Improving winter discharge estimates phase II – proposed new procedure and proof of concept

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Executive Summary

Producing winter discharge estimates (WDE) in streams and rivers affected by ice processes is challenging and, as a result, historical winter discharge (Q) records are associated with greater uncertainty compared with open-water records.

This project proposes a transition from the existing procedure (EP) for WDE towards a new procedure (NP) that would involve the development of:

- Adapted cold region hydrology knowledge making the link between the occurrence of ice processes and their stage variation signatures,
- Strategic analytical tools to support more accurate and reproducible WDE,
- Targeted instrumentation strategies to monitor parameters that support WDE.

These development fields should align with a proposed watercourse classification matrix with an objective to create river and stream categories affected by similar ice processes, and for which WDE strategies would compare.

This report presents:

- A literature review showing that WDE strategies have not evolved significantly over recent decades, not because of the lack of research, but mostly because of the disconnection between proposed approaches and the physical processes involved (Section 2),
- A review of the EP based on three (3) meetings with Water Survey of Canada technologists from different offices (Section 3),
- A preliminary version of the watercourse classification matrix (Section 4),
- A description of nine (9) studied rivers (hydrometric stations) with examples of knowledge that has been developed (Section 5),
- A list of five (5) tools developed within the NP to support WDE (Section 6),
- A proof-of-concept exercise with four (4) analyses, including a comparison of EP and NP results with event-specific discussions (Section 7),
- A summary or NP advancement and recommendations (Section 8).

The most important NP concepts that are proposed and tested in this report are the use of a backwater (BW) graph to validate and improve the accuracy of estimated winter flows (Q_{est}) and the use of Hydraulic Anchor Points (HAPs) to improve the reproducibility of WDE. The NP does not mean to eliminate analytical subjectivity, but to provide additional information and adapted tools to guide the judgement of analysts that have the responsibility to produce WDE.

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1. Introduction

1.1 Context

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 quality control steps. Within this process, a central element is the development of station-specific stage-discharge relation, or rating curves, that 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 gaps): Winter. The period when flow conditions in streams and rivers are affected by stationary ice, and during which the open water rating curve does not apply, represents a technical, technological, and scientific challenge. Indeed, there are essentially no rivers where the winter hydrograph consists in a smooth and predictable discharge recession. Ice-affected water level data has been qualified as “pathologies”, “erroneous”, and “operational problem” by different authors over the years. It is known that winter stage signals often seem chaotic, and that the uncertainty associated with ice-affected discharges can hardly be defined, but that does not mean that winter flows cannot be adequately estimated. Each winter, WSC staff visit hydrometric stations (e.g., Alford, 1986) to collect water depth and velocity measurements. Back in the office, the spiky stage data and other information are analyzed to produce the best possible discharge estimations.

The impact of stationary ice adds complexity to the already multifaceted science of open water hydrology, but this report develops and demonstrates practical steps that can be made to address this complexity.

1.2 Objectives

The National Hydrological Service (NHS, Standards, Training, Quality and Safety Unit) contacted Yukon University, YukonU Research Centre (YRC), to conduct a study exploring avenues to improve the accuracy and reproducibility of winter discharge estimations (WDE). This project was initiated in 2020 through Phase I (Turcotte, 2021), which involved field visits with WSC staff at some Yukon hydrometric stations and a list of preliminary recommendations for future phases. It had been proposed that long term project objectives would be met following three development fields (Figure 1.1). This meant that WDE improvements would be limited if only one or two fields were given most of the development attention and resources.

The central part of this diagram consists in a classification of cold region watercourses (CW). There are many ice processes and ice cover types, and these are associated with different levels of interpretation and computation challenges. Their occurrence mostly depends on weather and flow conditions (i.e., discharge, channel hydraulics, channel morphology).

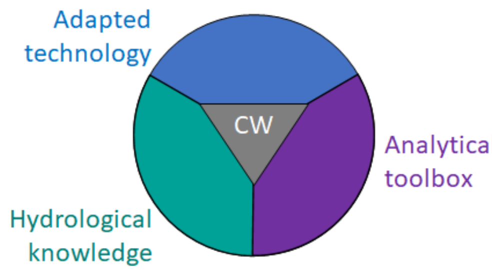

FIGURE 1.1. DIAGRAM PROPOSING THAT IMPROVED WDE RELY ON THREE DEVELOPMENT FIELDS, WITH THE CLASSIFICATION OF WATERCOURSES PLAYING A CENTRAL ROLE.

If streams and rivers can be classified, this will support the deployment of more targeted monitoring technologies, the development of adapted analytical toolboxes, as well as the preparation of efficient winter hydrological knowledge. It will take several years to reach the full potential of the project's vision, including the improvement Standard Operating Procedures (SOPs). This report is making significant progress towards that long term goal through a proof of concept. Specific objectives of Phase II are:

- Review previous research efforts about WDE improvements
- Meet with WSC hydrometry technologists and understand current WDE procedures
- Define a prototype river classification matrix for Canadian watercourses
- Develop a first set of tools to support and facilitate WDE
- Present a proof of concept through 4 examples

1.3 A word about the author

After completing a Doctorate in civil engineering at Université Laval (2010-2013) focusing on river ice processes with Professor Brian Morse, I worked as a Research Professional at Université Laval. Brian and I completed a two-phase research project with the *Gouvernement du Québec* to improve winter discharge estimates (Turcotte and Morse 2016, 2018). These reports are now mentioned in the *Gouvernement du Québec* guideline for winter discharge estimation. We also prepared material about winter hydrometry and ice processes for sections 1.5, 1.6, and 1.7 of a WSC SOP.

From 2018 to 2020, I worked as a senior scientist and flood forecaster for Yukon Government, walking in the steps of the late Richard Janowicz, renowned hydrologist, and working with the WSC office in Whitehorse (overseeing financial and technical aspects of the hydrometric network, meeting and collaborating with WSC staff several times). I heavily relied on hydrometric data for flood forecasting and for environmental assessments. In 2020, I became a Senior Research Professional with the Yukon Research Centre (YRC). In parallel, through the Membership of the Committee on River Ice Processes and the Environment (CRIPE), Canadian Geophysical Union – Hydrology Section, Dr. Jenifer Nafziger (Government of Alberta) and I initiated a Working Group on Cold Regions Hydrology and Hydrometry focusing on improving winter discharge data.

For the current project, I am wearing the hat of a hydrology researcher. However, given my background, I oversee and lead technical aspects of this project from the perspective of data users, field technologist, managers, programmers, and data analysts.

2. Literature review

2.1 Context

The science of hydrology, ranging from meteorology and hydrogeology to the design of engineering hydraulic structures, has been developing for centuries. Hydrological processes are well-understood, at least enough to develop models that can be used to forecast a wide range of streamflow conditions, including droughts and extreme floods. Millions of dollars are invested every year in supporting research projects that attempt improving the accuracy of hydrological models. At some point in the near future, their reliability could be mainly limited by the exactness of their primary input information (meteorological data and forecasts).

In comparison, the science of cold regions winter hydrology, which involves the understanding of the water balance in ice-covered river networks, has received little attention. Winter is often perceived as a simple season from a water cycle point of view, given the lack of runoff and the consequent progressive depletion of lakes and groundwater. Some hydrologists assume that the discharge in rivers is steadily declining between ice-in and ice-out dates, and this interpretation, with its associated discharge estimates inaccuracy, may satisfy a category of hydrometric data users. However, other users, those interested in representative ice-affected discharge estimates, may identify, or be affected by, estimation errors that are not acceptable for their own needs and operations. This includes hydroelectric producers, a wide range of industries, municipalities, environmental regulators, flood forecasters, biologists, geoscientists, and river engineers. Several cold regions hydrometric agencies understand that winter discharge estimation is far from simple but may be reluctant to address the situation because of the imbalance between the complexity of river processes and the availability of resources and winter-specific hydrology knowledge.

The river ice community has made several links between diverse ice processes and their impact on water levels and discharge. For example, it has been known for decades that a multi-day to multi-week discharge depression takes place at the beginning of winter as a consequence of upstream storage (in the form of ice, and water hydraulically stored in the channel as well as in the banks, e.g., Prowse and Carter, 2002). Turcotte et al. (2014) studied the link between ice formation in tributaries and the propagation of the early-winter discharge depression. The formation of different types of ice covers in cold region rivers has been associated with distinct stage variations, or signatures (e.g., Turcotte and Nafziger, 2021). It is also known that breakup triggers waves that travel down rivers to dislodge more ice downstream, eventually leading to large waves associated with the release of an ice jam (e.g., Jasek, 2003), and their associated water level variations (Beltaos, 1990). Interestingly, the hydrological and hydraulic signature of these processes is rarely taken into account by hydrometry agencies when winter discharge estimates are produced. This is partly due to the fact that, at some stations, the hydrological and hydraulic signature of different upstream and local ice processes overlaps in an apparently chaotic manner, which affects the ability of hydrometry analysts to objectively produce discharge estimates.

2.2 Winter hydrometry models and technologies

A diversity of hydrology philosophies exists to support the production of winter discharge estimates (WDE). Most of the methods developed over the years are either based on statistics, hydrological simulations, river hydraulics, or new monitoring technologies.

Chokmani and Ouarda (2006) and Turcotte et al. (2005) present a discharge estimation methodology based on hydrostatistics (Artificial Neural Networks and Regression Analyses) linking weather indicators to ice thickness measurements and discharge estimations. These studies are apparently motivated by the need to reduce subjectivity in WDE procedures. Although representing an interesting research avenue, the authors do not present hydrograph-type results that would enable readers to judge when and how these approaches best perform; there are only statistical summary results. Moreover, the statistical approach could hardly be adapted to complex ice processes, does not seem to consider the concept of a changing or variable ice cover roughness, and the ambition to improve the analytical objectivity does not only represent a solution to reducing potentially biased judgment, but also an unacceptable separation between WDE and river ice sciences, most importantly as it relates to the impact of river ice processes on stage and discharge variations.

In a similar way, Holtschlag and Grewal (1998) worked on a Kalman Filter (analytical, with no judgment involved) type of approach to estimate ice-affected flows. This computational approach was mainly based on air temperature indicators with no apparent scientific justification, and it was calibrated using site-specific historical discharge measurements. Although some concepts were of interest (e.g., discharge ratio and apparent discharge), the success of the approach was measured using statistics (compared with imperfect published flows) and it entirely overlooked the nature of ice processes taking place in the two studied rivers. Moreover, key parameters affecting winter flows such as liquid precipitation were ignored. Graphical results clearly showed that the filter was not able to simulate what seems to be a mid-winter runoff event in the first river and the approach seemed to diverge significantly for several days in a row for the second river.

Turcotte et al. (2005) also tested a deterministic hydrological model type of approach to estimate winter discharges. This approach forms part of a class of methodologies that can be used to improve WDE, especially when the discharge is expected to fluctuate as a result of runoff events that do not generate a complete breakup event. However, most hydrological models are poorly adapted to the simulation of discharge variations caused by upstream ice processes, and this is a non negligeable constraint. In the fall, the ice formation-induced flow depression can be severe, with flow abstraction ranging from 10% (very gradual and thermal formation of an ice cover) to 100% (dramatic formation of ice in small streams in the Arctic). At breakup, the release of an ice jam can multiply the flow by as much as 10 (e.g., Dow and Hicks, 2012). To our knowledge, there have not been significant improvements in hydrological models readily used in Canada to integrate the quantitative impact of river ice processes on flow, and much of the focus about deterministic model development remains at the level of adequately simulating snowmelt runoff.

Another family of approaches explores technological options to improve WDE: the Index-Velocity Method. This method has been studied for a couple of decades (e.g., Hamaï, 2006; Healy and

Hicks, 2004) and consists in measuring flow velocities at different depths in the water column using an acoustic type of instrument anchored to the channel bed (or a side looking device). Results are used to simulate a two-dimensional velocity field that considers the shape of the channel cross-section and that assumes known and relatively simple surface ice conditions. It represents a promising avenue to improve WDE at some hydrometric stations and it is currently being tested at several sites by the Water Survey of Canada and academic partners. It is important to mention that the performance of this technological and computational approach could be compromised by several, common river ice conditions: anchor ice (temporary or long-lasting loss of velocity measurement), hanging dams (frazil deposition patterns under an ice cover can vary from year to year and evolve during winter), dynamic river ice formation and breakup in small rivers (ice-induced roughness and channel blockage would be largely variable across the channel from year to year and during winter), and overflow (water flowing on the ice cover surface, or on the floodplain, would not be taken into account). Moreover, underwater instruments could be damaged by dynamic ice processes (e.g., ice jams and ice runs) as well as erosion, and they could be affected by sedimentation, all of which would inflate hydrometric station maintenance costs.

Other methodologies are considering the winter hydrology from a one-dimensional hydraulic point of view. Some practitioners suggest that an ice-affected rating curve could be developed under specific, stable ice conditions at some hydrometric stations. However, as pointed out by Hicks and Healy (2003), this is rarely applicable because of changing ice conditions (the rating curve shifts too frequently). Hicks and Healy (2003) propose another hydraulic-based method that involves bathymetric surveys, knowledge of ice cover thickness (to be constant over a long distance, therefore without frazil accumulations), knowledge of water surface profile, and the development of a one-dimensional model over a specific river length. This approach was used to identify a 300% discharge estimation error in WSC records. On the other hand, it can be considered data and resources intensive. A solution to this, as presented by the same authors, was the stage-fall analysis method that relies on two georeferenced hydrometric stations located not too far apart as well as on ice cover parameters. Overall, the method is defendable, but remains costly and complex, and the accuracy of the results could be affected by varying ice conditions. The idea of operating two nearby hydrometric stations could be used from another angle: distinguishing hydraulic and hydrological variations in stage time series.

In summary, new approaches that have been explored in recent decades are either too disconnected from river ice sciences, limited by current model capacities, restricted to a narrow range or watercourse (or ice cover) types, or relatively resources intensive. It is interesting to note that in most reports and scientific papers about WDE, researchers seem to propose a complete WDE philosophical change without truly understanding current SOPs, and without considering the implication of implementing new methodologies and technologies to a hydrometric network that includes very different streams and rivers. This may be the reason why, at most hydrometry agencies, WDE continue to rely on under-ice discharge measurements, on a partial knowledge of winter hydrology, and on a judgement-based (and often subjective) interpretation of winter water levels. Indeed, even though several studies have been published on the development and testing of objective methods to improve WDE, SOPs have barely evolved.

2.3 An acceptable revolution in winter hydrometry

It is true that discharge estimates are rarely reproducible, and this is problematic. Dahl et al. (2019) led a study that compares ice correction and discharge estimates performed by 17 technologists of varying experience. Each participant was given access to the same data and tools and used their own judgement to perform the assigned tasks. All the results were different, with occasional significant disparities. This reveals that technologists, with their own knowledge, experience, and diligence, are introducing bias in historical winter discharge records, they are humans after all. However, this does not mean that they should eventually be replaced by computer programs and new sensors. It is conceivable that they have not been given enough tools and knowledge to perform WDE tasks at a level corresponding to their true potential.

It seems that few authors have attempted to derive WDE from an approach that fully embraces the complex winter behaviour of cold region streams and rivers. This research angle can only materialize through a multidisciplinary effort; river ice specialists working with hydrologists to develop and improve winter and spring hydrological models, as well as with industrial partners developing adapted monitoring products. This group should closely collaborate with data users and hydrometry technologists and analysts. The two reports prepared by Turcotte and Morse (2016, 2018) for the provincial Government of Quebec (Gouvernement du Québec, ministère de l'Environnement, du Développement durable et de la Lutte contre les changements climatiques) proposed that new tools and instruments, as well as additional knowledge can facilitate the production of winter discharge time series in addition to improving their accuracy without a need for drastic changes to WDE protocols. The current project adopts the same research angle and emphasizes the need for more accurate and reproducible results produced by technologists and their managers, humans that can learn and use their judgement.

2.4 Yukon studies

In Yukon a large portion of the hydrometry research performed at various sites in the territory during past decades has been led by or has involved perseverant and ambitious WSC and ECCC employees. This subsection, just like this Phase II report, emphasizes winter hydrology studies in rivers and streams of Yukon.

In the 1980s, the Yukon Ice Seasonality Experiment (YISEX) led by Monty Alford and Eddy Carmacks significantly contributed to improving our understanding of river ice processes in sub-arctic regions while exploring different aspects of winter hydrometry. During the winter of 1983-84, Alford and Carmacks (1987a) planned and performed a comprehensive study involving 1. the spatial quantification of ice coverage, 2. regular stage measurements, 3. frequent under ice discharge measurements including velocity measurements at different depths and streamwise locations, 4. the definition of the shape of a hanging dam (a frazil accumulation) on several different dates, including penetration tests to evaluate consistency, 5. heat budget simulations and the evaluation of short wave radiation absorption through snow, ice, and frazil, 6. a description of ice processes at freeze-up, during winter as well as during breakup, including the quantification of water surface slopes over time, 7. A calculation of ice-induced flow resistance and its evolution over time, and 8. the evolution of velocity profiles for changing ice conditions.

This project took place on the Yukon River at Whitehorse, just downstream of the Whitehorse Rapids dam, and emphasized the importance of such research efforts for different stakeholders. A noteworthy quote about the winter flow regime is that “particular attention must be paid to the unsettled periods of freeze-up and breakup, wherein one cannot extrapolate to midwinter conditions”. The only limitation of this research is that it took place in a regulated context whereas large hanging dams, as documented in this report, are probably infrequent in Yukon, or along monitored river reaches across Canada in general.

The same research team performed other observations during subsequent winters at Whitehorse (Alford and Carmacks, 1987b, 1988), focusing on similar measurements and observations and comparing different winters, but also emphasizing the description of ice processes affected by regulation as well as the measurements of water temperatures. An important finding was that a single velocity measurement of under ice flow at a depth of 0.4 (ratio of the water column measured from the water-ice interface) multiplied by 0.86 (coefficient calibrated for that specific site) yielded a representative velocity estimate for specific verticals, which was time saving compared to the normal procedure involving two measurements at 0.8 and 0.2. A different coefficient was back calculated for several other stations and winters in Alford and Carmacks (1988) and ranged from 0.75 to 0.95. Nowadays, with the use of small ADVs or ADCPs, this approach might not be needed anymore.

Carmacks and Alford (1986) also investigated the formation of an extensive, but relatively shallow hanging dam downstream of Lake Laberge, a reach of the Yukon River called the Thirty-Mile. Their volumetric and heat budget evaluation is useful to determine the local and downstream impact of massive frazil production and deposition on stage and discharge, respectively, and this provides a great insight for discharge estimations at other hydrometric stations.

Russ Gregory, former manager of the WSC office in Whitehorse, led a study during following years documenting the early-winter discharge depression that takes place in cold region rivers, including the Liard River at Upper Liard (Gregory, 2018, personal communication). It is uncertain if this research effort was led after Yukon received unsubstantiated complaints from Alaska stakeholders suggesting that water was being stored in hydroelectric reservoirs at freeze-up (a true story; Janowicz, 2018, personal communication), but it was certainly useful to illustrate the extent of the natural phenomenon (e.g., Prowse and Carter, 2002). It is interesting to note that even in recent years, the reconstitution of the winter discharge based on ice-affected stage data at several WSC stations often excludes any defined discharge depression (its timing and intensity are probably hidden by the local stage variations) while it logically takes place every year, with varying shapes and amplitudes that mainly depend on air temperatures and river ice formation sequences.

More recently, while introducing the topic of winter water level monitoring, Hamilton (2004) stated that “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”. Although the terminology may differ, this aligns well with what is presented later in this report. Hamilton (2004) also describes, with the use of regular discharge measurements, the dynamic formation of an ice cover and underneath frazil accumulation followed by thermal erosion, a very common freeze-up sequence in rivers of Yukon and elsewhere. The same report explores thermal breakup events where the discharge rises whereas the stage tends to drop.

Another topic discussed by Hamilton (2004) is the use of uniform depletion curves to determine streamflow during consistently cold mid-winter periods, considered as a useful tool with some limitations. The tool is of interested because of its relative ease of application, but its period of applicability can be very challenging to confirm, as it will be demonstrated later in this report. Finally, the same paper comments on the apparent lack of correlation between discharge and air temperature indicators, based on flow measurements performed at Wolf Creek, Yukon (also refer to Hamilton et al., 2001). In this last paper (about the Estimation of Discharge Under Ice Project, EQUIP), the authors judiciously conclude that “hydrograph interpolation techniques should be limited to streams for which the hydrological and hydraulic processes contributing to streamflow variability are well understood”. Interestingly, this may very well exclude most hydrometric stations operated on rivers of Canada.

3. Overview of existing procedure for WDE

This report is presented to the National Hydrological Services (NHS) to support the development of a new procedure (NP) for winter discharge estimation (WDE). The existing procedure (EP) does not need to be entirely reinvented or redesigned, but it definitely needs to be understood. In this context, the YukonU Research Centre (YRC) requested access to Aquarius and organized three meetings with Water Survey of Canada (WSC) staff in order to understand the EP and the reasoning behind every action taken by analysts to produce WDE. The names of the people involved in this activity is not mentioned in the report, but the YRC would like to acknowledge their contribution to this research.

Aquarius is a powerful program that has been designed by Aquatic Informatics to be as friendly and simple as possible to users. The YRC dedicated time to explore different options in Aquarius before meeting with WSC staff in a perspective of being able to focus on the meaning of different actions rather than on the meaning of different functions, icons, and graphs.

3.1 Current discharge production steps and tools

This subsection presents a summary of the steps involved in production WDE. Steps are numbered in order to facilitate comparison between sample sites and collaborators.

<u>In a first meeting (November 2021)</u>, WSC staff presented a discharge production protocol for a small stream in Northern British Columbia, as well as for a relatively large river in Yukon. In both cases, the rating curve was investigated as a first step to ensure that recent open water discharge measurements agreed with the station rating curve (1). Then, the Stage Working data series was open and discharge measurements were added for the first station (2), a small stream that is apparently affected by anchor ice, ice dams, and a partially floating ice cover. Air temperature data was uploaded (3) and photos were consulted to describe channel conditions (4). Then, a discussion happened about the probable occurrence of discharge depressions for each ice dam cycle, as opposed to assuming a straight discharge estimate during ice dam formation and breaching cycles. In any case, in the absence of discharge measurement during these cycles, the override tool would have been used to estimate the discharge (5a). For the larger river, a dual-reservoir type of discharge recession is normally applied, with apparently satisfying results, whereas the override tool is generally used to estimate the discharge during freeze-up and breakup (5b).

<u>During the second meeting (January 2022)</u>, WSC staff presented winter discharge production steps for three distinct rivers from Ontario. For the first station (a) The first step consisted of consulting field notes that may include a detailed description of ice processes for the entire winter period (1). After a verification of the rating curve before and after winter (2), the Stage Working data series and discharge measurements were uploaded (3). Air temperature and precipitation data was also added to the graphs (4). The Open Water Equivalent (OWE) method was applied, which essentially consists in presenting a data series of the maximum possible discharge for the winter period using the open water rating curve (just as the apparent discharge data series in Holtschlag and Grewal (1998) (5). The freeze-up period was not analyzed for the first example (6-7). The estimation of the winter discharge during winter, including potential mid-winter runoff events, as well as during

breakup, was mainly performed using the override tool in Aquarius (8a). Since this seems to be a steep creek with significant stage variations, low points in the OWE series were identified and used as an envelope to produce WDE. In some instances, a synthetic, or pre-established rating curve cut-off was applied, which essentially represents a constant % adjustment of the OWE time series, or a backwater (i.e., the discharge ratio as presented in Holtschlag and Grewal, 1998), for a given period (9a). For breakup, most spikes were erased from the record because identified as ice-induced stage variations, as informed by an interpretation of air temperatures (10a). The end of the ice period was identified when the stage signal stopped to be jagged (11a).

For the second example (b), steps 1 to 5 were essentially the same. "First ice" was identified as the first stage spike in the fall, and weather data was consulted to verify this assumption (6b). For the first part of freeze-up, the initial interpretation of the discharge was completed using a straight line, and then more thoughts would be added to this assumption, based on stage and air temperature variations (7b). All the winter discharge production steps for this incomplete example would normally take half a day, or so, to complete.

For the third example (c), a regulated, urban channel, similar steps were also repeated. However, the first calculated backwater of 6% was carried back to the first ice (7c and 8c). Given the dominance of open water conditions, stage variations identified as backwater events were simply cut from the OWE method using the override function (9c). At the end, an estimated discharge data set from another station was used as a mean of comparison (12c). Generally, discharge estimation should be performed first at the easiest stations in a given region in order to support discharge estimation at more complicated sites.

The last meeting (February 2022) involved a working example from Alberta, an apparently very complex river where additional instruments are being tested (Innovation project site), such as an underwater velocity sensor used to derive flow from the Index Velocity Method (refer to subsection 2.2) and a Nupoint (telemetry-enabled) camera.

Discharge production actions started with a correction of the stage time series (1). The stage is corrected back linearly when no obvious single shift can be identified, as if the instrument had drifted monotonically between site visits. Then, the rating curve was verified, with special attention to the discharge measurements (2). The OWE method was applied to create an upper envelope for the estimated discharge (3). After identifying the beginning and end of the winter period using the stage signal (4), if there was a shift in the rating curve during winter, a linear correction would be applied. The next action consisted of opening discharge measurements in the same graph (5). The discharge at the beginning of freeze-up was drawn using the override function in Aquarius (6). The air temperature and OWE times series were used as indicators to guide discharge estimation to connect with the first winter discharge measurement (7). If there was confidence about the free-spanning state of the ice cover, the override could connect with the lowest values of OWE time series. In turn, a recession function would be defendable if most stage variations were caused by changes in hydraulic conditions. Once the entire mid-winter and breakup periods were processed (8), additional data such as water temperature, estimated flow at other stations, and station information (station analysis for an entire year) were visualized or consulted (9). The data could be modified ("massaged") to make it more realistic, graded (B for "ice affected"), and shared with another technologists (10) before being revised by supervisor. This entire procedure would probably take less than one hour to perform.

After the exercise was completed, the discharge derived from velocity measurements was uploaded. The data looked overall more realistic, but it was very spiky, and some segments of the data set were suspicious.

3.2 General considerations

From the three meetings between WSC and the YRC, the YRC identified a high likelihood for low reproducibility levels for free-hand (override function) discharge estimates. The override function itself works as intended, but the estimated discharge from some winter segments (freeze-up and breakup), or even for the entire winter period would be hard to replicate because of the limited data and (apparently) incomplete river ice knowledge that informs the interpretation. The reproducibility of discharge estimates based on science-based tools such as a dual linear reservoir (hydrological sciences) would probably be superior, but the beginning and the end of the period to which it is applied would still be subjectively defined and therefore associated with greater uncertainty (and some discharge measurements may not happen during the winter recession). Finally, the use of a constant shift (offset) from the OWE data set, the equivalent of a backwater adjustment (river hydraulic sciences), may be more reproducible than the override approach, and it may provide more realistic results for a short period immediately before or after discharge measurements (depending on the stability of weather and hydrological conditions during that period) compared with the recession equation, but its range of applicability would still remain subjectively defined and uncertainties would become significant several days or weeks after and before a discharge measurement. Other functions in Aquarius to support the production of winter discharge estimates include Drift and Trim. These are comparable to the Override function, and they may not improve the reproducibility because they depend on the identification of two points on data series that are relatively arbitrarily selected.

General river ice concepts are understood by WSC analysts. This includes understanding first and last stationary ice, the existence of an ice bite (or early-winter depression*), the occurrence of one or multiple winter discharge recessions, and the potential reaction of the discharge to air temperature variations. In turn, other concepts such as evolving ice cover roughness or blockage, the watershed hydrological response time (the time it takes for flow to peak after a warm day, considering different watershed characteristics), and the distinction between local and upstream ice processes affecting stage or discharge were identified as sources of uncertainty for WSC staff (more knowledge would improve the accuracy and reproducibility of the results). This was identified based on many statements, including a comment that the WDE data should be as smooth (compared with the jagged or unstable measured stage data from which it is derived) as an open water record. Also, it seems that having access to different sources of data from new instruments is welcomed by all technologists, but the extraction of meaningful information contained in additional data sets (e.g., photos, water temperatures, air temperatures) seems to be far from optimal. To adequately manage all the information, further effort to better understand the processes at stake and to be able to visualize several sources of information at the same time (instead of moving back and forth to programs and screens) would be needed (therefore the need for multiple computer displays).

The information presented in *Station Analysis* documents is critical, as it contains information that could otherwise be lost over time, especially if the WDE is not performed by the same technologist, or if the WDE is not immediately performed after the cold season. This type of qualitative and quantitative information, in addition to notes that can be left in Aquarius during discharge measurement visits, is useful to reduce the uncertainty associated with WDE, and it can serve as a training document for staff.

*Generally, the discharge depression caused by river ice formation in upstream reaches and tributaries is included in historical discharge records. However, it is often assumed that the stage rise corresponding to the formation of the local ice cover coincides with the end of the discharge depression. This assumption is rarely acceptable because it would imply that the river section where the station is located is the last to become ice covered (i.e., all upstream reaches would have already achieved their mid-winter ice coverage). This is also incompatible with the amount of heat loss required to dynamically generate an ice cover. The consequence of this assumption is that the freeze-up depression, or bite, has been misinterpreted at several stations and for several decades (its duration has been underestimated because hidden by the local ice formation signal). This will be illustrated in Section 7.

4. Stream classification for winter discharge production

Each watercourse is unique, not only locally, at a specific hydrometric station, but also because of the watershed characteristics, the upstream drainage networks. This statement, although true, is not very useful in a perspective of winter discharge estimation (WDE) strategizing. The stream classification effort presented as part of this work is meant to identify categories, or families of watercourses that could behave similarly in winter, therefore supporting the identification of optimal technological and analytical tools used to produce WDE as part of the proposed new procedure (NP). Classifying natural processes based on a combination of specific parameters almost inevitably leads to an "others" category and to grey zones. Nonetheless, this exercise is constructive because there are thousands of river hydrometric stations in Canada, and because adopting uniform and consistent WDE strategies is suitable from both scientific consistency and data user points of view.

Figure 4.1 illustrates the prototype watercourse (or hydrometric station) classification scheme developed through this phase of the project. It presents a balance between simplicity and comprehensiveness. It considers three parameters (Channel size, Channel gradient, and Winter regime) and two special conditions (Lake or reservoir heat and braided channels).

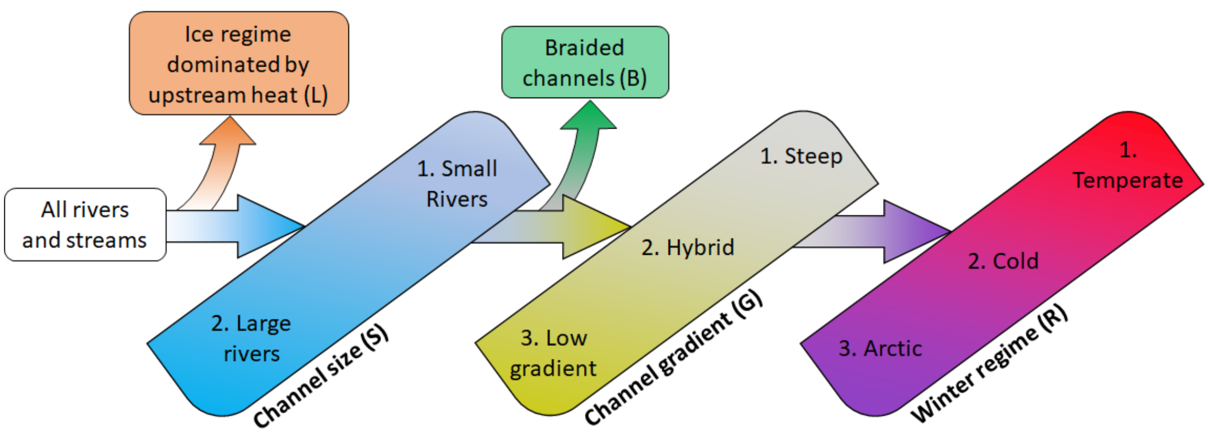

FIGURE 4.1. WATERCOURSE CLASSIFICATION SCHEME USED TO DEFINE MONITORING AND ANALYTICAL STRATEGIES THAT CONTRIBUTE IN IMPROVE WINTER DISCHARGE ESTIMATION.

Parameters defined Figure 4.1 are described as follows:

- Ice regime dominated by upstream heat (L): In some streams and rivers, the presence of large lakes or reservoirs, or the existence of urban heat, has a dominant impact on ice processes. If an ice cover forms at all, freeze-up is gradual and/or predictable, and breakup is also gradual and mostly thermal. This can significantly facilitate WDE although large natural lakes can generate surprising outlet winter discharge fluctuations (e.g., Hamilton, 2004).
- Channel size (S): A large spectrum of channel sizes exists, from small headwater streams in dryer areas of Canada to the gigantic Mackenzie River. However, from an ice processes point of view, the relative width, watershed size, average annual flow, or late winter flow, can be used to differentiate two categories: Small rivers (S1) and Large rivers (S2). This

differentiation mostly means that some rivers will present enough water depth and channel width for the impact of ice processes on stage to be distinct from what is observed in small rivers. For example, in large rivers, it is expected that the ice cover will float freely and that there will be enough water depth to install velocity measurement devices.

- Braided channels (B): Hydrometric stations are rarely installed in braided river segments simply because this morphology is very mobile and unstable. However, stations may be installed downstream of braided river segments, and water levels are therefore affected by very complex ice processes influenced by weather conditions. The interpretation of ice processes to derive discharge estimation at these locations may depend on a thorough local knowledge and/or on extensive monitoring. A higher level of discharge estimation uncertainty should be expected for this type of river.
- Channel gradient (G): It is known that ice processes, and their associated signature in winter water level time series (e.g., Turcotte and Nafziger, 2021), are very different in steep and low gradient streams. Turcotte and Morse (2013) had identified this distinction. Recent observations continue to support this conceptual model: channels that are steeper than 0.5% (G1) will be mostly affected by anchor ice in early freeze-up stages and could be the firsts to see their ice cover mobilized as the discharge rises, whereas gradients below 0.1% (G3) are low enough to generally produce a surface ice cover that is associated with a winter-long water storage. Between these thresholds, the channel gradient is considered hybrid (G2), and is mostly associated with a morphology composed of riffles and pools, where frazil and anchor ice both play dominant roles. Each of these three G categories can be associated, for a given stream size, to significantly different analytical tools and monitoring strategies. Finally, it is important to note that steep channels (G1) are rarely large (S2), at least not over long distances (hydrometric stations are unlikely installed in S2G1 reaches).
- Winter regime (R): Generally speaking, the colder the air temperature is, the thicker a floating ice cover will become. However, this winter intensity parameter targets another phenomenon: mid-winter runoff events. When a rain-on-snow or snowmelt event occurs in winter, the discharge may simply increase, but ice movements can also occur, and this tremendously complicates WDE. In some parts of Canada, mid-winter runoff events are frequent (Temperate climate, R1), and this means that additional efforts may be needed to obtain discharge estimates that are accurate. In colder areas (Cold climate, R2), mid-winter runoff events only occur occasionally, and rarely lead to mid-winter breakup. In arctic and subarctic areas (Artic climate, R3), there are several months every year during which a runoff event is unlikely to affect the integrity of the ice cover, and this justifies investing in a different discharge estimation strategy.

This results in defining 17 categories for hydrometric stations located on Canadian rivers, as identified in Table 4.1 with an associated dominant ice regime. This classification is based on the knowledge of ice processes along several rivers of Canada, but there is insufficient data to confirm if it is well balanced: further investigation may prove that some categories could be combined or eliminated, based on the number of stations / rivers that belong to each of them.

TABLE 4.1. STATION CATEGORIES DEFINED TO SUPPORT THE IMPLEMENTATION OF THE NEW PROCEDURE (NP) FOR WINTER DISCHARGE ESTIMATES (WDE).

Code	Dominant ice process
L	No ice, or largely thermal and predictable freeze-up and breakup processes
S1 B	Apparently chaotic stage variations caused by several superposed ice processes
S1 G1 R1	Defined anchor ice cycles intercepted by open water conditions
S1 G1 R2	Defined anchor ice cycles at freeze-up followed by free-spanning ice cover
S1 G1 R3	Anchor ice cycle potentially followed by solid ice (aufeis) with minimal flow
S1 G2 R1	Significant frazil and breakup jams, often grounded, largely varying backwater
S1 G2 R2	Combination of anchor ice and frazil with significant channel blockages
S1 G2 R3	Combination of anchor ice and frazil followed by icing (aufeis)
S1 G3 R1	Occasional thin surface ice, open water conditions, responsive to snowfalls
S1 G3 R2	Confined ice cover conditions, with occasional water flowing on ice
S1 G3 R3	Confined ice cover conditions and overflow (icing)
S2 G2 R1	Alternating frazil jams, breakup events, and open water conditions
S2 G2 R2	Formation of significant frazil accumulations responding to weather conditions
S2 G2 R3	Significant freeze-up jams and stable ice conditions afterward
S2 G3 R1	Alternating surface ice and ice jams, with possible open water conditions
S2 G3 R2	Stable floating ice cover for at least a couple of months
S2 G3 R3	Stable floating ice cover for several months and significant discharge depression

It is logical that the WSC would avoid installing stations at locations where ice processes are too dynamic or difficult to interpret, but accessibility occasionally justifies deployment in these environments. In turn, other parameters, such as the presence of major tributaries close to the station, or the snow regime, could be included in the proposed classification if enough outliers of comparable characteristics are identified.

This preliminary classification will be further discussed, optimized, and updated. Meanwhile it is necessary to illustrate how this central part of Figure 1.1 can be useful to the WSC. Table 4.2 presents a rough assessment of instruments and analytical tools that could be selected or avoided to inform more accurate and reproducible WDE. For example, at the White River station 09CB001 (S1 B), ice processes are extremely complex and stage variations are probably caused by a range of different upstream and local changes in ice cover conditions. For this site, a water temperature sensor, a secondary remote water level sensor placed at an upstream location, as well as upstream and downstream looking cameras would contribute to improving WDE. These instruments could only be needed for a few years and until the winter dynamics of the site is better understood and documented. In addition, mid-winter flow instabilities could mean that the application of a (dual reservoir type of) recession curve may not be adequate for that site. The ice-effect, shift from rating curve, or backwater effect is also known to change regularly, therefore a correction of this nature over long winter periods may not be applicable.

In turn, for the station on the Takhini River (09AC001, L), freeze-up and breakup are generally easy to interpret and installing a permanent water temperature sensor or a camera might not represent the most beneficial investment (data would be useful for a few days every winter).

Table 4.2. Assessment of complementary technologies and typical analytical tools that should be used (green), could be used in specific conditions (white), or should be avoided (red) to support the WDE procedure for different channel categories.

Category	Cameras	Water velocity sensors	Water temperature sensors	Dual reservoir recession	Informed free hand discharge
L					
S1 B					
S1 G1 R1					
S1 G1 R2					
S1 G1 R3					
S1 G2 R1					
S1 G2 R2					
S1 G2 R3					
S1 G3 R1					
S1 G3 R2					
S1 G3 R3					
S2 G2 R1					
S2 G2 R2					
S2 G2 R3					
S2 G3 R1					
S2 G3 R2					
S2 G3 R3					

5. Research sites

The project started through Phase 1 in 2020-2021 with an exploration of different ice conditions at some hydrometric stations in Yukon (Turcotte et al., 2021). Phase 2 more formally includes the analysis of historical data from nine (9) hydrometric stations located in Yukon:

- Takhini River near Whitehorse (09AC001): L
- White River at Kilometer 1881.6 Alaska Highway (09CB001): S1 B
- Nordenskiold River below Rowlinson Creek (09AH004): S1 G2 R3
- Klondike River above Bonanza Creek (09EA003): S1 G2 R3
- West Aishihik River near the mouth (08AA011): S1 G2 R3
- Pelly River at Pelly Crossing (09BC001): S2 G1 R3
- Yukon river above White River (09CD001): S2 G1 R3
- Stewart River at the mouth (09DD003): S2 G1 R3
- Liard River at Upper Crossing (10AA001): S2 G2 R3

Data such as stage-discharge relationships (most importantly the lower segment), discharge measurements (two to four per winter is the current practice in Yukon), available instantaneous stage times series (available every 5 minutes to every hour), measured ice cover thicknesses (currently once at the end of winter), air temperatures, and satellite imagery (Sentinel 1 and 2) were analyzed to better understand ice processes affecting each station and their upstream drainage network, as well as to determine the impact of different forms of stationary ice on what is referred to as the ice-induced backwater (BW, this is the terminology adopted in this report, and it corresponds to the shift from the rating curve, or discharge ratio): the greater the BW (in %, from 0 to 99%), the more significant is the effect of the ice cover on a combination of channel blockage and resistance to flow (see EQ 6.1 presented in Section 6).

Figure 5.1 presents a comparison of the evolution of the ice-induced BW from freeze-up to breakup onset expressed as a function of the cumulated degree-days of freezing (CDDF, in °C-days), a sum of negative air temperatures over time (the colder the air temperature, the faster CDDF increase, EQ 6.3 can be used to calculate this parameter, as presented in Section 6), for three stations categorized as S2 G1 R3. It is understood, based on the interpretation of different data sources, that river ice formation processes and mid-winter conditions are similar at all three sites. This figure supports that by showing BW values (associated with an evolving ice cover) presenting a similar average trend (long dash line) and envelope (small dash lines).

Figure 5.2 presents similar information for two rivers of the S1 G2 R3 category. In this case, freeze-up is generally more dynamic, it leads to a higher initial BW, and the mid-winter BW trend is either stable or slightly decreasing. This aligns well with observations revealing that the early-winter ice cover (often a proper freeze-up jam) is rough, and it would tend to thermally erode as the flow is logically decreasing.

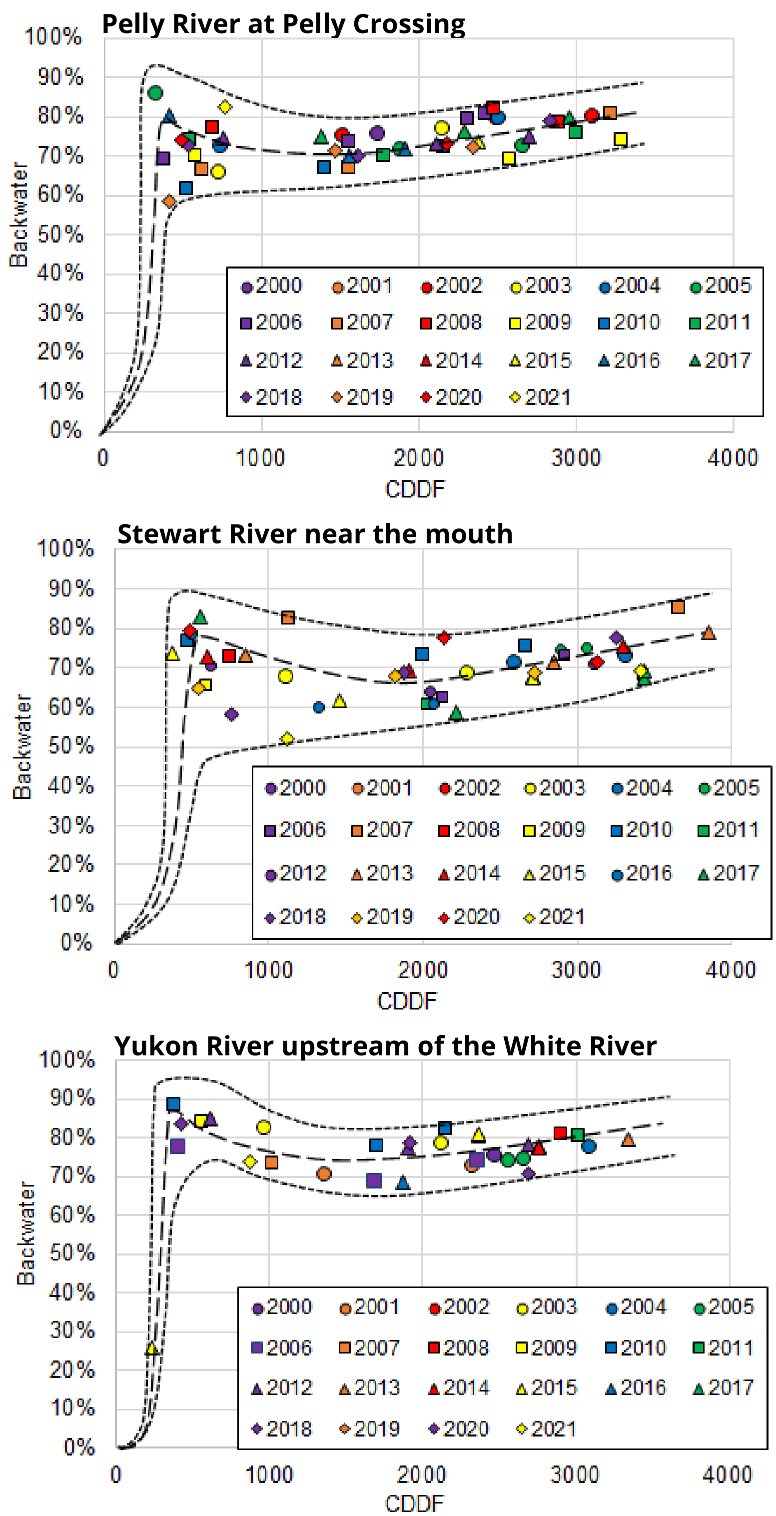

Figure 5.1. Calculated Ice-induced Backwater – Cumulated degree-days of freezing (CDDF) relations from 2000 to 2021 for the Pelly River at Pelly Crossing, Stewart River near the mouth and Yukon River upstream of the White River stations, and interpreted envelopes (small dash lines) as well as typical trends (long dash lines).

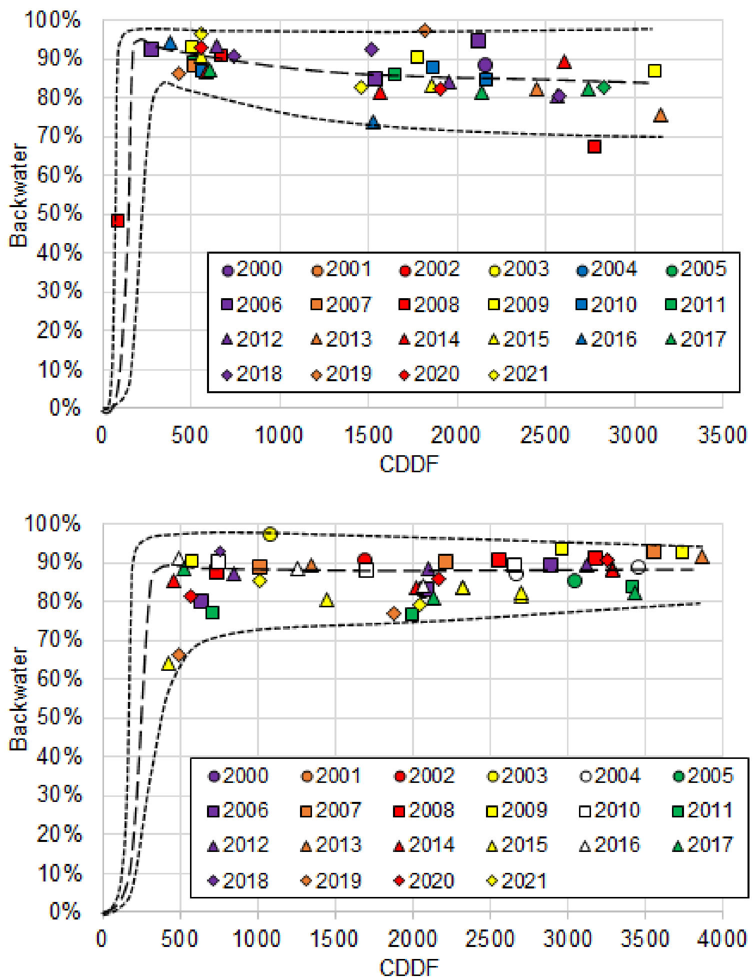

FIGURE 5.2. CALCULATED ICE-INDUCED BACKWATER – CUMULATED DEGREE-DAYS OF FREEZING (CDDF) RELATIONS FROM 2000 TO 2021 FOR THE NORDENSKIOLD RIVER BELOW ROWLINSON CREEK AND KLONDIKE RIVER ABOVE BONANZA CREEK STATIONS, AND INTERPRETED ENVELOPES (SMALL DASH LINES) AS WELL AS TYPICAL TRENDS (LONG DASH LINES).

In addition to mid-winter data interpretations, information was also extracted about the timing of first detected ice (and this was compared with identified First B dates by WSC), timing and stage rise associated with the dynamic formation of an ice cover, the first signs of spring breakup onset, the evolution of backwater during the spring breakup period, and the last day of ice as detected in the stage signal (which was also compared with the last B date identified by WSC). Figure 5.3 presents an example of an expected backwater envelope and typical trends for a S2 G2 R3 type of river in Yukon (Liard River at Upper Crossing) expressed as a function of effective degree-days of thaw (ECDDT in °C-days, refer to EQ 6.6 in Section 6). In this figure, two different trends are presented: a thermal melt trend and an ice jam and release trend. This type of data analysis even supports the development of river ice breakup models at specific sites, as shown in Figure 5.4 for the Yukon River above the White River.

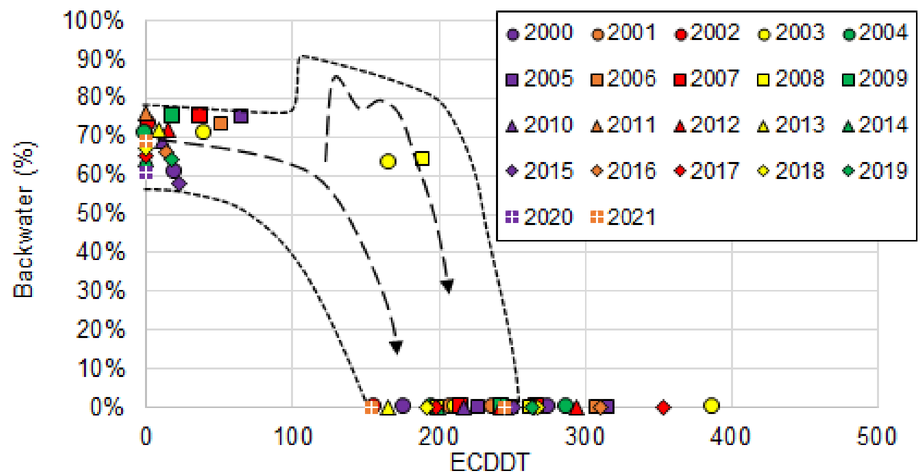

FIGURE 5.3. CALCULATED ICE-INDUCED BACKWATER – EFFECTIVE CUMULATED DEGREE-DAYS OF THAW (ECDDT) RELATIONS FROM 2000 TO 2021 FOR THE LIAR RIVER AT UPPER LIARD, AND INTERPRETED ENVELOPES (SMALL DASH LINES) AS WELL AS TYPICAL TRENDS (LONG DASH LINES, THE HIGHEST LINE PRESENTING THE ICE JAM SCENARIO).

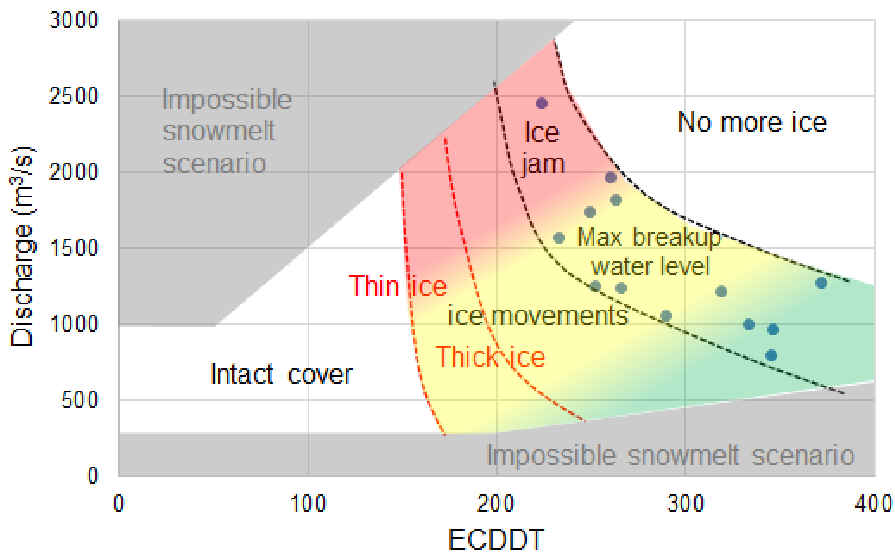

FIGURE 5.4. PRELIMINARY RIVER ICE BREAKUP TIMING AND INTENSITY MODEL FOR THE YUKON RIVER ABOVE THE WHITE RIVER, BASED ON ANALYZED WATER LEVEL, DISCHARGE AND AIR TEMPERATURE DATA. THE MODEL USES SIMPLE INDICATORS: THE ESTIMATED DISCHARGE AND EFFECTIVE CUMULATED DEGREE-DAYS OF THAW (ECDDT). DOTS ARE MAXIMUM BREAKUP WATER LEVELS FOR DISTINCT SPRINGS BETWEEN 2000 AND 2021.

Table 5.1 presents a summary of information extracted from the various analyses performed as part of this work, which is useful to guide WDE at these stations. For example, for the Yukon River above the White River, if there is a water level variation after 350 ECDDT, this is likely a discharge fluctuation, and the local rating curve applies (the ice-induced BW is nil). Several disparities for first and last B (ice-affected) date in WSC records were identified using these simple indicators.

TABLE 5.1. RIVER ICE FORMATION AND RIVER ICE BREAKUP AIR TEMPERATURE INDICATORS FOR THE STUDIED STATIONS.

Station	CDDF at first ice	CDDF at congestion	ECDDT at first ice movement	ECDDT at last ice
Takhini River	< 100	50-180	<100	150-320
White River	< 50	60-350	< 120	100-250
Nordenskiold River	First -5ºC	> 70	< 130	70-200
Klondike River above Bonanza	< 100	> 100	40-150	140-220
West Aishihik River	< 20	NA	<40	180-250
Pelly River at Pelly Crossing	< 70	60-220	< 80	180-300
Yukon river above White River	First -10ºC	150-300	150-230	180-350
Stewart River at the mouth	< 50	80-350	70-200	170-320
Liard River at Upper Crossing	< 50	60-180	80-200	150-250

In Table 5.1, air temperature indicators for each hydrometric stations are linked to a specific nearby weather station operated by Environment and Climate Change Canada. These weather stations can be a few kilometers to several tens of kilometers away from hydrometric stations. Improved assessments could be obtained if local air temperature measurements were consistently available at hydrometric stations (since they are linked to local ice conditions) and these improvements are already effective at some hydrometric stations.

Beyond representing useful hydrological knowledge that guide WDE, the information presented in this section can inform the development of analytical tools that make WDE more accurate and reproducible, as presented in Section 6.

6. Prototype procedure for WDE

As summarized in section 3, winter discharge estimates (WDE) are often considered adequate when the discharge data set (i.e., the winter hydrograph) is reasonable in terms of trend and amplitude, and when it remains within historical extremes. Over the years, because of diverse regional office realities (management philosophies, technical experience, nature of ice processes at stake, types of rivers), different WDE techniques have been preferred or adopted, and the existing procedure (EP) varies from one place to another. As a result, the level of accuracy and reproducibility for WDE is also expected to vary across the country and it is probably low for periods of greater uncertainty such as freeze-up, breakup, and mid-winter runoff events (or at stations where water level time series are affected by complex ice processes).

To address these challenges, the new procedure (NP) proposed in this report involves three development fields as presented in Figure 1.1. Two desired outcomes of this NP are to generate:

- More reproducible WDE: relying on more information and validation tools to guide the judgment of analysts and reduce the degrees of freedom.
- More accurate and realistic WDE: more scientifically defendable and preserving actual discharge fluctuations in hydrometric records.

This section emphasizes the development of an adapted toolbox. This includes slightly modified WDE production steps (described below in subsection 6.2) and new computation tools (subsection 6.3). In addition, the NP relies on two key components, as described next.

6.1 Key components of the NP

This subsection describes two key components of the NP: a BW graph that is as valuable as the estimated discharge (Q) graph, and the concept of a Hydraulic Anchor Point (HAP). Although these components are essential to the NP, they could also improve the performance of the existing procedure (EP).

6.1.1 Backwater (BW)

In order to distinguish (and adequately compute) stage variations that are caused by local ice processes from those caused by real discharge fluctuations, some tools developed for the NP (subsection 6.3) heavily rely on the estimation or calculation of the ice-induced backwater (BW), based on an assumed / known / estimated discharge (Q_{est}), or *vice versa*:

$$BW = 1 - \left(\frac{Q_{est}}{Q_{rated}}\right) \quad \text{or} \quad Q_{est} = Q_{rated}(1 - BW) \qquad \text{EQ 6.1}$$

Q_{rated} is the maximum possible discharge (derived from the rating curve, essentially the Open Water Equivalent [OWE] method). It is comparable to the concept of a perceived discharge. The ice-affected discharge, Q_{est}, can only be lower than Q_{rated} (in almost 100% of the possible ice conditions).

BW has been used by previous authors and is being considered by hydrometry analysts in the EP. However, it never seems to be presented in a graph as a time series, just like WDE (Q_{est}), and this is what the NP proposes.

6.1.2 Hydraulic Anchor Points (HAP)

It is known, when producing WDE, that some form of continuity in values and trends must be respected; this actually represents a very accessible data quality control in hydrology. The concept of a HAP is also currently used by WSC staff: It includes the last day of open water in the fall (know discharge, BW = 0%), the first day of open water in the spring (known discharge, BW = 0%), any mid-winter day during which the rating curve applies (as a result of a mid-winter melt or breakup), and any discharge measurement (know discharge, know BW > 0%, EQ. 6.1). These are **non-negotiable HAPs**: Q_{est} must meet these points and the Q_{est} trend before and/or after these points must be defendable. For most stations in Yukon, there are 5 non-negotiable HAPs per winter. Between these HAPs, the uncertainty in WDE can be significant.

The NP introduces the concept of **negotiable HAPs**: the value of these points is imposed by the analyst based on several sources of information for a given date and time, most often at transition points between ice processes or stage trends. Between these HAPs, different tools can be used to define the WDE. Negotiable HAPs can be modified at any time during the computation to improve WDE. As an example, after the dynamic formation of an ice cover (and once the associated stage rise reaches its peak), the analyst can initially impose a BW value of 80% (based on historical discharge measurement records, see example in Figures 5.1 and 5.2) or a given Q_{est} (based on the continuation of a discharge depression). Before and after this new HAP, different tools can be used to produce WDE over several days or weeks. After computing Q_{est} between two non-negotiable HAPs, it can be decided to fine tune this negotiable HAP by changing the imposed BW value to, say, 83%, in order to ensure better result continuity. The programmed tools can automatically recalculate Q_{est} before and after this HAP to ensure Q_{est} and BW continuity.

6.2 Prototype NP steps

This subsection describes the proposed steps involved in the prototype NP. Detail about parameters - acronyms, and equations - are provided in subsection 6.3.

Preparation steps to produce WDE:

1. Confirm validity of station open water rating curve and perform required stage adjustments
2. Produce graphs showing:
   - Stage working
   - Maximum discharge derived from the rating curve (Q_{rating})
   - Discharge measurements (Q_{meas})
   - Nearby air temperatures (T_{air})
   - Water temperature (if available)
3. Calculate and produce graphs showing additional river ice indicators
   - Cumulated degree-days of freezing (CDDF)
   - Effective cumulated degree-days of thaw (ECDDT)
4. Prepare empty time series and graphs for discharge estimates (Q_{est}) and backwater (BW)
5. Consult freeze-up, mid-winter, and breakup photos (if available)
6. Read station documentation about ice processes, historical discharge measurements (not historical estimates), thresholds, and reference weather stations.

WDE computation steps:

7. Identify non-negotiable Hydraulic Anchor Points (HAPs): first and last ice (there may be several cycles) using all the information available (and set BW to 0%, or $Q_{est} = Q_{rating}$), and discharge measurements (Q_{meas}) with their associated BW (EQ. 6.1).
8. Identify, using notes and/or time markers, universal winter events such as i. stage rises that cannot be explained by runoff or upstream storage release events, ii. maximum freeze-up stage, iii. apparent end of freeze-up depression, iv. any mid-winter runoff event, v. beginning of spring runoff or alteration in BW, vi. dynamic ice processes such as ice congestion, ice jam formation and ice jam release events. Some of these transitions will be tied to negotiable HAPs separated by winter segments of relatively homogeneous stage or BW trends.
9. Confirm whether all Q_{meas} took place during a single discharge recession, or if one Q_{meas} took place during the early-winter discharge depression, before or after a mid-winter runoff event, or once spring runoff had started.
10. Solve mid-winter segments by filling gaps between Q_{meas} that took place during a single discharge recession (post-freeze-up) period, ensuring that both Q_{est} and BW make sense. The most common tool for this is the recession approach widely used by WSC analysts. Other tools presented in subsection 6.3 may also provide representative results, in addition to preserving weather-induced discharge fluctuations. They can be used to:
    - Extrapolate of BW values backward in time from the first winter Q_{meas} to the end of the freeze-up depression,
    - Interpolate BW between two mid-winter Q_{meas}, or
    - Extrapolate BW forward from the last winter Q_{meas} until breakup onset (when runoff begins or when the ice cover roughness or blockage starts changing).
11. Estimate the discharge during freeze-up segments using a set of different tools (subsection 6.3) that will depend on the dynamic or passive nature of ice processes taking place at and upstream of the station (this requires knowledge about processes normally affecting stage and discharge at that station, refer to Section 5). Ensure continuity between the pre-freeze-up period (BW = 0%) and the end of the freeze-up depression towards the first winter Q_{meas} (merging with the Q and BW values from the mid-winter analysis performed at step 10).
12. Estimate the discharge between breakup onset and spring open water conditions (BW = 0%) using a set of different tools (subsection 6.3), which selection will depend on the nature of ice processes that generate stage and discharge variations at the station. Differentiate BW and Q variations by looking at different indicators (e.g., air temperature, secondary sensor, photos) and station characteristics (e.g., hydrological response time). Ensure continuity between the last mid-winter Q_{meas} and open water conditions.
13. Look at the results for the entire winter period. Both Q_{est} and BW times series should make sense in terms of shape, variations, and absolute values. Fine tune results from specific segments by changing HAPs values and dates. This should be relatively straightforward since most of the HAPs should be connected through equations (tools) applied to specific segments.
14. Compare results with those of other stations for the same winter as well as with historical results at the same station before sharing the WDE with colleagues and supervisors.

6.3 Proposed tools

This subsection presents a set of different tools, or equations, that can be used to perform WDE between HAPs (what is referred to as winter segments).

A. Rising backwater based on variable air temperature indicator

This equation means to simulate the hydraulic impact of the formation of border ice, or the thickening of a floating ice cover, two processes that are generally thermally driven. The air temperature indicator used here is the cumulated degree-days of freezing (CDDF). Between times t = 0 and t = F (final, also tied to a HAP), the backwater (BW_t) is calculated as follows:

$$BW_t = \left(\frac{CDDF_t - CDDF_{t=0}}{CDDF_{t=F} - CDDF_{t=0}}\right)(BW_{t=F} - BW_{t=0}) + BW_{t=0} \qquad \text{EQ 6.2}$$

$CDDF_t$ = Cumulated degree-days of freezing at any time t between 0 and F

$CDDF_{t=0}$ = Initial CDDF, at the beginning of the simulated ice process (HAP)

$CDDF_{t=F}$ = Final CDDF, at the end of the simulated ice process (HAP)

$BW_{t=0}$ = Initial backwater value (HAP)

$BW_{t=F}$ = Final backwater value (HAP)

$CDDF_t$, the degree days of freezing for any time step t, is obtained as follows:

$$CDDF_t = \frac{-T_{air\,t}}{n} + CDDF_{t-1} \text{ and } CDDF_t \geq 0 \qquad \text{EQ 6.3}$$

$T_{air\,t}$ = Air temperature at any time step

n = number of time steps per day (e.g., 24 for hourly $T_{air\,t}$)

$CDDF_{t-1}$ = Degree-days of freezing at the previous time step

$CDDF_t$ can decrease when warm temperatures occur, but it can never be less than 0 at the start of the cold season. In Yukon, it is usually calculated starting in October, but an early computation date does not matter, given the floor value of 0 before freezing begins.

Figure 6.1 shows an early winter of Q_{est} calculated from Q_{rating} and B_{Wt} using Eq 6.1 when BW_t is obtained from Eq 6.2. In this example, it is assumed that gradual ice formation depends on air temperatures (a reasonable assumption), it starts at $CDDF_{t=0}$ = 20, $BW_{t=F}$ = 15%, and stage variations are assumed to be caused by upstream ice processes (and therefore represent real discharge fluctuations, another reasonable assumption, supported by satellite observations).

B. Decreasing backwater based on fixed air temperature indicator

This tool means to simulate the thermal (or hydraulic) erosion of a recently formed ice cover (like a freeze-up jam) or the gradual melting of an ice cover in the spring over short periods. It can also be used to simulate an increasing backwater through a minor modification of the following equation (as well as the definition of its parameters).

$$BW_T = BW_{t-1} - \frac{T_{air\,eff\,t}}{\sum_{t=0}^{F} T_{air\,eff\,t}}(BW_{t=0} - BW_{t=F}) \qquad \text{EQ. 6.4}$$

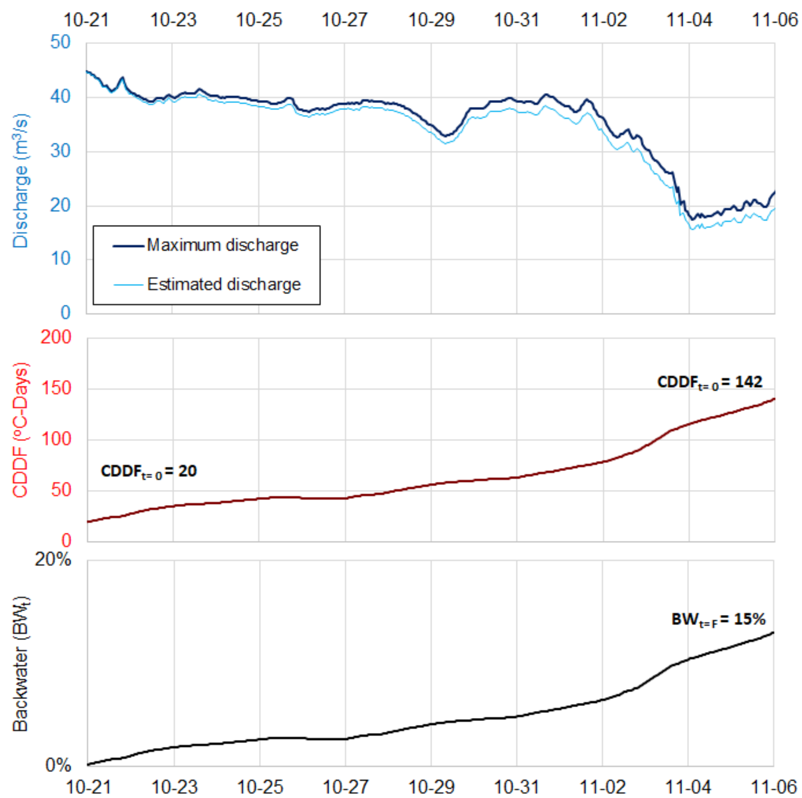

FIGURE 6.1. MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}), CUMULATED DEGREE-DAYS OF FREEZING (CDDF) AT A NEARBY METEOROLOGICAL STATION, AND CALCULATED ICE-INDUCED BACKWATER (BW) USING EQ 6.2.

BW_{t-1} = BW one time step before

$BW_{t=0}$ = Initial backwater value (HAP)

$BW_{t=F}$ = Final backwater value (HAP)

$T_{air\ eff\ t} = T_{air\ t} - T_{eff}$ and $T_{air\ eff\ t} \leq 0$ EQ. 6.5

T_{eff} = Threshold below which thermal erosion does not occur (an imposed constant or variable, based on judgement, that can be adjusted just like a negotiable HAP)

In other words, Equations 6.4 and 6.5 calculate a decreasing BW when T_{air} is warm enough (above T_{eff}). Figure 6.2 presents an example in which a freeze-up ice jam has just formed (prior to Nov 3), and it is assumed that its hydraulic (BW) impact decreases during the following weeks when T_{air} is above -10ºC (T_{eff}). Here again, it is proposed that stage fluctuations are caused by upstream ice processes (which is a reasonable assumption, since satellite images confirmed that the ice front had moved upstream of the hydrometric station). The reason why Q_{est} increases after Nov 24 is that this corresponds to the end of the freeze-up Q depression. It is also important to note that, at this station, freeze-up jams are often associated with significant BW values compared with most mid-winter calculated BW values. Therefore, a reduction in post-freeze-up BW is realistic.

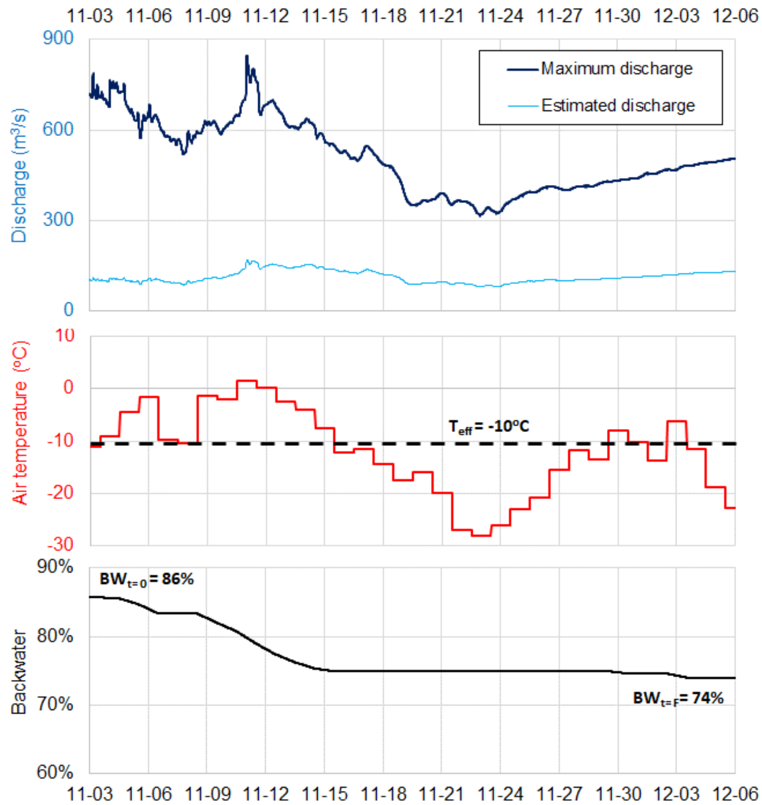

FIGURE 6.2. MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}), AIR TEMPERATURE (T_{AIR}) AT A NEARBY METEOROLOGICAL STATION (DAILY-AVERAGED), AND CALCULATED ICE-INDUCED BACKWATER (BW) USING EQS 6.4 AND 6.5.

If it was found that hydraulic erosion of the freeze-up jam dominates over thermal erosion, then the decreasing BW trend could be assumed monotonic between the value of 86% and 74% and Equations 6.4 and 6.5 would not be needed for WDE over that post-freeze-up segment.

C. Decreasing backwater based on variable air temperature indicator

This is comparable to the previously described tools, but it relies on a common ice cover weakening indicator, effective degree-days of thaw, or ECDDT, to calculate a decreasing BW during thermal breakup segments (often in the spring). In equation 6.2, CDDF can simply be replaced by ECDDT, the later being calculated using this equation for a fixed (T_{eff}) or variable over time ($T_{eff\,t}$):

$$ECDDT_t = \frac{T_{air} - T_{eff\,t}}{n} + ECDDT_{t-1} \text{ and } ECDDT_t \geq 0 \qquad \text{EQ 6.6}$$

In the river ice literature, T_{eff} t is often set as a constant of -5ºC (which means that $ECDDT_t$ become greater than 0 when T_{air} is above -5ºC). The purpose of this constant is to take short wave radiation (the sun heat) into account to track is cover decay (the sun represents an important component of the spring heat budget at the ice cover surface as well as within the ice cover, e.g., Alford and Carmacks, 1987a). For this research, a variable value of $T_{eff\,t}$ was set at -2ºC at the beginning of March (when the sun is still low in Yukon) to -6ºC in May (when the sun is higher and shines for a longer period), but more research is needed to quantify $T_{eff\,t}$, considering not only the latitude, but also average spring sky conditions (often cloudless in Yukon during breakup).

Figure 6.3 presents an example of the use of two consecutive EQ 6.2 using ECDDT instead of CDDF with an assumed BW value of 76% in between (a negotiable HAP at ECDDT = 79). These two late-winter (or early spring) segments follow a mid-winter period during which a very gradual BW rise was revealed (by 3 discharge measurements) and are preceded by the occurrence of an ice-jam release wave and a dynamic breakup event. Once again, the relatively smooth calculated BW trend (a reasonable assumption, given the lack of significant or sharp stage fluctuations that would be associated with local ice movements) enables Q_{est} to be realistically unstable (through equation 6.1). If the April 17 HAP was adjusted to 68%, then the BW drop would essentially be linear, and Q_{est} would automatically adjust backwater to April 5 and forward to April 23.

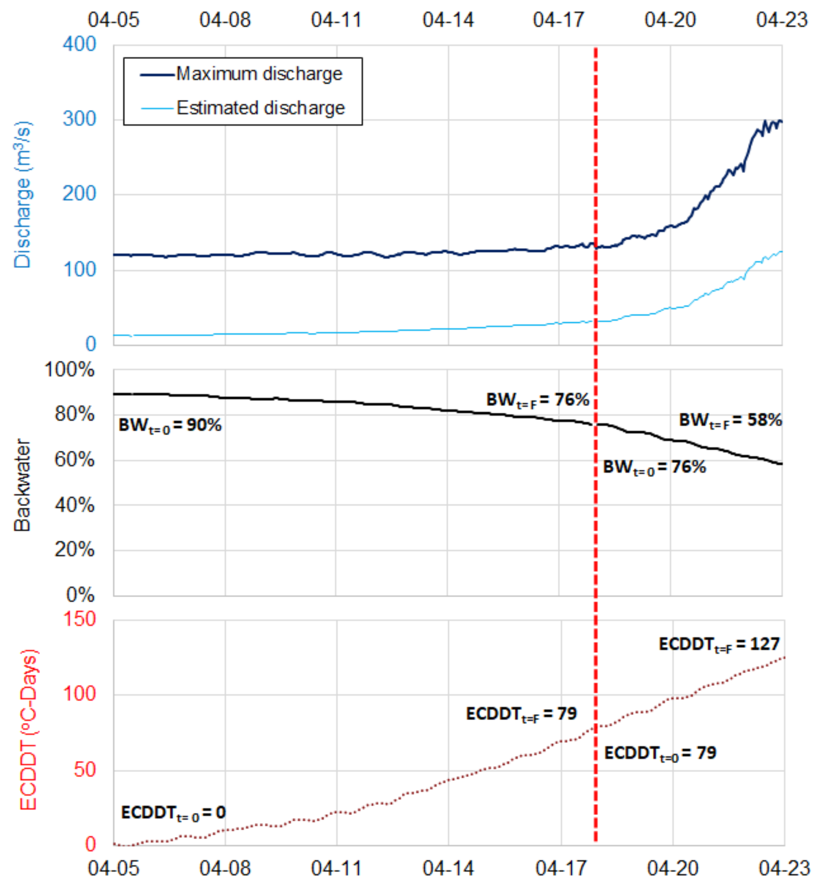

FIGURE 6.3. MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}), CALCULATED ICE-INDUCED BACKWATER (BW) USING EQ 6.2, AND CALCULATED EFFECTIVE CUMULATED DEGREE-DAYS OF THAW (ECDDT) USING AIR TEMPERATURE DATA (T_{AIR}) FROM A NEARBY METEOROLOGICAL STATION AND EQ 6.6.

As the ice cover starts to degrade in the spring, the underside of the ice cover (in contact with the water) starts forming ripples or dunes (e.g., Alford and Carmacks, 1987b; Buffin-Bélanger et al., 2015), which means that the ice cover roughness (resistance to flow) increases. It is uncertain if a stage rise associated with this additional roughness is common in rivers of Canada, but if this phenomenon was identified at a specific station or for a specific year (a stage rise that cannot be explained by additional runoff), a slight adjustment to Equation 6.2 could simulate a rising BW_t for increasing $ECDDT_t$ for a short winter segment (at breakup onset).

D. Fixed flow or fixed flow trend

This tool is meant to allow for an automatic adjustment of the BW_t when the stage (or $Q_{rating\ t}$) varies quickly over a short period (e.g., a few hours) as a result of local ice movements. For example, during the dynamic formation of an ice cover (e.g., freeze-up jam), or the formation or release of a breakup ice jam, the stage rises or drops significantly whereas Q varies more gradually, even monotonically. Imposing reasonable $Q_{est\ t}$ values (or a trend) for a limited number of time steps probably yields realistic results that could compare with those obtained from under-ice velocity measurements (without the risk associated with instrumentation damage).

Figure 6.4 presents an example of the use of a fixed flow trend (the steepening of a Q depression caused by upstream storage) to allow the BW_t to increase non-linearly during the dynamic formation of an ice cover (From Oct 31 to Nov 1). It this case, the $BW_{t=0}$ is 20% (negotiable HAP), and $Q_{est\ t=0}$ is calculated at 117 m^3/s (using EQ 6.1) whereas $Q_{est\ t=F}$ (after 42 hours) is set at 109 m^3/s, a reduction nicely merging with the post-event Q_{est} trend. The calculated $BW_{t=F}$ is 87%.

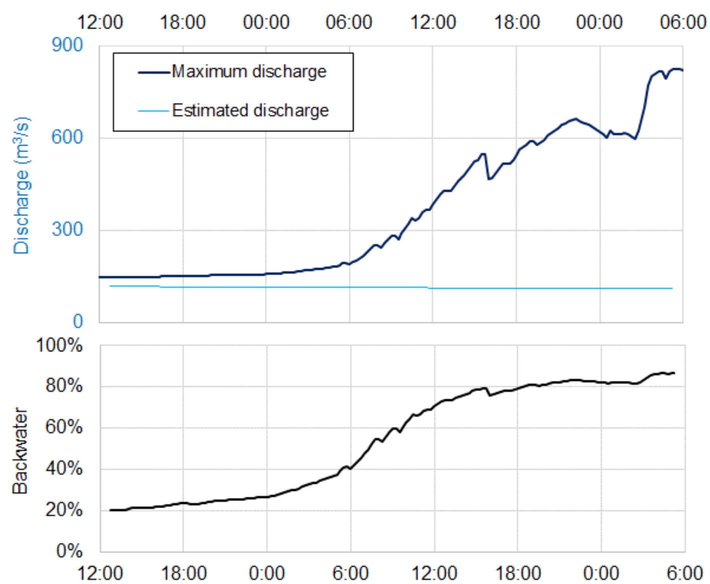

FIGURE 6.4. MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}), AND CALCULATED ICE-INDUCED BACKWATER (BW) DURING THE DYNAMIC FORMATION OF AN ICE COVER.

Note that the first Q_{meas} taking place two months later (100 m^3/s) is associated with a calculated BW value of 75%, which means that thermal or hydraulic smoothening has taken place after the formation of the ice cover. If $BW_{t=F}$ had been blindly set to a value the same value of 75% in Figure 6.4, then, $Q_{est\ t=F}$ would be calculated at 205 m^3/s (compared with 109 m^3/s), which would represent an unreasonable Q increase (from 117 m^3/s) following the dynamic formation of the ice cover at the station. This demonstrates the power of ensuring that both Q_{est} and BW make sense.

E. Fixed backwater or manual adjustment of the backwater.

This technique is mainly considered when both Q and BW are varying significantly (more than the uncertainty associated with a Q_{meas}, generally 5% to 10%) over a short period. This mostly happens during breakup events, when an ice-jam-release wave creates a Q fluctuation at the station, followed by the local ice cover (or ice jam) mobilization. During the event, as Q increases, it is expected that BW_t increases slightly (rise in hydraulic resistance) before dropping to a lower value, even 0%. Such dynamic process is triggered by an imbalance in structural and hydraulic forces ultimately related to weather conditions, but ice jam release events are unpredictable, and both Q and BW are largely independent of T_{air} or any other weather parameter.

Figure 6.5 presents the example of a WDE during the local mobilization of an ice cover in the spring in a relatively small river. This event lasts 4 hours, and it is associated with some form of momentary increased resistance (BW) because the stage initially rises. The imposed higher BW_t reduces the value of Q_{est}, delays the Q_{est} peak, and therefore may be more representative of the hydrograph leaving the station.

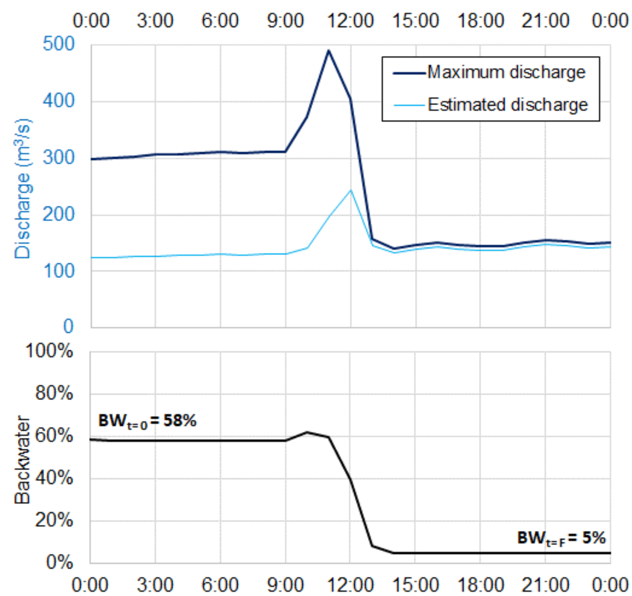

FIGURE 6.5. MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}), AND IMPOSED ICE-INDUCED BACKWATER (BW) DURING A DYNAMIC BREAKUP EVENT.

This tool is associated with more uncertainty than previously described tools, but Q_{est} and BW are more realistic than if the wave was simply erased from the Q_{est} record (with an unrealistic BW_t).

F. Adjustment of cyclic discharge and/or backwater variations

Some ice processes in smaller and steeper rivers (of the S1G1 and S1G2 category, Section 4) involve a superimposition of Q and BW variation cycles that are either ice or runoff driven:

- In the fall, or after a mid-winter breakup event, the formation and release (or breaching) of anchor ice (or ice dams) takes place during cold spells, and this cycle may happen several times over a few weeks. The typical signature associated with this process is a single day to multi-day stage rise (at a rate that may vary from 0.5 cm/hr to 2.0 cm/hr) followed by a sudden or equally gradual stage drop. Although driven by local ice processes (BW variations), it is also accompanied by a flow (Q) depression caused by storage of water and ice in upstream reaches. The interpretation of these cycles is depicted in Figure 6.6 (in this case, the Q depression was identified with a Q_{meas}).

- In the spring, when snowmelt begins, daily runoff cycles are expected. At the same time, the ice cover weakens and becomes more ductile (part of the ice cover may be grounded on gravel bars and rocks, but free-spanning ice cover sections may bend into the flow). A small rise in Q may lead to a significant stage rise as flow blockage (BW) rockets up, and overflow may result. Over the following days, as runoff cycles become more significant (Q variations should correspond to expected snowmelt rates), daily BW cycles may vary before dropping to 0% (when an open water channel has formed). Figure 8 in Turcotte and Nafziger (2021) presents a perfect example of this process. Another example is presented in subsection 7.3.

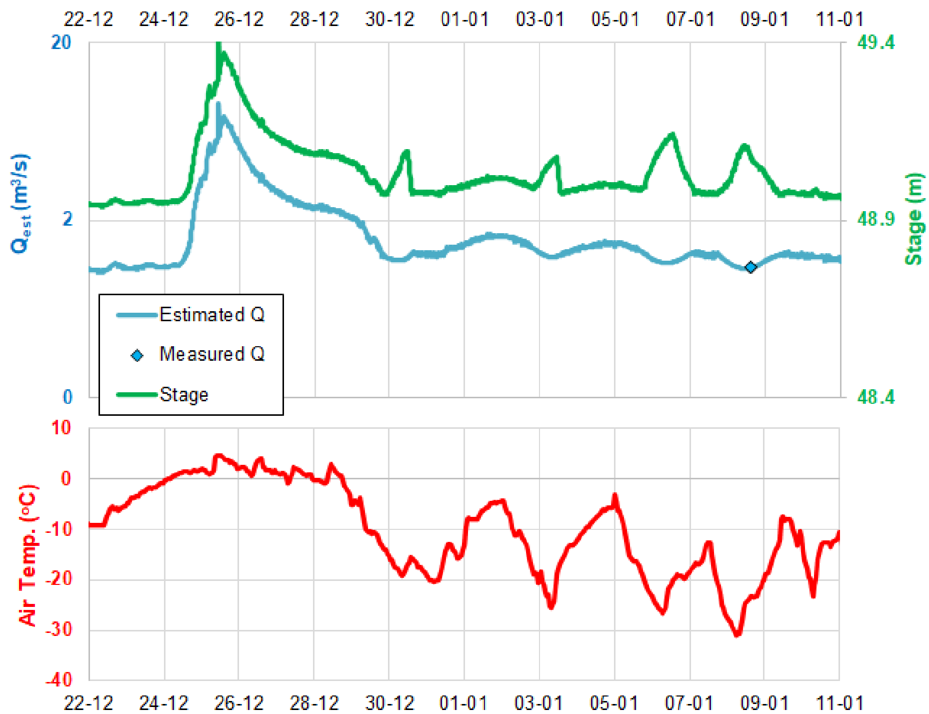

FIGURE 6.6. ESTIMATED DISCHARGE (Q_{EST}), STAGE, AND AIR TEMPERATURE (T_{AIR}) AT A NEARBY METEOROLOGICAL STATION DURING A RUNOFF EVENT AND FOUR ICE DAM FORMATION AND BREACHING CYCLES (GRAPH FROM TURCOTTE AND MORSE, 2016, PREPARED FOR LE GOUVERNEMENT DU QUÉBEC).

In both cases, it could be inappropriate to assume a constant Q trend, or constant BW trend, but producing representative WDE may be tedious. Through case studies reported in Section 3, it became obvious that the EP does not include analytical tools that are adapted to produce WDE when these cyclic ice processes happen.

No equation or algorithm has been created yet within the proposed NP to support the production of WDE when the above-described ice processes are taking place. The development and calibration of a tool that addresses these challenges would benefit from numerical simulations and targeted, temporary instrumentation deployment or monitoring efforts. An approach that would involve a time-evolving BW envelope should be considered.

7. Proof of concept and results

Data (instantaneous stage, discharge measurements [Q_{meas}], rating curves, air temperatures [T_{air}]) from 2000 to 2020 were used to understand ice processes and the typical range of winter discharge (Q) and ice-induced backwater (BW) for nine hydrometric stations in Yukon (Section 5). This section presents winter discharge estimation (WDE) results during a single winter for four different stations. Results obtained from the application of the proposed new procedure (NP, as described in Section 6) are then compared with WSC historical Q estimates (using the existing procedure, EP).

7.1 Pelly River at Pelly Crossing, winter 2016-2017

Figure 7.1 presents all the parameters considered (discharge obtained from the application of the rating curve [Q_{rating}], T_{air} at two weather stations, cumulated degree-days of freezing [CDDF], effective cumulated degree-days of thaw [ECDDT]) to produce discharge estimates (Q_{est}) and BW at station 09BC001 for winter 2016-2017 (river reach classified as S2G1R3 in Sections 4 and 5). Only the stage is not presented, but the trend essentially corresponds to that of Q_{rating}.

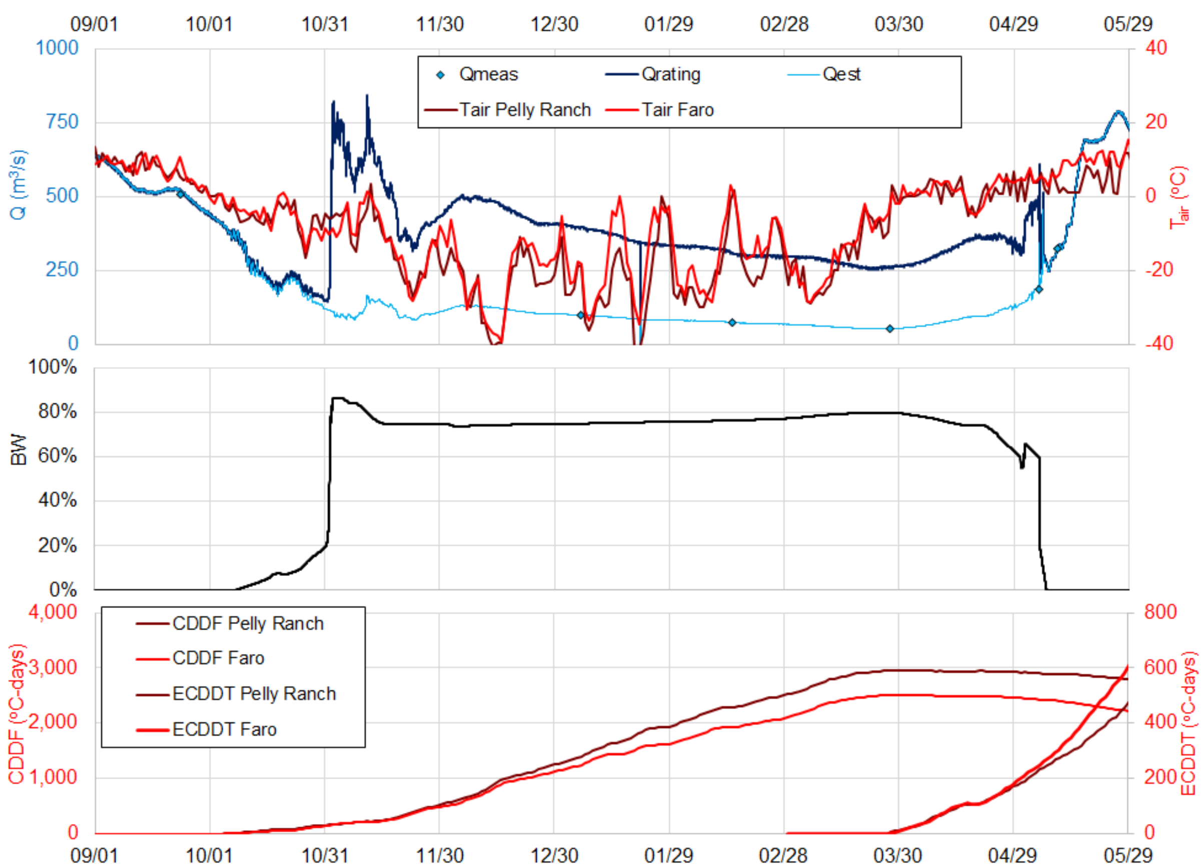

FIGURE 7.1. UPPER GRAPH: DISCHARGE MEASUREMENTS (Q_{MEAS}) PROVIDED BY THE WSC FOR STATION 09BC001, MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}, THE RESULT OF THE ANALYSIS), AND DAILY-AVERAGED AIR TEMPERATURES (T_{AIR}) AT TWO NEARBY WEATHER STATIONS. MIDDLE GRAPH: ESTIMATED OR CALCULATED BACKWATER (BW). LOWER GRAPH: CUMULATED DEGREE-DAYS OF FREEZING (CDDF) AND EFFECTIVE CUMULATED DEGREE-DAYS OF THAW (ECDDT) FOR THE SAME WEATHER STATIONS.

The BW graph in Figure 7.1 presents gradual and rapid variations tied to ice processes that are known or assumed to occur:

- Formation of border ice (the first stationary ice cover, which annual occurrence is confirmed by satellite images): this causes a gradual, generally steady rise in BW as T_{air} cools down.
- Ice congestion (the main river ice formation process along this river): this causes a sharp rise in BW while Q_{est} continues to be depressed by upstream storage.
- Freeze-up jam erosion (this is a normal process taking place after dynamic freeze-up): this causes a drop in BW.
- Ice cover thickening during cold winter months: this is associated with a gradual rise in ice-induced BW. The ice roughness is not assumed to change, but the relative channel blockage is increasing (flow area reduction).
- Ice melting at breakup onset, a process eventually counteracting the rising runoff (for that specific winter): The declining BW leads to a drop in stage (Q_{rating}) despite the rising Q_{est}.
- Weak ice jam formation (0.3 m stage rise) and release (0.5 m stage drop): Q_{meas} is assumed to be relatively steadily rising whereas BW and Q_{rating} rise and drop sharply.

Note that the early-winter Q depression is estimated to last two months (early-October to early-December), including more than one month after the complete formation of the local ice cover.

Figure 7.2 presents the tools and equations of the NP used to produce WDE for this specific winter (as described in Section 6):

- Known Q (Q_{meas} or Q_{rating} when no ice is present)
- Tool A. Rising BW based on CDDF
- Tool B. Decreasing BW based on $T_{air\ eff}$
- Tool C: Decreasing BW based on ECDDT
- Tool D: Fixed flow trend
- Tool E: Imposed backwater trend

Figure 7.2 also presents hydraulic anchor points (HAPs). Black dots are non-negotiable HAPs whereas white dots are HAPs that can be adjusted. There are only four negotiable HAPs in that analysis, which means that its level of reproducibility is relatively high when the NP is applied. This analysis took about 2 hours to complete but performing WDE for other comparable winters at that station would probably take less time, given the experience developed through this exercise.

Figure 7.3 compares the results obtained from the application of the NP with what was obtained by WSC through the EP. Considered alone, the interpretation of the winter Q by the WSC ($Q_{est\ EP}$) appears reasonable. However, when considering T_{air} and BW_{EP}, most of the freeze-up period does not make sense (the BW should not drop significantly before rising back). The difference between $Q_{est\ NP}$ and $Q_{est\ EP}$ reaches a maximum of 100 m^3/s (125%) on Nov 23rd. The mid-winter interpretation is comparable as both NP and EP are tied to the same HAPs, which reduces the uncertainty. Breakup is also interpreted similarly, but ice-jam release waves are kept in the record (Figure 7.3 presents the daily-averaged $Q_{est\ EP}$ and sub-daily details may be missing).

The reason why the BW_{EP} goes slightly below 0% prior to freeze-up is probably due to a small difference in the rating curves that have been used for this analysis.

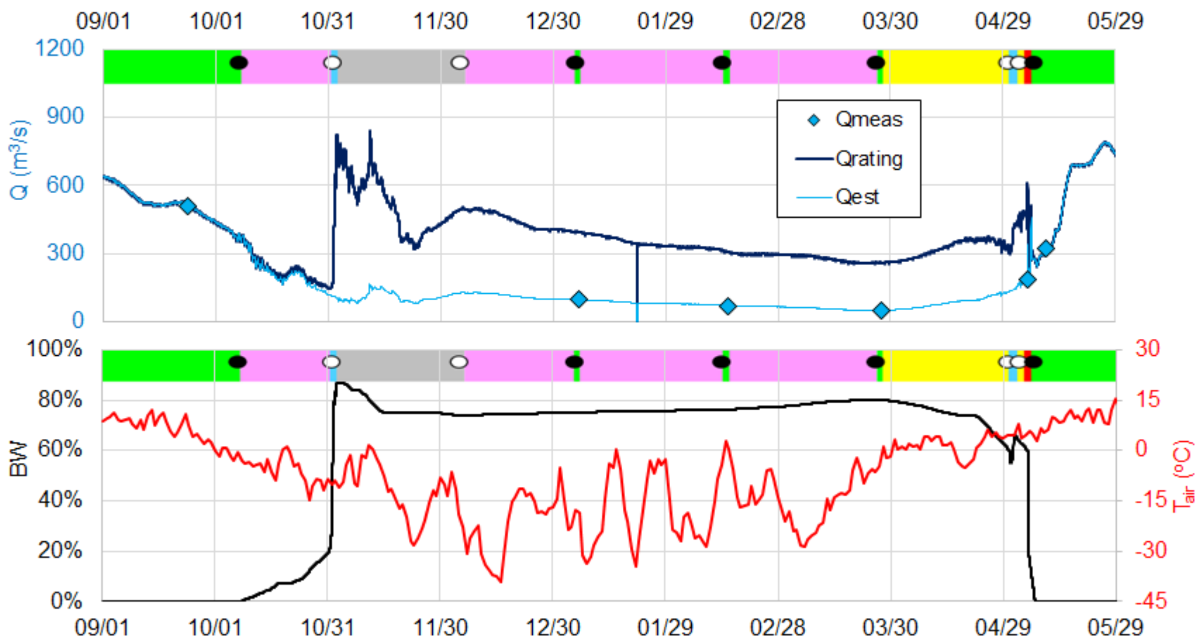

Figure 7.2. Discharge measurements (Q_{MEAS}), maximum discharge (Q_{RATING}), estimated discharge (Q_{EST}), backwater (BW) and air temperature (T_{AIR}) with an upper colored band showing the tools and information used to produce Q_{EST} (station 09BC001, winter 2016-17). Hydraulic anchor points (HAPs) are shown with dots (black dots are non-negotiable, white dots are negotiable).

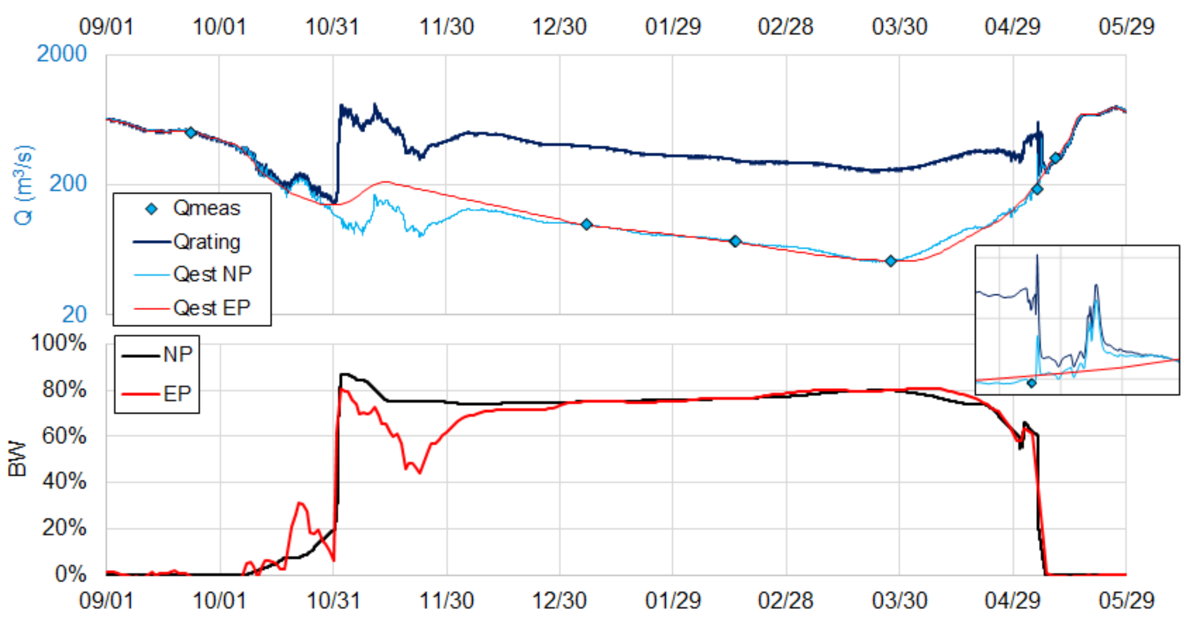

Figure 7.3. Comparison between the estimated discharges (Q_{EST}) and backwater (BW) using the new procedure (NP) and the existing procedure (EP) from Water Survey of Canada (WSC) records for station 09BC001 in 2016-17.

7.2 Klondike River at Bonanza Creek, winter 2011-2012

Figure 7.4 presents the time series and data considered to produce Q_{est} and BW at a very different station from what is presented in subsection 7.1. The 2011-2012 winter sequence at station 09EA003 (river reached classified as S1G2R3 in Sections 4 and 5) can be described as follows:

- The formation of border ice (a period during which frazil and ice pans pass by the station, with a concentration that largely depend on weather and sky conditions).
- Dynamic formation of a freeze-up jam (this is when the stage and BW rise sharply).
- Thermal erosion (this slight reduction in BW is associated with a gradual stage drop of 0.8 m over several days, extending through the second half of the freeze-up Q depression).
- A mid-winter period during which Q seems to respond to fluctuating T_{air} (this would be caused by the steepness of the upstream drainage system and the related ice cover type).
- A breakup onset characterized by an increased Q combined with a progressive melting of the ice cover (this is a thermal breakup and hourly T_{air} always drop below freezing at night). The relatively stable stage is the result of an assumed gradual drop in BW as Q rises.

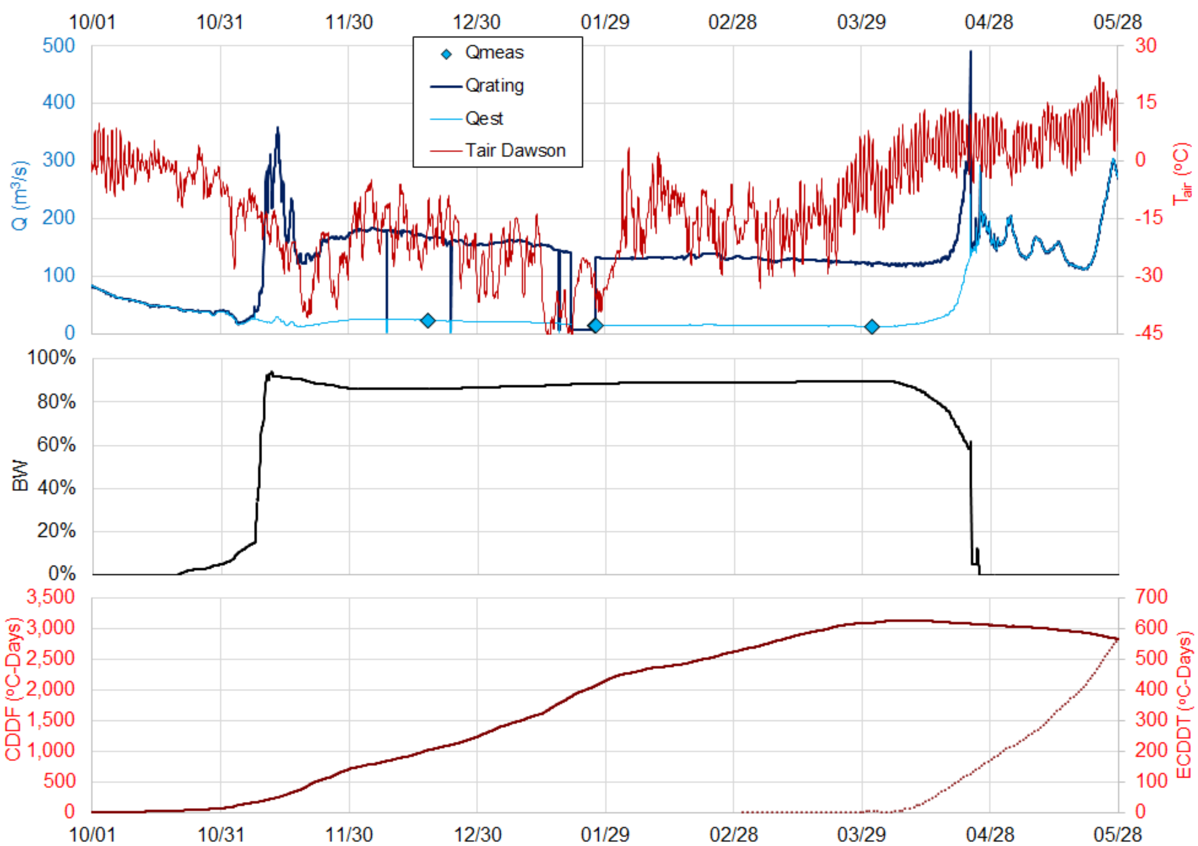

FIGURE 7.4. UPPER GRAPH: DISCHARGE MEASUREMENTS (Q_{MEAS}) PROVIDED BY THE WSC FOR STATION 09EA003, MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}, THE RESULT OF THE ANALYSIS), AND HOURLY AIR TEMPERATURES (T_{AIR}) AT A NEARBY WEATHER STATION. MIDDLE GRAPH: ESTIMATED OR CALCULATED BACKWATER (BW). LOWER GRAPH: CUMULATED DEGREE-DAYS OF FREEZING (CDDF) AND EFFECTIVE CUMULATED DEGREE-DAYS OF THAW (ECDDT) FOR THE SAME WEATHER STATION.

- A dynamic mobilization of the local ice cover caused by an upstream ice jam release wave (0.5 m high) followed by a stage drop (about 1 m, which is relatively modest for that river at station 09EA003). This wave is followed by two subsequent ice runs and associated waves.

Figure 7.5 presents similar data sets, but adding information about the tools and data used to perform WDE for different winter segments (Section 6):

- Known Q (Q_{meas} or Q_{rating} when no ice is present)
- Tool A. Rising BW based on CDDF
- Tool B. Decreasing BW based on $T_{air\ eff}$
- Tool C: Decreasing BW based on ECDDT
- Tool D: Fixed flow trend
- Tool E: Imposed backwater trend

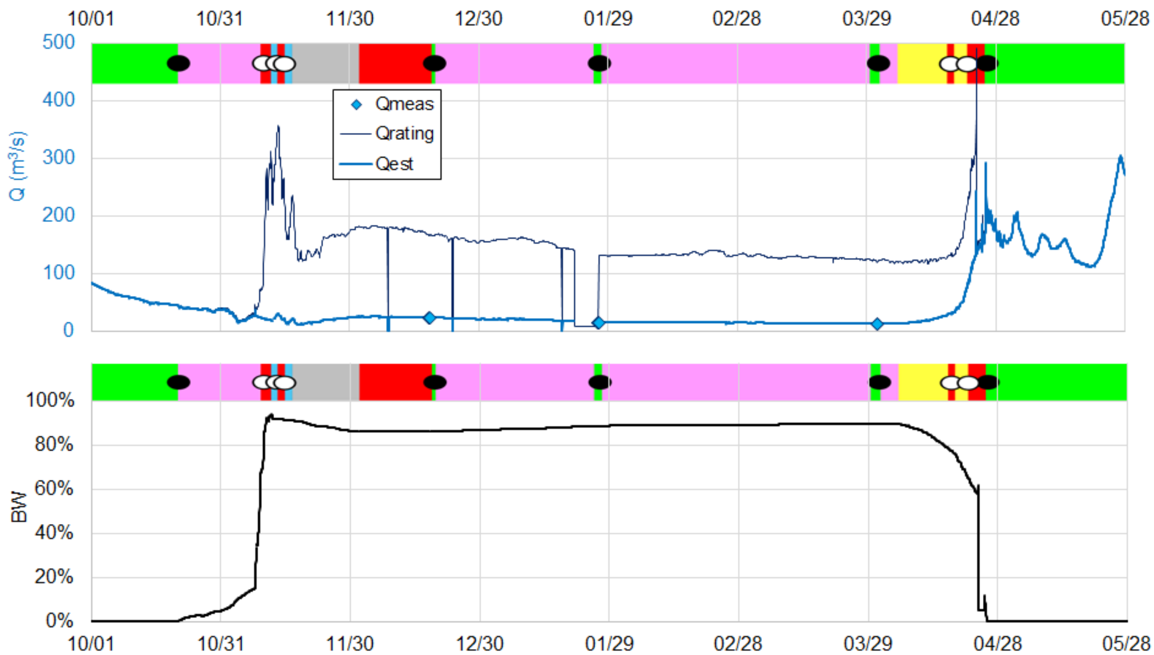

FIGURE 7.5. DISCHARGE MEASUREMENTS (Q_{MEAS}), MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}), BACKWATER (BW) AND AIR TEMPERATURE (T_{AIR}) WITH AN UPPER COLORED BAND SHOWING THE TOOLS AND INFORMATION USED TO PRODUCE Q_{EST} (STATION 09EA003, WINTER 2011-12). HYDRAULIC ANCHOR POINTS (HAPS) ARE SHOWN WITH DOTS (BLACK DOTS ARE NON-NEGOTIABLE, WHITE DOTS ARE NEGOTIABLE).

This exercise took about 2 hours and 15 minutes to perform, and it can be relatively easily adapted and reproduced (there are only five negotiable HAPs). There are alternate imposed flow trends and backwater trends at freeze-up because of a succession of freeze-up consolidation and assumed ice erosion events. The identification of such events was largely informed by T_{air} variations, but a camera at the station and/or at its hydraulic control would provide useful information to support Q estimation at freeze-up.

Figure 7.6 compares WDE results obtained from the application of the NP with the historical data produced by the WSC using the EP. Again, considered alone, the WSC interpretation could appear defendable. However, when considering T_{air} and the back-calculated BW, $Q_{est\ EP}$ for some winter segments are difficult to justify and would certainly be challenging to reproduce (the BW rise and drop as well as the BW drop and rise respectively taking place at the end of October and during the second half of November are impossible). The difference between both Q_{est} data sets reaches a maximum of 13 m^3/s (exceedance of 120%) on Nov 18th, as the Q depression interpreted with the NP is at its lowest. The mid-winter interpretation is comparable. During the breakup onset period, differences between both Q_{est} data sets reaches 50%, which is considerable from a breakup forecast perspective, for instance.

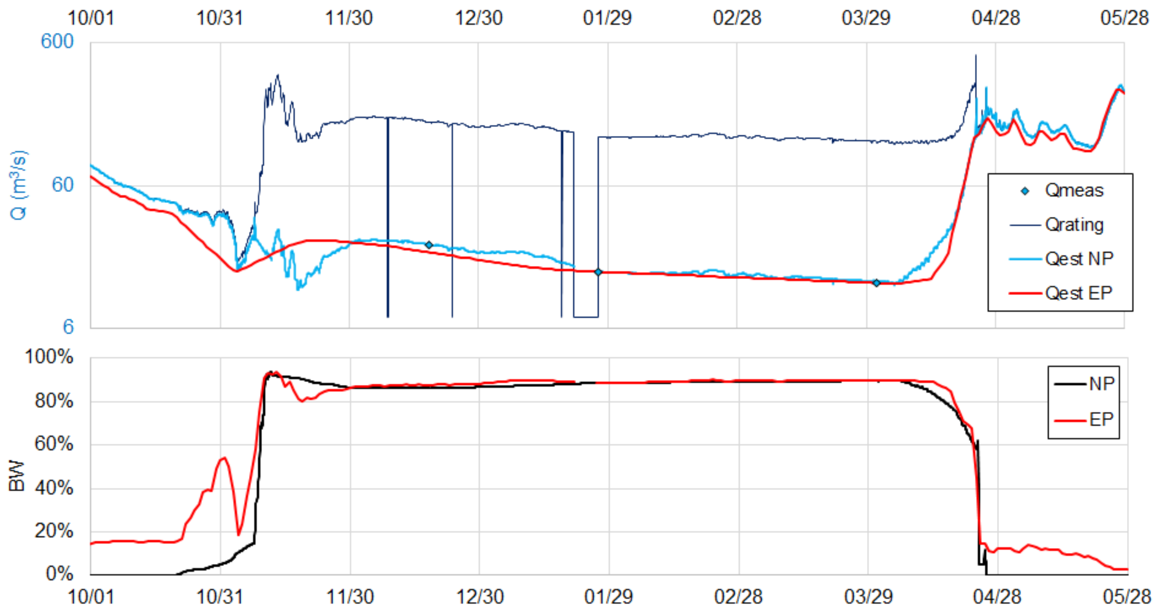

FIGURE 7.6. COMPARISON BETWEEN THE ESTIMATED DISCHARGES (Q_{EST}) AND BACKWATER (BW) USING THE NEW PROCEDURE (NP) AND THE EXISTING PROCEDURE (EP) FROM WATER SURVEY OF CANADA (WSC) RECORDS FOR STATION 09EA003 IN 2011-12.

Again, in this case, a finer time step presented for the NP allows to keep waves (real discharge fluctuations) in the entire record, especially at freeze-up and breakup (Figure 7.7). The post-winter residual BW on the WSC times series could be due to the use of a different rating curve. Even if this discrepancy does not affect the results and the discussion, it does warrant further investigation, especially since that residual BW varies to eventually reach a low value on May 28.

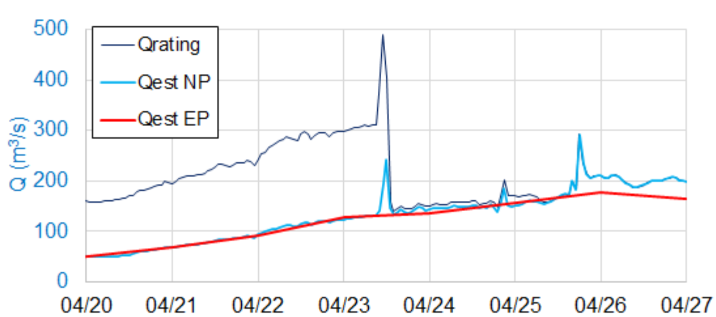

FIGURE 7.7. COMPARISON OF Q_{EST} USING THE NP AT A SUB-DAILY TIME STEP AND THE EP AT A DAILY TIME STEP FOR STATION 09EA003 FOR BREAKUP 2012.

7.3 White River at Alaska Highway, winter 2011-2012

This river is glacier fed and presents several braided reaches (S1B in Sections 4 and 5); it is the least understood of the studied rivers (Section 5), its channel is very unstable (the WSC rating curves changes on a quasi-annual basis) and a trip to the hydrometric station with WSC staff to better understand the river dynamics had to be cancelled for COVID19-related reasons. Therefore, producing WDE for this river represented a greater challenge.

Figure 7.8 presents the times series and data used for to produce WDE at an hourly time step for winter 2011-2012 at station 09CB001. The winter sequence can be described as follows:

- Freeze-up seems to include a sequence of different process leading to a fully ice-covered condition. Minor anchor ice cycles seem to take place before a combination of border ice, anchor ice and frazil congestion gradually occurs, in addition to upstream ice processes that are assumed to cause Q fluctuations. This translates into several BW adjustments.
- After freeze-up, the stage drop is interpreted as being partially driven by hydraulic and thermal smoothening. During that period, a large stage spike occurs, and it is interpreted here as a rise in Q (as described below).

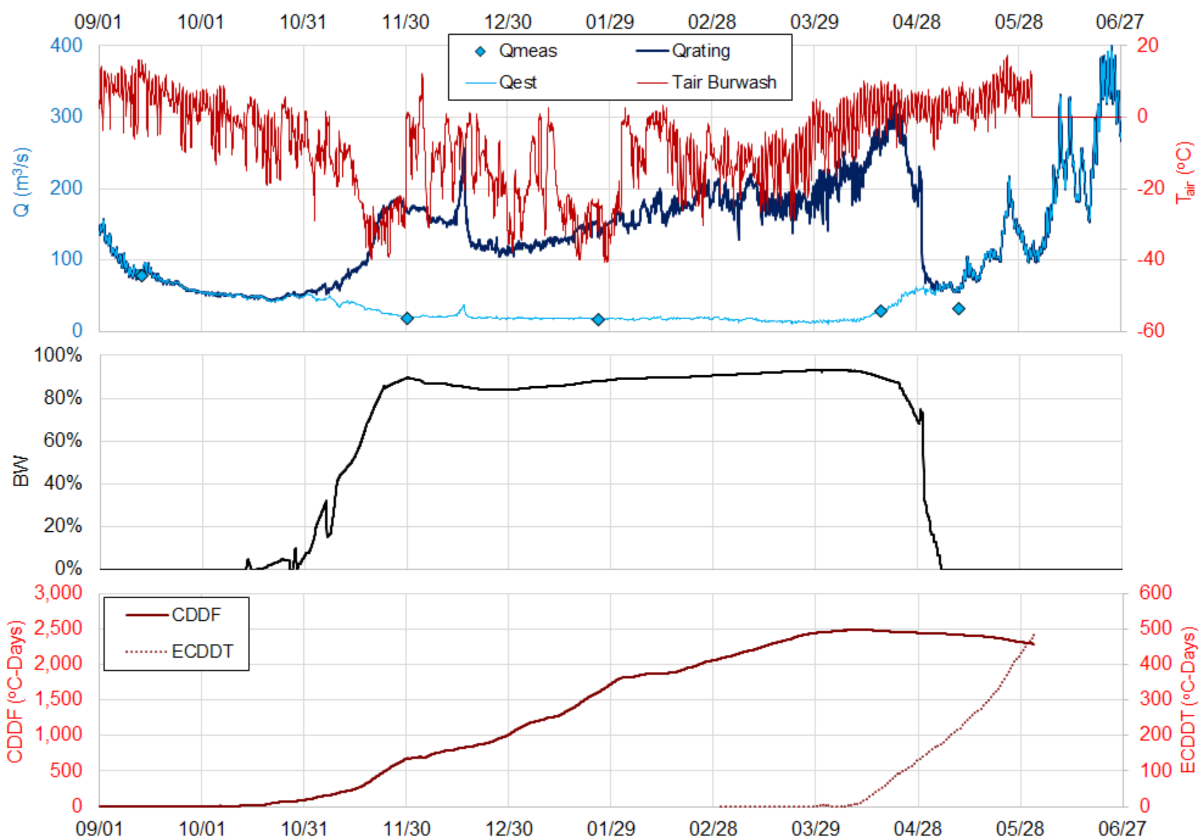

Figure 7.8. Upper graph: Discharge measurements (Q_{MEAS}) provided by the WSC for station 09CB001, maximum discharge (Q_{RATING}), estimated discharge (Q_{EST}, the result of the analysis), and hourly air temperatures (T_{AIR}) at a nearby weather station. Middle graph: estimated or calculated backwater (BW). Lower graph: Cumulated degree-days of freezing (CDDF) and effective cumulated degree-days of thaw (ECDDT) for the same weather station.

- During the entire mid-winter period, the stage gradually rises and given the unlikeliness of a rise in Q (only depletion of groundwater), this is associated with an increased BW with continuous Q instabilities that would be triggered by upstream ice processes.
- Breakup is generally very thermal (as interpreted from stage data for several springs), and in line with what is expected from that type of river. It is accompanied by a very weak ice congestion event (it cannot be considered as an ice jam, given its 0.2 m amplitude) soon followed by a rapid release (stage drops by 1.0 m), then by residual melting.

Note that the last Q_{meas} in this sequence, on May 10, 2012, is highly suspicious because it is virtually impossible, considering T_{air} and statistics derived from historical Q_{meas}, that a residual ice-induced backwater of 40% would remain when ECDDT are as high as 225°C-days at the nearby weather station, especially considering the open channel that probably formed 10 days earlier. This Q_{meas} was ignored from the WDE procedure (it is not a HAP).

Figure 7.9 presents some of the same data series, but adding information about the tools and data used to perform WDE for different winter segments (Section 6):

- Known Q (Q_{meas} or Q_{rating} when no ice is present)
- Tool A. Rising BW based on CDDF
- Tool B. Decreasing BW based on $T_{air\ eff}$
- Tool C: Decreasing BW based on ECDDT
- Tool D: Fixed flow trend
- Tool E: Imposed backwater (negotiable HAP)

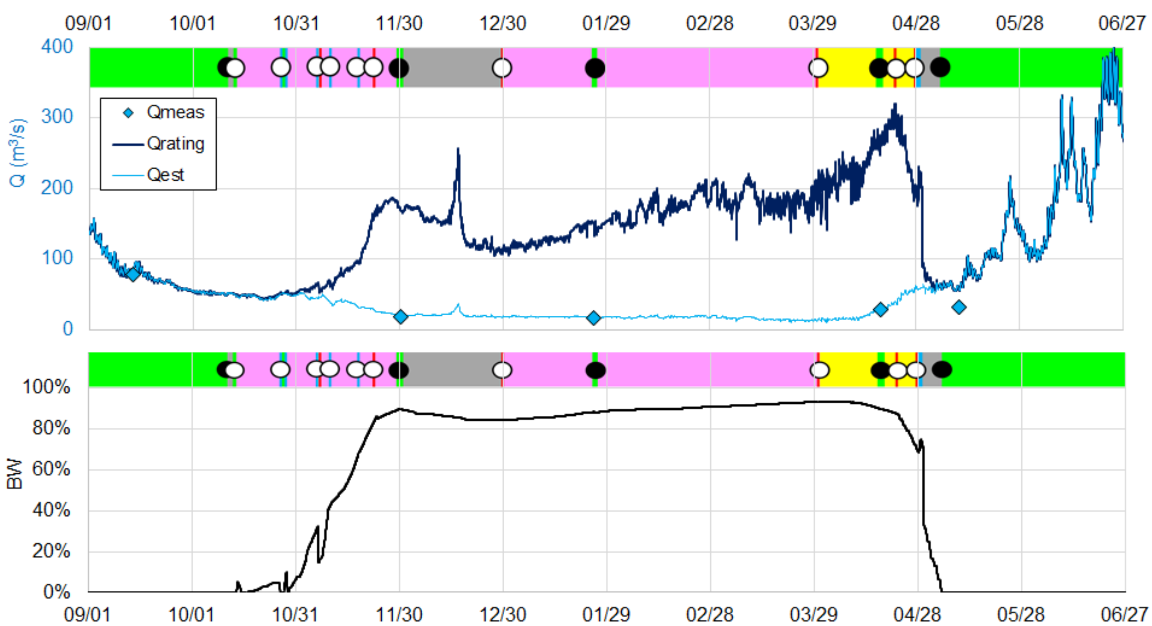

FIGURE 7.9. DISCHARGE MEASUREMENTS (Q_{MEAS}), MAXIMUM DISCHARGE (Q_{RATING}), ESTIMATED DISCHARGE (Q_{EST}), BACKWATER (BW) AND AIR TEMPERATURE (T_{AIR}) WITH AN UPPER COLORED BAND SHOWING THE TOOLS AND INFORMATION USED TO PRODUCE Q_{EST} (STATION 09CB001, WINTER 2011-12). HYDRAULIC ANCHOR POINTS (HAPS) ARE SHOWN WITH DOTS (BLACK DOTS ARE NON-NEGOTIABLE, WHITE DOTS ARE NEGOTIABLE).

More time was invested in this exercise (3 hours). This interpretation includes more uncertainty, given the complexity and lack of information about ice processes (hydrological and hydraulic signatures need to be better understood). The fact that WDE tools that would be adapted to this type of river are yet to be developed (Tool F in Section 6) also leads to imposing several negotiable HAPs (10).

Even with these considerations in mind, the Q_{est} data set obtained from the NP is probably more accurate and reproducible than the Q_{est} produced by the EP, as revealed by Figure 7.10. The following observations can be made:

- The WSC Q_{est} begins with a concave, smooth decline. The shape of this trend does not align with the pre-freeze-up Q decline, there is no obvious Q depression in that interpretation, and Q is completely independent from the numerous T_{air} and stage variations. Differences between Q_{est} obtained from the NP and EP reaches 100% during that period.
- The December – January $Q_{est\ EP}$ is also simplistic. All stage fluctuations are erased from the hydrological record. Even the large stage rise-and-drop event of unknown nature that occurred in mid-December is erased, and this may be a correct assumption, but it would require a justification. The NP interpretation of this spike is a release of upstream (water) storage at the end of freeze-up with water flowing on the ice cover at the station, an event potentially influenced by snowfalls (this could have easily been confirmed or discarded by camera records).

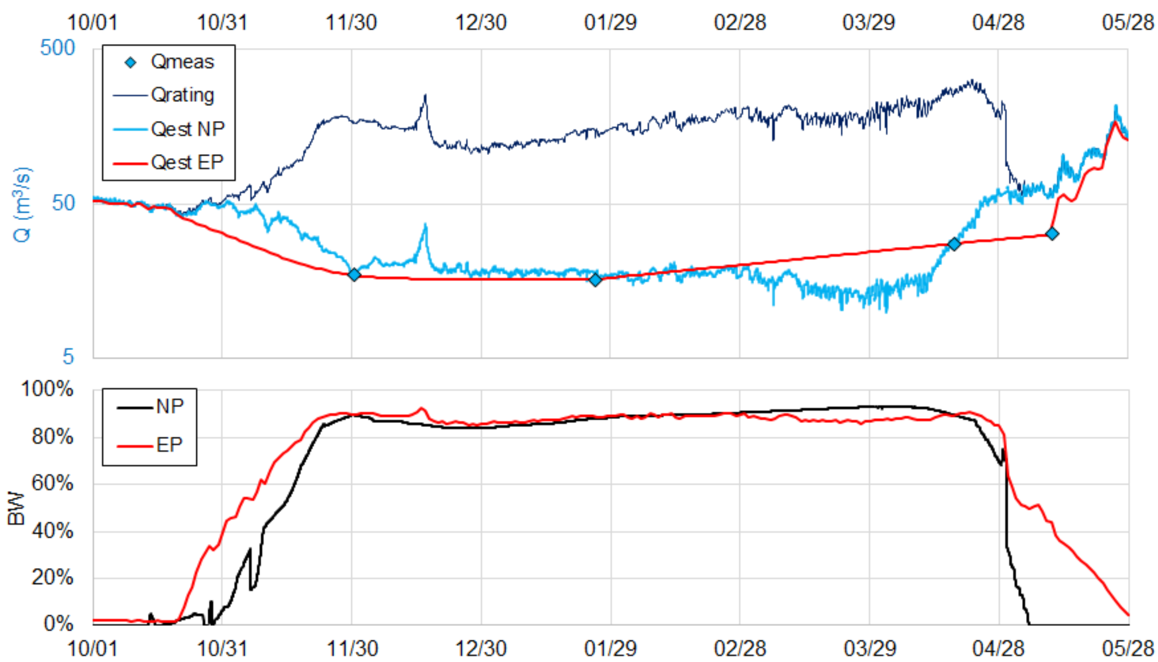

FIGURE 7.10. COMPARISON BETWEEN THE ESTIMATED DISCHARGES (Q_{EST}) AND BACKWATER (BW) USING THE NEW PROCEDURE (NP) AND THE EXISTING PROCEDURE (EP) FROM WATER SURVEY OF CANADA (WSC) RECORDS FOR STATION 09CB001 IN 2011-12.

- During the second half of winter, $Q_{est\ EP}$ presents a rising trend in line with the rising stage. There is limited evidence that this could happen: It is not tied to any Q_{meas}, and an increased runoff would be very unlikely, given T_{air}, the nature of the watershed (high mountains and glaciers), and the largely frozen state of several upstream tributaries. Differences in $Q_{est\ NP}$ and $Q_{est\ EP}$ reach 150% in April.
- The daily stage spikes that occur in March and April, in synchronicity with T_{air} variations, could have been kept in a sub-daily WSC record. It is very likely that these spikes represent simultaneous Q and BW daily cycles, as described in Section 6 (Tool F). This means that the amplitude of these Q spikes in Figures 7.8 to 7.10 is probably overestimated by the NP because a smooth BW trend was imposed.
- At breakup, $Q_{est\ EP}$ is maintained to an unrealistic and weather-independent straight (on a log scale) rising trend, and it is forced to the suspicious May 10 Q_{meas} before suddenly agreeing with stage variations. One could pretend that the rating curve adopted by WSC after winter had simply changed (and it is not possible to disagree with that), but this would not explain why the BW smoothly tends towards 0% while the daily-averaged stage fluctuates. Differences between $Q_{est\ EP}$ and $Q_{est\ NP}$ are greater than 100% during this period.

The difference between both NP and EP interpretations in Figure 7.10 are striking, given the existence of at least 3 Q_{meas} that can be used as HAPs. The White River is a remote water course, and the accuracy of its historical and real-time winter record is probably important to very few users. The station is operated at a high cost, and it is probably very frustrating for WSC analysts to process this type of data because they know that their efforts may not pay off. If the historical winter data from this station was to be used for a study (e.g., an evaluation of the impact of climate change on winter hydrology), it is very likely that the quality of the Q_{est} record would prevent obtaining meaningful conclusion. This station needs further attention, both from an ice processes documentation and from a monitoring technology point of view.

7.4 Yukon River above White River, winter 2009-2010

This last example brings the reader back to a simpler river setting where the NP, in its current state of development, seems to bring the most important gains (Q_{est} accuracy and reproducibility) for the least efforts. The Yukon River above the White River (station 09CD001) behaves similarly to the Pelly River (presented in subsection 7.1), it is a river classified as S1G2R3 (Sections 4 and 5).

$Q_{est\ NP}$ was produced for winter of 2009-2010 using the tools described in Section 6. Only 4 negotiable HAPs can be modified to change the shape and amplitude of the WDE hydrograph. Results were compared with those obtained from WSC using the EP, as applied about 10 years ago. The following comparison points need to be underlined:

- The interpretation of initial stage instabilities is essentially the same for both procedures: these stage spikes are probably local congestion and release events taking place under relatively stable flow conditions.

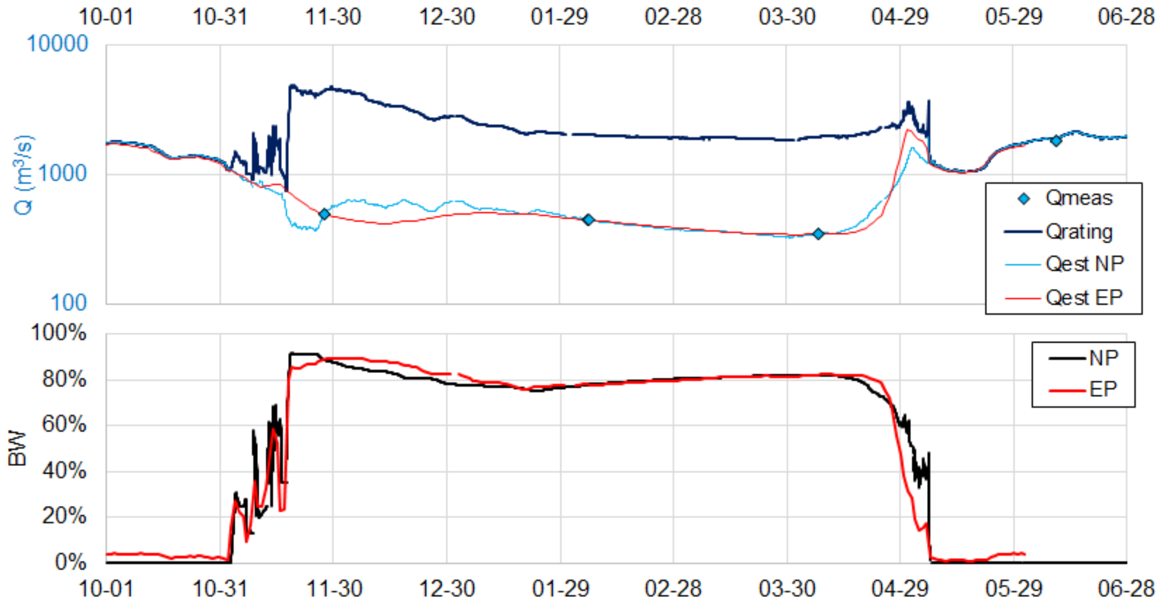

FIGURE 7.11. COMPARISON BETWEEN THE ESTIMATED DISCHARGES (Q_{EST}) AND BACKWATER (BW) USING THE NEW PROCEDURE (NP) AND THE EXISTING PROCEDURE (EP) FROM WATER SURVEY OF CANADA (WSC) RECORDS FOR STATION 09CD001 IN 2009-10.

- The freeze-up Q depression is interpreted differently despite a Q_{meas} on Nov 27. The NP considers a higher BW during the coldest episode of the river ice formation period (when the ice front is moving upstream) whereas the EP proposes a less-defendable smooth Q_{est} trend that leads to a rising BW several days after local congestion, when T_{air} is increasing. It is unlikely that the BW was increasing during that period several days after local congestions, especially in a context where the ice cover was stable enough for a Q_{meas} to take place.
- The NP considers that stage fluctuations in December and January are caused by residual upstream storage events, in line with T_{air} variations, and eventually leading to the smooth mid-winter recession trend under stable ice conditions in all upstream reaches and tributaries.
- At breakup, the historical record includes a $Q_{est\ EP}$ of 2200 m^3/s on May 1. NP results suggest that the peak flow prior to breakup was more likely about 1550 m^3/s on May 1. Indeed, the $Q_{est\ EP}$ drop from May 6 (1950 m^3/s) to May 7 (1250 m^3/s) is hard to defend in the historical record and applying the NP backward in time from May 7 reduces the peak flow on May 1. Interestingly, the ice jam release wave that caused the mobilization of the residual local ice cover on May 6 could have caused the instantaneous Q to rise to 2250 m^3/s. This type of historical Q reinterpretation may be important to flood forecasters (for the development of breakup models) and engineers (for the design of river structures), among other data users.

Results obtained from the NP may not be perfect, but they are defendable from two perspectives (Q and BW), which means that they are likely more accurate. Moreover, they are also more reproducible because of the absence of hand-drawn (override) Q_{est} segments.

8. Discussion and steps forward

8.1 The vision behind the proposed procedure

If it was possible to replicate the exact same weather for two years in a row, a river system would probably not generate the same ice cover and stage variations, and therefore, winter hydrographs would be different. Adding this to the fact that the river discharge (Q) cannot really be measured (especially in winter), this means that there is a limit to what should be expected from analysts and computers in terms of ice-affected Q estimation (Q_{est}) accuracy.

On the other hand, the science of river ice has evolved over the years, key observations have been made, processes that impact stage and Q are now better described and understood. There is an opportunity to update the existing procedure (EP) for winter discharge estimation (WDE). Producing improved WDE would rely on an updated sequence of actions, from continuous monitoring to data approval, that would rely on adequately trained analysts having access to adapted tools and data from reliable instruments (Figure 1.1). This is the vision behind the proposed new procedure (NP).

This study confirms, mainly through Section 3 (review of EP) and 7 (comparison of results from EP and NP) that accessible actions can be taken to reduce the subjectivity and to improve the reproducibility of WDE. The transition from EP and NP can materialize through a better structured WDE sequence of actions that respects and values the experience and judgment of analysts and supervisors. Time can be saved, Q_{est} can be increasingly scientifically defendable (therefore more accurate) and better supported (therefore more reproducible), and analysts can feel more confident about their work.

Preparing targeted hydrological trainings, developing new analytical tools, and installing adapted monitoring instruments at the WSC network scale may sound overwhelming, especially if one simply considers that each river and each winter are producing unique winter stage and flow variations. However, as proposed in Section 4, and as demonstrated in Section 5, there are families of similar rivers affected by a limited and predictable range of ice processes, and by continuity, WDE strategies can be adapted to each family member to improve the efficiency of the EP to NP transition. Therefore, finalizing and adopting a river classification matrix represent important components of the NP.

Key advances in cold regions hydrometry presented in this report include the following:

- If there was only one concept that could be preserve from this report, it would be the use of the backwater (BW) graph to validate and improve WDE. This is the most powerful idea that this study has presented; it enables analysts to perform an evaluation of their own Q interpretation. Simply stated, if Q_{est} seems to make sense but the BW graph is not defendable, then Q_{est} should be reassessed.
- The NP has introduced the concept of Hydraulic Anchor Points (HAPs) to make WDE more reproducible. Discharge measurements (Q_{meas}) and the last and first open water conditions (respectively in the fall and in the spring, when the open water rating curve applies) represent non-negotiable HAPs: these dates and time stamps are associated with specific Q

and BW values (with a small degree of uncertainty, generally assumed to vary from 5% to 10%). Based on different sources of information, and depending on the tools used to produce WDE, analysts can also introduce negotiable HAPs: adjusting their location and value (either a Q or BW) leads to an automatic adjustment of the Q_{est} and BW forward and/or backward to the next HAP. As analytical tools are being developed to support WDE during the occurrence of different ice processes (and as sets of tools are developed to perform WDE for specific river types, Section 4), the number of negotiable HAPs will decline, and this will make WDE more reproducible while still relying on analysts' experience and judgment.

- Working with instantaneous stage data and converting it to sub-daily Q_{est} contributes to providing more accurate and representative WDE to users. No user should complain about the availability of sub-daily winter discharge estimates.
- The early-winter Q depression seems often miss-understood, underestimated, or overestimated by analysts (and supervisors). This can be relatively easily addressed by imposing a justification for both Q_{est} and BW variations.
- The EP for WDE, and the tools that are readily used to convert stage to Q_{est}, often assume that stage variations observed in winter hydrometric records are BW variations rather than Q fluctuations. This is probably an erroneous assumption for several sites, especially in large low-gradient rivers, because it would imply that the station location presents an unstable ice cover whereas all upstream reaches and tributaries present a more stable winter behaviour that does not cause Q fluctuations. In fact, most stage fluctuations should appear in Q_{est} time series unless it can be justified (and not the opposite).

8.2 Limitations of the study

Several topics in this report could only be partially addressed:

- The literature review does not include much cold regions hydrometry research from the United States, Europe, and Asia. This work should be completed, but it does not prevent other aspects of the project to move forward.
- In Yukon, the lowest Q of the year occurs during late winter in most streams and rivers. This means that the lower end of the open water rating curve is associated with greater Q (and BW) uncertainty. This should have a limited impact on the proof-of-concept and on the overall results of the study: an approximate lower rating curve only means that the range of BW may be inaccurate, but the impact on WDE is limited because these are ultimately based on Q_{meas}. Q_{meas} during extreme dry open water conditions are very valuable.
- When the BW reaches values above 80%, which is the case for most stations in Yukon, especially for small rivers, any increase in BW has a significant relative impact on the calculated Q (through EQ 6.1). For example, the contrast between an 80% and 82% BW (only 2%, barely visible on a BW graph) results in a 10% Q difference. For a BW of 91% vs 93%, the Q difference becomes 22%. In comparison, for a BW of 20% or 22% (still the same 2% difference), the difference in Q is only 3%. It may be worth exploring a BW expressed in metres at some point in the future, but this would also lead to the modification of some of the tools and Equations presented in Section 6.

- The BW is a simple but imperfect ice-effect indicator because it combines both the blockage effect of the ice cover (92% or more of a floating ice cover thickness) and the roughness of the ice cover (or the associated shear). This is an acceptable simplification in most cases, but it may fail to provide representative Q_{est} during specific processes. For example, during a small mid-winter runoff event (with no ice cover movements involved), the relative importance of the ice thickness to total water depth is temporarily reduced whereas the roughness of the ice cover remains fairly constant (at least from a Manning Equation point of view). For a small runoff-induced stage rise, Figure 8.1 shows that a BW approach and a Manning approach generate different Q_{est}. In one case, a constant trend is imposed to the BW (the ice cover does not change) whereas for the other data set, a more realistic constant ice cover roughness n_i is imposed. The different in Q_{est} is about 5%, but it could be greater in different circumstances.

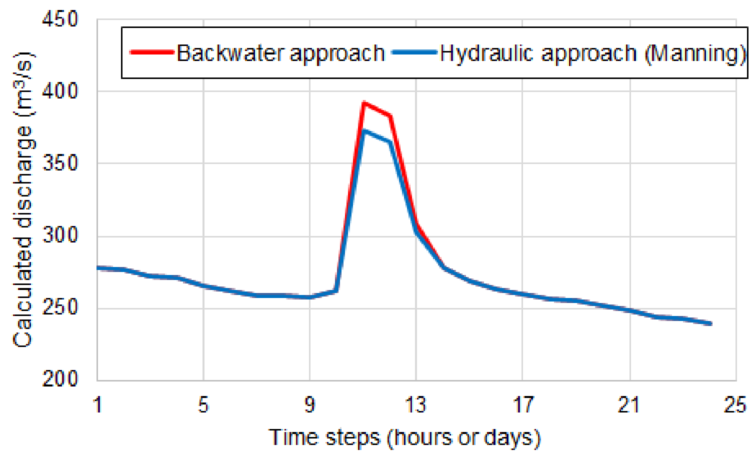

Figure 8.1. Differences in estimated discharge (Q_{EST}) obtained from a calculation based on a constant backwater (BW) or a constant ice cover roughness during an hypothetical discharge-induced stage rise.

  Alford and Carmacks (1987a) performed a similar calculation based on recurrent ice cover thickness measurements on the Yukon River at Whitehorse. Adopting a Manning's approach over a BW approach could yield more accurate Q_{est} in specific case. On the other hand, this approach requires more data. It is therefore suggested that the hydraulic approach should be adopted for Q_{est} during specific winter segments and for specific sites whereas the BW approach could be applied in most cases.

- When the ice cover starts forming in rivers and streams, there is still residual summer heat in the bed and banks. In this case, cumulated degree-days of freezing (CDDF) may not be an accurate proxy for ice formation and melt. For example, one can imagine that a day with an average T_{air} of -8°C would produce border ice, and this ice could melt on the following day if the daily-averaged T_{air} is 1°C (or even -2°C). CDDF would not return to 0 whereas the ice would have melted entirely. The early-winter BW interpretation could be further improved with a correction to the CDDF, just like it is done for ECDDT (E standing for effective, and taking into account other heat sources, Section 6).

8.3 Recommendations

Based on challenges encountered throughout this study, general recommendations include:

- Tools and equations developed through this study should be programmed in Aquarius and pilot tested for some stations in and outside of Yukon, and benefits should be quantified.
- Continuous stage measurements without gaps represent the most important source of information, by far, to produce WDE. There are still many gaps in winter stage records that are associated with different problems and conditions. Through this study, mostly gap-free data sets have been analyzed (Figure 7.6 does contain gaps), and this has not been the focus of the report. However, no winter data users appreciate gaps (for some of them, e.g., flood forecasters, they represent a significant problem), and gaps only complicate the production of WDE. This needs to be addressed as a priority: more robust, resilient, and climate adapted hydrometric setups should be considered. Instrument duplication probably represents part of the solution.
- From an employee scheduling point of view, it is generally easier for managers to plan field trip dates (for Q_{meas}) well in advance, especially in remote areas. On the other hand, it may be valuable, at least for some winters, to perform Q_{meas} immediately after freeze-up (during the Q depression, once the ice cover is stable), during mid-winter conditions, and/or once some spring runoff has initiated, rather than performing three Q_{meas} during the mid-winter recession (currently the norm in Yukon). Indeed, three Q_{meas} during the same recession may be unnecessary. Moreover, the upper graphs in Figures 5.1 and 5.2 show that Q_{meas} have not happened between 800 and 1300 CDDF for 20 years in a row, and this impacts our understanding of ice processes and their associated BW.
- Instruments such as cameras (real-time or remote), water temperature loggers, and upward looking ADVs should be deployed primarily at stations where they are the most useful. It should also be understood that their presence at some sites would be inappropriate. The classification matrix presented in Section 4 can support targeted instrumentation and maximize investment benefits.
- The existence of different data users has been identified in Section 1. However, in this report, no investigation was completed about data user needs, nor about the degree of priority for stations located outside Yukon. This represents a key consideration in the multiple decisions that managers make on an annual basis (e.g., this may justify additional investments at specific priority stations or further attention when producing WDE).
- A record of measured ice cover thickness during field trips should be kept for all hydrometric stations and a description (or a classification) of ice cover types should completed. This information is important to improve the accuracy of WDE, and it could be integrated into analytical tools.

8.4 Future steps

Based on the outcomes of this study, and moving towards Phase III, the following activities are proposed as future research steps:

- Improve the literature review (Section 2) with the assistance of graduate students.
- Develop a document that would describe the most common river ice processes and that would quantify their impact on stage and Q. At some point, a pre-recorded webinar on the topic could be presented, focusing on typical ice processes that are often misunderstood or misinterpreted. This represents one knowledge development and training aspect of the NP.
- Continue to develop knowledge about the impact of complex ice processes on stage and Q. Subsection 7.3 presents an example of a river where different upstream and local ice processes generate unique stage fluctuations.
- Similarly, explore the relationship between stage variations and other readily available parameters such as snowfall.
- Improve the preliminary river and stream classification presented in Section 4 and confirm if categories can be merged, removed, or added. Further consider if an ice cover-based classification would be more useful that a morphology-based one.
- Organize a proof-of-concept exercise involving various technologists and some researchers to demonstrate the potential performance of proposed NP tools and concepts. Some comparative results are presented in Section 7, but a more formal exercise, as presented by Dahl et al. (2019), would be valuable.
- Involve more academic partners in the project, more specifically regarding the use of new technologies (e.g., underwater instruments, satellites), and develop a synergy that could involve international partners.
- Support the development of new analytical tools (e.g., Section 7, tool F) and test their applicability in different contexts.
- Program NP concepts, tools, and equations in Aquarius (most importantly the concept of HAPs and BW) and test a prototype.
- Identify test stations where additional winter Q_{meas} should be performed and where additional instruments should be tested (secondary sensors installed at a nearby location should be a priority). Some station families may present a winter behaviour that is poorly understood, and this effort could eventually lead to stable (or reduced) operational costs while contributing to improving data quality and WDE reproducibility. In turn, at least for some stations, the number of Q_{meas} could be reduce, and this represents a significant operational cost reduction, especially for remote stations.
- The long-term objective of this project is to improve WDE accuracy and reproducibility. It is also to reduce subjective actions and to reduce WDE computational time. Project success targets, in terms of data quality improvement and time saved, should be defined.

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