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A new winter discharge estimation procedure: Yukon proof of concept

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The quantity of water flowing in streams and rivers represents the most important hydrological parameter to several water data users. Critical societal activities depend on the availability of accurate discharge estimations. A significant constraint to cold regions hydrometry, the science of monitoring water, is the absence of simple tools to convert water level (or stage) measurements into accurate discharge (flow) estimates when different types of stationary ice are present in the channel. Beyond the complex departure of the actual discharge from the open water rating curve, upstream river ice processes can also generate significant discharge fluctuations, especially when ice conditions are rapidly changing. The overlapping effect of local and upstream (watershed scale) ice processes on stage means that producing continuous winter discharge estimates involves uncertainties that some users may find unacceptable.

A solution to this complexity would be to seek alternative monitoring technologies and data processing models. However, our understanding of the impacts of ice processes on stage and discharge is still rudimentary and most proposed winter discharge estimation techniques to date have shown limitations that prevent their application to a broad range of hydrological contexts.

This paper proposes and tests a new approach to support the production of winter discharge estimates from three complementary angles (improved understanding, adapted tools, and targeted technology). The research presented emphasizes the development of hydrometric station-specific knowledge that applies to a broad range of winter scenarios as well as analytical tools that use readily available information in order to guide the judgment of hydrometry technologists and their supervisors. Results, presented for Yukon stations, reveal that discharge estimation errors in the order of 100% are probably common, especially during freeze-up. Significant improvements to winter discharge estimates, in terms of reproducibility and accuracy, can unquestionably be obtained using parameters that are currently monitored. Main research outcomes are listed, and future research steps are proposed.

1. Introduction

Freshwater is the most valuable resource on Earth. Quantifying the amount of water in our environment represents a necessary path towards healthy ecosystems and sustainable living. Accurate water quantity data provides useful information to hydroelectric dam operators, industries and municipalities, environmental regulators, flood forecasters, river engineers, commercial shipping operators, a wide range of scientists, and the public.

The Water Survey of Canada (WSC) is the authority responsible for the collection, interpretation and dissemination of standardized water resource data and information in Canada. In partnership with the provinces, territories, and other agencies, WSC operates over 2800 active hydrometric gauges across the country, most of which are located on rivers. The production of water-related information is not trivial. It involves a range of technological devices deployed in the field or in the office, as well as multiple levels of quality control. Within this process, a central element is the development of station-specific stage-discharge relation, or rating curves. Nature rarely reveals itself as accurately through comparably simple models; rating curves are used to derive discharge from continuous stage measurements at nearly all river hydrometric stations.

Historical hydrological records in cold regions include a period of greater uncertainty (and data gaps) called Winter. The season when flow conditions in streams and rivers is affected by stationary ice, and during which the open water rating curve cannot be used, represents a technical, technological, and scientific challenge that several hydrometric agencies around the world are reluctant to report on (Turcotte and Morse, 2016). Ice-affected stage data has been labeled “pathologies”, “erroneous”, and “operational problem” by different authors, and this reveals a level of hydrology misconception or winter exasperation that is incompatible with the level of adaptation that should be expected from our northern societies.

This study recognizes that the impact of stationary ice adds a thick layer of complexity on the already multifaceted science of open water hydrology and emphasizes the need for a new approach to produce better winter discharge estimates (WDE). The proposed approach is meant to be simple (but not simplistic), modern (based on the latest science), reproducible (less subjective and further guided), efficient, and adapted to different cold regions hydrological settings. It involves the classification of watercourse (CW), and for each category, a logical sequence of actions involving a combination of winter-adapted technology, analytical toolbox, and hydrological knowledge (Figure 1), leading to optimal WDE improvements. As a first step of the broader vision of the project, this paper reports on two objectives: (1) describing new knowledge and tools to support more accurate WDE, and (2) presenting the results of a new procedure for WDE on a sample of rivers located in the Yukon in northwest Canada. The paper begins with a literature review and ends with a discussion about future research steps for the development of a comprehensive WDE operational procedure adapted to rivers of Canada.

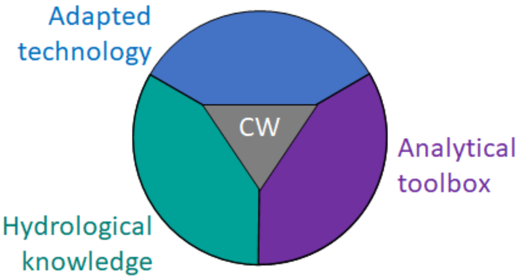

Figure 1. Main components of the proposed winter discharge estimation (WDE) procedure.

2. Background

In Yukon, a winter hydrograph typically includes a notable flow depression caused by upstream ice and hydraulic storage (and which shape depends on a combination of pre-winter runoff, air temperature variations, and upstream drainage network morphology) followed by a well-defined (but not necessarily smooth) midwinter recession, an early spring flow rise as snowmelt runoff begins, a few discharge instabilities associated with upstream ice movements and storage release, and a transition to open water freshet. This sequence however is often hidden by stage variations caused by local ice processes, especially during shoulder seasons when the ice cover forms or breaks up, either dynamically or progressively. Hamilton (2004) wrote: “It is uncertain how much of the water level response is due to change in flow volume and how much is due to change in flow resistance”, a statement that summarizes most challenges faced by hydrometry technologists when interpreting winter stage signals. Turcotte and Nafziger (2021) proposed that distinguishing local (hydraulic) from upstream (hydrological) changes in ice conditions is possible, at least at some hydrometric stations, if enough site and winter-specific information is available, and if ice processes are adequately understood.

Challenges associated with WDE in Yukon has been reported in Alford (1986). During the same period, Alford and Carmacks (e.g., 1987), through the Yukon Ice Seasonality Experiment (YISEX), performed regular measurements of snow, ice, hydrological, and hydraulic parameters during successive winters on the Yukon River near Whitehorse. Among their findings, the calculation of the ice cover hydraulic resistance over a winter cycle represents a major contribution to river ice sciences, more so as it was performed in the presence of an evolving hanging dam (accumulation of frazil and ice under an ice cover). Hamilton (2004) described a similar process, common in rivers of Yukon, that make discharge estimations complicated: the dynamic formation of an ice cover followed by thermal erosion (revealed through regular discharge measurements). The same author outlined the complexity of a thermal breakup event during which the discharge rises whereas the stage drops.

Russ Gregory, former manager of the WSC office in Whitehorse, led a study during subsequent years documenting the early-winter discharge depression that takes place in cold region rivers through regular flow measurements, including on the Liard River at Upper Liard (Gregory, 2018, pers. com.). Starting in 1993, historical discharge records at WSC station 10AA001 include a significant early-winter discharge depression that may be realistic or exaggerated. However, after 1997, records show no discharge depression at all. This reveals that historical winter flow records at this station may be significantly influenced by procedural or staff changes. Historical records from other stations in Yukon (or elsewhere in Canada and abroad) also reveal changes in winter discharge interpretation philosophies, especially during shoulder seasons when no discharge measurement occurs, a form of bias that could be misinterpreted.

Some researchers suggested methodologies to support objective WDE. Moore et al. (2002) proposed the use of uniform depletion curves to determine streamflow during consistently cold winter periods. The dual reservoir approach was eventually adopted by WSC offices and applied to specific hydrometric stations. This tool has the merit to be simple to use and to produce realistic estimates (in the absence of mid-winter runoff events) by relying on winter discharge measurements as anchor points. On the other hand, its period of applicability is often difficult to confirm (e.g., it is unclear when the freeze-up discharge depression ends) and it neglects a common winter hydrological behavior: a synchronism between stage and air temperature fluctuations most likely induced by upstream channel storage.

Chokmani and Ouarda (2006) and Turcotte et al. (2005) proposed a WDE methodology based on hydrostatistics (Artificial Neural Networks and Regression Analyses) linking weather indicators to ice thickness measurements and discharge estimations. This type of black-box approach, motivated by the need to improve analytical objectivity and to reduce potentially biased judgment, seems bound to failure through an oversimplification of winter hydrology concepts. Turcotte et al. (2005), among others, also tested a deterministic hydrological model to support WDE. This alternate water balance approach seems particularly useful to improve WDE in temperate regions where mid-winter runoff events are common. On the other hand, most hydrological models are still poorly adapted to the simulation of discharge variations caused by ice processes (e.g., upstream storage and release events, the later being particularly difficult to forecast), and most model development efforts to date seem to focus on the weather and snowmelt aspect of the water cycle rather than on in-channel ice-hydraulic interaction.

Another angle of attack to improve WDE is new technologies. The use of cameras (telemetry-enabled or not) may provide useful qualitative information about changes in ice conditions, especially during shoulder seasons. On the other hand, photos cannot be used to quantify the discharge or the ice cover strength. Another possible technological approach consists in measuring flow velocities at different depths using a permanent acoustic instrument and to process the results using the Index-Velocity Method (a simulated two-dimensional velocity field in the entire river cross section, e.g., Healy and Hicks, 2004). However, beyond an applicability and performance that could be compromised by several common river conditions (e.g., formation of anchor ice or hanging dams, overflow) or by sedimentation or erosion, tests recently performed by the WSC also reveal high maintenance and operational costs. In summary, there is currently no reliable equipment that can revolutionize WDE.

After decades or research, hydrometric standards of procedures to produce WDE have evolved at a slower pace than river ice sciences. It seems that developing a one-size-fits-all solution (equation, model, or instrument) that would consider the complexity and the wide range of ice processes affecting cold region rivers is still inaccessible, and it may remain so. Therefore, the authors propose that a more comprehensive strategy involving watercourse category-specific combinations of adapted technologies, analytical tools, and up-to-date winter hydrology knowledge (Figure 1) represents the key to accurate and reproducible WDE.

3. Current procedure at WSC

Three meetings took place in 2021-2022 between WSC staff from different offices and the research team at YukonU in order to explain current WDE procedure. Although specific steps in the software used by WSC to compute records slightly differed, they can be summarized as:

1. Validate open water rating curve and determine shifts prior to and after winter,
2. Produce the Open Water Equivalent (OWE, which is the maximum possible discharge in the presence of ice) time series,
3. Upload discharge measurements, air temperatures, station and winter notes, as well as other pertinent information,
4. Determine date of first ice (usually based on stage signal stability and trend)
5. Free-hand draw (“override” option in the software) the discharge following first ice,
6. Determine discharge during winter using override, dual reservoir recession, or periodic shifts (i.e., departure from open water rating curve),
7. Use override or a pre-defined equation to define the discharge during breakup with a smooth transition to open water conditions,
8. Validate interpretation by comparing results with those of nearby stations and adjust (“massage the data”).

The use of free-hand discharge drawing indicates that the estimation procedure is subjective, but most importantly, it makes the WDE difficult to reproduce by others, and difficult to explain. In working examples, most stage variations were assumed to be caused by local hydraulic (ice roughness or blockage) processes and were therefore discarded as potential upstream hydrological fluctuations without justification. Overall, site-specific ice processes and the nature of the ice cover seem to be understood by technologists (i.e., during station visits), but the link between these processes and stage variations is not fully recognized.

4. Proposed procedure

Rather than attempting to automate the production of WDE, the proposed new procedure (NP) aims at providing additional tools, abilities, and station-specific information to guide the judgment of hydrometry technologists. Indeed, WSC technologists currently have access to some useful data, but very few tools exist to convert this data into quantitative indicators that ultimately support WDE (i.e., actions are often based on a qualitative interpretation that happens to be erroneous).

As a first procedural improvement, the NP involves the analysis of historical station and river reach-specific data, including discharge measurements, satellite images, and stage signals, to better understand the spatial and temporal winter dynamics. Of importance, each time a winter discharge is measured (Q_m), it can be associated with an ice-induced backwater (BW):

$$BW = 1 - \left(\frac{Q_m}{Q_{OWE}}\right) \qquad [1]$$

Q_{OWE} is the discharge derived from the application of the open water rating curve, as if no ice was present (the Open Water Equivalent). The BW reflects river ice conditions as they change over a winter season and can be associated with different environmental indicators. Figure 2 presents an analysis that expresses 20 winters of BW values (generally 3 BW values per winter) as a function of the cumulated degree-days of freezing (CDDF) at a reference weather station. It reveals, for this specific river location, that freeze-up is generally dynamic, occurs before 500 CDDF, and is followed by a reduction in ice roughness (thermal or hydraulic erosion). Then ice cover thickening occurs above 1500 CDDF, with a relatively narrow range of possible BW values until breakup onset (trends presented as dashed lines are approximations).

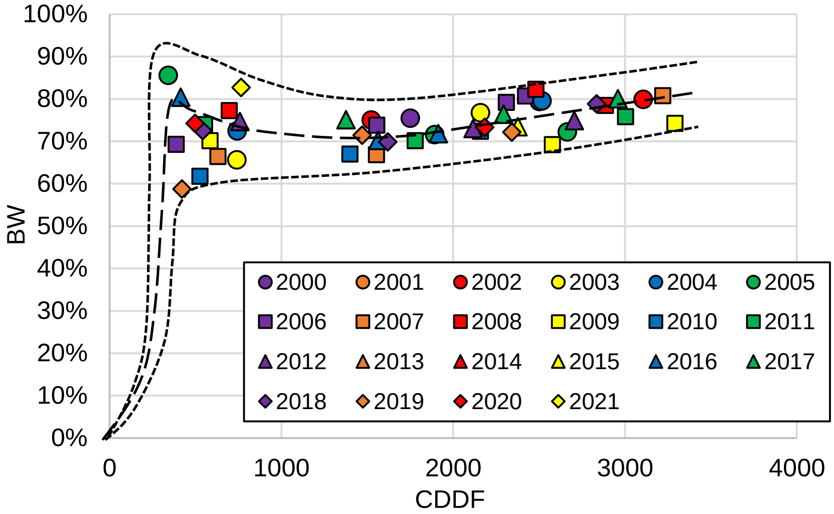

Figure 2. Calculated backwater (BW) from Equation 1 expressed as a function of cumulated degree-days of freezing (CDDF) from 2000 to 2021 for a hydrometric station located in Yukon.

Historical satellite images may also reveal what ice processes are taking place at the station hydraulic control of large rivers as well as in upstream reaches, especially during shoulder seasons, and these conditions can be linked with specific stage signals for corresponding dates. The development of a station-specific documentation (i.e., hydrological knowledge; Figure 1), contributes to a better interpretation of stage times series to derive WDE, even in real-time.

The creation of new tools (i.e., toolbox; Figure 1) is made possible through the availability of additional (unexploited) quantitative data. WSC technologists often use a free-hand drawing of the discharge (subjective and hard to reproduce), or the dual reservoir recession (easier to reproduce, but often yielding simplistic results). Complementary tools developed through this project include an empirical BW rise equation based on CDDF to simulate the gradual change in ice condition (e.g., the formation of border ice or the thickening of a free-floating ice cover):

$$BW_t = \left(\frac{CDDF_t - CDDF_{t=0}}{CDDF_{t=F} - CDDF_{t=0}}\right)(BW_{t=F} - BW_{t=0}) + BW_{t=0} \quad [2]$$

The subscript t represents a timestep, t = 0 is the first timestep when this equation is applied, and t = F is the final time step (F could be a few hours to several weeks after 0). Equation 2 means that the BW (%) evolves linearly following CDDF (like the Stefan equation), not simply as a function of time. The main strength of this type of empirical equation is that it lets the estimated discharge (Q_{est}, replacing Q_m in Equation 1) vary when stage fluctuations are caused by upstream rather than local changes in ice conditions. Other comparable tools developed through this project include a decreasing BW equation based on air temperature indicators to simulate hydraulic (or thermal) ice erosion, a defined Q_t trend to let BW_t adjust to a significant short-lived stage variation caused by local ice movements, and a fixed BW_t trend to let Q_t adjust during a short-lived wave (e.g., ice-jam-released). In addition to support WDE, these tools (and the strategic used of existing tools used by the WSC) are meant to reflect that, at most hydrometric stations, there are winter segments during which BW_t changes significantly, but a majority of stage variations often are actual Q_t variations.

The combination of station-specific hydrological knowledge and an improved toolbox are integrated to the NP. Once the local rating curve is approved and once all the accessible and pertinent data is processed (e.g., degree-day calculation) and visually accessible, the hand and judgment of technologists can be guided more consistently, and the WDE is facilitated using different tools constrained by what we refer to as hydrometric anchor points (HAPs). These HAPs can be non-negotiable (e.g., a measured discharge or a confirmed end of ice presence) or negotiable (e.g., defined by the user, often just before or after a notable change in ice conditions). HAPs can represent a known or user-defined Q_t but are most likely calculated (through Equation 1) or assumed BW_t. Between two HAPs (from t = 0 to t = F), during winter segments of consistent changes in ice conditions (gradual or dynamic, local or upstream), different tools are selected and applied to generate WDE, either forward or backward in time. The value and location of negotiable HAPS can be changed later (before final approval), and the WDE is recalculated automatically (or reassessed) for a specific winter segment.

The outcome of the NP is the production of two graphs (Q_{est} and BW, expressed as a function of time). Both parameters are connected through Equation 1 (either Q_{est} or BW is imposed), and both should be scientifically defendable (in terms of shape, amplitude, etc.) when compared with other driving parameters and indicators (e.g., local air temperature, CDDF). Otherwise, HAPs can be modified, or tools can be swapped. The use of free-hand tools to define Q_{est} should be kept to a minimum to promote reproducibility and minimize subjectivity.

5. Results

Figure 3 presents results from the application of the proposed procedure for the Pelly River at Pelly Crossing (WSC station 09BC001) during winter 2016-17. The top of each graph presents non-negotiable HAPs (black dots) associated with a known discharge (derived from the open water rating curve or obtained through a measurement) and negotiable HAPs (white dots, an assumed Q or BW). Different data and tools have been used to produce these estimates:

- Green: Known discharge
- Pink: BW_t = f (degree-days of freezing) during border ice formation and ice thickening
- Blue: fixed Q_t trend during ice jam formation
- Grey: BW_t = f (air temperature) during post-freeze-up ice cover erosion period
- Yellow: BW_t = f (degree-days of thaw) for ice cover melt (open areas forming)
- Red: fixed BW_t trend during and following an ice jam release wave

Figure 3 presents one of the simplest possible winter scenarios in terms of number of decisions to make; only 4 HAPs can be modified to change the results, and these are defined based on a careful analysis of historical data (e.g., Figure 2) and satellite images.

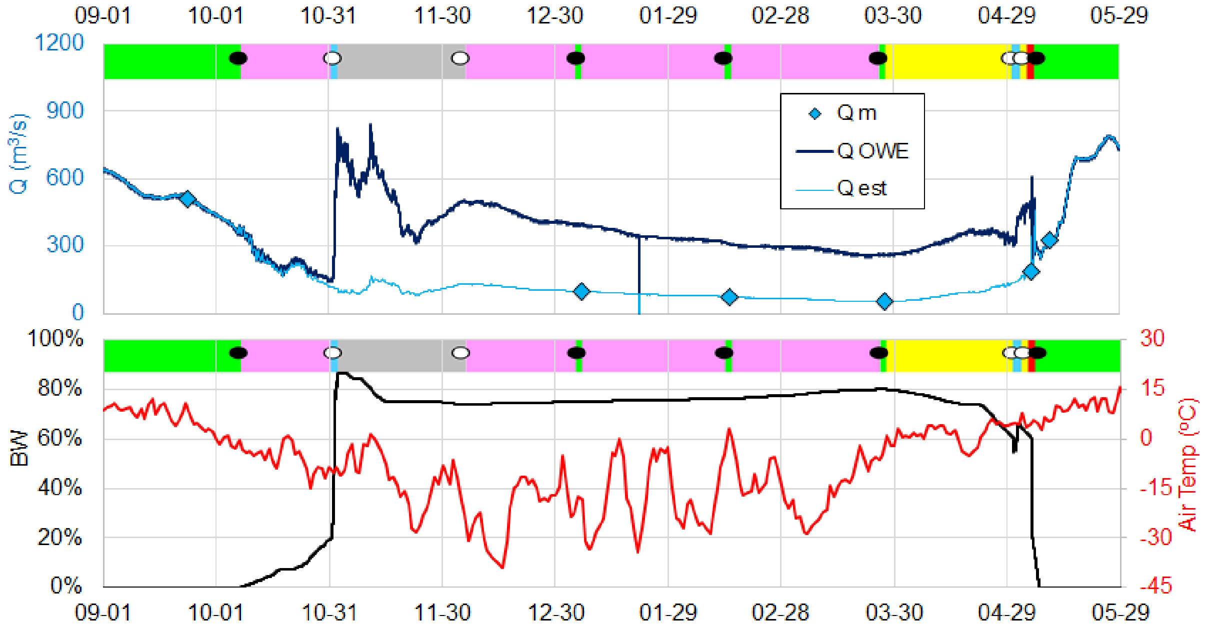

Figure 3. Estimated (Q_{est}) and Open Water Equivalent (Q_{OWE}) discharge (top graph) and estimated backwater (BW) and measured Air Temperature (Air Temp., bottom graph) for the Pelly River at Pelly Crossing from Sept. 2016 to May 2017.

Figure 4 presents the same NP results (15-minute time steps) and compares them with daily-average WSC results (Q_{est} and back-calculated backwater, BW_{cal}) obtained from the existing procedure (EP) and current tools. The following remarks can be made:

- $Q_{est\ EP}$ is smooth and through Equation 1, the spiky stage means an unstable $BW_{cal\ EP}$.
- $BW_{cal\ EP}$ presents variations that cannot be scientifically justified, and the freeze-up depression is misinterpreted (only the BW graph can easily reveal this). As a result, flows in November are probably overestimated by 10% to 120%.
- The mid-winter period is adequately interpreted by both procedures because of the three non-negotiable HAPs (discharge measurements, Figure 3).
- The interpretation of the breakup period is similar for both approaches, but flow instabilities, including two ice jam release waves, are preserved in the sub-daily flow record based on the NP.

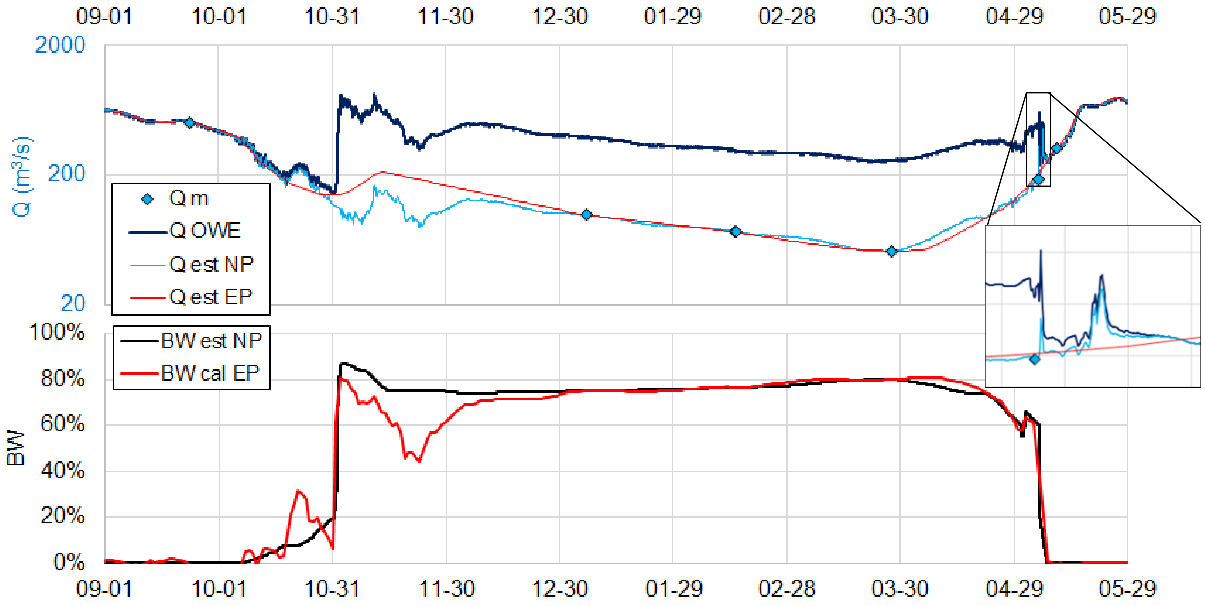

Figure 4. Open Water Equivalent (Q_{OWE}) and estimated discharge (Q_{est}) (top graph), and estimated or calculated backwater (BW) for WSC station 09BC001 from Sept. 2016 to May 2017. The new procedure (NP) is compared to existing procedure (EP).

A defendable interpretation of the freeze-up, mid-winter, and breakup periods (from stage signal analyses as well as through Q and BW graphs) depend on a number of factors, including staff experience, available tools, and the complexity of local and upstream ice processes. Generally, in Yukon, discharge estimates produced by the EP during the mid-winter period, informed by two or three measurements, and the associated BW_t, are defendable. Breakup is also often reasonably interpreted by the EP (i.e., ice jams are rarely interpreted as snowmelt runoff events). However, based on the analysis of several historical WDE at different stations, it appears that freeze-up processes are largely misunderstood and associated with unreasonable simplifications leading to inaccurate results. In addition, first ice-affected (B) dates are often associated with uncertainties, and probable errors in the order of two to four weeks have been seen (e.g., station 10AA001 in the fall of 2005 and station 09DD003 in the fall of 2000).

Figure 5 presents a last example from the Yukon River (station 09CD001) where the 2010 breakup discharge produced by WSC was suspicious, with an estimated flow as high as 2200 m^3/s (May 1) prior to the end of local ice clearance. The NP was applied using the hourly stage data set. Results suggest that the peak flow prior to breakup was more likely about 1550 m^3/s on May 1. Interestingly, the ice jam release wave that caused the mobilization of the residual local ice cover could have reached 2250 m^3/s on May 6. This type of historical flow reinterpretation may be important to flood forecasters (for the development of breakup models) and engineers (for the design of river structures), among other flow data users.

6. Discussion and recommendations

Dahl et al. (2019) confirmed, through an experiment involving many hydrometry technologists of varying experience, that subjectivity can lead to very different winter discharge estimates (WDE). This project proposes to reduce subjectivity and improve reproducibility of WDE by introducing a new procedure (NP) that involves adapted technologies, a diversification of the WDE analytical toolbox, and the creation and transfer of hydrological knowledge, all of which would be organized around a classification of Canadian watercourses (CW, Figure 1).

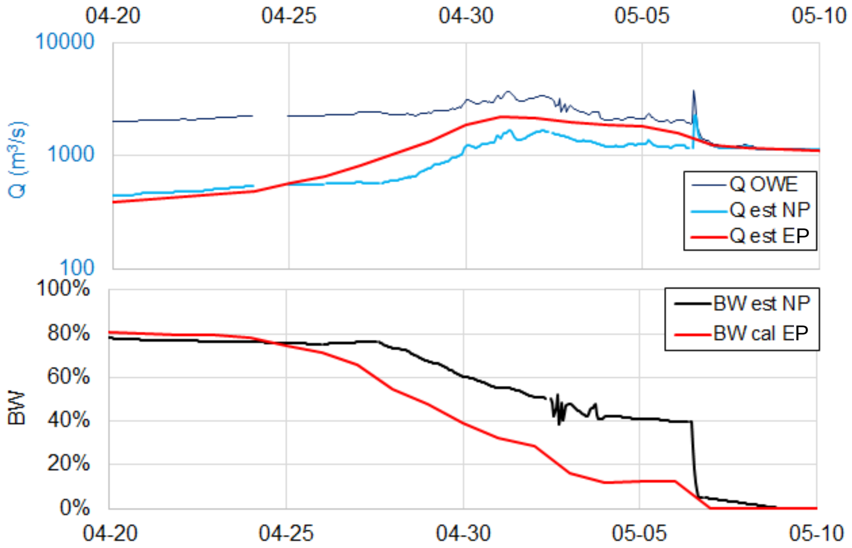

Figure 5. Open Water Equivalent (Q_{OWE}) and estimated discharge (Q_{est}) (top graph), and estimated or calculated backwater (BW) for station 09CD001 from Sept. 2016 to May 2017. The new procedure (NP) is compared to existing procedure (EP).

The proof of concept was performed for WSC hydrometric stations located in the Yukon. The 2000-2021 winter data from several stations was analyzed, knowledge was built, and a set of equations (part of the proposed toolbox) was developed to support WDE. Results suggest that significant WDE improvements can be obtained, especially during shoulder seasons, even without the use of new data from additional instruments (the benefit of new technologies will be explored in a future project phase). If suggested equations can be programmed into the computation software used by the WSC, and if station-specific (or river type-specific) hydrological knowledge can be presented efficiently, then more accurate WDE would be obtained while reducing data production time. During winters where no-midwinter runoff event occurs (a common condition in Yukon), two winter discharge measurements could provide enough hydrological anchor points (HAPs) to guide WDE.

It is expected that the color sequence presented in Figure 3 (which refers to the sequence of tools used to compute WDE for different winter segments) could be similar from year to year at this hydrometric station (09BC001), but also at other stations of similar characteristics (affected by a comparable sequence of ice processes). Indeed, other large-low gradient rivers in the area (e.g., stations 09CD001, 09DD003) present a comparable winter stage signal. This illustrates how a river classification effort linking specific sequences of ice processes (in terms of type, timing, and amplitude) to targeted technologies and predefined tools could become part of a NP.

Important outcomes of this paper are:

- When producing WDE, the debate should not be about opinions, but about facts (what ice processes are involved and what tools should be used to analyze the data).
- An ice-induced backwater (BW) graph is key to the production of realistic WDE. If the BW is not scientifically defendable, the discharge is probably wrong.
- Dividing the winter hydrological period in segments of consistent changes in ice cover conditions creates an opportunity to use adapted tools and to generate reproducible WDE.
- The duration and shape of the early-winter discharge depression is often misinterpreted. Imposing an end to the depression after local freeze-up (stage rise) is not scientifically

defendable as it would mean that the ice cover forms in the station reach after stable ice conditions are achieved in all upstream reaches.

- Similarly, at most hydrometric stations, a majority of stage fluctuations, especially post-freeze-up daily and sub-daily variations, are likely real discharge fluctuations influenced by weather conditions. Otherwise, it would mean that the local ice cover continues to be affected by dynamic changes whereas ice conditions in all upstream reaches and tributaries are relatively stable.
- These last points illustrate the need to better connect hydrometry technologists with river ice geoscientists and engineers and to develop knowledge that supports WDE.

Future research steps would include: 1. Applying the NP to other stations and quantifying the WDE accuracy improvement (i.e., through additional flow measurements), 2. Developing new tools and programming them in computation software, 3. Testing new monitoring technologies, (a priority would be to ensure, through adapted technology and redundancy, that stage data sets are gap free because the stage represents the most important hydrometric information) and 4. Creating a watercourse classification matrix. At some point, it would also be of interest to compare, in terms of performance and ease-of-use, the ice-induce BW (%) tested in this paper with an approach that distinguishes changes in ice thickness and roughness (the ice cover Manning's n). Indeed, BW should change slightly during weak mid-winter runoff events.

Acknowledgments

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