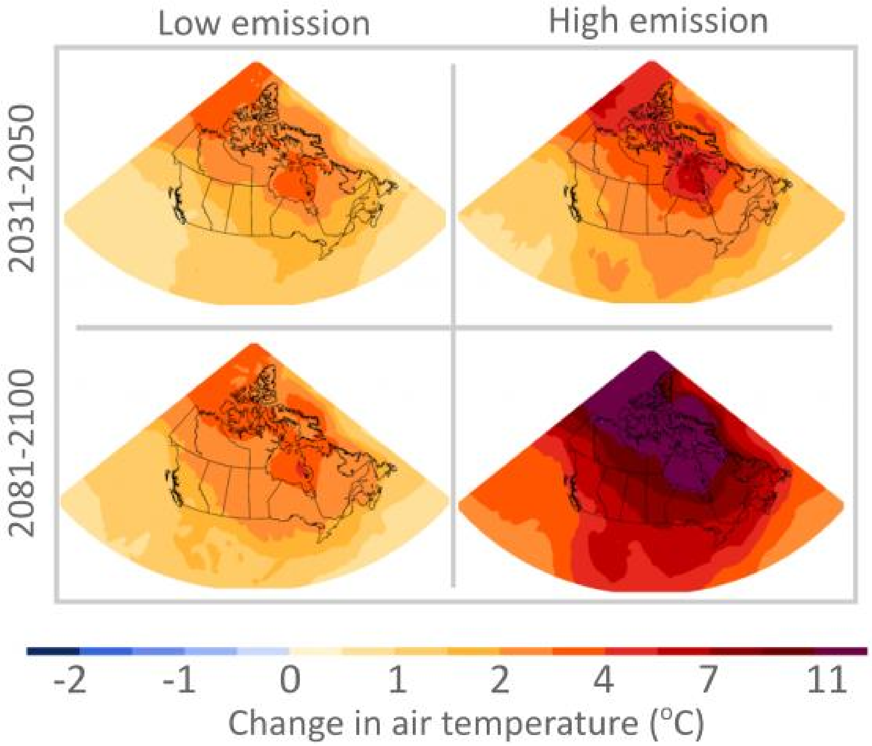

Figure 20: Changes in average air temperature relative to the 1986–2005 period.[15] Low emission is a drastic reduction in greenhouse gases; high emission is 'business as usual'.

Despite the inherent variability and uncertainty of their outputs, climate models offer valuable insight into how ice conditions could evolve over the years in a given river.

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[15] Adapted from Bush, E. and Lemmen, D.S., editors (2019): Canada's Changing Climate Report; Government of Canada, Ottawa, ON. 444 p. https://changingclimate.ca/CCCR2019/chapter/4-0/

4. Site-specific assessment of river ice

River ice conditions and processes can vary considerably from year to year in a river and even from one reach to another within the same river. Before deploying an HkT system in a river that is expected to freeze, it is important to have an understanding of historical ice conditions.

Assessing these conditions over the longest period permitted by available data is desirable to capture the natural variation in ice processes from year to year. In addition to river characteristics and flow regimes, consideration should be given to weather and climate. As discussed in Section 3. air temperature, flow, and turbulence play important roles in ice formation timing, location, and characteristics.

ECCC weather station and climate modeling data are available for most regions of Canada. Modeling may also be downscaled to give higher spatial resolution of the predictions around a region of interest. Historical records of hydrological parameters are archived for many rivers by the WSC.

Ice-related parameters of interest for the planning of HkT deployment and operation include:

- Dates at which the ice cover begins to form and breaks up
- Ice thickness and strength
- Surface ice coverage throughout the season, including border ice, dynamic ice, and open water reaches
- Frazil ice activity
- Frequency and timing of mid-winter thaws
- Locations and timing of ice jam formation and release.

4.1. River ice data sources

When evaluating the historical ice conditions on a river, local knowledge is an important resource. For example, local communities or conservation authorities may have valuable insights or records on ice patterns or past issues related to ice formation or movement. Planning activities should therefore include meaningful community engagement as an *integral part* of the process.

In areas where HkTs are deployed near existing infrastructure (such as municipal water intakes, bridges, or hydropower dams), ice may already be monitored, and data may be available from the facility operators.

Field observations at a given site can be gathered through ground-based observations, fixed cameras, drones, aircraft surveys, and in-river instruments. In some locations, portions of these data may already exist from previous monitoring efforts. Field data are used to validate satellite imagery analyses; using these methods together provides complementary perspectives that enhance the overall understanding of river ice processes. Satellite imagery has become an important part of ice surveys and is a rapidly advancing area. Satellite data archives can be used for the analysis of historical ice patterns, while current imagery is used for ice monitoring in near real time.

4.1.1. Field observations and monitoring

Field observations and measurements, whether collected before or during deployment, are important for understanding site-specific river ice conditions. Following are examples of the equipment, platforms, and instrumentation that are commonly used for that purpose.

- *Shore-based cameras* can capture time-lapse imagery of ice formation and movement. These systems are typically installed at bridges, dams, or other accessible sites and may be feasible only for major rivers with existing infrastructure. In a number of municipalities, cameras are already present to monitor traffic or weather.
- *Uncrewed aerial vehicles (drones)* offer flexible, high-resolution imaging and can cover sections of a river that are difficult to access from the shore (Figure 21, left). They are well suited for short-term surveys and for documenting spatial variability in ice thickness or roughness.

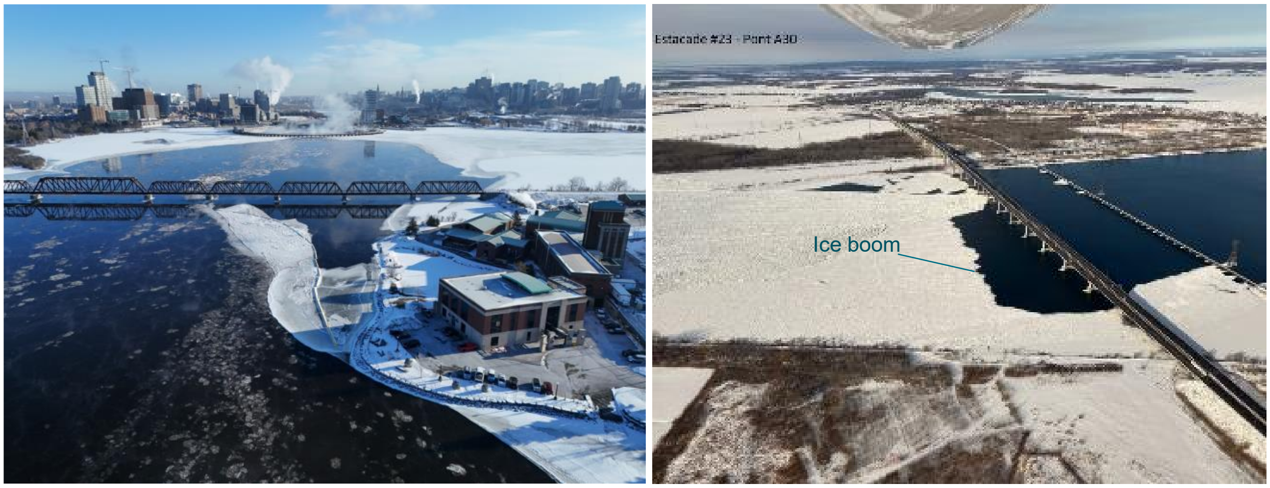

Figure 21: Examples of images from, at left, drone flight over the Ottawa River, between Gatineau and Ottawa (photo: NRC), and at right*, an aircraft survey of the St. Lawrence Seaway (photo: International Joint Commission).*

- *Aircraft-based observations* can cover larger areas than drones and are sometimes used by authorities during break-up or flood events (Figure 21, right). Aerial photography provides valuable context for interpreting satellite images and monitoring ice jam development.

- *In-river instruments,* such as acoustic devices, can directly measure ice thickness and movement. However, these are not widely used due to cost, deployment challenges, and the risk of damage during ice events. For some rivers, information on ice can be inferred from data collected under the hydrometric monitoring program of the WSC.

4.1.2. Satellite imagery

Recently, satellites equipped with *optical* and *radar* sensors have become essential tools for monitoring and classifying river ice (Table 1). To illustrate the difference, optical and radar images were obtained from an area along the St. Lawrence River, between Kingston and Montreal (Figure 22, Figure 23a).

Optical sensors, for the most part, passively capture images in the visible or near-visible portion of the electromagnetic spectrum. “Visible” imagery uses reflected sunlight to capture an image in the same way as a human eye or standard camera. These images are relatively easy to interpret. For example, water expanses in a river can be distinguished from frozen-up expanses (Figure 23b). Optical satellites can also capture energy reflected from the earth that is invisible to the human eye, including the ultraviolet and infrared wavelengths. Optical sensors have important limitations—*they cannot see through cloud cover,* and *many can only operate in daylight*.

Synthetic aperture radar (SAR) sensors, on the other hand, emit radar signals that penetrate clouds and return to the satellite (visible light is not used). This makes them ideal for *consistent, year-round monitoring*. The challenge with SAR imagery is that it does not allow us to easily distinguish ice from open water—this is shown in Figure 23c. Radar response depends on factors such as wavelength, polarization, and the angle at which the signal hits the surface. However, the determination of ice versus water *can* be done (with some degree of uncertainty) by a computer algorithm; an example of the results is shown in Figure 23d. The processing of SAR data into a useful image is not trivial, and for river ice applications there are some known issues, such as discerning open water from a wet ice surface (such as when it is covered with water puddles or water-saturated snow).

Optical and SAR imagery can complement each other. A limitation of both technologies is that the spatial resolution and revisit frequency (how often the satellite passes over the area of interest) vary based on the sensor and the area being observed. These factors affect how clearly features are captured and how often new images are available. In Canada, imagery is used operationally to monitor ice and manage flood risks on a number of rivers; an example is the Churchill River ice app.[16]

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[16] https://www.churchillriver.app/

Table 1: Summary of the salient characteristics for optical and SAR sensors.

Feature	**Satellite sensor**	
	Optical	**SAR**
Source of Signal	*Use the sun's radiation (visible, infrared, ultraviolet) reflected from the Earth's surface*	*Emit their own microwave radar signals and measure the reflections*
Day/Night Operation	*Most sensors only operate during daylight*	*Operate day and night*
Weather Conditions	*Affected by clouds, rain, and atmospheric conditions*	*Can penetrate clouds, rain, and smoke; less affected by weather*
Type of Image	*Photo-like images similar to what the human eye sees, or "false colour" images from wavelengths outside the visible spectrum*	*Processing is required to generate a useful image*
Examples	*Sentinel-2 (ESA), Landsat-8 and 9 (NASA/USGS), SPOT-6/7 (Airbus), PlanetScope (Planet Labs), WorldView series (Maxar)*	*Sentinel-1 (ESA), RADARSAT Constellation Mission (Canada), TerraSAR-X (Germany), SAOCOM (Argentina), ALOS-2 (Japan), ICEYE (Finland)*
Typical Spatial Resolution	*Varies from sub-meter (e.g., WorldView-3: 0.3 m) to 30 m (e.g., Landsat), or 10 m (Sentinel-2) for medium-resolution mapping*	*Typically 1–100 m, depending on mode and frequency band (e.g., TerraSAR-X: 1 m, Sentinel-1: 5–20 m, RADARSAT: 3–100 m)*
Revisit Time	*Usually 5–16 days depending on the satellite and orbit (e.g., Sentinel-2: 5 days, Landsat: 8 days).*	*Often 1–12 days, depending on satellite configuration and mode (e.g., Sentinel-1: 6 days, RADARSAT Constellation: daily coverage for Canada).*

Figure 22: Location of Figure 23(a)-(d) in eastern Canada.[17]

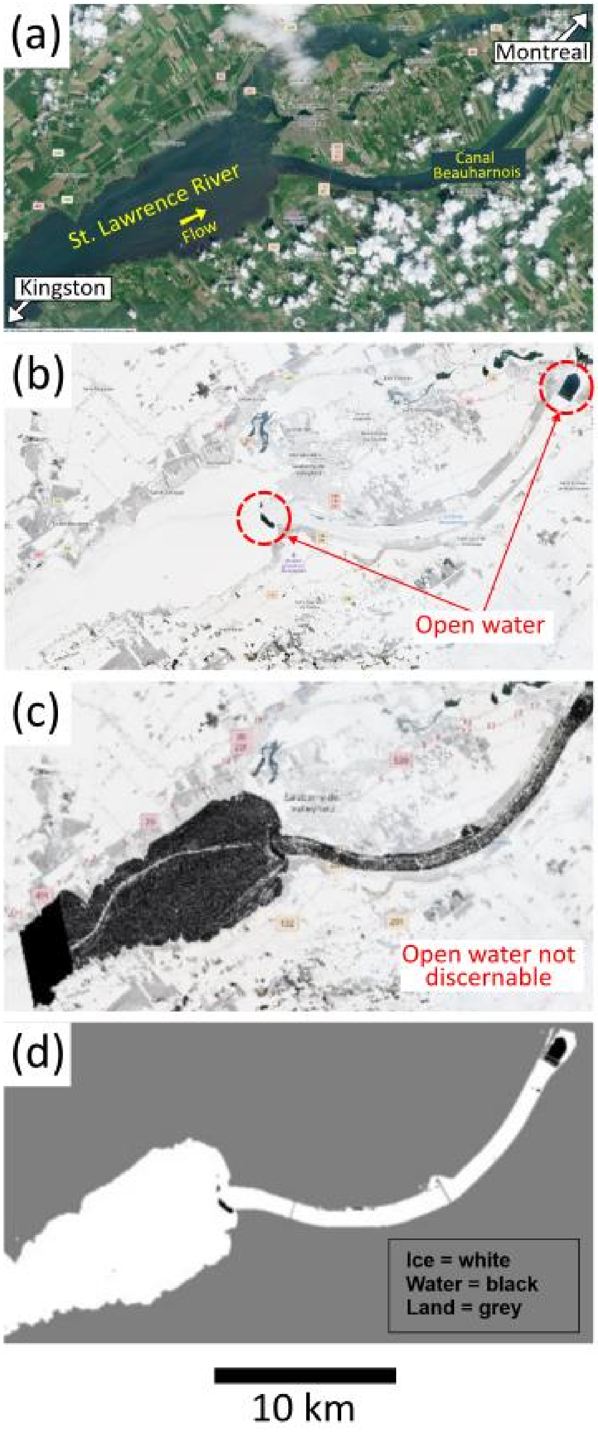

Figure 23: Satellite imagery over the St.Lawrence River, illustrating the difference between optical and SAR imagery and the outcome of an analysis of SAR imagery to interpret ice cover.
a) Optical image from the Sentinel-2 satellite, July 20, 2017.
b) Optical image from the same region and sensor, January 26, 2018.
c) SAR image from Sentinel-1, overlaid on the optical image, January 26, 2018. The white line is a navigational channel. The open water reaches are difficult to see.
d) Automated ice and water coverage analysis of the SAR image to identify open water reaches in (c), without which that distinction could not be made.

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[17] Map data: Data SIO, NOAA, U.S. Navy, NGA, GEGCO Landfast/Copernicus IBCAO U.S. Geological Survey.

4.2. River ice modeling

River ice modeling is conducted to anticipate the state of the ice cover ahead of time, typically in the short term (days to a few weeks) for operational purposes. The focus of most investigations is to understand and prepare for flooding events induced by ice jams. These models can also be useful for other purposes, such as for hydrokinetic turbine assessments, since they provide information on the effects of ice on river hydraulics.

Additionally, these models provide guidance on potential impacts of various climate change scenarios on ice and river parameters years to decades in the future.

River ice models belong to two broad families: *process-based* and *data-based*.

4.2.1. Process-based models

These methods consider the physics that control ice dynamics; they are known as *hydraulic models*. Examples of processes include water cooling, border ice formation, frazil and anchor ice generation, ice cover decay, and ice jam formation. Different methods address different requirements, with the main ones being water level rise or fall, the timing of ice break-ups, understanding the intricacies of ice cover development and flood analysis progression, and real-time flood forecasting. The models are one-dimensional (1D)—they simulate the processes along a vertical plane running along the river channel—or two-dimensional (2D)—they also capture what happens along the width of the channel. Examples of these models are CRISSP1D/2D, HEC-RAS (1D), River1D/2D, RivICE (1D), and VARY-ICE (1D).

Process-based models are computer programs (Fortran, C++, and others) that contain equations describing the various physical processes they attempt to reproduce. They follow a sequence of line-by-line instructions (analogous to a cook using a recipe when preparing a meal). These algorithms are highly interpretable, i.e., one can understand how the data are processed. This contrasts with data-based methods, in which the prediction method is fitted to existing data, and a computer program may even learn from data.

4.2.2. Data-based models

These methods use the data that are associated with the ice dynamics, including environmental (air temperature, wind, solar radiation, and many others) and hydraulic (water level, current velocity, etc.). Because these data can amount to a substantial volume, they are generally processed computationally.

This brings us to the concept of *artificial intelligence* (AI), a term coined in the 1950s that has evolved technologically to encompass powerful systems. *Machine learning* is a subset of AI. As with the process-based models, they are also computer programs, i.e., they consist of line-by-line instructions, but they reside inside ‘packages’ that instruct the computer to figure out what to do with these data. Because they typically lack transparency in the way they deliver information, some are referred to as black boxes.

Data-based models may be as simple as a *linear regression* or as complex as large machine-learning models. The AI tools that are better known among the public are the large language models (LLMs): GPT, Gemini, Claude, and Perplexity are examples. They are mostly used for general queries.

There are many thousands of other AI models across the industry and government sectors, designed to address specific tasks: speech recognition, fingerprint analysis, spam detection, medical imaging (X-rays, MRIs, CT scans), automatic translation, and autonomous driving, to name a few.

For river ice phenomena, the most popular AI tools are referred to as artificial neural networks, fuzzy logic systems, and genetic programming.

5. Implications for turbine operations

A given deployment setup may be well suited for open water conditions, but in freezing waters, that same setup must withstand the various actions of ice. A brief outlook of the implications is now presented.

Although this is not addressed in this document, *working in the cold* presents its own set of complex challenges that must be considered in all workplace safety procedures. Low temperatures can also negatively affect equipment performance and make tasks that are routine in warmer weather significantly more difficult.

5.1. Ice at the water surface

5.1.1. Effects on current velocity

Under a stable ice cover, the underside may be smooth and remain so for river lengths of hundreds of meters or kilometers. As seen before (Figure 6, Figure 17), friction along that surface reduces current velocity next to that interface, with an overall reduction in current velocity.

If the roughness of that underside increases, which is the case with a broken-up ice cover, there will be more resistance to flow (i.e., more friction along that interface).

Either way, the maximum current velocity in an ice-covered river is at a distance below the ice-water interface. An increase of turbulence below that interface, especially if it is rough, is also expected. An understanding of the current velocity under these conditions may therefore be required as part of a site evaluation.

5.1.2. Ice growth

The components of the installation (e.g., platform hull and floaters, mooring lines, cable, instrumentation) that are above the water surface can be growth sites for ice (Figure 24), possibly to a considerable thickness. This type of ice formation, known as *icing*, happens mainly for two reasons:

- Any solid surface exposed to the cold air draws heat out of the water more effectively than does the air itself. Metals are particularly effective heat conductors.
- The surface is subjected to water splashing (due to wind or wake) or deposition of atmospheric ice (for example, frost, freezing rain, or wet snow).

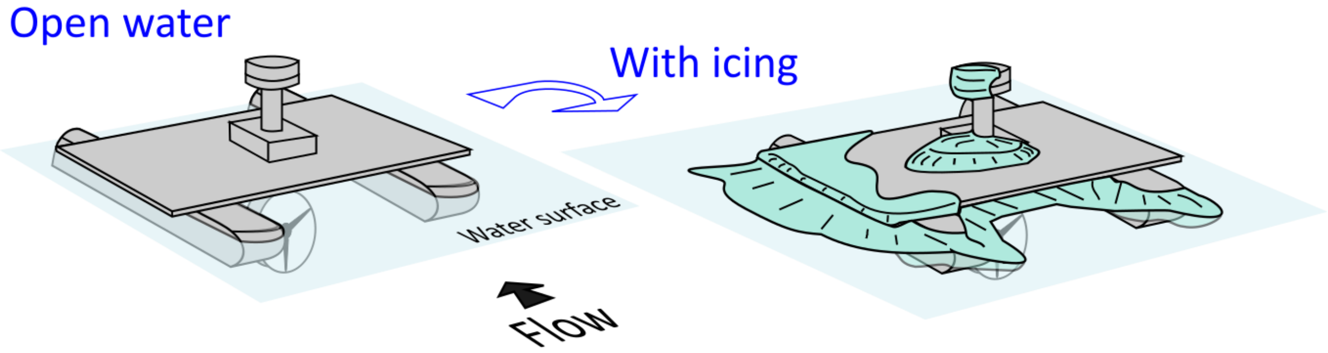

Figure 24: A conceptual platform-mounted turbine with ice growth at and above the water line.

5.1.1. Mechanical interaction

If the platform is in an open-water channel where there are many drifting ice floes or any large pieces of solid ice, that ice can accumulate against the platform and its mooring lines (Figure 25). It may even cause the platform to tip, as can woody debris and other floating objects. This may happen any time in the winter. Mooring lines and riverbed anchors must withstand the forces applied by that ice to the platform.

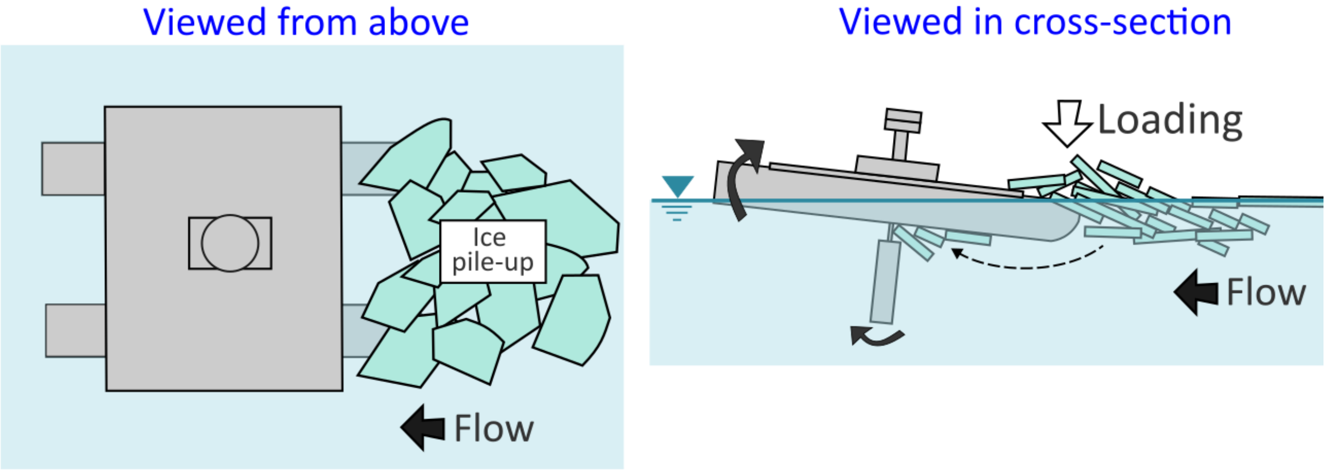

Figure 25: Mechanical interaction at the water surface between drifting ice and a platform-mounted turbine.

While the turbine is expected to remain at a safe depth below the platform, i.e., away from drifting ice, there might still be the occasional impact from ice fragments that are pulled down inside local turbulence patterns. A bottom-founded HkT would be relatively safe from drifting ice. *But no design should be expected to withstand the passage of a jave or of a significant volume of drifting ice*.

5.1.2. Implications for a cable crossing the shoreline

If the setup includes a cable that connects the turbine at the riverbed directly to installations on a shoreline (rather than a floating platform), shorefast ice could freeze around and incorporate that cable as it grows outward toward the center of the channel. This is undesirable because during break-up, depending on where fracturing occurs near the shoreline, that ice may be pulled out by the currents, drawing the cable with it. Alternatively, the cable could be exposed to the pulling action of drifting ice. Abrasion of the cable if it is laid loosely on the riverbed could also occur if it shifts back and forth due to current action.

Burying the cable offers a means to protect it from these eventualities (Figure 26). Also, the weight of a long cable should not be underestimated if it must be moved or replaced.

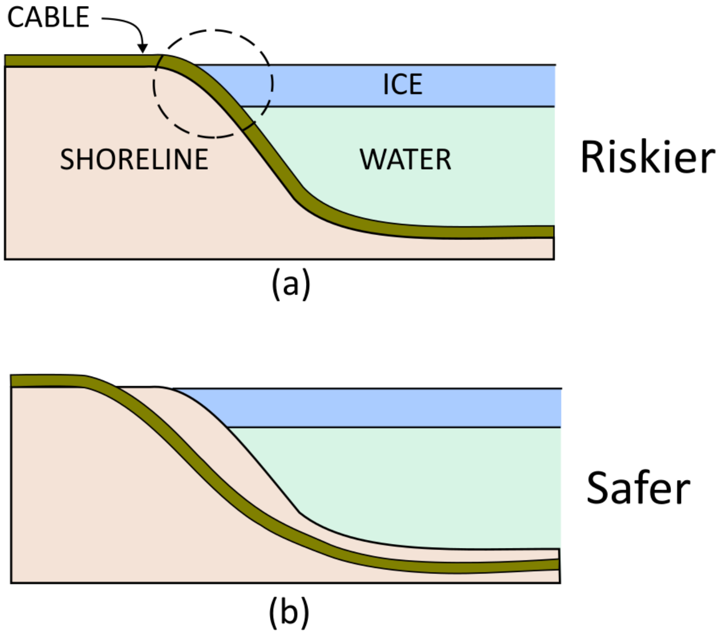

Figure 26: a) A cable connecting a turbine to on-shore equipment is exposed to shearing action from the ice and from rubbing against the riverbed; b) burying the cable would keep this from happening.

5.1.3. Ice break-up

As discussed earlier, ice break-up in the spring can be of two types:

- *Thermal break-up*: The ice cover melts in place, more or less as it does in a lake. Under these conditions, ice action on a turbine (or its platform, if it is used) will be minimal. But that type of break-up also tends to occur where current velocity is low and may not justify turbine deployment along that reach in the first place.
- *Dynamic break-up*: When the ice cover undergoes dynamic break-up, it may begin with fracture planes extending hundreds of meters along the river next to the shoreline. Fracturing across the river may also occur, leading to open water expanses and the establishment of a drifting broken ice cover.

The consequences of a dynamic break-up and the ensuing release of a thick ice accumulation can be severe, as it can physically impact a turbine downstream of them. Large tabular ice fragments may also be generated during break-up, which may exert a considerable load on a floating platform. Depending on the hydraulic conditions, these could also be pushed up the platform.

At some locations and in some years, there might be one or more mid-winter thaws, which can lead to corresponding break-up/freeze-up cycles.

5.2. Ice below the water surface

5.2.1. Underwater ice is difficult to monitor

There are very few studies that have specifically examined the development of frazil ice in a natural environment. The reason is that field observation is risky for both personnel and equipment and is challenging from an instrumentation perspective. Instrument effectiveness is hampered by the propensity of frazil ice to cling to instrument surfaces. The conditions can be harsh and unpredictable, and instruments may be lost or become inoperable. This is why most of the information available on frazil ice has been obtained from laboratory experiments.

5.2.2. The likelihood of frazil ice events

Frazil ice generation occurs as distinct events, under specific circumstances—namely, colder air (below -5°C), favorable wind conditions, and an open sky (no clouds), often overnight—as these favor the removal of heat from the water. In some winters, there may be many frazil events, while in others, there might be few or none.

Installing a hydrokinetic turbine in fast-flowing water is advantageous from an energy production perspective. Recent studies have shown that this water often corresponds to open-water reaches in winter. However, these reaches are *also* where frazil ice is generated, because even modest current velocities (0.5–1.0 m/s) can lead to frazil ice generation. Water turbulence can carry the supercooled water down to the riverbed, irrespective of channel depth, such that water depth may offer little or no protection against this type of ice.

In those cases:

- Where there is open water and immediately downstream from it, all underwater components will be exposed to frazil ice adhesion, the extent of which is difficult to predict. Frazil ice is known to adhere to many materials, even ABS plastic, Teflon, and other ice-phobic coatings.
- Extensive anchor ice formation along the riverbed, if it occurs in the turbine's immediate surroundings, can reduce water depth and change the flow patterns.

5.3. The time of year

The implications of ice on hydrokinetic turbines in a river will vary from the fall through the spring.

5.3.1. Fall

The fall months can be rainier than the summer months, in which case flow is expected to increase during that time. The initiation of an ice cover growing from the shorelines is an indication that the water has reached the freezing point—this is an important indicator: if ice-related data collection is planned, it should begin no later than this stage.

Cold spells during the fall are conducive to frazil ice generation. The turbine and its associated components may be exposed to its action, as described earlier, if they are located in those reaches or downstream of them. This is also the period of the year when freeze-up jams occur.

5.3.2. Winter

Low flow may be expected during that time of year, namely because of a reduction in liquid precipitation. The ice cover achieves its maximum extent, and river ice dynamics slow down. Some open water reaches remain in places; they are an indication of currents high enough to prevent freezing. Where there is a reduction in the channel's cross-sectional area, typically at shallower depths and with an increase in current velocity, rapids are observed.

At many locations, this seasonal pattern has become less consistent—there have been more frequent warm spells and liquid precipitation events. These can lead to mid-winter break-ups. Under those circumstances, a turbine would be expected to see fluctuations in current velocities in the course of the winter. It will also be exposed more often to ice action at and below the waterline.

5.3.3. Spring

The spring months could be the riskiest time of the year for a turbine, depending on where it is located. In river reaches where the current velocity is low, the ice is expected to quietly melt away, similar to what happens in a lake. However, the flow tends to be higher in the spring, as the snow cover and other ice formations melt. Where the velocity is higher, ice cover break-up scenarios are likely to be more dynamic and break-up jams may occur. This means higher water level fluctuations and the drifting of extensive amounts of ice fragments. Fracturing of the ice cover along the shorelines is also a common occurrence under these circumstances. Cables that cross the shorelines may be more exposed to that action.

5.4. Downstream of a hydroelectric dam

If planned, the deployment of hydrokinetic turbines in rivers that are regulated by hydroelectric dams must consider several factors:

- In the winter, operators of hydroelectric dams may manage flow to minimize flood risk upstream or downstream. For instance, early in winter, they may reduce flow through their facility to allow a full ice cover to form, then increase it again once it has formed.
- By reducing the discharge at the dam, the water level upstream of the dam will rise while the water level downstream will fall. Because the water discharge is controlled at the dam, there may be less variation than in a natural river. Communication with the dam operator would help in understanding and preparing for these fluctuations.
- There may be warmer water downstream of a dam, depending on the depth at which the intake is located. That is because the water temperature upstream is stratified with warmer water at greater depth. This phenomenon could mitigate frazil ice formation.
- Conversely, the presence of a dam itself also means open water may exist immediately downstream of it throughout the winter, with the generation of frazil ice due to exposure to cold air.
- Water release from the dam can lead to uplift of the ice cover and formation of shoreline cracks, followed by flooding along these fracture planes, which eventually freeze.

Overall, flow regulation can either simplify or complicate the development of river ice during a given winter. This added uncertainty compounds the natural variability of river ice processes, making their behavior more difficult to predict.

5.5. Beware of flooded shorelines

The deployment of a hydrokinetic turbine will likely take place in the open water season. Care should be taken when choosing the location of the ancillary equipment on the shoreline. The reason is that the waterline may move inland, beyond the original shoreline, during the winter due to backwater (or regulation by a dam). Equipment resting on the dry soil in the open water season would then get flooded, possibly without the operator being aware of it.

Figure 27a shows the extent of the dry floodplain one year. The assumption is that field equipment is located at a point (red dot lower left). In (b), the scenario at the same location is analogous, but in the winter. In (c), what could be interpreted as dry land at the point of interest is actually in water, and the ice seen in that picture is border ice.

(a) (b) (c)

Figure 27: Dauphin River, Manitoba, looking toward the SW (downstream): a) The light-colored area along the left side of the river is the dry floodplain. A reference point is indicated in red.[18]*; b) Frozen river—the boundary between the floodplain and the river can be deciphered.*[19] *c) The water level that year was high, such that the floodplain got inundated and got overlain with ice that extended outward from the sides (border ice).*[20]

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[18] June 16, 2024, © 2025 Google Earth
[19] February 24, 2025, © 2025 Google Earth
[20] November 21, 2025, photo courtesy of K.E. Lindenschmidt.

6. Mitigation measures

Deploying a hydrokinetic turbine in ice-affected rivers involves navigating two interrelated layers of complexity:

1) *River ice dynamics*: Although the general behavior of river ice is well understood, the real challenge lies in characterizing the specific conditions at the deployment site, particularly those occurring below the water surface.
2) *Turbine operations*: This encompasses all aspects of the system—maintenance, monitoring, instrumentation, data collection, power generation, and overall management.

The following considerations, based on the earlier sections of this report, take both dimensions into account.

6.1. General guidance

6.1.1. Assessing river ice

- *A reasonable understanding of river ice evolution at the target site* should be part of any site assessment method before turbine deployment.
- *Satellite imagery* is an important resource for that purpose—others include local knowledge from the communities as well as previous studies in the scientific literature.
- Because river ice evolution varies on a year-to-year basis, conducting that survey as far back as data availability allows would help understand historical patterns and, thus, what might be expected for a planned deployment.
- Relevant information would include dates of river freeze-up and break-up, total ice coverage, location of open water reaches, extent of shorefast ice, water level, and ice jam occurrence, timing, and location.
- An understanding of border ice is also desirable. If it gets thick enough, that ice would represent a convenient working platform. It can also modify flow patterns.
- *Be aware of floodplains*. Flat, low-lying areas along the river that are dry in the summer or fall may get inundated in the winter due to high flows and to backwater. It is preferable to avoid these areas to install instrumentation.
- The existence of open water reaches in a frozen river, as seen in satellite imagery, has been associated, not unexpectedly, with higher flows. While this is of interest from a power generation perspective, these reaches are also prone to underwater ice generation. That activity should, where feasible, be documented using site-specific instrumentation designed for that purpose.

6.1.2. Planning the operation

- *Be aware of ice jams that could form upstream of the HkT*, because these events can be associated with large amounts of ice drifting downstream when the jam breaks up. The vertical extent, above and below the water level, of that drifting ice can be on the order of a few meters.
- If the HkT is located at the upstream end of an open-water reach, where the water column has not yet supercooled, such a deployment could benefit from high flows *without* the impediment of frazil ice adhesion or clogging. This would correspond to zone A in Figure 9, provided the water is deep enough at that location to accommodate deployment.
- If the HkT is in zone G in Figure 9, the turbine could also be spared from the clogging action of active frazil ice below the water surface. However, *it could still be exposed to large volumes of slush ice (passive state)*. This can be problematic for a platform-mounted HkT but is generally less problematic for a bottom-founded unit.
- In frazil-prone areas, *detection or warning methods should be considered* an integral part of turbine operations—acoustic sensors, underwater cameras, and high-resolution thermometers (0.01°C) to monitor the presence of frazil ice in the water column and on the turbine components.
- Frazil ice is known to adhere to many materials, including ABS plastics, Teflon, and other ice-phobic coatings. However, the ice may be easier to dislodge when it sticks to these materials than on metallic surfaces. The latter are very effective heat conductors and should be avoided if possible.
- If it is feasible *to cover some components of the turbine* with a blanket, a plastic film, or some other type of shroud, this can protect them from frazil adhesion.

6.1.3. Ice booms

Ice booms are a standard part of many operations in icy rivers. In most cases, they are used to retain or divert drifting ice. For some HkT deployments, successful operation over the winter could depend on the judicious use of these booms. This method could be especially valuable for a reach that is good for power generation but where there is frazil ice (inside zones B-F in Figure 9).

Booms promote the formation of a stable ice cover, as illustrated schematically in Figure 28. Depending on flow conditions, this ice cover gradually extends upstream from the boom, eventually reaching beyond zones B to F shown in Figure 9. As a result, frazil ice production in these fast-flowing waters should diminish or cease altogether, since open-water areas in that region are no longer present.

Bottom-founded HkTs located downstream of the boom would benefit from the high flow in that reach without being hindered by underwater ice. This same principle can also support the deployment of platform-mounted HkTs. Figure 29 shows another scenario in which booms are used to keep drifting ice away from a platform-mounted HkT. The boom’s pontoons would need to be designed to minimize the amount of ice passing beneath them.

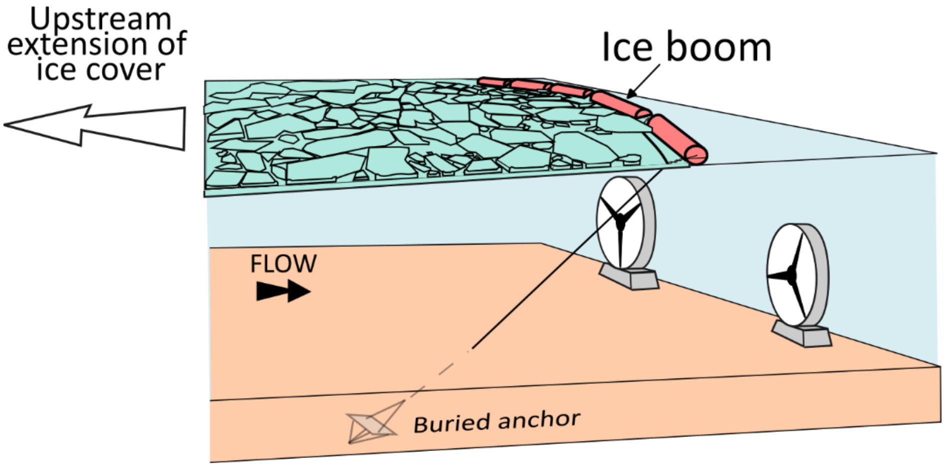

Figure 28: Ice booms are commonly used to promote the formation of an ice cover, thereby preventing the generation of frazil ice upstream.

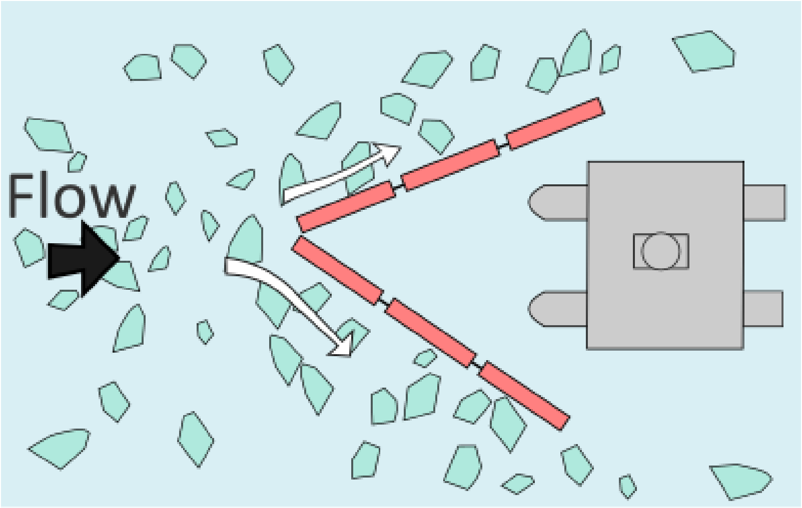

Figure 29: Ice booms divert driftng ice away from a platform-mounted turbine dowstream of them.

6.2. Installation-specific counter-measures

6.2.1. Platform-mounted turbines

- Platform-mounted HkTs are practical from a transportation and relocation standpoint, as well as for access to the turbine (from the platform).

- In reaches where the ice dynamics are expected to be less intense, a stable ice cover may grow from the platform outward, until a full ice cover has formed.
- This ice cover would allow foot access to the shoreline once the ice has reached a safe thickness.
- In this scenario, however, current velocity may or may not be satisfactory for power generation.
- Some effort will be required to remove the ice in the center if or when the turbine needs to be taken out of the water (maintenance, ice-clearing). A low voltage heating source could be considered on an ongoing basis to keep the shaft connecting the turbine to the generator above it from freezing at the water surface.
- A platform-mounted deployment is not recommended for reaches where the ice dynamics are more intense, because it will be exposed to mechanical interaction that is difficult to anticipate and can be extreme. Also, the layout of the mooring lines and power cables would need to be designed for the potential loads and action from drifting ice and ice break-up.

6.2.2. Bottom-founded turbines

- A bottom-founded HkT could be considered in reaches where flow is low enough to favour the development of a full ice cover. Once that cover has achieved a safe thickness, access to the turbine can be done by cutting a hole through the ice using a chainsaw.
- For more intense river dynamics, which is also where higher current velocities are expected, a bottom-founded HkT is likely the option of choice, bearing in mind it can still be exposed to drifting ice.
- If feasible, avoid river reaches where you suspect (or have demonstrated) that frazil ice occurs. This would simplify the winter operations considerably.
- By default, assume frazil ice will extend down to the riverbed, unless shown otherwise in the site assessment phase.
- Consider hydrophobic coatings to prevent or reduce frazil ice adhesion, but do not count on their effectiveness.

6.2.3. Cable for energy transmission

- Burial at the shoreline crossing will afford protection against ice action, and along the riverbed, to help prevent excessive abrasion. Armored sheathing could also be considered.

6.2.4. Instrumentation

- If frazil ice formation is expected, a shroud around instruments located below the waterline could reduce ice adhesion—this would have to be tested. Similar protection can also be applied to instruments above the waterline to guard against atmospheric ice.

- All instruments should be sufficiently robust to withstand the environmental conditions, as indicated in their specifications.
- Recommended instruments include high-resolution thermometers for water temperature (+/- 0.01°C), lidar for monitoring ice accumulation, acoustic sensors (such as ADCP and ADV) and an underwater camera to observe frazil ice activity. When designing the instrumentation scheme, it is useful to distinguish between detection and quantification objectives, as each may be associated with a threshold-based alarm system. Tension sensors on mooring lines and ice booms may also be considered.
- An HkT deployment offers a valuable opportunity to gather data on environmental and hydraulic conditions, analyze how these factors influence river ice dynamics, support informed decision-making during deployment, and record observations to guide future operations. Including this data collection as a core element of every deployment plan is strongly recommended.

6.3. An ice cover as a working platform

6.3.1. Principle

If an HkT is meant to operate below a complete ice cover, as opposed to within an open-water reach (or where conditions are dynamic), and assuming the flow conditions are adequate for energy production, this can minimize surface ice action. Under these circumstances, a floating platform frozen in that cover is likely to remain stable throughout the winter. Surface ice in rivers can achieve thicknesses exceeding one meter, depending on air temperatures, snow cover, and other factors. As such, it can sustain large vertical loads and be used as a working surface, for deployment and maintenance (Figure 30).

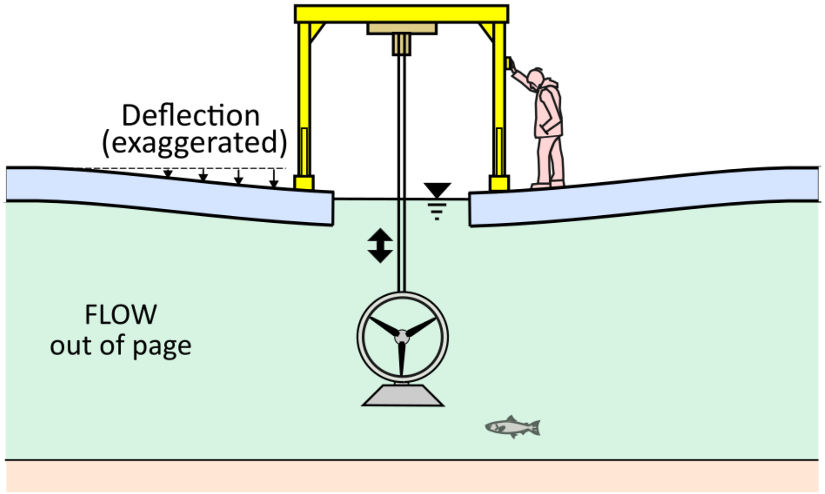

Figure 30: Hypothetical deployment of a HkT from the surface of an ice cover.

6.3.2. Ice loading

The challenge with using an ice cover to work on, also faced by winter/ice road operators, is to know when it is safe enough to step on it, so as to measure its thickness.[21] This can be done with a standard ice auger. A safety plan must be in place for this type of work.

When an ice cover is pushed downward as is the case when it supports a vertical load—e.g., the equipment required to lower or raise the HkT—, it slowly sinks under the load. The longer the load remains, the higher the deflection, which in turn depends on ice thickness and amount of load. It is imperative that the water never makes its way to the ice surface. The best way to know how much time this represents is to monitor freeboard through a hole in the ice during the operation. If the water in that hole reaches the ice surface, the load should be removed.

The load-bearing capacity of an ice cover can be estimated using a well-known equation commonly referred to as the 'Gold Formula'.[22] This method is widely accepted and referenced in winter road construction manuals:

$$P = Ah^2$$

In that formula, *P* is the vertical load in kilograms, *h* is the ice thickness in centimeters and *A* is a coefficient. This relationship is shown in Figure 31. The value for A based on operator experience, and is prescribed in most manuals. The quality of the ice cover is also important—transparent ice is stronger than layered, porous ice.

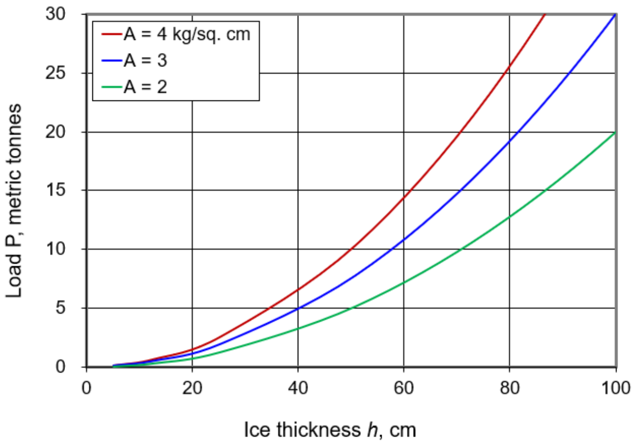

Figure 31: Relationship between the vertical load P in metric tonnes as a function of the ice thickness h in centimeter, for different coefficients.

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[21] It is a chicken-and-egg dilemma—one needs to know the ice thickness before stepping on it, but one usually have to step on it to find out. Operators of winter roads know their routes well and use experience to make those calls.

[22] Lorne Gold was a researcher at the NRC.

7. Conclusion

This document is intended to provide high-level guidance for hydrokinetic turbines in rivers that experience seasonal ice cover. Deployments of these devices under such conditions remain rare and sparsely documented, and the available experience for informing best practices remains limited. The existing literature has been reviewed and synthesized into the material presented here, and, based on our current understanding of river ice dynamics, potential mitigation measures are discussed.

Two main challenges are noteworthy:

1. ***Drifting ice**, particularly following ice break-up*. The first step is to gain a reasonable understanding, through historical observations, of river ice behavior at the target site, as well as upstream and downstream of it. The judicious use of booms could then be considered, to allow drifting ice to collect at a pre-selected location as a a preventative measure. If the operator observes a jam has developed upstream of that location during the winter, a plan should be developed to remove the HkT from the river at short notice. No measures can ensure its protection against major ice jam events.

2. ***Frazil ice** and its tendency to adhere to underwater components*. Subsurface processes involving frazil ice are poorly documented in the scientific literature, largely because underwater ice formation is difficult to observe. If a HkT must be installed in a frazil-prone reach, one option is to select a site, within that reach, where frazil has not yet begun to form (zone A in Figure 9). Another approach is to use ice booms to promote the formation of a stable surface ice cover that extends over frazil-producing areas, which is a common ice-engineering practice.

Key to a successful operation is a sound understanding of river ice behaviour, bearing in mind the considerations outlined in this report. Because river ice behaviour is unique to each river reach, implementing any strategy will inevitably involve some degree of trial and error, along with appropriate adjustments and a certain measure of creativity.

To understand river ice dynamics at a prospective deployment site, there are no better alternatives than studying that site through an appropriate instrumentation and observation program over several winters before deployment, including a pilot phase. This study may be complemented by analysis of historical, archived satellite imagery.

8. Recommended sources

This section contains a listing of selected publications that are relevant to HkT deployment in freezing waters. Most sources are specialized, i.e., they are written with an expert audience in mind. The enclosed references in these sources may also be of interest. To facilitate access, an Internet link address is provided when available.

8.1. River ice

Beltaos, S., 2013. **River ice formation**. Proceedings of the 17th Workshop of the Committee on River Ice Processes and the Environment. Committee on River Ice Processes and the Environment (CRIPE), Canadian Geophysical Union, Hydrology Section, Edmonton, pp. 553. ISBN: 978-0-9920022-0-6- *This monograph, which contains thirteen individually authored chapters, is one of the most comprehensive sources of information on river ice. It contains 13 chapters dealing with most aspects, such as the formation of the various river ice types and processes.*

Lindenschmidt, K.-E., 2024. **River ice processes and ice flood forecasting - A guide for practitioners and students.** Springer Nature, Cham, Switzerland, 483 pp. ISBN-13: 978-3031490873. *This is a textbook that introduces the readership to fundamental concepts of river ice dynamics. It then describes RivICE, one of several hydraulic models used by engineers to investigate floods induced by river ice.*

Jasek, M. and Beltaos, S., 2008. **Ice-jam release: Javes, ice runs and breaking fronts.** In: S. Beltaos (Editor), River ice breakup. Water Resources Publications, Highland Ranch, CO, pp. 247–303. ISBN 978-1-887201-50-6. *A review of the dynamic aspects of ice break-ups, focusing on jave development and how wave behavior interacts with the ice cover.*

Barrette, P.D., 2021. **Understanding frazil ice: The contribution of laboratory studies**. Cold Regions Science and Technology, 189: 103334. *A comprehensive review of laboratory set-ups, methods and outcome of over 80 test programs over the past few decades that focused on frazil ice development. While helpful for modeling purposes, the outcome is still of limited usefulness in informing planning and deployments on frazil ice activity.* https://doi.org/10.1016/j.coldregions.2021.103334

Gharari, S., Whitfield, P.H., Pietroniro, A., Freer, J., Liu, H., and Clark, M.P., 2024. **Exploring the provenance of information across Canadian hydrometric stations: implications for discharge estimation and uncertainty quantification**. Hydrol. Earth Syst. Sci., 28(19): 4383-4405. *This document describes the procedures used to interpret water levels collected at hydrometric stations so they can provide reasonable estimates of discharge when ice is present in the river.* https://doi.org/10.5194/hess-28-4383-2024

Barrette, P.D., Khan, A.A., and Lindenschmidt, K.-E., 2024. **A glance at 25 process-based hydraulic models for river ice**. Proceedings of the 27th International Symposium on

Ice. International Association for Hydro-Environment Engineering and Research (IAHR), Gdańsk, Poland. *This is a brief review of hydraulic models, including the scenarios they can model, their applications, and the processes they can simulate*. https://www.iahr.org/library/infor?pid=30349

Salimi, A., Ghobrial, T. and Bonakdari, H., 2024. **A comprehensive review of AI-based methods used for forecasting ice jam floods occurrence, severity, timing, and location**. Cold Regions Science and Technology, 227: 104305. *This paper summarizes the prediction models based on AI that have been devised to anticipate ice jams.* https://doi.org/10.1016/j.coldregions.2024.104305

Abdelnour, R., Abdelnour, E. and Comfort, G., 2008. **The design, construction, and observation of permanently installed safety booms in ice covered waters**. Proceedings of the 19th International Symposium on Ice. Association of Hydraulic Engineering and Research (IAHR), Ann Arbor. *This paper describes the design, implementation and performance of a boom. It factors in bathymetry, hydraulics, various forcings, cabling and anchors*. https://www.iahr.org/library/infor?pid=27584

Morse, B., Francoeur, J., Delcourt, H. and Leclerc, M., 2006. **Ice control structures using piers, booms and nets**. Cold Regions Science and Technology, 45(2): 59–75. *This source expands on the concept of a boom, with a discussion of several types of ice-retaining structures.* https://doi.org/10.1016/j.coldregions.2006.02.003

Daly, S.F. and Barrette, P.D., 2023. **Prevention of water intake blockage by ice during supercooling events.** Journal of Cold Regions Engineering. *This is an overview of methods and approaches to mitigate the action of active frazil and its propensity to clog water intakes and related components of shoreline facilities (potable water plants, hydro dams)*. https://doi.org/10.1061/JCRGEI.CRENG-676

Burrell, B. C., Beltaos, S., & Turcotte, B. (2023). ***Effects of climate change on river-ice processes and ice jams***. International Journal of River Basin Management, 21(3), 421–441. *This is a review of the effects of a changing climate on river ice properties and processes.* https://doi.org/10.1080/15715124.2021.2007936

Barrette, P.D. and Lindenschmidt, K.-E., 2023. ***Frazil ice events: Assessing what to expect in the future***. Hydrology Research, 54(6). *This review general concepts and models reported in several studies relevant to that question. An increase in the frequency of MWBs due to warm spells is expected, such that, in addition to the already existing challenge of anticipating year-to-year variability, climate models would have to capture month-to-month variability.* https://doi.org/10.2166/nh.2023.008

Government of the NWT, 2015. ***Guidelines for safe ice construction***. Department of Transportation, Yellowknife, Canada, 44 p.*This document provides information on the construction of ice crossings along winter roads. This includes ice behavior under loading, work hazards and the determination of what a safe ice thickness is for the expected load.* https://www.inf.gov.nt.ca/sites/inf/files/resources/0016-001_norex_ice_road_constr._web.pdf

Gold, L.W., 1971. **Use of ice covers for transportation**. Canadian Geotechnical Journal, 8: 170–181. *This paper explains the origin of the Gold formula, used to estimate the bearing capacity of an ice cover*. https://doi.org/10.1139/t71-018

8.1. Remote sensing for site identification

Zakharov, I., Puestow, T., Khan, A.A., Briggs, R. and Barrette, P., 2024. **Review of river ice observation and data analysis technologies.** Hydrology 11(126). *This is a comprehensive review of observations methods targeting river ice, including satellite, airborne and ground-based sensors*. https://doi.org/10.3390/hydrology11080126

Zhu, K., Ghobrial, T. and Loewen, M., 2021. ***Exploration of Google Earth Engine for monitoring river ice***. Proceedings of the 21st Workshop on the Hydraulics of Ice Covered Rivers. CGU HS Committee on River Ice Processes and the Environment (CRIPE), Saskatoon, Canada. *Google Earth Pro is a tool that is freely available desktop application that gives the user access to advanced GIS tools and data importing. This paper describes how it can be adapted to provide information on river ice.* https://cripe.ca/docs/zhu-et-al-2021-pdf?wpdmdl=1449&refresh=69bd7a87d535b1774025351

Bhattacharjee, K., Sushama, L., and Cousineau, J., 2025. **Hydrokinetic resource assessment for the Canadian Arctic for turbine-based power generation**. Journal of Water and Climate Change, 16(4): 1238-1259. *Assessment of hydrokinetic potential in Northern Canada within the next 20 years based on remote sensing data and assuming a high emission scenario. https://doi.org/10.2166/wcc.2025.353*

d'Auteuil, S., Birjandi, A., Bibeau, E., Jordan, S., Soviak, J. and Friesen, D., 2019. **Riverine hydrokinetic resource assessment using low cost winter imagery**. Renewable and Sustainable Energy Reviews, 105: 293-300. *In this paper, satellite imagery was used to locate open water surfaces in rivers during winter, which are tied to higher current velocities. https://doi.org/10.1016/j.rser.2019.01.057*

Geldsetzer, T., van der Sanden, J.J., Ranjitkar, G., Huang, J., Perry, B. and Bibeau, E., 2025. **An approach for Canadian river hydrokinetic resource assessment with synthetic aperture radar satellite images**. International Journal of Applied Earth Observation and Geoinformation, 140. *Novel approach that uses Synthetic Aperture Radar (SAR) satellite imagery to identify river sections with persistent, stable, high-flow water.* https://doi.org/10.1016/j.jag.2025.104573

Sudom, D., MacMillan, C., Soleymani, A., Qu, Y., and Scott, K. A., 2025. ***Characterization of ice coverage in the St. Lawrence River using satellite imagery and an operational ice status index***. Proceedings of the 23rd Workshop on the Hydraulics of Ice Covered Rivers. CGU HS Committee on River Ice Processes and the Environment (CRIPE), St. John's, Canada. *This is an example of how satellite imagery can be processed in a way to better convey information on ice conditions along a given river.* https://nrc-publications.canada.ca/eng/view/object/?id=b00ea7e2-d0a3-46d8-b242-bfc5b3c57fdd

8.2. Hydrokinetic turbines in freezing rivers

Bibeau, E., Kassam, S., Woods, J., Molinski, T., and Bear, C., 2009. **Operating a 5-kW grid-connected hydrokinetic turbine in a** river **in cold climates**. Renewable Ocean Energy, 4. *Testing of a Darrieus-type HkT in Manitoba from a floating platform and*

related challenges, which included icing at the water surface and adverse action of passive frazil ice. A discussion on improving the blade arm is also provided.

Bibeau, E., Kassam, S., Woods, J., Gole, A., Mosallat, F., Vauthier, P. and Molinski, T., 2011. **Design of in-situ river kinetic turbines test facility in cold weather.** Proceedings of the Canadian Engineering Education Association (CEEA). *Demonstration over one year of a 60 kW turbine from a floating platform, including the anchoring system, the platform and the use of a fish louver.*

Johnson, J.B. and Pride, D.J., 2010. **River, tidal, and ocean current hydrokinetic energy technologies: Status and future opportunities in Alaska**. Alaska Center for Energy and Power, 28 pp. *A review of Alaska's resources, turbine types and deployments, as well as of various projects with hydrokinetic turbines and their outcome.*

Kasper, J.L., Duvoy, P. and Konefal, N., 2017. **Kvichak River frazil ice study final report**, Fairbanks, AK., 58 pp. *Deployment of a real-time telemetry system and shore-based remote power generation, designed to monitor current velocity and frazil ice generation*.

Woods, J., 2017. **Hydrokinetic turbine systems for remote river applications in cold climates**, Ph. D. Thesis, University of Manitoba, Winnipeg, 221 pp. *This thesis reports on the design, deployment and operation of an experimental HkT for cold regions, conducted in a river from a floating platform. It is a comprehensive account of many aspects related to this equipment: assessment of the site and environmental factors, anchoring, electrical cabling and controls, and turbine performance.* https://mspace.lib.umanitoba.ca/items/077ceb0b-c9a1-4b1c-9b2b-8294027afcc3

8.3. Turbine deployment in Igiugig, Alaska

Kasper, J.L., Duvoy, P. and Konefal, N., 2017. **Kvichak River frazil ice study final report**, Fairbanks, AK., 58 pp. *This is a description of a study done along the river reach next to Igiugig, with the purpose of understanding frazil ice development*.

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