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[Frontispiece: An opening in the Yukon River prevented the Dawson City ice bridge from being built in the winter of 2016-2017 (Jassin Godard/CBC)[1]].

[1] https://www.cbc.ca/news/canada/north/ice-road-bridge-dawson-city-yukon-river-1.3980576?cmp=rss

SUMMARY

The Dawson City ice bridge is located at the George Black Ferry crossing of the Yukon River – the ice bridge links the district of West Dawson to the main part of Dawson City east of the river (acting as a replacement to the ferry during the winter). The ice bridge is 400 m in length and its width is typically about 60 m. The bridge has been operated since the 1960's by the Yukon Government (YG). It accommodates light traffic across the river as well as heavy-haul equipment that services the mining industry. There is no overlap between the ice bridge and ferry operations, i.e. there are time windows during which river crossing is not available. The ice bridge opening dates vary considerably, from early November to early February. Bridge closure usually occurs between the end of March and mid- to end of April. A gradual decrease of the yearly operational lifespan has been reported, i.e. 1.75 days/year since 1995.

The Yukon Government communicated to the National Research Council (NRC) that in the last few years, there was an open water lead in the center of the river. This occurred in the winters of 2013-14, 2016-17 and 2017-18. In the winter of 2013-2014, an alternative route for the bridge was necessary because the ice conditions did not allow it to be built at the usual location. In the two most recent cases, the open water channel prevented the construction of the ice bridge, thereby cutting off the link between West Dawson and Dawson City. The Yukon Government engaged the NRC to recommend areas of research ('investigation avenues') to determine why the river has not been freezing completely.

Consultation with the local community in Dawson City on the ice bridge operation was organized by YG. It took the form of an Open House, which was held on August 22nd 2018. The purpose of this event was to gather feedback from the community – comments, questions, concerns – on the ice bridge operation. The discussions centered around eight themes: 1) General comments, 2) The river bottom, 3) Ice jams and other ice-related issues, 4) How 'to bridge the gap' – Booms, 5) Alternate route, 6) Operational aspects, 7) Safety, and 8) Moving forward.

Various environmental factors could prevent freeze-up. A brief overview of river ice dynamics is provided, pointing out the importance of flow velocity and air temperature amongst other factors, in determining freeze-up conditions. When drifting ice pieces are pushed against each other, they begin to overlap, and may occasionally develop into fields of ice blocks or hummocky ice that could induce what is known as 'freeze-up ice jams'. Pieces of ice which could contribute to ice bridge initiation are prevented by the jam from drifting further downstream.

The sediment deposit located at the confluence of the Klondike River and the Yukon River near Dawson is characteristic of a channel junction bar and many mid-channel bars can be observed on the Yukon River upstream of Dawson. Such an evolving riverbed is conceivable, and could tentatively be linked with a possible increase in current speed at the George Black Ferry crossing.

Climate change is a complex phenomenon – it could affect the Yukon River's freeze-up behavior in several ways. A number of investigation avenues may be envisaged, namely a physically-based regional climate model. Also, it would be helpful in understanding if a change in low flow regimes is a causative factor. During low flow periods, rivers draw from groundwater. If winter low flows are increasing then that will be an indication that warmer water released from soil stores is a contributing factor. The influence of human activity, including operations at the Dawson City wastewater treatment plant (WWTP), may also play a role.

The Dawson City ice bridge has historically been a relatively successful operation. But these new circumstances – i.e. the existence of an open water lead – call for new or novel procedures and techniques. The conventional bridge building methods are no longer sufficient. New investigation avenues are therefore proposed, including: 1) Extending a line across the river channel, to act as a tow line to safely mobilize equipment across the channel; 2) recourse to an ice boom; 3) enhancing freeze-up with spray ice; 4) addressing the sand bar; 5) addressing the influence of Dawson City's WWTP.

These might be considered in the short term, possibly for the winter of 2018-2019. Longer term strategies could include: 1) the design and implementation of a system to ensure this bridge will operate effectively and safely; 2) to examine all relevant databases that have not yet been collected and conduct analyses on those that exist and are available; and 3) to devise a field instrumentation scheme that would target data gaps and provide the required information to help optimize adaptation measures and complement the already existing databases.

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1 Introduction – Background on NRC involvement

The earliest communication between NRC and YG regarding the ice bridges in the Yukon Territory occurred in early 2015. NRC was then gathering information on winter roads in Canada, to assess the status of that infrastructure and identify outstanding issues impeding these operations. At that time (winter 2014-2015), the Dawson City operation was performing satisfactorily.

From January to May 2018, several discussions took place between the Yukon Government (YG) and the National Research Council (NRC) about an issue YG currently has with their Dawson City ice bridge. In the last few years, open water in the Yukon River have prevented bridge construction. This occurred in the winters of 2013-14, 2016-17 and 2017-18. In the two most recent cases, the open water channel in the center of the river prevented the construction of an ice bridge, thereby cutting off the link between a small community of about 150-200, herein referred to as 'West Dawson', located on the west side of the river and the main section of Dawson City located on the east side of the river. In the winter of 2013-2014, an alternative route for the bridge was necessary, because the ice conditions did not allow it to be built at the usual location [2, 3].

In May 2018, YG invited NRC to investigate why the river is not freezing completely. In the discussions that were held at that time, YG has suggested three possible reasons explaining why the river remains open throughout the winter:

1) warm effluent from a wastewater treatment plant (WWTP) outlet;
2) the existence of a sand bar upstream of the bridge; and
3) an ice jam upstream of the bridge.

Moreover, it was determined that the impact of climate change on the future operation of the ice bridge should also be assessed. YG also asked if NRC could provide some innovative solutions in bridge design, based on an informed understanding of river dynamics.

NRC and YG agreed on a preliminary desktop phase to address these concerns, possibly with an extension afterward into a follow-up phase if/as need be. This report presents the outcome of the preliminary desktop phase, conducted in the summer of 2018. It also includes examples of what could be considered in the follow-up extension later in 2018. This report summarizes NRC's provisional stance on the Dawson City ice bridge, based on limited information that could be gathered during the preliminary phase. None of its content should be taken as formal endorsement for any particular course of action without further investigation and engagement with all stakeholders.

1.1 Objectives of this Desktop Study

The objectives of this desktop study are two-fold:

1) To conduct a preliminary desktop assessment of the factors possibly responsible for the river not freezing completely (Section 4).
2) To offer preliminary guidance aimed at making the Dawson City ice bridge operational this winter at the ferry crossing, assuming the river will not freeze completely (Section 5).

1.2 Methodology

In order to assist YG, NRC needed to first acquire a reasonable understanding of the issue. Therefore, in this preliminary phase, the authors brought together currently available information, identified the data that are (or are not) available, and collected historical information on bridge design/construction (including information on the spray ice operation in the winter of 2017-2018). This work will build on that already done elsewhere [1].

To address this study's two objectives, two distinct streams were undertaken in parallel:

1) NRC completed a preliminary assessment of the Yukon River's environmental conditions and relevant anthropogenic effects at Dawson City, to attempt to understand, at least on qualitative grounds and in consultation with stakeholders (e.g. YG, TMB staff, engineering consultants, City of Dawson, local communities), why the Yukon River remained open in the recent past and may do so again in the future.
2) NRC presented tentative options to prepare for the challenge of building the ice bridge next winter, assuming incomplete freezing of the river. This was done in consultation with stakeholders, including a three-hour community Open House held at the Downtown Hotel in Dawson City on August 22nd 2018.

The outcome of these two streams are presented in this report (Section 4 and Section 5, respectively). On that basis, recommendations to YG on a way forward are made, including some suggestions in terms of bridge design, planning and construction (Section 6). The assumption will be that, based on recent winters, the Yukon River will not freeze completely next winter (2018-2019) and special measures will likely have to be devised so as to make this operation work. But prior to this, an overview of the Dawson City ice bridge (Section 2) and a brief account of the challenges faced by that bridge (Section 3) are provided.

2 The Dawson City ice bridge

The purpose of this section is to present some background information on the Dawson City ice bridge. The most recent documents on the subject are consultants reports [1-3], one of which includes references to a number of earlier studies [1]. The information in this section was drawn from those reports.

2.1 Ice bridge description

The Dawson City ice bridge is located at the George Black Ferry crossing of the Yukon River – the bridge links West Dawson to the main part of the community east of the river (acting as a replacement to the ferry during the winter). The ice bridge is 400 m in length and its width is about 60 m.

2.2 Ice bridge construction

Once the river has frozen entirely to the required thickness, the snow on the ice cover is cleared with ATVs equipped with a front plow[2]. Snowmobiles may at times be used either to first flatten the ice cover when it is too rough or pack the snow to improve trafficability for the ATVs. The ice is allowed to thicken further until a point where light vehicles can start using it. With an increase in ice cover thickness, heavier vehicles and equipment can be hauled onto the ice to flood it so as to keep increasing its thickness. YG reportedly spends about $80,000 each winter to build and maintain the crossing[3].

Various provincial and territorial guidelines provide information on bearing capacity [4] – most are based a formula proposed L. Gold's [5, 6], based on his research at the National Research Council in the 1950's and 1960's. The guidelines recommended by [1] are those of the Government of the NWT [7]. Vehicle weight guidelines are provided in [1, 2]. For instance, an ice thickness of 0.46 m is recommended for vehicle weights up to 10,000 kg; a thickness of 2.18 m is required for loads up to 70,000 kg. For very heavy loads, stress analyses are performed by specialized consultants to determine minimum ice thickness.

2.3 Ice bridge usage

The bridge has been operated since the 1960's by the Yukon Government (YG). It accommodates light traffic across the river as well as heavy-haul equipment that services the mining industry across the river in the Yukon. West Dawson is also "where the Top of the World Highway begins, linking the Klondike Highway with the Alaska Highway, a popular tourist route in the summer"[4]. It is used extensively by snowmobilers.

There is no overlap in time between ice bridge and ferry services. In fact, there are time windows in between these services when neither the ferry nor the ice bridge is in operation, such that river crossing is not available during that transition. The shortest service closures on record (since 1995) in the Fall were 18 days (2005-2006), and 26 days (1999-2000) in the Spring. The longest service closures in the Fall, and 116 days and 99 days in the Spring [1, Table 2.3]. The shortest and longest operational lifespan in any given year are 47 days (2005-2006) and 158 days (2008-2009).

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[2] Snow acts as an insulator. The purpose of snow clearing is to increase heat exchange between the ice and the cold air so as to accelerate ice growth.
[3] http://www.cbc.ca/news/canada/north/yukon-river-ice-bridge-spray-suspended-1.4500692
[4] http://www.cbc.ca/news/canada/north/ice-road-bridge-dawson-city-yukon-river-1.3980576?cmp=rss

Bridge opening dates vary considerably, from early November to early February. Bridge closure is usually between end of March to mid- to end of April. A gradual decrease of the yearly operational lifespan is reported, i.e. 1.75 days/year since 1995 [1](Figure 1).

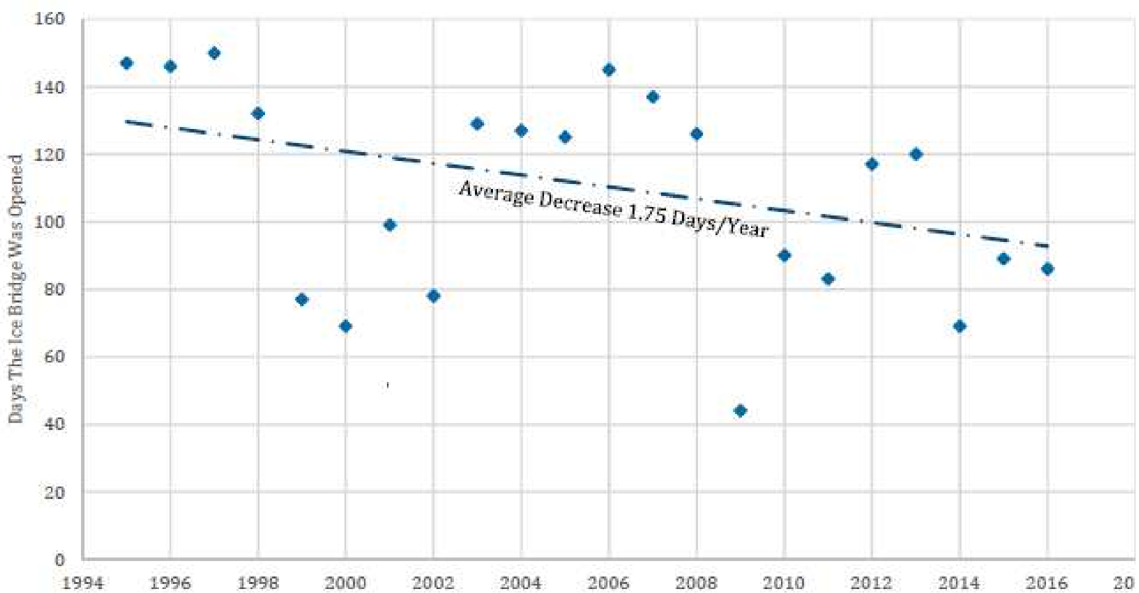

Figure 1: Number of days the ice bridge was open from 1995 to 2016 (from [1]).

3 Bridge unable to enter into service

As stated earlier, bridge operations did not run in the winters of 2016-2017 and 2017-2018. In the winter of 2013-2014, an alternative routing was required because the river remained open at the ferry crossing, which is the usual bridge location. Figure 2 is an aerial view of the Yukon River in April 9, 2018 (see also Figure 3). It shows full ice coverage, except for a thin sliver of open water condition at the bridge location that extended downstream from the ferry crossing.

Figure 3 to Figure 9 are examples from a number of previous years.

A number of possibilities were raised by YG and stakeholders as to why the river did not freeze across its full width in these years: a change in flow patterns and current velocity, debris accumulation upstream, an ice jam further upstream, a new sand bar, the effluent of a nearby wastewater treatment plant and a change in climate. The possible impacts of these factors will be discussed in Section 4.

Figure 2: Satellite image of the Yukon River ice cover at Dawson City, April 9 2018 (ESA Sentinel-2).[5] River flow is northward. The dashed red line is where the bridge is usually located – that winter, however, there was no sanctioned ice bridge.

[5] https://apps.sentinel-hub.com/eo-browser/?lat=64.06676&lng=-139.44629&zoom=14&time=2018-04-09&preset=1_TRUE_COLOR&datasource=Sentinel-2%20L1C

Figure 3: The Yukon River, April 12 2018 (Landsat). The ice cover is light blue. Dark narrow bands in the river are open water. Because these formed at the bridge location, indicated with a yellow dotted line (upper right), that bridge could not be built that winter (2017-2018).

Figure 4: The Yukon River, April 16 2017 (Landsat). Dark narrows bands in the river are open water. The ice bridge was not built that winter (2016-2017) – its usual location is indicated with a yellow dotted line (upper right).

Figure 5: The Yukon River, March 17 2015 (Landsat). Dark narrows bands in the river are open water. Bridge location is indicated (upper right). According to stakeholder consultation, the bridge was operational but required more work than usual.

Figure 6: The Yukon River, March 30 2014 (Landsat). Dark narrows bands in the river are open water. That year, an alternative route (yellow line, upper right) for the bridge was necessary, because the ice conditions did not allow it to be built at the usual location [1, 3].

Figure 7: The Yukon River, April 2 2013 (Landsat). There are very few signs of open water. Bridge location is indicated (upper right).

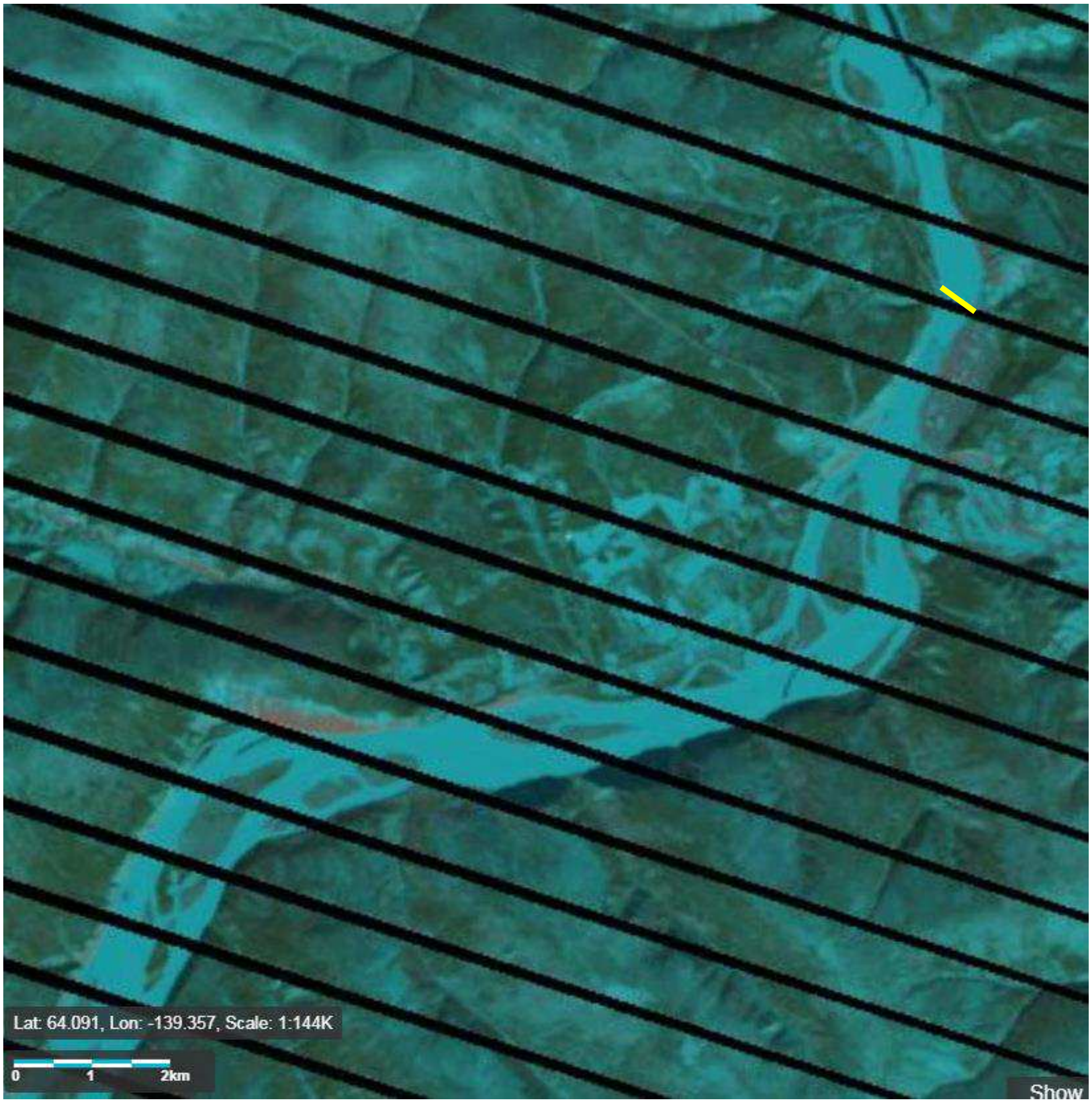

Figure 8: The Yukon River, April 10 2012 (Landsat). Bridge location is indicated (upper right). A dark narrow band in the river downstream from the bridge is an open water lead. The black stripes are due to a sensor failure on the satellite.

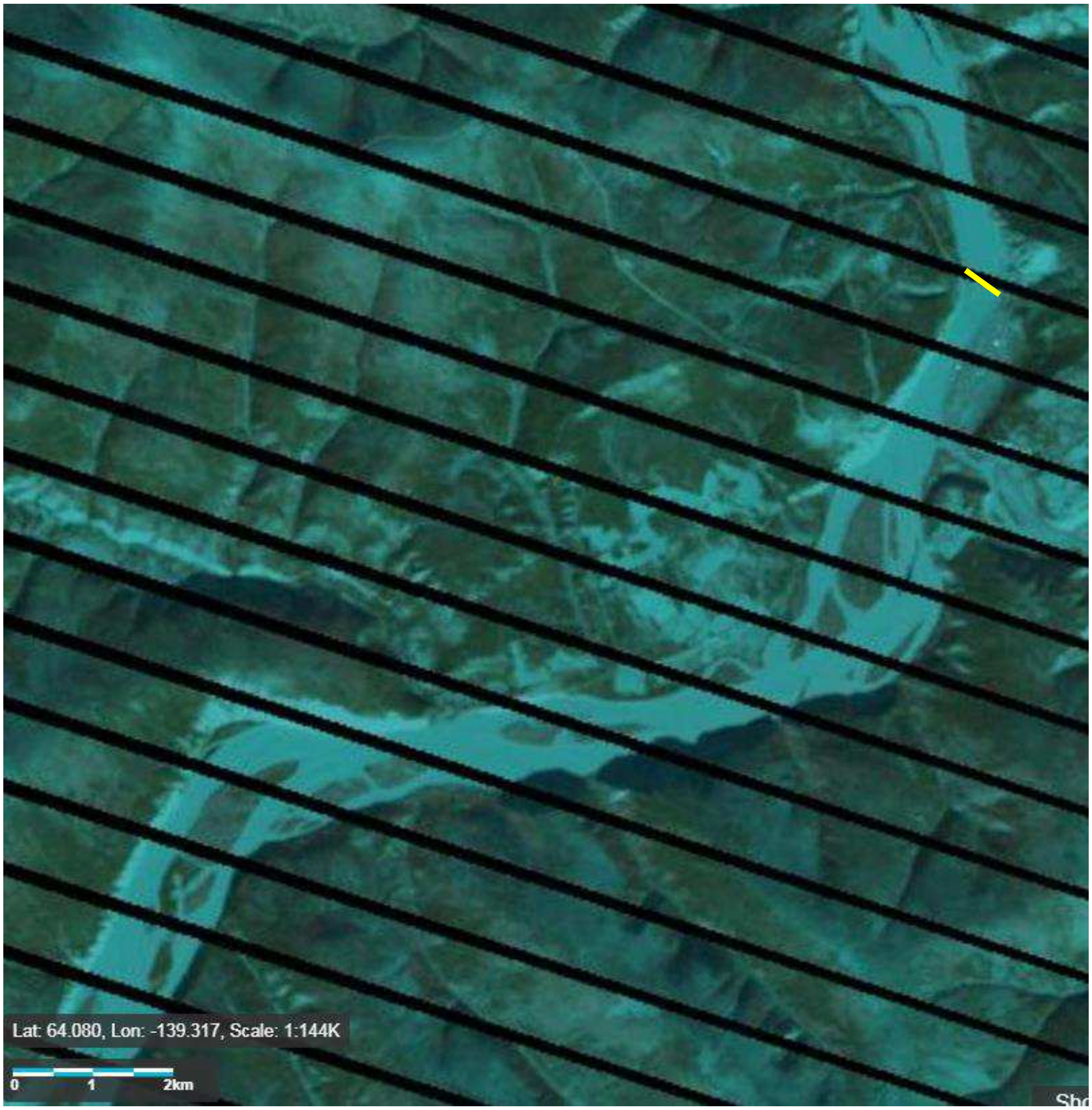

Figure 9: The Yukon River, March 23 2011 (from USGS LandsatLook). Bridge location is indicated (upper right). A few open water leads in the river can be seen on that image. The black stripes are due to a sensor failure on the satellite.

3.1 The spray ice operation in 2017-2018

Spray ice is produced by spraying water into the cold air to induce precipitation of ice crystals onto the water surface. This technique has been used extensively (Figure 10)[8-12] and commercial operations are reportedly using it [1][6]. YG hired Tetra Tech over the last few years to look at the ice bridge [1-3] – that organization has become familiar with it and with the river at that location.

Figure 10: Example of a spray ice operation[7].

In late 2017, a decision was made by YG to have Tetra Tech attempt to fill in the open water channel, using spray ice. This operation, which ended up costing $125,000[8], only lasted one week. Factors that played against the operation include:

- The contract was set up relatively late (December), giving the consultants little time to plan.
- The operation began with a favorable (-15°C to -20°C) air temperature, but it was followed two days later with a warm spell and rain (the consultant relied on 14-day weather forecasts).
- The plan was initially for the consultant to out-source the spray operation to a specialist. Instead, they did the work themselves with a spray ice unit they procured from the

[6] See also http://bigice.ca/products/
[7] http://bigice.ca/gallery/
[8] http://www.cbc.ca/news/canada/north/yukon-river-ice-bridge-spray-suspended-1.4500692

Northwest Territories, and used by Yukon's Transportation Maintenance Branch. That unit was available only for a limited amount of time.

- The operation was not backed up with sufficient knowledge of the water temperature and flow behavior at the bridge location. Instead, historical data from a nearby site was relied upon.
- An ice boom adapted for that purpose could have been used to retain spray ice that settled on the water surface, but was not – it is conceivable that the a good portion of the spray ice that settled on the water was carried away by the river current.

3.2 Media response

In many cases, where they exist, winter/ice roads are the only supply road to communities during the winter. They are an essential part of the surface transportation network in Canada. When they fail to operate, the communities are significantly impacted. This state of affairs can have negative sociological, economic and psychological implications: the community is unable to bring in their yearly supply of fuel and bulk commodities; access to health and emergency services is reduced or are no longer available; normal social activities, such as family gatherings and sporting events, are hampered. These impacts are often closely monitored and reported by the media. This has been the case for the Dawson City ice bridge. Examples of media report include:

"Dawson City ice bridge across Yukon River now open" [9]
This news post, dated January 2016, reports that the community across the river is "no longer cut off" from emergency services because the ice bridge is officially open to traffic.

"On thin ice: West Dawsonites wait for an ice road that may not come" [10]
According to this news post, dated December 2016, an ice jam is allegedly preventing the river from freezing completely, pointing out to the logistical challenges that entails for the community.

"West Dawson makes do with unofficial ice crossing while Yukon River remains open" [11]
This news post, dated February 2017, reports that the usual operation was unfeasible that winter, but an unofficial trail across the river was made for snowmobiles and pedestrians. However, emergency and maintenance vehicles cannot make it across.

"Climate warming leads to changes in river ice across the Yukon Territory" [12]
This news post, also dated February 2017, raises the issue of climate change and its likely role in the earliest ever ice river breakup of the Yukon River at Dawson.

"Yukon halts river-freezing experiment at Dawson City" [13]
Yukon's Highway and Public Works Minister explains that "spray technology", a plan that was announced in late December of 2017 to close the 90-m gap of open water in the Yukon

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[9] http://www.cbc.ca/news/canada/north/dawson-city-ice-bridge-opens-1.3396514?cmp=rss
[10] http://yukon-news.com/life/on-thin-ice-west-dawsonites-wait-for-an-ice-road-that-may-not-come/
[11] http://www.cbc.ca/news/canada/north/ice-road-bridge-dawson-city-yukon-river-1.3980576?cmp=rss
[12] http://arcticjournal.ca/health-science/science/climate-warming-leads-to-changes-in-river-ice-across-the-yukon-territory/
[13] http://www.cbc.ca/news/canada/north/yukon-river-ice-bridge-spray-suspended-1.4500692

River, has not met expectations and the operation was aborted. The bridge would not be available again that year (winter 2017-2018). The post brings out the fact that the operation only lasted a few days when the air temperature happened to be relatively high.

"*Climate warming leads to changes in river ice across the Yukon Territory*"[14]
This article points out to a gradual downward trend in the number of days in the year to river break-up in the spring (Figure 11).

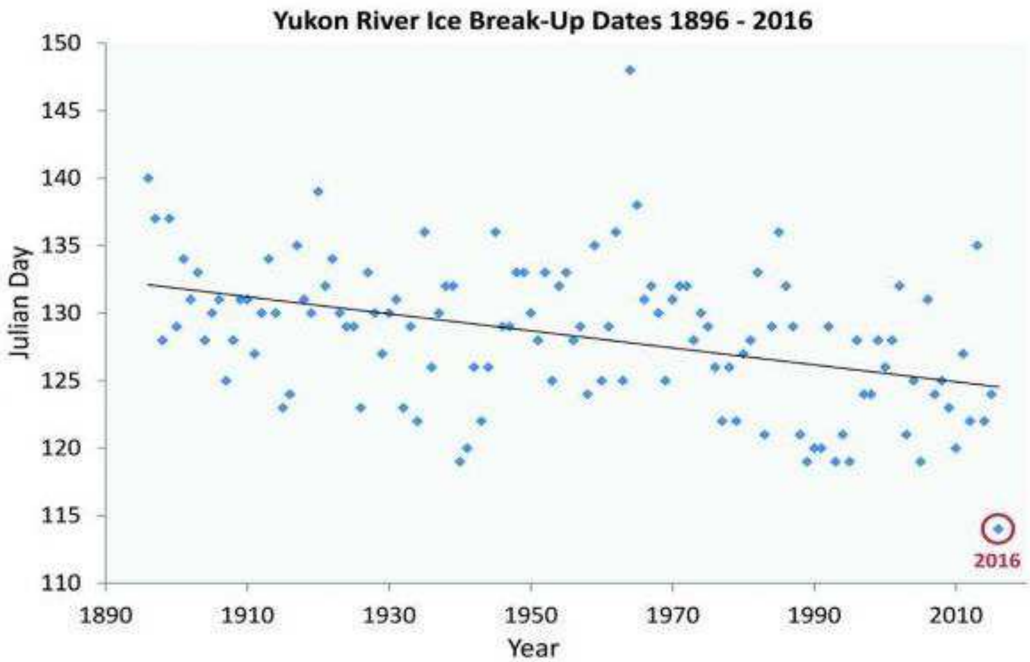


Figure 11: Spring break-up dates of the Yukon River over the last century, as reported in a news post[15] - the vertical axis indicates the number of days from January 1st. The year 2016 was the lowest on record.

3.3 Follow-up by the YG

YG mobilized resources and expertise to find out why the river remains open throughout the winter, and most importantly, to see what can be done to have a fully operational ice bridge in following winters. Consultation with NRC was undertaken in that context.

3.4 The August 2018 Dawson City Open House

Engagement with the local community in Dawson City on the ice bridge operation was organized by YG. It took the form of an Open House, which was held on August 22nd 2018, from 1600h to 1900h at the Downtown Hotel in Dawson City. YG invited Paul Barrette, the first author of this report as the NRC representative. Several YG representatives were also in attendance including

[14] http://arcticjournal.ca/health-science/science/climate-warming-leads-to-changes-in-river-ice-across-the-yukon-territory/

[15] http://arcticjournal.ca/health-science/science/climate-warming-leads-to-changes-in-river-ice-across-the-yukon-territory/

local road foreperson Bruce Taylor, YG engineers Paul Murchison and Brian Crist, environmental coordinator Erik Pit and communication staff member, Heather McKay. The purpose of this event was to gather feedback from the community – comments, questions, concerns – on the ice bridge operation. About 40 people participated over its 3-hour duration.

3.4.1 Summary of discussions at the Open House

Below is a summary of the Open House's outcome and the feedback and comments from the individuals who attended.

These minutes were collected by YG and NRC – due to a significant amount of interaction, not all comments could be collected. *Note that many of these comments and opinions may not necessarily be aligned with what is happening with the river or reflect the views of all the participants.* They are gathered here for information purposes.

They are conveniently grouped into eight themes: 1) General comments, 2) The river bottom, 3) Ice jams and other ice-related issues, 4) How 'to bridge the gap' between the shores – Booms, 5) Alternate routes, 6) Operational aspects, 7) Safety, and 8) Moving forward.

3.4.1.1 General comments

- There has been a drastic increase in the population of West Dawson in recent years.
- The Klondike is not 'behaving' as it has in the past. Why is that?
- The open water lead is getting "bigger and longer".
- Three winters ago, the ice bridge building operation worked, but required a lot more effort to build a workable ice bridge.
- One conceivable sequence of causes: Low water levels (e.g. if river freezes later) lead to an increase in amount of silt which lead to ice jamming upstream of junction.
- The Klondike River is also not 'behaving' either – sometimes people cross in the morning but cannot get back later in the day.
- A river glacier upstream is outputting less water than usual. Could this not affect river flow at Dawson City?
- Thought that the hydro dam near Whitehorse could play a role?
    - It is a long way up in the watershed.
    - This could be checked by comparing historical records of water levels at Dawson and dam operations.
- Some expressed belief that there has been more wind from the north.
    - Could this promote sublimation?

3.4.1.2 The river bottom

- The current in the Yukon River has become faster because of a sand bar at the Klondike junction.
- Dredging (to remove this bar or reduce its size) is deemed good option (suggested by several people).
- Work was done on the river bed next to the east shoreline about 30 years ago which included construction of new berms.
    - Could this be affecting river behaviour today?
- Several years ago, a small island upstream the Klondike River was washed away and deposited at the junction of the Klondike and Yukon Rivers.

3.4.1.3 Ice jams and other ice-related issues

- When ice jams occur, they are usually in front of town; if they don't occur, there is an open water lead.
- Several 'jam points' in river flow were reported: 1) at the junction of the Klondike and Yukon Rivers, 2) further upstream, and 3) downstream from current ferry crossing.
- Since river freezing occurs later, because of water levels are getting progressively lower, ice jams typically occur further upstream.
- Paul B. (from NRC) asked what people thought about what a safe ice thickness is. Replies:
  - No blanket answers. Charts provide that information. It depends on the vehicle's weight and configuration (from YG).
  - Jurisdictions across Canada normally have their guidelines.
- Paul B. asked whether people are aware of the existence of 'wet cracks' (These are cracks that span the full ice thickness.)
  - Because of them, water makes its way to the surface (hence the word 'wet').
  - People are not aware of this being an issue – there are lots of cracks, but they are dry (surface cracks that don't penetrate down to the water).

3.4.1.4 How 'to bridge the gap' between the shores - Booms

- Boom option could work but anchoring would need to be strong enough (nets across the river could also work).
- Navigation hasard, possible environnemental objections.
- Two boom deployment options were discussed:
  - Placing booms in open water before freeze-up.
  - Placing booms on the ice surface.
  - Preference for the latter option was expressed.
- Use of natural rope was suggested (i.e. biodegradable) to span the open water lead, along with willows and alders, to offer support for ice to form – these would also provide structural integrity.
- A suggestion was made to allow ice to grow around a series of floating wood boards laid on the water surface, then extend the procedure progressively toward the center of the river.
- Flood risk: What about the chances of a boom inducing flooding, or otherwise affecting river break-up?
  - The bridge never did promote jams, so why would a boom?
  - To have a jam, the full water column has to be blocked by ice.
  - Because flooding could have severe consequences, the potential impact of booms on water levels should be investigated.
- As an experiment, wood chips were once dropped into the water, promoting ice formation.
  - Because it contains no bark (whose high acidity is objectionable), it would be environmentally acceptable, i.e. no objections should be expected from DFO.
- The long-term weather forecast is often inaccurate – this was a problem last year when YG used spray technology and could be a problem again in the future.
- Temporary (floatable) bridges – Could this be a viable option?

3.4.1.5 Alternate routes

- The usual location is ideal; close to it is the second best option; away from it is better than nothing.
- The shorter the route the better.

- Paul B. asked how important is the length of the road?
    - It depends where you live on the west side.
        - Current location (at the ferry crossing) favors West Dawsonites.
    - The longer the route, the trickier it is for big rigs.
- Why is the long alternate route option being considered this year but not considered last year?
    - Last year, the freeze-up looked very promising in the fall.
    - Also, it crosses various jurisdictions, and it takes time to go through all the permitting procedures.
- YG would discuss potential alternate route with affected landowners.
- Why not just use the ice that already exists in the river (instead of making it artificially)?
    - Wait to see the state of the ice coverage, then plan route accordingly (adaptive planning).
- Could potentially use the grounded shore ice, along the east shoreline.
    - Shore ice is unsafe – it tends to collapse and may not be able to support heavy vehicles.
    - Concerns were expressed about falling rocks.
- The Sunnydale loop is not suitable for big rigs – it is too long and too hard to maintain.
- The 'unofficial' road.
    - It is maintained mostly by western residents.
        - There are no historical records of how it performed over the years.
        - Apparently, it once accommodated passage of a 10-ton vehicle.

3.4.1.6 Operational aspects

- There is not much awareness about how vehicles affect the "unofficial" bridges.
    - Example: A snowcat is heavy but the load is distributed, such that very low vertical stress are exerted onto the ice, i.e. the ice is able to support that weight.
    - However, a common misconception is to assume lighter vehicles can make it if the snowcat can. What people are not aware of is that though the vehicle is lighter, its small footprint exerts higher stresses on the ice.
- Paul B. asked whether the speed of vehicles have an impact?
    - Waves can be felt on ice as a vehicle goes by.
    - Speeding is a concern to the community, more in terms of traffic safety than load bearing capacity.
- Paul B. asked whether snow an issue?
    - Not really – snow storm are not common.
    - However, significant snow accumulation can happen because of drifting snow, especially at some locations.

3.4.1.7 Safety

- Paul B. asked - NRC and YG value health and safety – what is everyone's view on this?
    - What kind of control, measures, monitoring are implemented to mitigate risks of accidents?
        - Occupational health and safety guidelines were raised in the discussions.
- Crossing the "unofficial" bridge in the last 3 years has been "nerve wrecking", according to a witness, because ice is unpredictable; one would rather not cross, especially with children.
- There have been close calls on the "unofficial bridge", and dogs have fallen through.

3.4.1.8 Moving forward

- YG should get prepared ahead of time, as opposed to doing things last minute.
- It was stated in that some operations, such as last winter's spray ice, should be non-stop, i.e. around the clock. In order to do that, floods lights are needed (Occupational health and safety requirements).
    - These should be available in Dawson as needed.
- YG should inform people on the Open House's outcome.
    - All should have access to NRC's report, which will contain discussions on these options.
- A participant indicated that permitting ("red tape") may delay implementation of a practical solution.
- This year, YG is being pro-active, which is good.
- When will a plan be decided upon? Will we be informed?
    - YG staff said they are currently discussing options– no set date yet.
- Make decisions when opportunities present themselves, and don't get stuck to a target date to make decisions.
- Is there a budget available to do the work? YG staff said there is.

3.4.2 NRC's position with respect to the Open House

From NRC's perspective, the outcome of the community engagement is considered *anecdotal evidence*, i.e. it is a form of data. Although such information needs to be assessed from a holistic perspective, it can provide very useful guidelines in evaluating follow up options. In the report's following sections, NRC will address the report's two objectives: 1) Understanding the Yukon River (Section 4), and 2) Conceivable options for a successful ice bridge at the ferry crossing (Section 5). It should be mentioned that several of the items raised during the Open House had already been captured by NRC (through stakeholder consultation pre-dating the Open House). That overlap is desirable, as it indicates a consistency in stakeholder viewpoints between different groups of stakeholders.

4 Understanding the Yukon River

A practical understanding of the Yukon River and of the parameters that affects its behavior is a prerequisite to providing guidance for future ice bridge operations, so as to try to identify the source of the problem. A preliminary review is provided in this section.

4.1 Data sources

As part of this study, NRC compiled a listing of the parameters of interest, related to hydrology, hydraulics, meteorology, river morphology (e.g. bathymetry) and ice regime. NRC also compiled a listing of factors stemming from human activities, which may explain a lack of river icing at the crossing. Tables are provided at the end of this report and summarize these listings, sorted into three classes of data:

- ‘Type A’: Data that can be obtained in the short term, i.e. within the project lifespan
- ‘Type B’: Data that are not readily available, but could be obtained after the project lifespan
- ‘Type C’: Data that do not exist but could be generated in the future

These sources are included in this report for the purpose of awareness. The information they contain has yet to be assessed.

4.2 Ice river dynamics

Ice river dynamics have been studied by many investigators. There are good overviews on it, including theoretical treatments, numerical modeling and reference to the influence of climate change [13-18]. The information most relevant to this study relates to river freeze-up processes, namely the evolution of the ice cover in the fall and winter. The river-ice dynamics (including ice growth, thickening and jamming) will determine the state of the ice cover on which the ice bridge will be constructed.

4.2.1 Ice growth

Ice growth in rivers is considerably different from that in lakes. The primary difference is the presence of currents. Depending on river width, channel configuration and water regime, currents can be significant at some locations, while minimal in others. Currents impact ice growth by preventing the accumulation of ice crystals at the surface, either by mechanical or thermal means. Currents can also have an erosional effect on the bottom of the ice that has already formed.

The first requirement for ice growth is a decrease in water temperature during the Fall and into the Winter. Snow fall can also initiate river freezing. Ice growth from the shoreline, especially in shallow, relatively calm waters (flow velocity less than 0.1 m/sec), may begin the freezing cycle. This ice is called ‘border ice’ or ‘shorefast ice’ (Figure 12). In more turbulent river sections, small ice crystals (known as ‘frazil’) can accumulate and produce ‘flocs’ that drift and eventually form ice ‘floes’ known as ‘pancake ice’. These may collect along the border ice or achieve progressively higher surface concentrations until a continuous or near-continuous ice cover is formed.

The growth of ice on a river surface may be prevented by current action. Even with very low air temperatures, water currents can do two things: 1) they can raise warmer water to the surface through turbulence, preventing an ice cover from forming; 2) they can bring ice particles (frazil, snow) down in the water column where they will melt because the water is warmer (further from the water-air boundary).

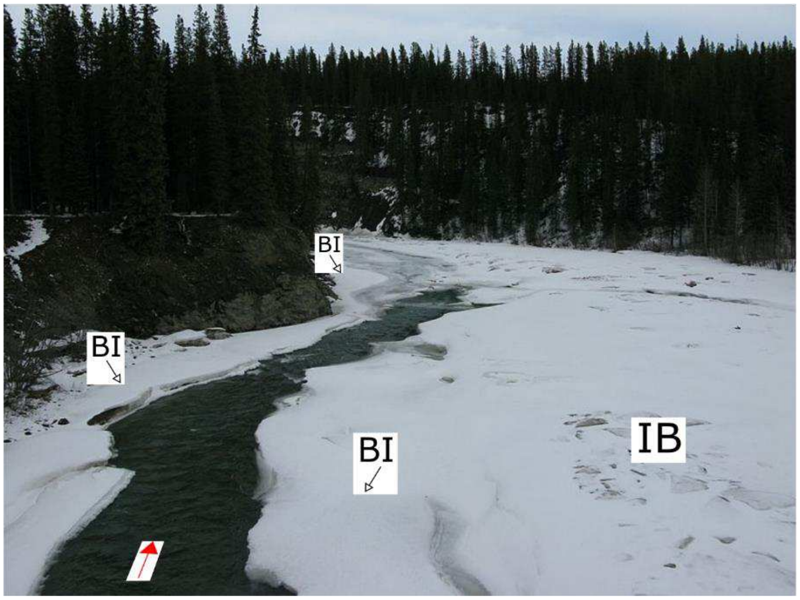


Figure 12: Examples of border ice (BI) and ice blocks (IB). The red arrow lower left indicates current direction – at that location, the current is presumably strongest, which explains why the river has not frozen at that location. Brazeau River, Alberta, April 2008. From Wikimedia Commons[16].

4.2.2 Ice thickening and ice jams

Thickening of the ice cover may occur in various ways. One is downward growth (accumulation on the underside of the ice cover) – this leads to what is known as 'black ice'. Another is when water manages to find its way to the surface of the ice cover, either from below, or flooding through other sources. If there is a snow layer present during flooding, it will become saturated with flood water. This leads to the formation of 'white ice', which has a lower density and is mechanically weaker than the underlying black ice [19]. Yet another ice cover thickening mode is through 'hydraulic thickening', when drifting ice pieces are pushed against each other and begin to overlap. These may occasionally develop into fields of ice blocks or hummocky ice (Figure 13).

[16] https://commons.wikimedia.org/wiki/File:Brazeauriverfrozen.JPG

Figure 13: Ice blocks or 'hummocky ice' on the Bow River in Calgary [14].

Thickening of the ice cover may be such that it induces what is known as a 'freeze-up ice jam' because what was originally flowing has become frozen into a stable surface. Pieces of ice which could contribute to ice bridge initiation are prevented by the jam from drifting further downstream. Lower water levels will promote grounding. 'Break-up ice jams' are also well documented in rivers, but they are not relevant to this report, as they occur in the spring, when the ice bridge is no longer in operation.

4.2.3 Open water

Rivers do not always freeze over entirely during any given winter. The amount of freezing depends on a number of parameters, namely current speed, as can be seen in Figure 12. Average air and water temperatures over the winter do matter as well.

A review of satellite imagery (Figure 3 to Figure 9) indicates that localized open water conditions have occurred at various sites along the Yukon River over the last number of years, as indicated in several figures, even the years when the bridge was operational.

4.2.4 The Yukon River at Dawson City

As of this writing, no field photography was obtained that would allow detailed interpretation of ice formation processes in the Yukon River. However, the satellite imagery in Figure 14 does provide an indication of river freeze-up evolution. In order to confirm these observations, one would require better visual information on the ground, as well as flow data across the river width, depth and locations. A proper understanding of the ice regime at and near the bridge location, preferably a historical record, would prove highly beneficial.

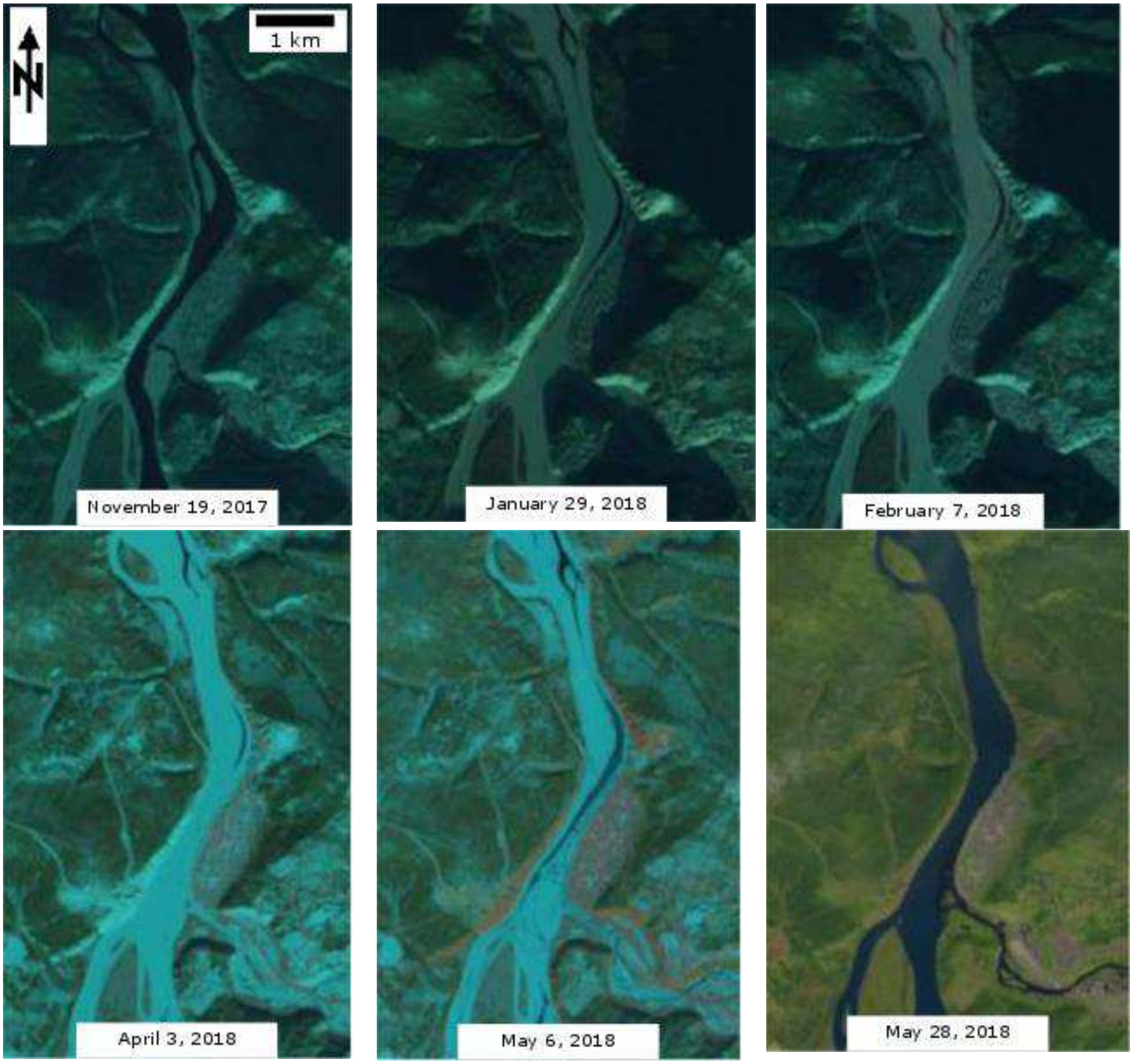


Figure 14: Ice cover evolution of the Yukon River at Dawson City, over the winter of 2017-2018 (from USGS LandsatLook). Dark narrows bands in the river is open water.

4.3 River morphology and hydraulics

A brief overview is provided in this section on this topic, and more background information can be found in Appendix A.

4.3.1 Why river bathymetry can be in constant evolution

Water flowing in open channels, such as the Yukon and the Klondike Rivers, are subject to two principal forces: gravity and friction. Gravitational forces drive the downstream motion of the flow along the slope of the channel, whereas friction resists the downslope motion of the flow [20-22].

In a natural river with an alluvial bed (i.e. mobile sediments, typically sand and gravel), such as the Yukon River, a complex feedback relationship exists between flow hydraulics, channel geometry and sediment transport. Frictional forces exerted by the flow can mobilize and transport sediment, thereby reshaping the channel geometry. Hence, adjustments in geometry can influence the flow. Natural channels never truly achieve a state of static equilibrium (no or nearly no erosion of the riverbed) because, in addition to other contributing factors, upstream flow and sediment inputs vary in time. In other words, natural rivers are constantly evolving, and the nature of that evolution depends on a number of parameters, namely: flow, sediment supply and channel slope.

However, over time, natural channels will adjust toward an equilibrium state by altering their channel geometry. For this reason, natural alluvial channels rarely have a straight course and a flat bed. Instead, they display a degree of meandering across the land and features on the riverbed known as ‘bedforms’. Some common bedforms include bars, ripples, dunes, and antidunes. Bars may be further categorized as follows:

- Point bars: form on the inner bank of meanders
- Alternate bars: distributed periodically along one and then the other bank of the channel
- Channel junction bars: form at the confluence of a tributary and the main channel
- Transverse bars: form diagonally to the flow (i.e. riffles)
- Mid-channel bars: commonly form in braided and anastomosing rivers with abundant sediment supply

4.3.2 Relevance to the Yukon River at Dawson City

The sediment deposit located at the confluence of the Klondike River and the Yukon River near Dawson is characteristic of a channel junction bar and many mid-channel bars can be observed on the Yukon River upstream of Dawson (Figure 15). The channel junction bar needs to be investigated to see if it has grown in recent years. If so, further investigation may be required to characterize the growth and to assess the impact on the river flow. Characteristic of channel junction bars, the bar development is related to the sediment influx from the entering tributary (i.e. the Klondike River). Has sediment influx from the Klondike River increased significantly in recent years? Are there any human activities upstream which could have caused such an increase?

The consequences of increased sediment influx and changes to bedforms are not trivial. The bar exerts a direct influence on current behavior, i.e. a large bar may constrict flow and intensify current velocity in the vicinity of Dawson (Figure 16), which would adversely affect ice cover growth.

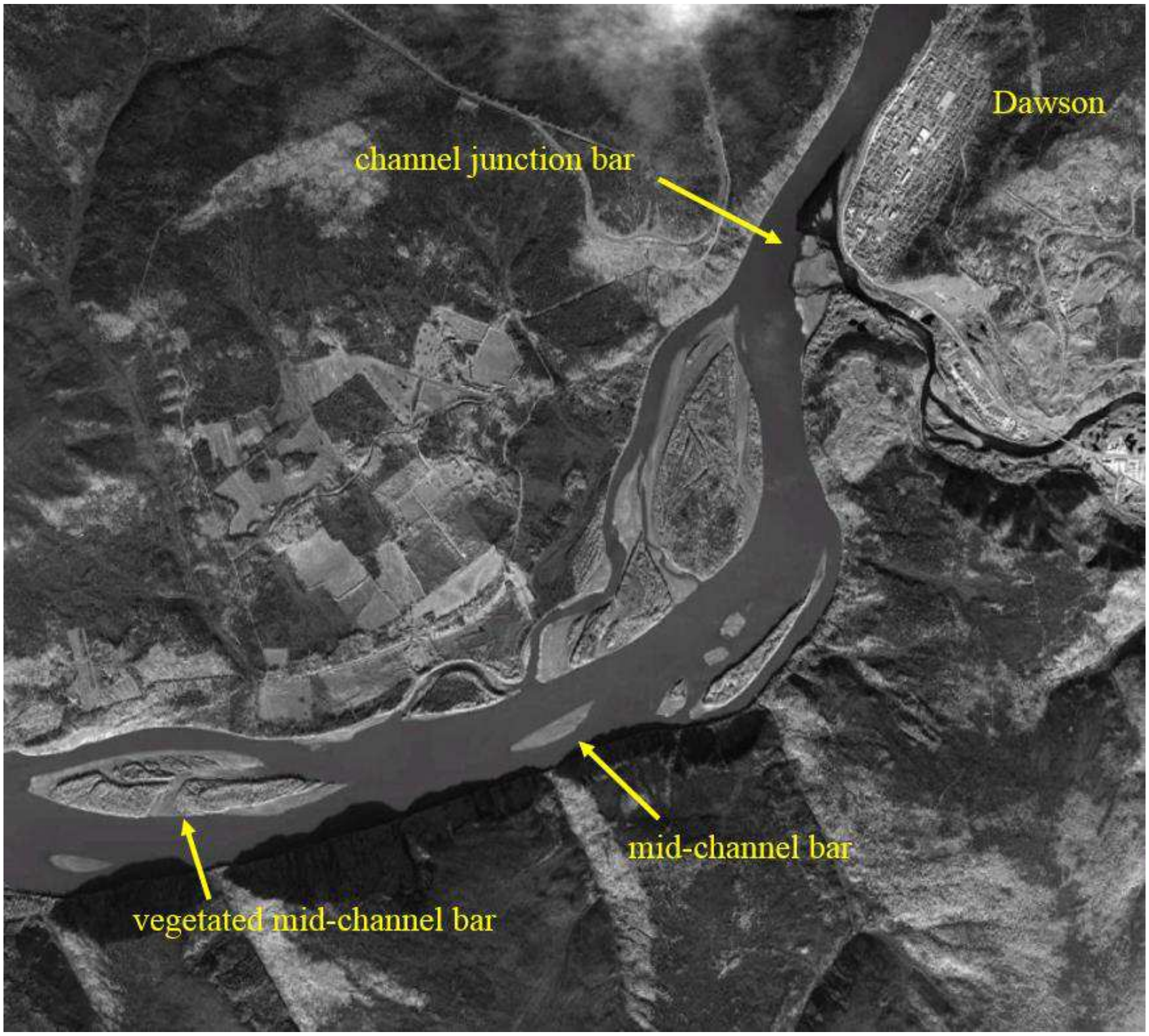


Figure 15: Examples of channel bars in vicinity of Dawson, YK. Base image obtained from Google Earth.

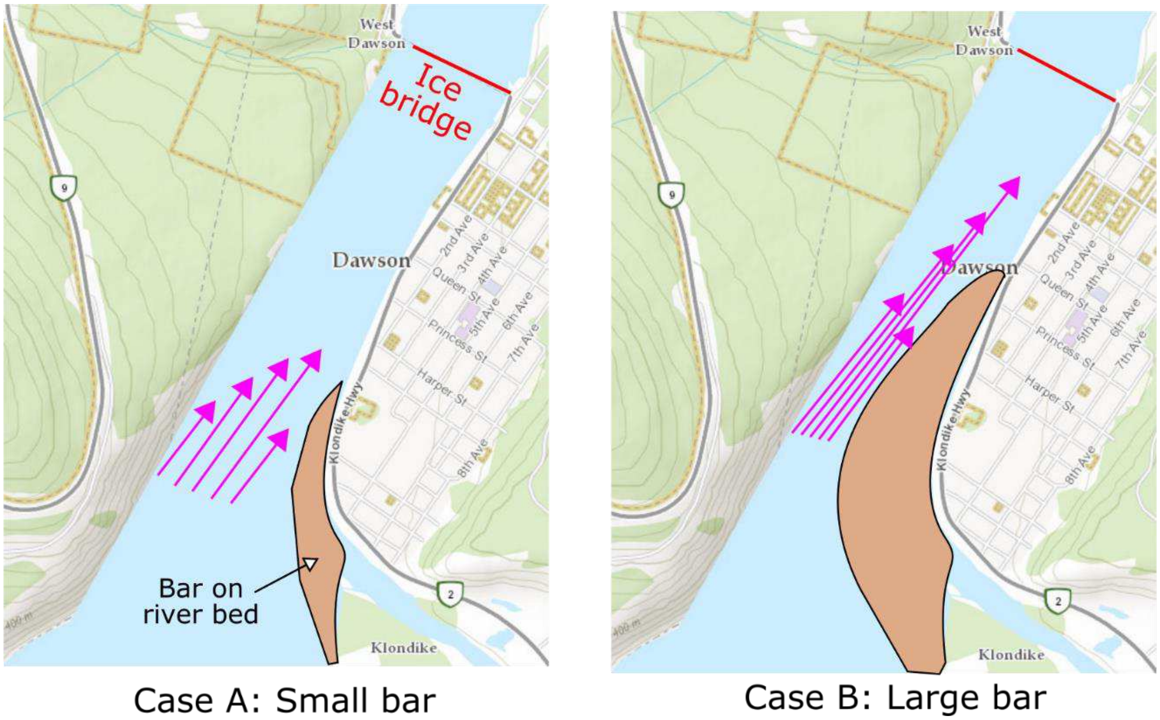


Figure 16: Simplified illustration of current behavior as a function of sand bar extent. The arrows are hypothetical water displacement vectors. The bar in Case B is significantly larger than that in Case A – a narrower channel results in an increase in current velocity.

4.4 Global warming and Climate change

According the USGS[17], ‘Global warming’ alludes to a general albeit very slight (a few degrees) increase of the Earth atmosphere’s average temperature to result from greenhouse gas (GHG) emissions. ‘Climate change’ is the “increasing changes in the measures of climate over a long period of time”. It is important to realize that phenomena related with climate change not only include global and regional temperatures but also variables such as precipitation, evaporation, wind patterns, permafrost, wet and dry spells, snowpack and, ultimately, river flow regimes. Appendix B provides additional background information in that regard.

4.4.1 Relevance to the Yukon River

Some climate models predict a substantial temperature increase in Northern Canada (Figure 17). There is little doubt climate change could also be a contributing factor for the Yukon River problem. To determine unequivocally if its impact is real and significant, or to see if there has been an alteration in the river’s natural behavior regardless of climate change, a careful analysis of the available information (river flow, bathymetry, river ice dynamics, air temperature, precipitation, etc.) would be required.

[17] https://www.usgs.gov/faqs/what-difference-between-global-warming-and-climate-change-1?qt-news_science_products=0#qt-news_science_products

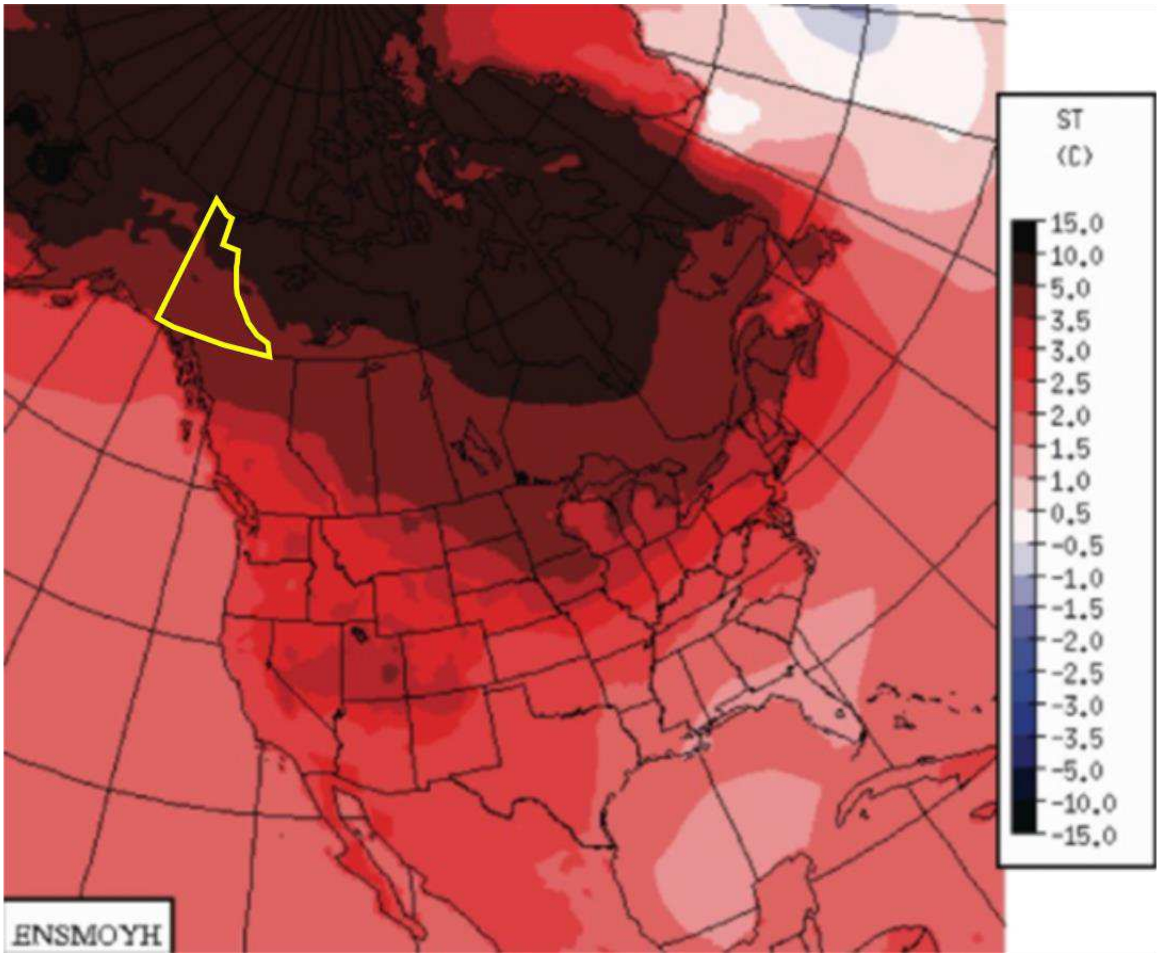


Figure 17: Mean temperature increase in the winter [23].

4.4.2 Prospective investigation avenues

Concerning the effects of climate change, a number of investigation avenues may be considered. The presence of an open water lead may have been the result of warmer than usual winter temperatures in air and water (and even shoreline ground). Consequently, it is important to study local and regional temperature patterns and their projected future evolution in order to understand the severity and frequency of such events.

Along with temperature-related investigations, it is also important to study how the characteristics of rain-on-snow events have evolved over the historical period and how such events will be impacted by climate change. Increased frequency of such events during the winter period can cause rapid melting of snowpack and warmer water temperatures. For this study, a physically-based regional climate modeling exercise can be conducted to produce an ensemble of present day and future simulations. Physically-based Regional Climate Models (RCMs) – see Appendix B – are suitable for such investigations. Data analyses can be conducted following [24] and can be supported further by an independent investigation based on climate change simulations available through CORDEX (https://na-cordex.org/). A regional analysis of changes in snowpack characteristics would be helpful.

An analysis of local and regional winter low flows would be helpful in understanding if a change in low flow regimes is a causative factor. During low flow periods, rivers draw water from soil water stores (groundwater). If winter low flow levels are increasing, then that will be an indication that warmer water released from soil stores is a contributing factor. Noting that the Yukon River cuts through different permafrost zones, it would be informative to evaluate how low flow regimes and permafrost will change in the future. Some preliminary conclusions can be drawn from previously published studies [e.g. 25, 26] and territorial government documents.

5 Options for a successful ice bridge at the ferry crossing

Notwithstanding the proposed investigations discussed in Section 4 to identify the source of the problem (as to why the river has not been freezing entirely at the ferry crossing in the last few years), YG must ensure there is a fully operational ice bridge next winter and in subsequent winters.

The Dawson City ice bridge has historically been a relatively successful operation. But these new circumstances – i.e. the existence of an open water lead – call for new or novel procedures and techniques. The conventional bridge building methods may no longer be sufficient. This section will address the report's second objective, which is to examine options for constructing and maintaining the ice bridge at the ferry crossing, assuming the worst case scenario, i.e. *there will be a central channel of open water all along the river between Dawson City and West Dawson.*

5.1 Safely assessing the ice cover

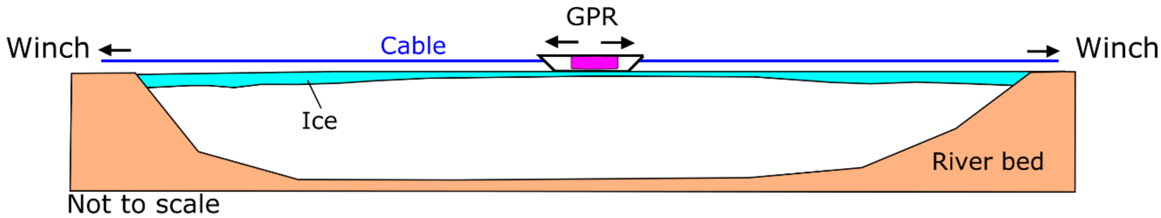
Safety is paramount – this has to be kept in mind from the start. A robust health and safety plan has to be implemented before the beginning of any on-ice operation. Such a plan should take into account all threats (breakthroughs and others), and have to be mitigated well ahead of time through consultation with all relevant authorities. Details on safety procedures are provided in [2] for the Dawson City ice bridge operation. These procedures could be used as a starting point and adapted as required in moving forward with ice bridge construction and operation.

Since ice cover breakthrough is the most serious threat, it is important to avoid working on the ice until it is deemed thick enough to support whatever load one needs to bring on it. This is a universal challenge with ice roads and bridges wherever they are used, because to check ice thickness accurately, one needs to step on it. Compounded to this challenge is the fact the water is moving – the current at the ferry crossing is about 1.5 m/s (Table 3.2 in [1]). Although operator experience and adequate guidance from engineering consultants alleviate these risks, accidents can and do happen.

5.1.1 A safer means of monitoring ice thickness

One possibility would be to extend a light cable across the width of the river, i.e. from one shoreline to the other, so as to be able to tow a ground penetrating radar (GPR) on a small floatable craft across (Figure 18, top diagram), back and forth as required. This assumes the ice cover is complete – see later for discussions on cable deployment and options as to how to close up open water areas.

The GPR is a standard tool to measure ice thickness, but it needs to be validated against auger holes. NRC is currently investigating the deployment of an unmanned, GPR-fitted remotely controlled hovercraft, fitted with an auger and other instrumentation. The Dawson City ice bridge would be an example of an operation that would benefit from the data gathered by that tool. Technology development, however, is still in the early planning stage.



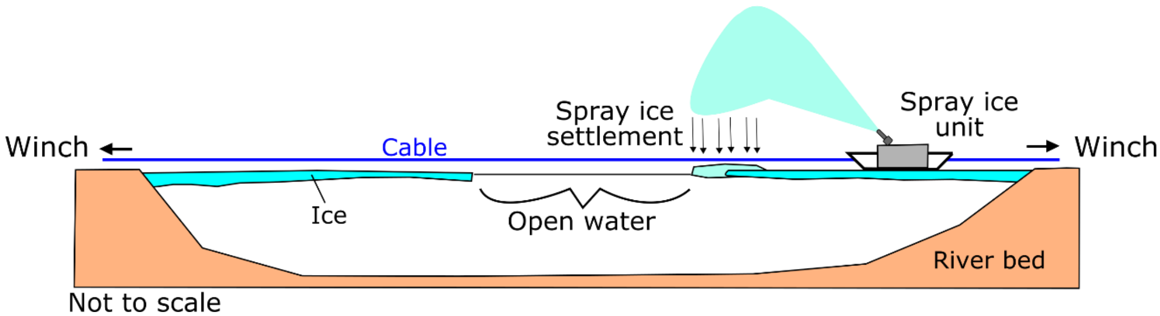


Figure 18: Top) Hypothetical system that might help making the ice operation more secure at the beginning of the winter – a ground penetrating radar (GPR) that can be pulled from each side of the river. Bottom) A similar system with the spray ice unit. Note that, for both deployment system, a line would first be laid on top of the ice from one shoreline to the other, e.g. using a helicopter – this line could then be connected to a proper towing cable.

5.2 Ice booms

An ice boom typically comprises a floating line of cable and pontoons at regular intervals that spans the river in order to accumulate ice on the upstream side. An ice boom is commonly used to assist in the formation of a stable ice cover during the winter months [27-30], by bringing together the drifting ice to allow it to freeze into an ice sheet. They are typically made from timbers or steel pontoons joined with a cable and anchored to the shoreline or to riverbed anchor (Figure 19).The length, size and type of floating elements, retention capacity (i.e. kN/m) are amongst the factors that need to be considered.

5.2.1 Relevance

The use of an ice boom on the Yukon River has already been suggested by Tetra Tech [1]. Ice booms can be deployed late in the fall so as not to interfere with normal usage of the waterway and are removed in the spring. They are known to have "a negligible effect on the natural hydraulic conditions in the river, have little influence on [river bed dynamics, and do not impede fish migration" [27, p. 53].

5.2.2 Options for boom deployment

The following are some prospective options for deployment of ice booms on the Yukon River.

5.2.2.1 Open water

Open water deployment is the most commonly used approach in other rivers. It is scheduled when navigation activities have ceased and before the river begins to freeze. Removal is done in the spring, when the ice has thawed completely. Note that open water boom deployment would be a preventive, pro-active measure, in the sense that it would be implemented even if the river ends up freezing entirely (no open water).

Figure 19: Examples of ice booms used by Ontario Power Generation: Left) timber; right) steel pontoons.[18]

5.2.2.2 Below-ice installation

This option, summarized in Figure 20, assumes there will have been a cable installed in open water from one shoreline to the other at the bridge location. As is the case for the open water installation, below-ice installation is a contingency measure. If the river happens to freeze entirely that winter, that cable will not be needed – it can remain on the riverbed. However, if there is strong suspicion an open channel will remain, then it can be dislodged from the ice at both ends and used to pull a boom from below the ice.

5.2.2.3 Sink-and-float approach

With this option, a brief account of which is presented in [30], the pontoons making up the boom are lying on the riverbed in the summer with the individual pontoon filled in with water. They are allowed to float up in the fall by inflating the pontoons with air, and filling them with water again in the spring to allow them to sink back to the river bed. This procedure is a more elaborate version of the preceding below-ice option, the advantages and disadvantages of which would have to be carefully considered.

[18] https://www.opg.com/news-and-media/our-stories/Documents/20161209_IceBoom.pdf

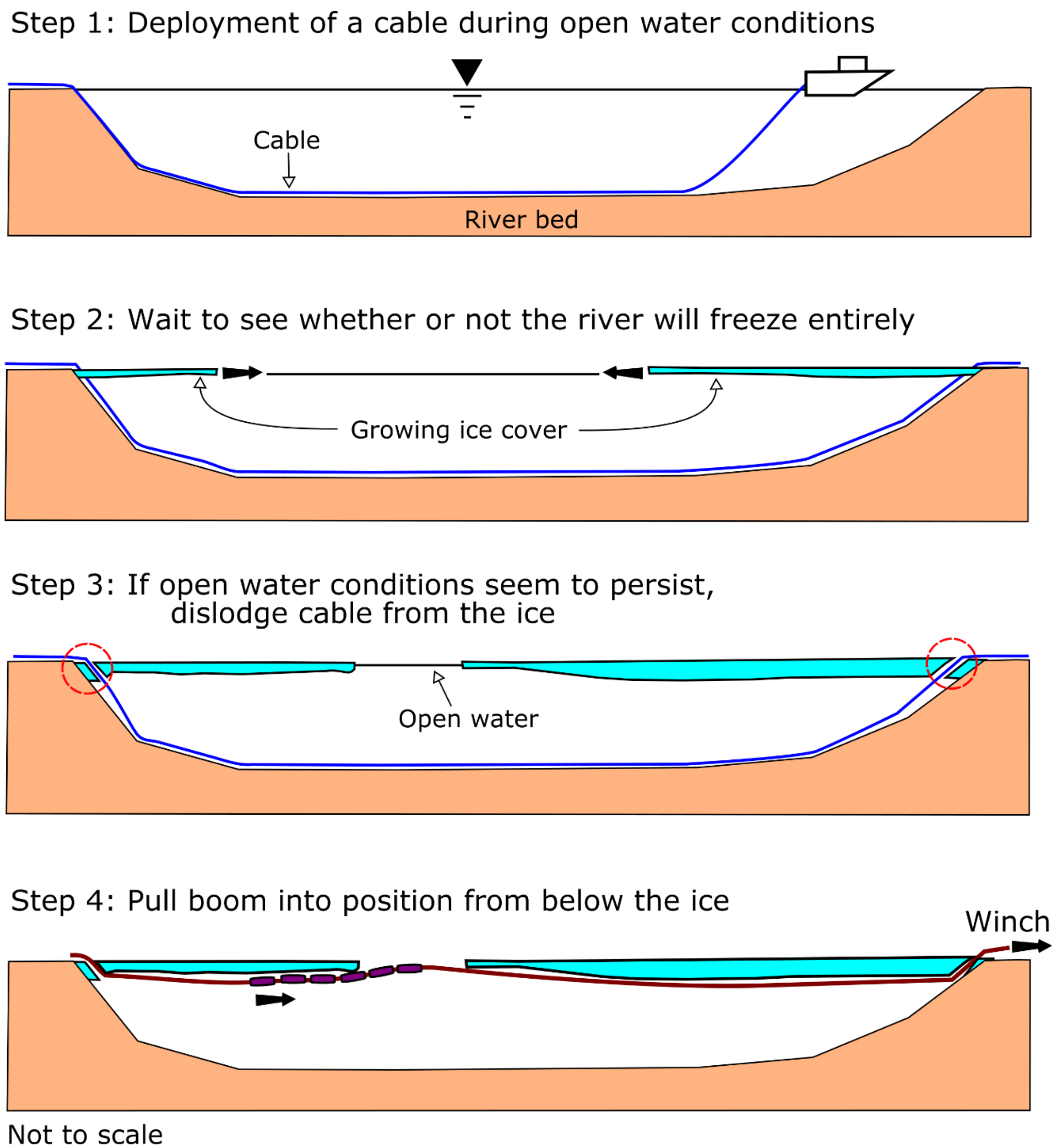


Figure 20: Simplified representation of below-ice boom deployment.

5.2.2.4 Over-ice installation

This option is similar to the sink-and-float approach, except that deployment occurs from above the ice. It has the advantage that the ice boom will not freeze into to ice at the two shorelines, since it does not lie on the seabed. The challenge may be deployment from one shore to the other – it could hypothetically be done with a helicopter, as mentioned earlier. The end result would be similar to what is shown with the GPR, but where a cable would be used to bring the boom to the open water channel (Figure 15, bottom diagram). Once in place, the ice boom would be expected to freeze into the ice, and be retrieved after the spring thaw.

5.3 Spray ice

The success of a spray ice operation would be optimized if certain conditions are met, namely:

1. Air and water temperatures are low enough *at the location of interest*.
2. The water cannon is powerful enough to reach the entire width of the open water channel from ice that is thick enough to support the spray ice unit.
3. A boom is set up to capture the ice (unless it can be shown that the current is not strong enough to remove the ice as it settles on the water surface).
4. Appropriate time is allowed to prepare, deploy and operate the unit.
5. A robust safety plan is available for approval by government officials.

Point (2) above assumes the spray ice unit will operate from the east shoreline, since the other shoreline will not be accessible. Also, if the border ice is not thick enough, it will have to operate from the land, i.e. the water cannon may need to spray water at a distance of 250 m or more. This would present a challenge operationally, and also with regards to safety – the thickness of an ice cover on a partly frozen river has to be carefully considered.

One way this could be dealt with is by housing a spray ice unit on-board a small floatable craft. Assuming a cable is available between the two shorelines (as discussed in section 5.1 with the GPR), and a boom is in place (Section 5.2), the craft may be mobilized as required. Once a uniform surface is achieved, the GPR can be substituted for the spray ice unit in the same craft.

5.4 Ice reinforcement

The ability for an ice cover to withstand a load can be increased by artificially increasing its thickness through flooding or spraying operations. This can be done by flooding the ice surface with pumps that draw water from a hole in the ice. Spray ice is another possibility. A very different alternative is to reinforce the ice cover with a structural material, either organic (trees, branches, wood,… as was pointed out in the Open House), or with an artificial material (e.g. a geomembrane).

Ice reinforcement has been shown to work, but only at a small scale. The only material used fairly systematically for that purpose were trees in remote areas where there is an abundant supply of them. The National Research Council is beginning a three-year test program to identify and test an appropriate membrane incorporated into the ice, which would fulfill that role. This will be done in the laboratory – if proven feasible, it will be extended to a target field location for further validation.

Although this option is entirely hypothetical as of this writing, it could conceivably be applied in the future to an operation such as the Dawson City ice bridge. The principle is illustrated in Figure 21. The first step would be to deploy the geomembrane over the open water lead. The second step would be to pull a spray ice unit next to the geomembrane. That system would have a dual purpose:

1. To collect the spray ice.
2. To reinforce the resulting ice cover.

Interestingly, such a scheme, if it could be made feasible in the near future, could allow not only to maintain the bridge's operational lifespan in spite of climate change, but also extend it. This could be done by deploying the geomembrane as soon as the water and air temperatures are low enough. If that technology can be made to work, however, it will likely not become available before 4 or 5 years.

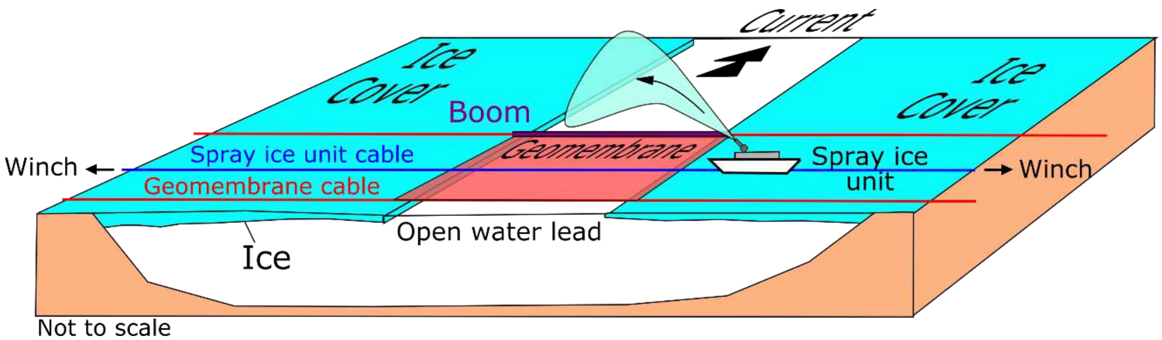


Figure 21: Simplification of a two-step procedure: deployment of a geomembrane followed by spray ice operation.

5.5 Mobile bridges

A mobile bridge system is "a deployable piece of equipment that acts as a bridge for crossing rivers, ditches, craters, and other natural and man-made hindrances" [31]. There are a number of possibilities [32], however, few would be adequate in the current context because deployment rely on a strong ground, i.e. either the shorelines or the shorefast ice if it is deemed strong enough to support the weight of the equipment used for deployment. One exception could be that shown in Figure 22 – it is an amphibious system, able to access an ice cover even if it does not withstand its weight. Once in the middle of the open water channel, it could deploy, so as to link the two sides of the ice cover. There are a number of challenges with such an option, namely that the ice would still need to be thickened away from the bridge. It would also need to be anchored so as not to move with the current. Another example, for a wider river crossing, is shown in Figure 23.

Figure 22: An amphibious mobile bridge system [32].

Figure 23: An alternative option, for a wider river crossing [32].

A mobile bridge may seem inappropriate in the current context, as there are more practical solutions. However, YG could keep that option in mind, as it might be a valid alternative to a structural bridge in future years. Ideally, such a system could be specifically adapted for the winter road infrastructure in the country (approximately 10,000 km) and elsewhere. Designing this tool is not unrealistic but would entail a collaboration effort between all levels of government and the private sector. This topic lies beyond the scope of this report.

5.6 Management of the Dawson City wastewater treatment plant (WWTP) effluent

It is conceivable that the Yukon River at the ice bridge location is influenced by anthropogenic action. Effluents from wastewater treatment plants, like the one in Dawson City, have been known to affect ice formation, e.g. in the Saguenay River (H. Babaei, NRC, pers. comm.). According to Dawson City Public Works[19], the waste water facility is located on 5th Avenue and is discharged mid-channel, about 200 m west of the dyke at Church Street (Figure 24). According to Annika Palm, Senior Project Manager with the Yukon Government in Dawson City (written comm. May 10, 2018), "before the current WWTP was operational, Dawson's wastewater went through the screening plant and discharged from the same outfall that is currently in use [which means that] in recent history, Dawson's wastewater has always been discharging at that same location".

The annual sewage discharge for 2007, according to the same source, was 807,000 m^3. Figure 24 shows the approximate location of the discharge point and a hypothetical 'plume' downstream from that point. The plume is likely warmer than the river water in the winter. Only numerical modelling and detailed field sampling could determine the significance of the WWTP effluent on ice formation.

In order to investigate the possible impact of the WWTP effluent on the river dynamics and the ice bridge, NRC could conduct a preliminary investigation, using a combination of remote sensing and numerical modeling, as explained elsewhere [33] of the likely path and thermal dilution of the effluent plume from the WWTP under a limited range of river discharge and effluent discharge conditions. NRC could further provide a preliminary assessment of whether the plume is likely to impact the ice bridge. The outcome of the study would provide:

- A better understanding of the hydrodynamics at the bridge site;
- a prediction on the fate and mixing of effluent discharged into this dynamic environment for a limited set of flow conditions selected on the basis of available data, and targeting anticipated 'worst case' and more 'typical' conditions for effluent dispersion;
- an assessment of whether or not thermal dilution effects are likely to affect river freezing near the crossing.

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[19] http://www.cityofdawson.ca/municipal-info/city-departments/public-works

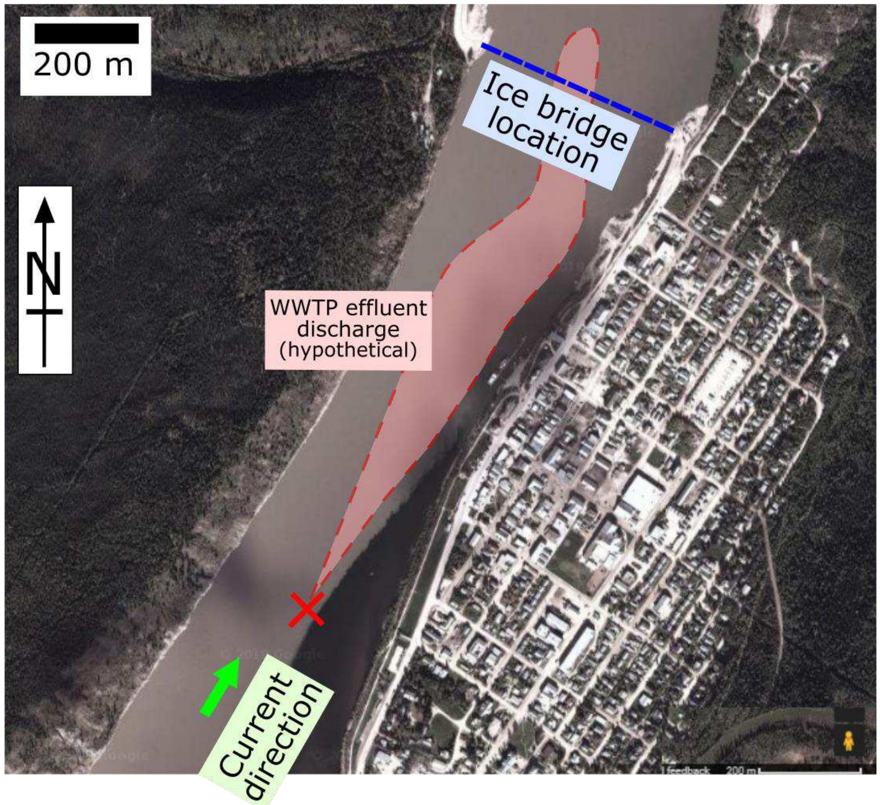

Figure 24: The Yukon River at Dawson City[20], with approximate effluent discharge point (indicated by an 'X'), and a hypothetical flume.

[20] https://www.google.ca/maps/@64.0642997,-139.4423083,2567m/data=!3m1!1e3!4m2!10m1!1e1

6 Discussion

General recommendations are offered below on the premises that the Yukon River will not freeze entirely next winter (2018-2019) and/or any other winter the following years. These recommendations are provisionary – they are based on the evidence the authors have had time to review as of this writing. If any of the proposed measures are retained, the details of their implementation would then need to be carefully refined.

6.1 Two main strategies

A preliminary analysis of satellite imagery by NRC suggests that, almost every year, small sections somewhere along the Yukon River do not freeze entirely. It is only when this happens at the usual bridge location (the ferry crossing) that it presents a real issue for YG and the community. Two main strategies have thus been envisaged so far by YG (and discussed at the Open House): 1) avoidance and 2) mitigation. Advantages and drawbacks are summarized in Table 1. One does not exclude the other, i.e. both could be implemented every year, even though this would require more resources.

The proposed options in Section 5 of this report only relate with the mitigation strategy. The reason is the avoidance strategy is about applying conventional ice-bridge making methods to another section of the river. No novel solutions should thus be required for that strategy, as YG should already have the required knowledge-base for its implementation.

Table 1: Strategies to prepare for future river scenarios.

Strategy	Description	Main advantages	Main drawbacks
Avoidance	Plan new routing around the open water section.	Measures to fill in open water spaces in the river are not required. If the river happens to freeze completely, as it normally has in the past, then no additional cost are incurred.	Longer crossing, extra costs in preparing contingency access road(s). Less time for safety assessment. May or may not be able to accommodate heavy vehicles (firefighter equipment, city maintenance). Users may need to adapt to the new crossing.
Mitigation	Retain the *current* bridge location, and prepare to fill in the open water space.	Same system in place year after year (no need to adapt every year), e.g. same connections with land roads. Users remain familiar with operation. With this solution, open water will no longer be a concern in future winters.	New procedures will have to be developed. All contingencies for filling in open water need to be in place ahead of time (i.e. additional costs) even if the river happens to freeze entirely any given year.

6.2 Avoidance

This strategy would be put into effect when there are strong suspicions the river will not freeze entirely at the usual bridge location. It would be based on a reliable ice thickness record, preferably monitored with a GPR. At this time, there are few alternatives for access to the ice. For instance, an old logging road (connecting to a golf course road) on the west side of the Yukon River just upstream of the junction with the Klondike River would require an upgrade. There may be times, however, when the river remains open at that junction (Figure 4). Hence, other alternatives for access roads could be prepared elsewhere, either further upstream from that junction or, conceivably, downstream from Dawson City. Each would be available as a contingency measure, depending on where the open water section is located.

6.3 Mitigation

With this strategy, open water has to be dealt with. To that effect, it is helpful to reflect on the following question: Why does the river freeze completely some years and remains open other years? As discussed earlier, a number of parameters are involved in ice dynamics – flow regime, ice regime, air temperature and water volume. Anthropogenic influence may also be involved. In essence, however, incomplete river freeze-up has two underlying, independent causes:

A. The supply of ice, either via vertical growth or from drifting ice, is insufficient; and/or
B. river flow regime is such that it does not allow full ice coverage.

In the short term, measures should be implemented to counteract these two root causes, so as to ensure the operation is successful next winter (2018-2019) and the following ones. Longer term approaches should also be devised. Is there a cost effective system the YG could have in place on a year-to-year basis, which would make the bridge operational in future winters, whether or not the river freezes completely? Both the short and long term approaches are discussed below.

6.3.1 Short term – Winter 2018-2019

Depending on the logistics (costs, timing and resources), which would have to be carefully assessed, short term approaches could conceivably be implemented in time for a 2018-2019 ice operation.

6.3.1.1 Extending a line across the river channel

This is seen as a contingency approach that may turn out to be pivotal. The reason is it would open the door to a number of options. Some are proposed in this report, others may stem from later discussions. The strength of that line would depend on deployment and planned usage. It could be a light steel cable that would be brought across the partly frozen ice surface with a helicopter, should this option be retained looking forward. That line could then be used to bring across heavier gage cables as required. If the line is meant to lie on the riverbed before freeze-up, it would have to be strong enough to withstand the pulling action from above the ice, as the case may be.

6.3.1.2 Recourse to a boom

Recourse to a boom would address both causes (A and B) mentioned above. On the one hand, it would capture and immobilize ice drifting from upstream, if any, allowing it to freeze in place an establish a stable platform that could then be thickened. A number of options for deployment of that boom are included in this report – there might be others. This approach would require some anchoring considerations and line load analyses.

6.3.1.3 Spray ice – a valid alternative

Spray ice can be an effective method to address cause A above. But it has to be well planned (as discussed in section 5.3).

6.3.1.4 The sand bar at the Klondike River junction

There is little doubt that, if the sand bar's dimension has increased significantly in the recent past, this will have an impact on the Yukon River flow behavior. Reducing the size of that bar, i.e. through dredging, would probably promote a more uniform flow across the river channel. If so, that would help river freeze-up. This would have to be confirmed with a detailed analysis of river behavior, namely via hydrodynamic modeling (Appendix A).

6.3.1.5 Dawson City's WWTP

It is also likely that the WWTP's effluent is affecting the river's temperature, but it is not known whether or not this effect is significant. Again, this would have to be looked into more closely, e.g. via a plume modeling exercise (Appendix C). In the short term, it might be helpful to divert the effluent outlet further downstream, e.g. by adding an extension to the existing pipes, if there is a quick, affordable and practical way of doing so. Another possibility is to find a way to cool down the effluent before it reaches the river.

6.3.2 Long term – Winter 2019-2020 and later

If the Dawson City ice bridge is to be used in the long term despite climate change, YG may have to adopt an overall strategy that would ensure the structure remains available. There are ways to get this bridge to operate safely and effectively every year, as it has historically. An enticing benefit from the implementation of a mitigation strategy is that YG and the community would no longer have to be as concerned about whether or not there will be an open water lead at the ferry crossing any given winter. In order to achieve this, however, YG's traditional modus operandi with regards to bridge construction would have to be revisited, and new field procedures would have to be devised and honed.

6.4 Understanding the river

During the Dawson City Open House, it was acknowledged via various comments that the river is not behaving the way it used. This can be investigated. In that regard, a general course of action may be envisaged, with three basic objectives:

1) To examine all relevant databases that have not yet been examined or collected, and conduct analyses on those that exist and are available. A preliminary listing has been tabulated in this report – they are a good source of information – some have been examined by NRC already.
2) To devise a field instrumentation scheme that would target data gaps and provide the required information in support of the new modus operandi, i.e. a standard protocol for the yearly bridge construction and maintenance. A means of improving local weather forecasting should also be explored.
3) To devise a protocol that will allow the on-going use of that crossing, so as to offset the impact of a warming climate. Said impact is likely to change over the years, which will be reflected by factors such as water and air temperatures. An understanding of these changes would guide bridge construction. For instance, if the average water temperatures over the fall are considerably higher than the historical ones, this could indicate bridge construction should start later.

7 Way forward

From an engineering perspective, ice is a highly convenient building material, for a number of reasons, namely: it is not only 'self-created' but it also removes itself at the end of the winter. For this reason, it has been used extensively throughout history for transportation purposes. The challenge is that we have little control over these processes. Our ability to predict them (e.g. when is the river going to freeze? Will it freeze entirely or will we see open water leads again) is also very limited. Hence, the way forward needs to be carefully assessed, and in a timely manner.

For the winter of 2018-2019, YG is currently leaning toward implementing the mitigation approach, i.e. preparations will be put in place to build an ice bridge at the George Black Ferry crossing location. As it stands, YG is considering the boom solution. Procedures for deployment have yet to be decided upon. Similarly, the details of ice bridge construction will be looked into – they will depend on the state of the river in December.

YG will be issuing a tender in the fall of 2018 for construction of an ice bridge on the Yukon River at Dawson City at the George Black Ferry crossing location. The project includes, but is not limited to:

1. Supply and installation of a boom
2. Construction of the Ice Bridge
3. Traffic Control
4. Environment Compliance

High level milestones for the way forward are summarized in Table 2. In this report, we discussed the possibility of improving our understanding of the Yukon River in the longer term. YG could mobilize its internal expertise and that of other organizations as required to address this topic.

Table 2 - High level milestones for the construction of the Dawson City ice bridge for the winter of 2018-2019.

	Milestone	Date
Design and Construction	Draft Tender Document Complete	October
	Risk Management Plan and Initial Risk Assessment Complete	October
	Final Tender Document Complete	October
	Tender Advertisement	October
	Tender Close	November
	Construction Contract Secured	November
	Construction Start	November-December
	Construction End	January-March
	Final Contract Completion (Close-out)	End of March

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TABLES ON DATA SOURCES

- The following tables contain links to information and data that could provide guidance in future analyses. The data was divided into three types (right-hand column):
  - Type 'A': Data that were obtained while working on the present work.
  - Type 'B': Data that exist, but could not be obtained as of this writing.
  - Type 'C': Data that do not exist but should be generated starting this year, to help with bridge operation in future years.

Table 3: Hydraulic, Hydrologic, and Watershed Data

Description	Source	Notes	Links	Type
Water Level at Dawson	Water Survey of Canada	Additional water level measurements may be required if hydrodynamic modeling is desired.	https://wateroffice.ec.gc.ca/	A/C
Flow at Dawson	-	A water level gauge exists at Dawson. The gauge can be used to measure flow if a stage-discharge relationship is developed. Other estimation methods may be employed to estimate flow at Dawson based on downstream gauge at Eagle, AK or based on hydrologic analyses.	-	C
Flow through other channels in Yukon River Watershed	Water Survey of Canada	66 gauges identified in Yukon River watershed with flow data for unregulated streams.	https://wateroffice.ec.gc.ca/	A
Permafrost Data	U.S. Geological Service	Data include active layer depth, soil moisture, soil temperature, and air temperature. One dataset collected in vicinity of Dawson, and one dataset collected in vicinity of Eagle, AK.	https://www.sciencebase.gov/catalog/item/5941496be4b0764e6c64a4db	A
Permafrost Probability Map	Bonnaventure and Lewkowicz [34]	Interpolative combination of seven local high-resolution empirical-statistical models (30 x 30 m grid cells), each developed by using the measured temperature at the bottom of the snowpack in winter and by verification of frozen-ground in summer.	http://permafrost.gov.yk.ca/data/permafrost_probability_map/	A

Borehole Data	Geological Survey of Canada	Borehole data are available along Alaska Highway route, but not in the vicinity of Dawson.	http://permafrost.gov.yk.ca/data/arcgis/	A/C
Surficial Geology	Geological Survey of Canada and Yukon Geological Survey	Data are available within the Yukon River watershed at scales of 1:20k, 1:25k, 1:50k, and 1:250k. In the vicinity of Dawson, surficial geology data are available at a scale of 1:250k.	http://www.geology.gov.yk.ca/digital_surficial_data.html	A
Vegetation	Yukon Government	Vegetation inventory data are available at a 5k or 40k resolution.	http://mapservices.gov.yk.ca/GeoYukon/; ftp://ftp.geomaticsyukon.ca/GeoYukon/Forestry/VEGETATION_INVENTORY_5K; ftp://ftp.geomaticsyukon.ca/GeoYukon/Forestry/VEGETATION_INVENTORY_40K	A
Elevation	Yukon Government Department of the Environment	A 30 m and 90 m digital elevation model is available from the Yukon Government Department of the Environment. However, the download link appears to be broken.	http://www.env.gov.yk.ca/publications-maps/geomatics/data/30m_dem.php	B
Bedrock Geology	Yukon Government	-	http://mapservices.gov.yk.ca/GeoYukon/; ftp://ftp.geomaticsyukon.ca/GeoYukon/Geological/BEDROCK_GEOLOGY	A

Table 4: Satellite and Other Imagery

Description	Source	Resolution	Years	Notes	Links	Type
Optical Satellite Imagery	Landsat 1-5, 7, 8;	15 – 120 m	1972 – present		https://earthexplorer.usgs.gov/	A
	Sentinel 2	10 – 60 m	2014 – present		https://earthexplorer.usgs.gov/	A
	Sentinel 3	-	2016 – present		https://sentinel.esa.int/web/sentinel/sentinel-data-access	A/B
	Resourcesat 1 & 2	24 – 56 m	2003 – present		https://earthexplorer.usgs.gov/	A
	Terra and Aqua (MODIS)	250 m	2000 - present		https://worldview.earthdata.nasa.gov/	A

Radar Satellite Imagery	Radarsat 1-2	8x8 – 1x3 m	1995 – present		https://neodf.nrcan.gc.ca/neodf_cat3/; https://earthexplorer.usgs.gov/	A/B
	Sentinel 1	5x5 – 25x100 m	2014 – present		https://sentinel.esa.int/web/sentinel/sentinel-data-access	A/B
	Sentinel 3	-	2016 – present		https://sentinel.esa.int/web/sentinel/sentinel-data-access	A/B
Thermal Satellite Imagery	Landsat 4-5, 7, 8	60 – 120 m (resampled to 30 m)	1982 – present		https://earthexplorer.usgs.gov/	A
	Sentinel 3	-	2016 – present		https://sentinel.esa.int/web/sentinel/sentinel-data-access	A/B
Commercial Optical Satellite Imagery	WorldView 1-4	0.30 – 7.5 m	2007 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	GeoEye	0.5 – 2 m	2009 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	QuickBird	0.6 – 2.4 m	2001 – 2015	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	IKONOS	0.8 – 4 m	1999 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B

	KompSAT	0.55 – 5 m	2005 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	Pleiades	0.5 – 2 m	2012 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	SPOT 6-7	1.5 – 6 m	2013 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	SPOT Mosaics	1.5 – 2.5 m	2005 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	RapidEye	5 m	2008 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	TerraColor NextGen	15 m	2015 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
	Harris Globe	15 m	1999 – 2003	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
Commercial Radar Satellite Imagery	TerraSAR-X	≥ 0.25 m	2007 – present	Some commercial satellite imagery products have already been purchased by the Yukon Government.	https://www.harrisgeospatial.com/	B
Aerial Photographs	Skyline Air Photo Locator Map Tool			Additional photographs during winter may be valuable.	http://www.emr.gov.yk.ca/library/skyline.html	A/C
	GeoYukon Map Tool			Additional photographs during winter may be valuable.	http://www.geomaticsyukon.ca/maps	A/C

Ground-level photos	Yukon River Breakup Blog			Annual photo documentary of Yukon River ice breakup at the confluence of the Yukon and Klondike Rivers.	http://www.yukonriverbreakup.com/	A
Webcam	Dawson City Fire Hall webcam			Webcam positioned at Dawson City Fire Hall facing west-north-west at the Yukon River. Additional, strategically placed, webcams may be valuable.	http://dawson.meteomac.com/	A/C

Table 5: Water quality

Description	Location	ID	Years	Measurements	Link/Source	Type
Placer Water Quality Monitoring	Yukon River upstream of Klondike River	YN16	2007, 2010 – 2012	Total suspended solids; pH; conductivity; settleable solids; turbidity; flow; daily loading; air temperature; water temperature.	http://mapservices.gov.yk.ca/PlacerAtlas/Load.htm	A/B
	Yukon River at Dawson City ferry landing	YN15	2010 – 2013	Total suspended solids; pH; conductivity; settleable solids; turbidity; flow; daily loading; air temperature; water temperature.	http://mapservices.gov.yk.ca/PlacerAtlas/Load.htm	A/B
	Klondike River mouth	KL01	2007 – 2008, 2010 – 2016	Total suspended solids; pH; conductivity; settleable solids; turbidity; flow; daily loading; air temperature; water temperature.	http://mapservices.gov.yk.ca/PlacerAtlas/Load.htm	A/B
	Klondike River at Marcels Sauna	KL03	2007 – 2016	Total suspended solids; pH; conductivity; settleable solids; turbidity; flow; daily loading; air temperature; water temperature.	http://mapservices.gov.yk.ca/PlacerAtlas/Load.htm	A/B
	Klondike River downstream of Goring Creek and upstream of Hunker Creek	KL04	2008, 2015	Total suspended solids; pH; conductivity; settleable solids; turbidity; flow; daily loading; air temperature; water temperature.	http://mapservices.gov.yk.ca/PlacerAtlas/Load.htm	A/B

Water Licence Water Quality Monitoring	Sewage treatment effluent	DC-3	1989 – present	Effluent discharge; effluent temperature	Provided by Yukon Government	A
	Yukon River immediately upstream of sewage treatment plant outfall	DC-4	1990 – present	-	http://www.yukonwater.ca/monitoring-yukon-water/water-data-catalogue	B
	Yukon River 300 m downstream of sewage treatment plant outfall	DC-5	1990 – 1999	-	http://www.yukonwater.ca/monitoring-yukon-water/water-data-catalogue	B
	Yukon River 750 m downstream of sewage treatment plant outfall	DC-6	1989 – 1999	-	http://www.yukonwater.ca/monitoring-yukon-water/water-data-catalogue	B
Current water quality measurements downstream of sewage treatment plant outfall	-	-	-	-	-	C

Table 6: Channel Morphology

Description	Source	Notes	Links	Type
Historical bathymetry of Yukon River near Dawson	Ice jam flood assessment: Yukon River at Dawson (Gerard et al., 1992 in [1])	11 cross-sections of the Yukon River are included in the report, 9 of which are located in the vicinity of Dawson.	-	B
Recent bathymetry of Yukon River near Dawson	-	Required if hydrodynamic modelling is desired.	-	C
Sediment deposition at confluence of Klondike and Yukon River	-	Characterized through survey or through change detection conducted on satellite, aerial, or ground-level imagery, for example.	-	C
Sediment transport measurements along Klondike River near Dawson	Placer Water Quality Monitoring	Some data regarding total suspended solids are available from Placer Water Quality Monitoring reports.	http://mapservices.gov.yk.ca/PlacerAtlas/Load.htm	B/C

Table 7: Meteorology (within ~50km radius of Dawson, YK) (*: Hourly data not available for that parameter).

Description and Link	ID	Air Temperature	Precipitation	Hourly	Daily	Monthly	Type
Environment and Climate Change Canada historical weather and climate (http://climate.weather.gc.ca/historical_data/search_historic_data_e.html)	2100400	Yes	Yes*	Yes (1953 – 1976)	Yes (1897 – 1979)	Yes (1897 – 1979)	A
	2101062	Yes	Yes	No	Yes (1984 – 1986)	Yes (1984 – 1986)	A
	2100398	Yes	No	No	Yes (1890 – 1901)	No	A
	2100405	Yes	Yes	No	Yes (1974 – 1976)	Yes (1976)	A
	2100164	Yes	Yes	No	Yes (1975 – 1976)	Yes (1975 – 1976)	A
	2100407	Yes	No	Yes (2014 – 2018)	No	No	A
	2100401	Yes	No	Yes (2013 – 2018)	No	No	A
	2100402	Yes	Yes*	Yes (1976 – 2013)	Yes (1976 – 2015)	Yes (1976 – 2007)	A
	2100LRP	Yes	Yes*	Yes (1995 – 2018)	Yes (1995 – 2018)	Yes (1999 – 2007)	A
	2101070	Yes	Yes	No	Yes (1918 – 1929)	Yes (1918 – 1929)	A
Community Service Weather Stations (http://www.yukonwater.ca/monitoring-yukon-water/water-data-catalogue)	KLONDIKEFC	-	-	-	-	-	B
	ANTIMONYYCK	-	-	-	-	-	B
Placer Water Quality Monitoring – Compliance Monitoring and Inspections Weather Station	KL02	-	-	-	-	-	B
	KL_BO01	-	-	-	-	-	B
	KL_BO_EL01	-	-	-	-	-	B

(http://mapservices.gov.yk.ca/PlacerAtlas/Load.htm)	KL_BO08	-	-	-	-	-	B
	KL_NK01	-	-	-	-	-	B
	KL_HU09	-	-	-	-	-	B

Table 8: Adjusted and Homogenized Canadian Climate Data

(http://www.ec.gc.ca/dccha-ahccd/?wbdisable=true)
Supplementary to the meteorology data table, this table summarizes long-term Adjusted and Homogenized Canadian Climate Data (AHCCD) available in Yukon Territory. Any weather stations within ~50km of Dawson, for which an AHCCD record exists are identified.

Description	Number of Stations in YK	Stations within ~50km of Dawson (Years of Record)	Type
Surface Air Temperature	11	2100LRP (1901 – 2017)	A
Precipitation	16	2100402 (1901 – 2015)	A
Wind Speed	5	-	A
Sea-Level Pressure	22	2100400 (1953 – 1976) 2100402 (1976 – 2014)	A
Station Pressure	22	2100400 (1953 – 1976) 2100402 (1976 – 2014)	A

APPENDIX A – RIVER HYDRAULICS

A brief overview of channel evolution

In natural rivers with alluvial channel substrates such as gravel and sand, a complex feedback relationship exists amongst flow hydraulics, channel geometry, and sediment transport [20]. The term 'channel geometry' refers to the three-dimensional form of the channel including cross-sectional form, the bed configuration, planimetric geometry (straight channel, meandering channel, braided channel, etc.), and the channel bed slope [20]. Figure A1 illustrates some examples of planimetric alluvial channel forms [22]. Hydraulic flow characteristics are largely governed by the form resistance imposed on the flow by the geometry of the channel which is essentially characterized by the arrangement of alluvial sediments. However, shear forces exerted by the flow can mobilize and transport sediment, reshaping the channel geometry. Accordingly, sediment transport and channel geometry are influenced by the flow, and the flow is influenced by the reshaping of the channel geometry driven by sediment transport and deposition.

Conceptually, an 'equilibrium channel' is one that is just capable of conveying the sediment load that is delivered to the system over the long-term such that erosion and deposition are approximately balanced. Natural channels never truly achieve a state of static equilibrium because, in addition to other contributing factors, upstream flow and sediment inputs vary temporally. However, over time, natural channels will adjust toward an equilibrium state by altering channel geometry, and consequently, form resistance [20].

To better understand the relationship between flow hydraulics and channel geometry, a discussion of erosion and deposition is warranted. Erosion (scour) tends to occur in areas of flow convergence where fast flow velocities are capable of mobilizing sediment and forming a scour pool [20, 35]. Conversely, sediment deposition tends to occur in areas of flow divergence where the capacity to mobilize sediment is diminished. Likewise, channel bars tend to form in areas of flow divergence where sediments are deposited by the flow.

This phenomenon can be illustrated through a discussion of flow through a meander bend and point bar formation. In general, flow through a meander bend can be described by the following characteristics:

- Superelevation of the water surface against the outer bank;
- a transverse current directed toward the outer bank at the surface of the flow, and toward the inner bank at the channel bed (referred to as secondary flow or secondary circulation); and
- a maximum velocity current which tends toward the inner bank in the upstream limb of the bend, crosses the channel at the apex of the bend, and descends below the surface past the apex of the bend.

These characteristic flow patterns are illustrated in Figure A3. Accordingly, scour tends to be concentrated on the outer bank of a meander bend downstream of the apex where flow converges and where secondary flow is directed downward toward the bed. Close to the channel bed, secondary flow conveys mobilized sediment toward the inside of the bend where it is deposited. Point bars form as sediment accumulates on the inside of the meander bend. Upon exiting the bend, the flow diverges before entering the next bend and sediment is deposited in the form of a riffle. This process is illustrated in Figure A4.

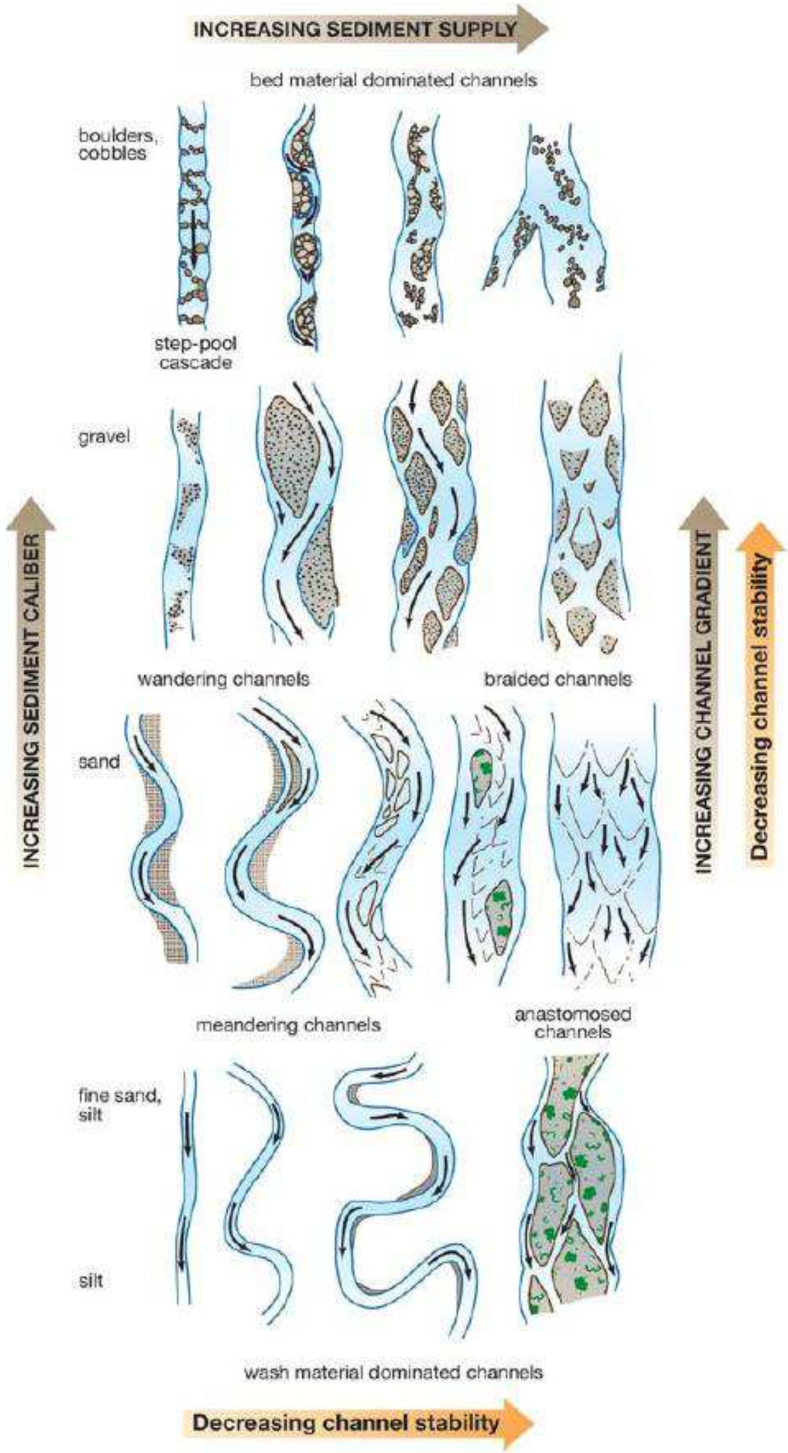

Figure A1: Examples of alluvial channel forms [22].

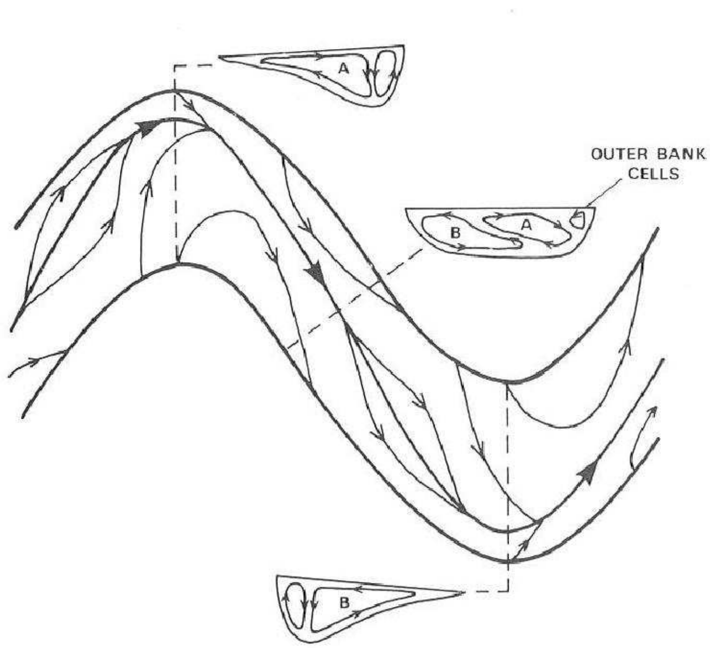

Figure A3. Flow through a meander bend. Arrows depict the direction of flow. Flow converges toward the outer bank at the bend apex and diverges upon exiting the bend. Cross-sections, displayed from the perspective of a downstream observer looking upstream, illustrate secondary flow. Figure obtained from [20] and adapted from other sources.

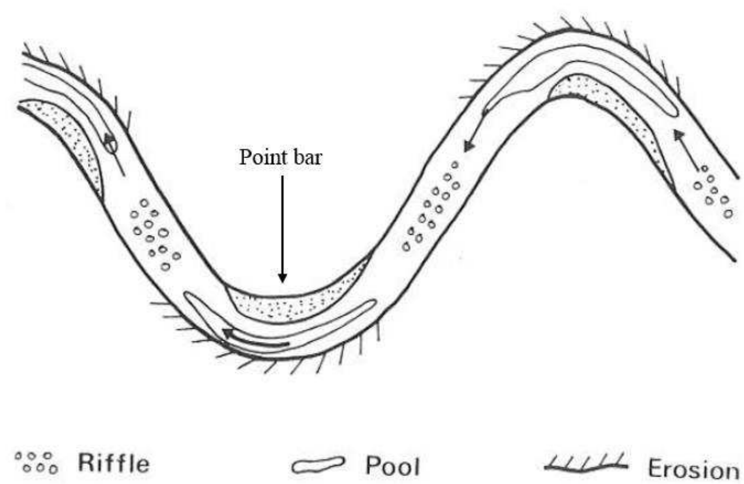

Figure A4. Characteristic bed geometry of a meandering channel. Mid-stream arrows depict the general direction of flow. Figure obtained from [20] adapted from other sources. Label added to figure to indicate location of point bar.

In summary, flow hydraulics, channel geometry, and sediment transport are intrinsically linked to one another in natural rivers with alluvial channel substrates. The channel geometry is shaped and altered by sediment mobilized and deposited by the flow. Likewise, the geometry of the channel influences hydraulic flow patterns and the capacity for the flow to mobilize and deposit sediment. The tendency for natural channels to adjust toward an equilibrium state brings rise to cross-sectional, planimetric, and longitudinal adjustments in channel geometry as well as the formation and alteration of bedforms such as bars and dunes.

One-Dimensional, Two-Dimensional, and Three-Dimensional Numerical Hydrodynamic Modeling

Numerical models are frequently used to characterize and predict hydrodynamic conditions (principally meaning water levels, and flow velocities) in riverine, coastal and estuarine systems. A variety of open-source and commercial software tools are available to simulate free surface hydrodynamics in one, two, or three dimensions. Prerequisites for developing site-specific hydrodynamic models typically include bathymetry and topography data, and field hydrographic data (e.g. measurements of water levels, flow velocities, river discharges). The latter are required to provide boundary conditions and to support model verification.

Three-dimensional models, based on the numerical solution of the incompressible Navier-Stokes equations [36] are the most complex and computationally demanding. These models are capable of predicting water levels, and flow velocities in all three spatial dimensions (downstream, across-stream, and vertically in the water column). They are often required to simulate hydrodynamic conditions in systems where there is significant vertical variability in the flow field, e.g. resulting from steep gradients in bathymetry, or baroclinic effects (i.e. density-driven flows).

Two-dimensional models typically simulate hydrodynamics based on the depth-averaged shallow water Saint Venant equations, derived from the Navier-Stokes equations [37, 38]. As the equations are depth-integrated, these models are capable of predicting depth-averaged horizontal flow velocities (e.g. along x- and y- axes of a Cartesian co-ordinate system) but not vertical velocities or gradients [38].

One-dimensional models simulate hydrodynamics based on the one-dimensional Saint Venant equations and are capable of simulating flow in one dimension (downstream) only [37]. The simulated results from a one-dimensional model represent quantities that are averaged over the entire channel cross-section. One-dimensional models are not capable of simulating across-stream or vertical flow velocities, velocity gradients, or across-steam water level gradients.

APPENDIX B – CLIMATE CHANGE

Relationship between global, regional and local

This appendix dwells into the specifics of climate modeling – it is provided as a general reference, for the readers who have a particular interest in this topic. It attempts to capture the overall impact of climate change, i.e. it goes beyond air temperature and how it may affect the Yukon River. For more information on this topic as it pertains to Dawson City, see [39, 40],

An overview of climate models

According to the Intergovernmental Panel on Climate Change (IPCC), climate change impacts are generally evaluated based on simulations performed with Global Climate Models (GCMs) under prescribed GHG emissions scenarios, such as SRES (Special Report on Emissions Scenarios) [41] and more recently introduced, Representative Concentration Pathways (RCPs) [42]. Currently, simulations from over 40+ GCMs are available through CMIP5 (Climate Model Inter-comparison Project Phase 5) corresponding to various RCPs. Irrespective of the origin and complexity of the climate model, the majority of these simulations predict warming of the Earth's temperature with increases or decreases in precipitation at different temporal and spatial scales in different parts of the world (see Figure B1). There is a direct effect of these changes on the hydrological cycle and this will have a significant effect on local and regional water resources, and water conveyance, storage and distribution systems. Different climate change scenarios are based on various assumptions about population growth, energy needs and means of energy production, geographical distribution of production and wealth, and expected economic developments. These assumptions are the main sources of uncertainty of the IPCC's assessments.

GCMs operate at much coarser resolutions of the order of 100–300 km and hence their outputs are not directly useful for many practical engineering applications, which are generally of a local nature. Additionally, guidelines on their practical usages are not yet available widely for many parts of the world. In order to understand the impacts of climate change on various local and regional scale variables or phenomena of interest, as well as to generate appropriate knowledge and scientific information from GCM outputs, scientists have devised downscaling approaches. These approaches can be classified broadly into statistical and dynamical downscaling [43].

In dynamical downscaling, Regional Climate Models (RCMs) driven by outputs from GCMs are used to study impacts of climate change [44]. RCMs, due to their higher spatial resolution (10-50 km) compared to that of the GCMs, are able to resolve many local scale topographic features and characteristics of extreme events better than GCMs (e.g. [45]). Despite being more efficient in capturing local scale features than the driving GCMs, RCMs are computationally expensive and consequently multiple simulations from RCMs for uncertainty analysis are still limited. As the RCMs are nested within the domains of GCMs, RCM simulations are likely to inherit some of the biases of the driving GCMs. In spite of the above mentioned difficulties and challenges, the use of RCM simulations for climate change impact analysis is consistently on the rise [46-64] and some modeling groups have even started producing RCM simulations with 2-5 km horizontal resolution.

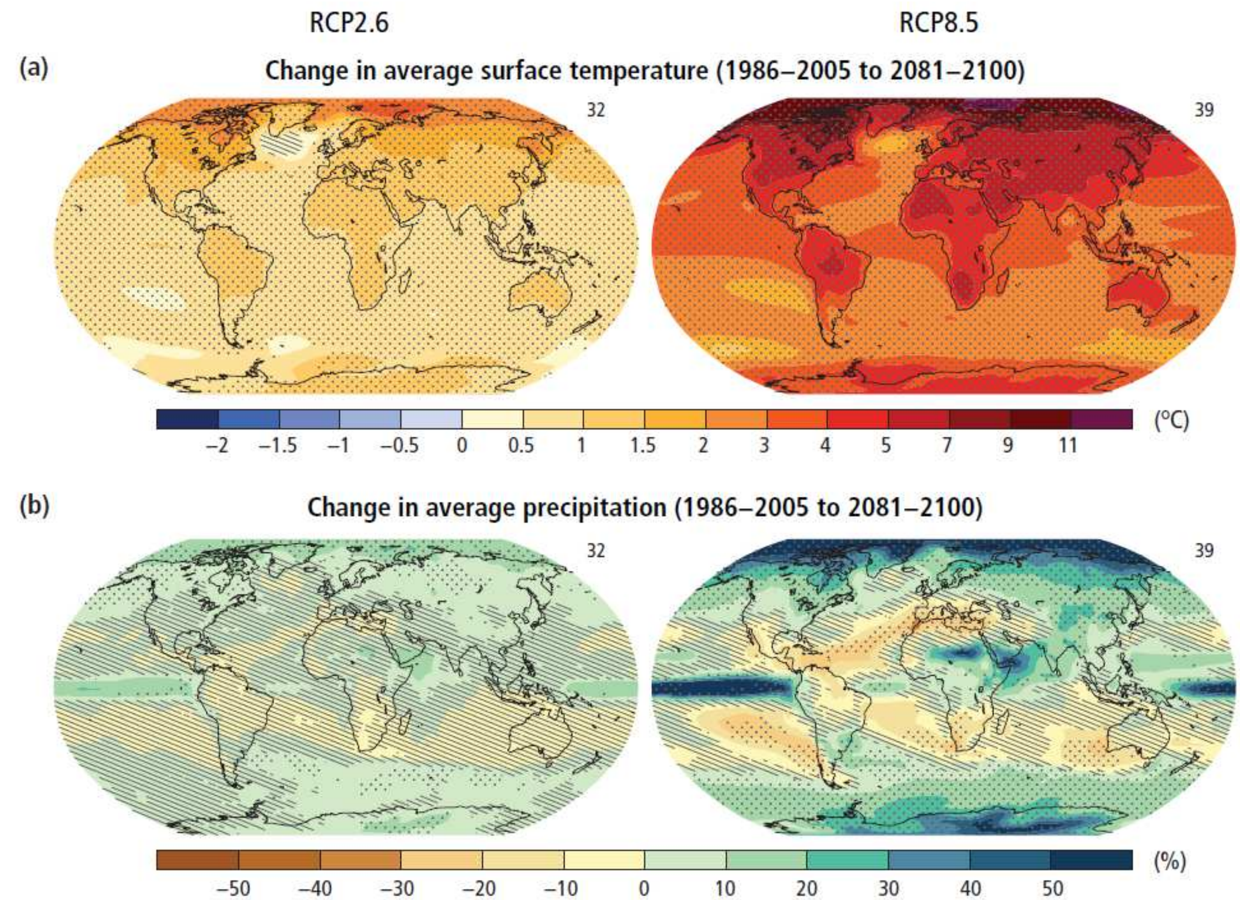

Figure B1: CMIP5 multi-model mean projections (i.e., the average of the model projections available) for the 2081–2100 period relative to the 1986–2005 period under the RCP2.6 (left) and RCP8.5 (right) scenarios for (a) change in annual mean surface temperature and (b) change in annual mean precipitation, in percentages. The number of CMIP5 models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (dots) on (a) and (b) indicates regions where the projected change is large compared to natural internal variability (i.e., greater than two standard deviations of internal variability in 20-year means) and where 90% of the models agree on the sign of change. Hatching (diagonal lines) on (a) and (b) shows regions where the projected change is less than one standard deviation of natural internal variability in 20-year means. Figure adopted from [42].

Compared to the dynamical downscaling approach, the statistical downscaling approach is based on empirical relationships between observations and large-scale GCM features [47]. This methodology has the advantages of being inexpensive and computationally simple. Some statistical downscaling approaches can also produce ensembles of simulations, allowing better quantification of uncertainty in the projected climate change. Wilby and Wigley [43] provide classification of statistical downscaling approaches. These approaches can be classified into three main categories: (1) regression methods or transfer functions, (2) weather typing, and (3) weather generators. Transfer functions are based on direct quantitative statistical relationships between predictand and predictors, while weather typing approaches involve grouping of atmospheric circulation patterns in relation to selected climatic variables. Weather generators consist of several statistical relationships that depend on large-scale atmospheric features for deriving their parameters. A common assumption involved in all statistical downscaling approaches is that the physical relationships underlying the statistical relationships identified over a selected historical period are also valid for the targeted future period [43, 65].

As the climate continues to change, the difficulty of maintaining a robust and reliable water infrastructure system increases. This is especially true because the infrastructure sectors have developed into highly technical and interconnected systems. If one sector or component of the system is at risk, so is the rest at various levels of hierarchy. If extreme weather (e.g. floods) damages energy or water supply systems, then all other services will be affected too, causing a cascade of failure [66]. The interdependencies between climate change and infrastructure need to be managed well considering both the present day and future warming effects.

Implications of climate change for water resource systems and river flow dynamics

Various reports of the IPCC on climate change impact studies (e.g. [41, 42]) suggest large differences in the vulnerability of water resource systems to changes in climate variables. Long-range water availability and short-term variability are expected due to climate change. Potential regional impacts of climate change could include changes in the frequency and magnitude of high flows, low flows and long-term changes in mean renewable water supplies through changes in precipitation, temperature, humidity, wind speed, duration of snowpack, nature and extent of vegetation, soil moisture, and runoff [67].

Temperature is an important factor in determining key vulnerabilities for water resources. Higher temperatures will intensify the hydrological cycle, resulting in increased evapotranspiration, hence increased risk of droughts, and intense precipitation events as a warmer climate can hold more moisture. In cold climates, higher temperatures will also result in more precipitation as rain rather than snow. This could have important consequences for regions dependent on snowpack [68]. An obvious example is the Yukon River basin.

While global precipitation will rise with higher temperatures and broad patterns of change in precipitation are becoming clearer, there is still substantial uncertainty about how regional patterns of precipitation might change in the future. Precipitation in its different forms is the main driver for river flows. Nonetheless, some statements can be made about differences in vulnerability of water infrastructure to changes in water supplies across regions and watersheds.

A word on climate risk management

It is important to note that the future can no longer be assumed to be like the past, and that the future is uncertain. Scientists agree almost universally that more unusual weather patterns are expected to occur in the future. Water infrastructure and other systems are not built to withstand a rapidly intensifying hydrological cycle and unusual weather patterns due to climate change. Managing climate risks across appropriate scales and different groups and locations is a formidable task. The present management of any infrastructure or facility is becoming more important and complex due to the projected effects of climate change. Therefore, it will be necessary to undertake targeted investigations and modeling exercises to understand the causes and consequences of unusual hydro-meteorological events in order to inform appropriate adaptation measures or adapt other cost-effective alternatives (i.e. essential engineering structures) in order to sustain human society and regional/local economic activities.

APPENDIX C – DAWSON CITY'S WWTP PLANT

Prospective effluent impact on the river's freeze-up behavior

In this appendix, we look at the effluent from the Dawson City's Waste Water Treatment Plant (WWTP) located upstream of the bridge and its potential impact on the river dynamics. An overview of the plume nature and the dominant factors on its behavior will be discussed, the possible impacts of the WWTP effluent on the region of interest will be explained, and some practical approaches will be suggested for the future investigation of the phenomenon.

Effect of a WWTP on a receiving water body

A waste water treatment plant effluent normally has a higher temperature than its receiving environment. It can thus can be classified as a thermal plume. Thermal plumes are normally less dense than the ambient environment and move toward the water surface. Plume mixing is typically studied in two stages, based on the proximity of the region of interest to the outfall:

- Near-field: The near-field is the region in close proximity to the outfall (typically on the order of meters to a few hundred meters) where the effluent plume or jet behavior and trajectory is predominantly governed by the momentum and buoyancy of the discharge relative to ambient conditions.
- Far-field: The far-field is the region where plume mixing processes are dominated by ambient advective and dispersive processes (driven by tides, river discharges and baroclinic effects), and may extend several kilometers from the outfall.

Effluent discharges can be conveyed through open channels, a single pipe, a multiport diffuser, or other outfall structures. In general, the rate of dilution and the behavior of an effluent in the near-field is dependent on the nature of the receiving environment. Parameters include: hydrodynamics and temperature, discharge characteristics (flow rate, temperature) as well as the outfall specification (e.g. orientation, size, port location along a diffuser, surface discharge or depth of submerged discharge, distances from walls). Figure C1 provides some examples of effluent behavior depending on the outfall design, location and the receiving environment.

The plume dynamics and behavior in the near-field of an outfall is controlled by its dominant driving forces. The forces may be originated from the difference in the momentum (velocity/flow rate) or density (temperature) of the effluent, and the ambient environment.

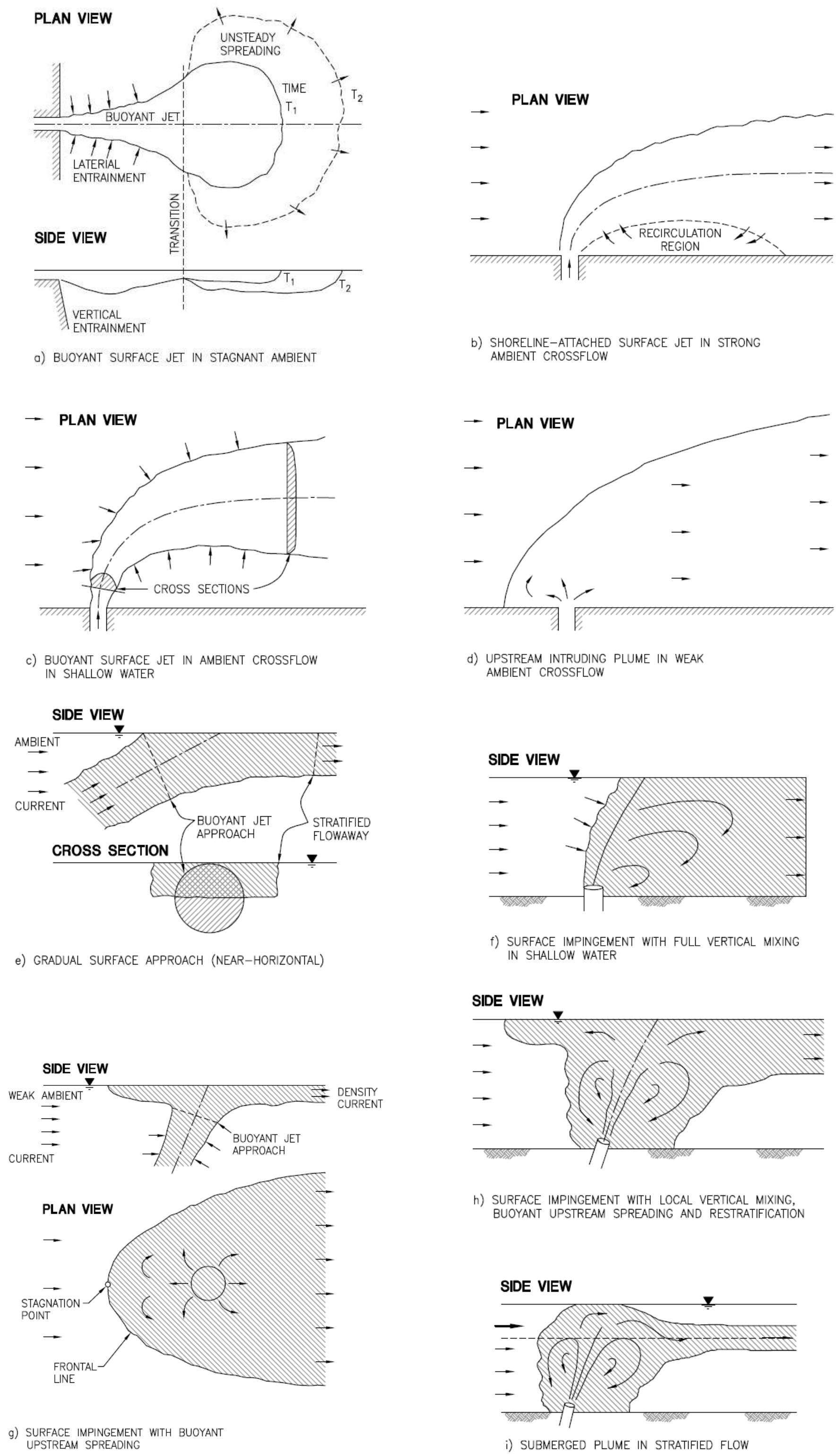

Figure C1: Range of effluent plume behavior depending on outfall configuration and receiving environment [69].

When a thermal plume enters the receiving environment, the momentum exchange caused by the difference in the water particles velocity in the effluent and the ambient flow may cause linear spreading of the plume in the near-field of an outfall both in horizontal and vertical directions. This mechanism is also known as jet-mixing. The outflow and the ambient flow velocity are the parameters that control the jet-mixing process of an outfall. The initial momentum of the outflow dissipates gradually with distance from the outfall while the buoyancy forces become more significant. The buoyancy-derived forces generated from the lighter density of the effluent move the effluent to the surface of the ambient water. These forces enhance the mixing process through the buoyant-mixing mechanism. The buoyant mixing is more significant when farther from the high-momentum region in the vicinity of the outfall. The extent of the regions dominated by the jet-mixing and the buoyant-mixing mechanisms is determined by the outflow and the ambient flow characteristics such as flow rate, temperature, salinity etc.

The far field is the region where the plume is transported by the ambient current and mixed by the background turbulent diffusion. Effluent mixing in the far-field is mainly caused by the ambient flow advection and diffusion. The far-field mixing process in a river is controlled by the river hydrodynamics affected by several main parameters, such as river geometry, depth, discharge, flow speed, width and ice cover [70].

Relevance to Dawson City WWTP

In Dawson City, a WWTP is located upstream of the bridge which is expected to continuously discharge heated effluent into the river. The highest temperature difference occurs in the near-filed of the outfall which will be gradually dissipated as it mixes with the ambient water, and due to the heat loss at the water surface. As previously discussed, the dissipation rate of the excess temperature is directly related to the discharge characteristics of WWTP, as well as the hydrodynamic and temperature of river flow in the region surrounding the outfall. The hydrodynamic of the river is also controlled by its discharge, morphology and geometry. As the thermal plume moves up toward the water surface, it is likely that under specific effluent or ambient flow conditions the small mixing rate of the effluent prevents rapid dissipation excess temperature and consequently impacts the ice formation pattern both upstream and downstream of the outfall.

To what extent does the WWTP affect ice cover formation?

In order to understand how an effluent behaves in the receiving environment and identify its extent and boundaries, a plume delineation study is required. It provides insight on the fate and the trajectory of the effluent in the receiving water body under different discharge and ambient condition. The study involves a two-stage approach in the near-field and far-field of the outfall and is typically conducted using a combination of monitoring means such as field measurement and remote sensing for assessing the current situation, and numerical modeling for simulating the worst case scenarios.

Field surveys of thermal plumes have been traditionally conducted using temperature sensors. However, recent advances in remote sensing technology has greatly enhanced the popularity of remote sensing approaches in mixing studies, especially in regions where a field survey is not convenient, for instance due to access difficulties. These approaches are based on using remote sensors to measure the volume reflectance. The remittance may be in the visible, near-infrared, or thermal infrared wavelengths. As remote sensing sensors only measure the reflectance, they are normally used in addition to field measurements for calibration purposes. Due to their high spatial resolution and coverage as well as free availability of data, thermal infrared (TIR) photos have been used in a number of previous water surface temperature studies. In one of the most recent studies, _ENREF_67Pilechi [33] used landSat7 (TIR) for the study of the near-field mixing of thermal surface plumes. Thermal infrared satellite images in that case were calibrated using surface water temperature data (see Figure C2).

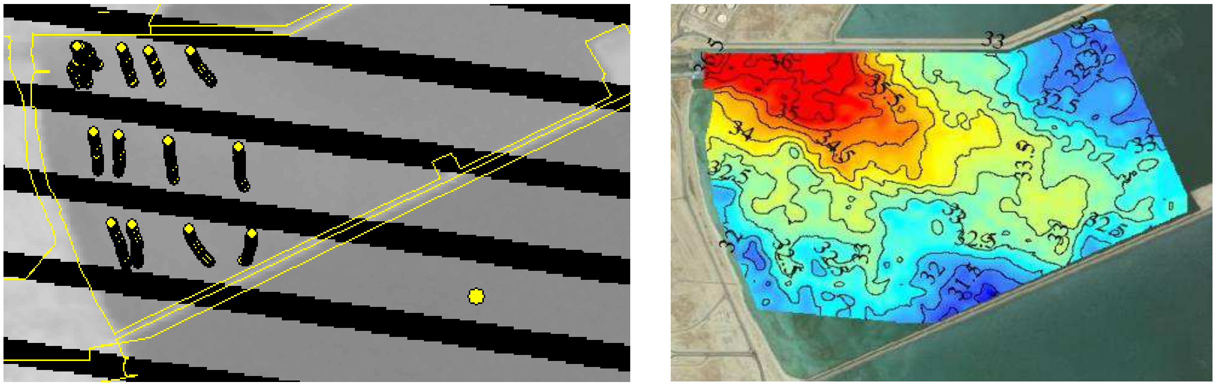

Figure C2: Raw LandSat7 imagery (left) and Calibrated LandSat7 (right).