Yukon University

Improving Winter Discharge Estimates, Phase I – Yukon Pilot Project

Identification of Yukon sites for research to improve winter discharge estimation methods

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1.0 Context

The National Hydrological Service (NHS), an entity of Environment and Climate Change Canada (ECCC), is responsible for the quantification of hydrological parameters at thousands of sites across the country, and for sharing the most accurate and reliable hydrology information with users and stakeholders. In a perspective of continuous improvement of its practice, and in a context of climate change and evolving user needs, the NHS has initiated an exploration project with the Yukon University Research Center (YRC). One component of this project involves the visit of some Water Survey of Canada (WSC) monitoring sites (hydrometric stations) with WSC staff, during winter flow measurement field trips. This short document reports observations made during three field trips, and briefly discusses the implication these observations for the next phases of the collaboration between the NHS and the YRC.

2. Site-specific reports

2.1 Dezadeash River, March 3, 2021, Haines Junction, Yukon

The YRC team (Benoit Turcotte and Stephanie Saal) drove from Whitehorse to Haines Junction to meet with WSC (Wade Hanna and Aaron Donohue) at 13:00. It was a sunny day with a temperature of approximately -10°C. Figure 1 presents a view of the secondary channel in mid-afternoon.

Figure 1. View of the secondary channel of the Dezadeash River, looking downstream, on March 3, 2021.

Technical observations

- The Dezadeash River is partially regulated, with the presence of the Aishihik Generating Station (AGS) far upstream. The operation of AGS often generates daily flow fluctuations on the Aishihik River, in the order of 5 to 8 m3/s) and these are significantly attenuated by the presence of other tributaries fed by large lakes (Dezadeash and Kathleen). Nonetheless, flow variations during winter are detected at Haines Junction through gradual water level variations of a few centimeters, potentially accompanied with measurable flow velocity changes.
- The river at that location is formed by the main channel and two secondary arms, one of which carries water throughout winter. This complicates stream gauging in winter and might also complexifies the development of a rating curve during the open water season.
- The station is located just downstream of Highway 3 bridge. This means that bridge piers and abutments may affect sediment transport and sediment deposition patterns (mostly sand and finer material) on an annual basis, therefore potentially creating annual modification cycles in the shape of the channels cross section.
- The vegetation along the banks at that location is mostly composed of shrubs and bushes while more mature trees grow away from the multi-channel flood plain. This indicates that the channel might not be stable, which is expected, given that the whole area was the bottom of a very large lake less than 2 centuries ago. This means that the channel is still adjusting to these recent geographic changes thought sediment transport.
- On March 3rd, the ice thickness was in the order of 90 cm, which is normal in the area. The ice cover is of the floating type, with grounded ice along the banks. However, banks are relatively steep, and the grounded, thinner portion of the ice cover only represents a small fraction (<10%) of the main channel width.
- There was no loose frazil (slush) detected (during drilling) under the ice cover, which is normal for this time of year (late winter). However, WSC staff confirmed that there is often frazil under the ice cover at that location during the first stream gauging trips of winter, which follow initial river ice formation by frazil interception and consolidation.
- The snowpack in March 2021 is significant in the area (roughly 200% of snow water equivalent historical median), which means that the ratio of white ice (made of frozen saturated snow) is probably more important than usual compared with the lower layer of thermal ice (made of long columnar crystals). This should not have any measurable

impact on the flow distribution but could affect the expected (simulated) ice cover thickness and its backwater effect.

- The WSC team used an ADV to perform the discharge measurement, given that the water depth and flow conditions allow it at that location. This approach provides 2D information about flow distribution under the ice cover and allows for a visual comparison of cross-sectional velocity distribution from year to year.
- The ratio of flow in the secondary channel (Figure 1) was less than expected. This may be caused by unusual freeze-up patterns in October, given that September was characterized by heavy rain and high flows in the watershed (freeze-up might have been more dynamic than usual, but the data at station 08AA003 contains too many gaps to confirm this).

2.2 Takhini River, March 17, 2021, Ibex Valley, Yukon

Benoit Turcotte drove to station 09AC001 to meet with WSC (Pat Maltais and Berenger Rethore) at 11:00. It was a partially sunny day with an air temperature of about -8oC. Stream gauging activities had almost ended at that time, but several observations were made. Figure 2 presents a view of the cross-section.

Figure 2. View of the cross-section of the river (about 100 m) from left bank on March 17, 2021.

Technical observations

- This river is fed by a large lake (Kusawa, 142 km2), and freeze-up and breakup processes are typically of the thermal and gradual types. This winter behaviour is also supported by the low gradient profile of the river in the wide Takhini River valley (meandering morphology with a single channel delimited by mature vegetation or steep sand cliffs along most of the river length).
- Most of the discharge is normally flowing along the left bank at that location, especially at low flow, given the channel alignment. The bed along the right bank is mostly covered by sand whereas the left bank, where velocities are higher, is covered by gravel.
- Both the flow measurement site and hydrometric station are positioned just upstream of the Alaska Highway (Highway 1) bridge. This infrastructure has an impact on the channel cross-section (and on the open water rating curve): It is an artificial narrowing of the channel and its central pier can intercept woody debris (Figure 3). This may affect the link between the ice cover thickness and its backwater effect, which would translate into a poor year-to-year correlation between the ice cover backwater effect and ice cover thickness indicators (such as cumulated degree-days of freezing, CDDF), even during the second half of winter (Figure 4).

Figure 3. Wood accumulation on the upstream side of the pier under the Alaska Highway bridge on the Takhini River. The photo is looking towards the right bank where the station is located.

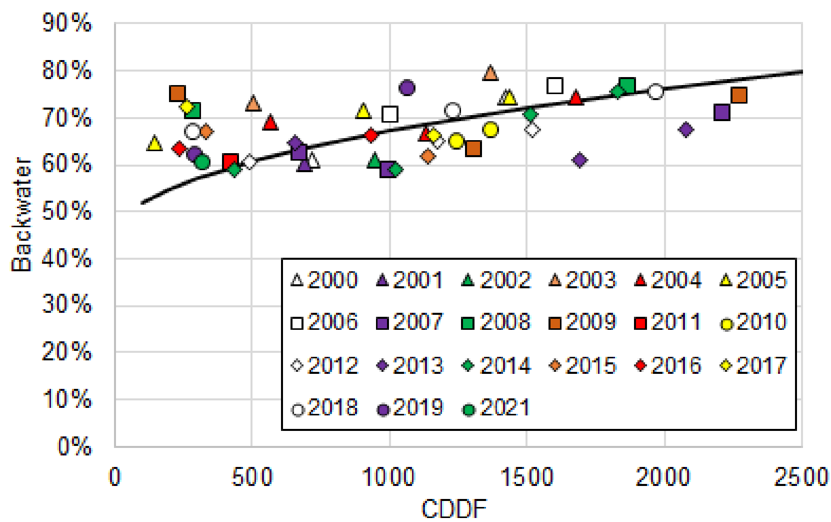

Figure 4. Testing the relationship between calculated historical backwater (%) and cumulated degree-days of freezing in Whitehorse for the Takhini River at the Alaska Highway. There is a large initial scatter, which is a normal post-river ice formation reality, but this scatter does not seem to attenuate over winter.

- On March 17th, the thickness of the ice cover was only 60 cm, which is less than normal. This is probably caused by a combination of mild and snowy winter (with very light and insulating snow). The type of ice cover on this river at that location is floating, with some grounded ice, mostly along the right bank where the water depth is less. Further upstream, in steeper reaches, anchor ice has been observed in the past.
- There can be frazil under the ice cover at that location and this may also affect hydraulic conditions, at least during the first part of winter and until any residual frazil gets incorporated into the ice cover by heat loss from the ice cover surface. In a case of a cold winter following a very dry summer, frazil may get incorporated into the ice cover during the first weeks of the cold season. On the other hand, a snowy and mild winter following a rainy summer (like in 2020) may cause loose frazil to remain in place under the ice cover for several months.
- The flow was measured with a Price current meter (propeller type of instrument), with a mid-depth or 0.2/0.8 velocity measurement at more than 20 locations along the cross-section. This approach is well accepted in winter hydrometry.

2.3 Nordenskiold River, March 18, 2021, Carmacks, Yukon

Station 09AH004 was visited at 11:00 during a winter flow measurement performed by WSC (Pat Maltais and Berenger Rethore). It was another sunny day with a temperature of about -8oC. Figure 5 presents a view of the cross-section (about 30 m) at the beginning of flow measurement activities, starting from the left bank.

Figure 5. View of the channel cross-section just downstream of Station 09AH004, looking at the left bank from the right bank. There is a middle gravel bar with grounded ice.

Technical observations

- This section of the Nordenskiold River is steeper than upstream reaches. The bed is composed of multiple side and mid-channel gravel bars. As a result, most of the ice cover in the channel is grounded and its thickness is largely heterogeneous. This is reflected by the hilly surface of the snow cover in the channel high points corresponding to gravel bars and low points corresponding to fast flowing locations.
- On the left bank, there was virtually no ice right against the bank, which is normal, given 1. that the ice cover elevation drops with the discharge and breaks along the banks and 2. that there are probably additional heat sources in the area (groundwater and increased channel friction) that prevent ice cover thickening. In the main flowing channel, the ice thickness was about 100 cm.
- The freeze-up level was very high in October and November 2020, it followed a rainy summer and fall. As a result, the elevation of the first ice cover formed in the fall (frozen against the bank) was close to the elevation of the floodplain. Intense freeze-up events are typical in that river and often generate the highest water level of the year (Figure 6).

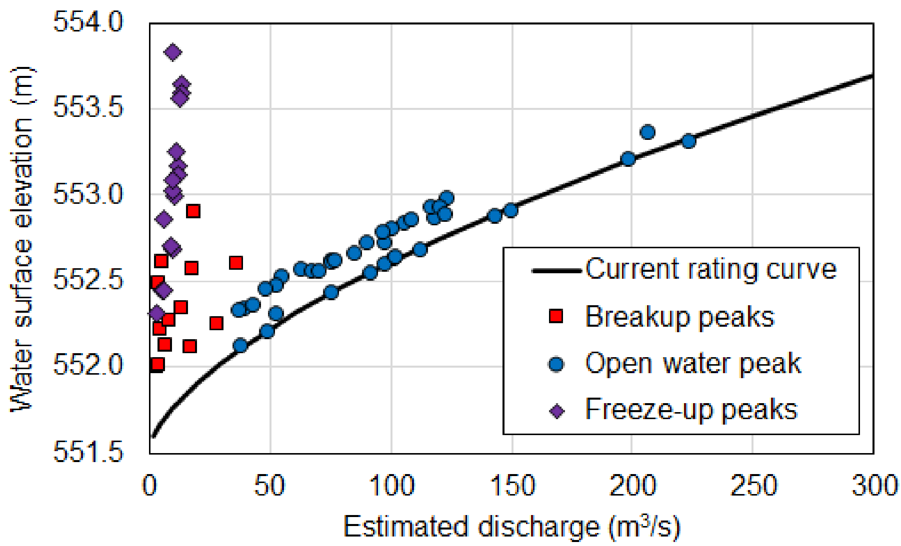

Figure 6. Annual maximum water levels at station 09AH004 during spring breakup (2005-22020), open water (1983-2020) and fall freeze-up conditions (2005-2020). The data suggest that freeze-up conditions most often generate the highest water levels on an annual basis.

- The small and steep characteristic of the channel, and its direct consequence on the type of ice cover, make it very difficult to use the ice cover thickness as a proxy to evaluate the winter backwater effect and discharge.
- The ice cover in the secondary channel (right bank) was dirty, which means that sediment is transported in winter, at least for small particles (sand or smaller, including organic matters). This is expected, given that the channel is very unstable, that broken ice pieces, some of which collapse sideways into the water, generate local erosion conditions. It was also observed that trees have been falling in the water. It is expected that gravel bars are evolving over time. The open water data presented in Figure 6 suggests the rating curve has changed in recent years (probably in 2009). On March 18th, there was a significant amount of snow on the ice cover (snowpack is about 130% of historical median in the area) and there was a subtle transition towards spring conditions, with some border ice slabs starting to collapse under their own weight added to weight of the snow.
- Ice conditions at this site are very complex and may involve anchor ice, border ice, frazil congestion, ice dams, overflow and icing, as well as partially floating and partially cantilevered surface ice. The intensity of one process or another likely varies from year to year and from one channel segment to another.
- The flow was measured with a propeller type of instrument. Holes in the ice cover were close to one another, given the relatively narrow main active channel (less than 10 m).

One could see the water level fluctuation (pressure waves) in the holes, where velocities were the highest under the ice cover.

3. Discussion

Observations and data collection during these trips represent key information for two important aspects of the next project phases.

3.1 Channel classification

Classifying different Yukon watercourses, in terms of channel size, morphology and ice cover types, is important for the development of a national strategy to improve discharge estimations in a broad range of climate and geographic contexts. Here are some key outcomes based on observations made during the three field trips as well as on notes taken over recent years.

- Climate in Yukon is cold (sub-arctic), with mild winters in the south (Whitehorse area) corresponding to 1600 CDDF and cold winters in the north (Old Crow area) corresponding to 4500 CDDF. As a result, a floating ice cover thickness should normally vary from 80 cm to 130 cm between the end of March and end of April.
- The ice cover in smaller rivers, as observed on the Nordenskiold River, is largely heterogeneous and it may compare to what is observed in warmer locations in Canada, even if winter in Yukon is colder. However, in Yukon, the ice coverage does reach 100% of the channel area, and more observations are needed to document the early-winter ice formation process, especially the transition from anchor ice to surface ice formation at the beginning of winter.
- In very small streams (not common within the list of sites monitored by WSC in Yukon), the ice cover thickens faster than the flow recedes, and the groundwater heat is limited. As a result, anchor ice and ice dams generate overflow, and this evolve into massive icing fields. Some streams may stop flowing for several months every winter, which means that the backwater effect reaches 100%.
- Steep streams that are fed by significant groundwater sources or by small lakes during the entire winter period will generate thick icing accumulations. This is especially observed in large braided streams (e.g., the White River, station 09CB001), where more winter observations and research are needed. The WSC staff reports very challenging winter flow measurement conditions in this type of environment and a bridge that constricts the flow in a narrow location is virtually the only hope for a reliable winter discharge measurement in braided rivers. Even in this case, the rating curve may change

drastically from year to year. It is uncertain whether this is due to high open water flows, unusual or common ice conditions, or another geophysical process.

- There are very few bedrock sections along rivers of Yukon compared with what is observed in the Canadian Rockies and on the Canadian Shield that extends from Northwest Territories to Newfoundland and Labrador. As a result, most channels, especially those of large rivers, present a relatively constant gradient. This means that freeze-up events, in terms of spatial and temporal evolution, are relatively easily predictable. In turn, it also means that breakup events are difficult to predict (and the water level signal, difficult to interpret), given that the ice cover resistance and channel geometry are fairly constant over great distances. Finally, the significant amount of sediment available for transport and the relatively young geography generally translates into very mobile channels, with rating curves that are often affected by dynamic breakup events or by high open water flow events.
- Occasional rain-on-snow or melting events rarely generate enough runoff or a measurable rise in discharge. This facilitates winter discharge estimation compared with the more challenging mid-winter hydrological conditions of southern watersheds. Climate change may cause an increase in the frequency of winter runoff events, especially during the first months of winter. The duration of winter (and the hydrologically stable mid-winter period) is also known to shrink as a result of warming temperatures.
- Climate change also results in permafrost thawing and this has an additional impact on channel stability, sediment supply, and river ice processes.

Given these observations, it seems that there are 3 main channel types in Yukon where WSC is producing discharge times series year-round:

- Large, low-gradient rivers located in subarctic climates (e.g., Takhini River and Whitestone River [minimal size for this category], Liard River, Pelly River, Stewart River, Yukon River, Porcupine River), some of which are fed by large lakes and/or by glaciers.
- Steep rivers located in subarctic climates (e.g., Lower Nordenskiold River, Klondike River, Alsek River, Ross River, Ogilvie River)
- Steep streams located in subarctic climates (e.g., Ibex River, Big Creek, Takhanne River, Wheaton River)

There are also regulated rivers, streams located downstream of large lakes, and the large braided White River that represent a unique hydrological environment (comparable to the unmonitored Donjek River). More efforts will be dedicated to classifying all the monitored rivers and streams of Yukon into well-defined (in terms of consistent quantitative parameters) categories, a task that will be greatly facilitated by the documentation of channel gradients.

3.2 Winter streamflow estimation strategies

There is a need to document the stability of channel cross sections during the winter period and from one winter to another in order to develop tools that will facilitate and improve the accuracy of discharge estimation techniques. There is also a need to better document freeze-up and breakup processes than represent “black boxes” from a discharge estimation point of view.

In term of new technologies and more resilient stations, recent and past observations suggest the following ideas:

- In Yukon, it seems that rivers are either very wide (more than 200 m) or unstable (significant sediment supply, unstable banks, etc.). This reduces the feasibility of installing permanent upward looking ADCPs far from the banks in order to obtain continuous discharge estimations (based on estimated 2D velocity distribution) during winter. The same conclusion applies to smaller rivers, where anchor ice, sediment transport and channel mobility represent challenging conditions for permanent velocity measurements.
- In turn, satellite images can inform the evolution of freeze-up and breakup conditions, especially along large rivers, which facilitates discharge estimations during a few weeks at each end of the cold season.
- Automated cameras have been deployed by WSC in Yukon in recent years. These cameras are mostly useful to document evolving ice conditions (as opposed to water levels). Since the mid-winter period characterized by a stable and complete ice cover in Yukon may last more than 6 months, the benefit of installing permanent remote cameras is reduced at many locations. The fact that river ice formation and river ice breakup may last only one day at either end of the winter season also reduces the benefit of using permanent automated cameras. In turn, given the presence of high banks along most rivers, automated cameras could document ice conditions on relatively long stretches of river channels (e.g., at the Takhini River hydrometric station). Automated cameras would also be pertinent to better understand ice processes in steep channels (e.g., at the Nordenskiold River).
- There are many gaps in hydrometric records in Yukon during the winter season. It appears critical to make these stations more resilient to cold weather and dynamic hydrological processes. This could include installing pressure lines well-below the elevation of the bottom of the ice cover, using systems that would protect pressure lines

from filling up with water, even if the bubbler stops working, duplicating instruments (both real-time and internal memory only), and installing downward looking instruments above the channel to document obvious upward and downward movement of the channel surface (ice or water).

- Water temperature and air temperature sensors could also be used to better document the freeze-up and breakup periods.

In terms of discharge estimation tools and empirical techniques, some thoughts emerge:

- Some rivers have a very predictable winter regime with very abrupt changes in ice conditions. In this case, simple river ice indicators such as air temperature, water temperature, and precipitation could provide enough information to develop station-specific empirical tools that would facilitate real-time estimation of the discharge and the development of winter discharge time series.
- There are several hydrometric stations in Yukon that are located downstream of large lakes. These lakes release heat during winter, and depending on air temperatures, this may generate an upstream or downstream migration of the ice front. When the ice front moves, even by a kilometer, this temporarily modifies the discharge downstream by a few %. Also, when snow falls on a large lake (e.g., Kusawa Lake), it pushes down on the ice cover and this moves water to the outlet of the lake. Both processes will generate a departure from a typical smooth flow recession trend that is associated with progressive groundwater depletion. This is especially true for large air temperature fluctuations and significant snowstorms (e.g., 20 cm of snow falling on Kusawa Lake can increases the winter discharge by more than 10% for several days and this compares to the impact of a small runoff event).
- Small and steep rivers, which represent a fair portion of the monitored channels in Yukon, present a very complex winter behaviour. Nonetheless, it is possible to understand the origin of most water level fluctuations through a better knowledge of local and upstream ice cover dynamics. For example, in the spring, border ice may collapse and bend into the flowing water beneath, which may generate a rise in water levels that is not caused by the initiation of surface runoff. It also seems that there are two dominant freeze-up processes in the Klondike River above Bonanza Creek.

The development of operational tools that inform discharge estimation efforts during the winter period in Yukon may depend on future activities such as:

- Testing and installing complementary instrumentation
- Performing additional streamflow measurements during specific winter conditions,

- Exploring the link between the discharge and position of ice fronts (at freeze-up and breakup) using satellite products, riverbank cameras, or airborne photographs (drone or flights)
- Developing water balance models (this should be tested in the Yukon River watershed, more specifically in the lower Yukon River, downstream of Lake Laberge, and downstream of Kusawa Lake),
- Developing heat models to better understand the heat balance at specific stations that impact ice processes and water levels.
- Installing temporary water level loggers away from existing hydrometric stations to better distinguish hydraulic (ice effect) from hydrological water level fluctuations,
- Supporting knowledge development on the hydrology of steep rivers in sub-arctic environments, especially at freeze-up and breakup.
- Paying special attention to any mid-winter runoff events and documenting runoff rates as well as discharge variations at many locations.
- Dedicating efforts to better document the winter hydrological regime of braided rivers such as the White River or the Donjek River (not currently monitored).