Author Responses to Referee's Comments

The authors would like to thank all three reviewers for the time and effort reviewing this manuscript (MS). The reviews are favorable with indication that this database will be widely used. We appreciate the numerous suggestions, to which the vast majority have been incorporated into the revised MS. This document compiles: (1) comments from referees, (2) author's response and (3) author's changes in manuscript that include the page, line and a statement on the revision. First, Reviewer 1: Benoit Turcotte (RC1) comments are followed by author response (AR1) and applicable changes (Action1). Then, Reviewer 2: Anonymous Referee (RC2) comments are followed by author response (AR2) and applicable changes (Action2). Finally, Reviewer 3: Zoe Li (RC3) comments are followed by author response (AR3) and applicable changes (Action3). In a few cases, where no changes are made, we state 'No Action' followed by appropriate reviewer number.
A revised version of the MS using Track Changes is included. The page and line number refer to those in the Track Changes version when 'All Markup' is selected.
After addressing all the reviews comments, we did a final read through and make a few minor editorial changes to the text, figures and tables to improve the readability of the MS.

We have added the following statement in Acknowledgments: Page 45, Line 900-901: "Thank you very much to Dr. Benoit Turcotte, Dr. Zoe Li and Anonymous Referee for the detailed reviews that improved this manuscript.

Interactive comment on "A Canadian River Ice Database from National Hydrometric Program Archives" by Laurent de Rham et al.

Benoit Turcotte (Referee)
benoit.turcotte@gov.yk.ca
Received and published: 19 April 2020
Dear Authors,
I am pleased to provide a review for this paper. It represents a tremendous amount of work and a significant publication that will generate a positive impact on river ice research in years to come. I will definitely use the CRID and it will soon become a widely understood acronym within the river ice community and Canada and abroad. I know how it feels to analyze hundreds and hundreds of data sets, and then having to do it again in the most consistent way possible because of the need to add another winter variable.

AR1: We appreciate Dr. Turcotte's comprehensive review of the manuscript. The feedback is very constructive and it is encouraging to hear a vision for the CRID from a prospective user.

No Action1

General comments:

RC1: The tone of the introduction could be slightly adapted (see specific comments). It is true that this type of publication and database has not been seen in the past, but I believe that the absence of a CRID before now never prevented meaningful research to be completed and published. The hydrometric data has always been accessible and it was analyzed as needed. A research paper about ice processes at a specific location is valuable and should not be overlooked because it only includes data from a single or a handful of sites.

AR1: The authors acknowledge and appreciate the excellent research over the years on river ice processes at specific locations and have no intention of diminishing the value of those works. We just want to indicate that there is no previous pan-Canadian river ice study because of the lack of a national database. Therefore, the objective of this database/paper is to compile and report on Canada wide river ice information from NHP archives. This follows on Beltaos and Prowse (2009) recommendations described on page 3, line 108-14. We have now included additional introductory material to highlight the importance of other river ice science and activities.

Action1: Page 1, line 20/21 – added statement: "single locations or regional assessments, are season-specific and use readily available data"

Action1: Page 2, Line 47-52 – added statement: "While there are growing number of publications on river ice processes focusing on specific locations or river reaches and looking at a specific part of the ice period, such as the spring break-up, there are only few large-scale (countrywide) studies on the complete river ice season because of the absence of a comprehensive and multi-site river ice database. It is not commonly known by the wider hydrology research community that a valuable source on river ice information can be extracted from the archives of hydrometric networks."

Action 1, Page 3, line 87-89 – added statement: Other well studied Canadian locations include, to mention but a few, the Hay River (De Coste et al., 2017); Red River (Wazney and Clark, 2015) and Chaudiere River (De Munck et al., 2016).

Action1: Page 3, line 102/103 – added statement: "A compilation and analysis of Norwegian rivers ice was described by Gebre and Alfredsen (2011)."

RC1: The authors could state more formally (in the Data Disclaimer, but also elsewhere in the paper) that even a data rating of 0 may not replace the Engineer's professional responsibility for the conception of flood maps and for the design of hydraulic structures.

AR1: The Data Disclaimer used is based on generic ECCC standard. We thank the reviewer for his recommendation and have incorporated this in the text.

Action 1: Page 38, Line 717-718 – add sentence: "The data quality ratings should not replace the professional responsibility of engineers and geoscientists for the conception of flood maps and for the design of hydraulic structures"

RC1: Specific comments: The sum of the experience of all authors is spectacular, and these comments will hopefully be perceived as constructive. Most of them are suggestions. There are lots of comments, but I am really taking this at heart and hope that this publication can be as perfect as possible.

AR1: Thank-you. This review is very constructive and improves the manuscript

RC1: Lines 17-18: This is a typical expression used on the Canadian West Coast, in Southern Ontario or in Eastern and central United States. River ice is not only common in cold regions, it is a part of the annual cycle, like open water conditions. I suggest rewording this.

AR1: Agree with the reviewer, remove word "common" and revise to:

Action1: Page 1, Line 17-18: reword sentence: “River ice, like open water conditions, is an integral component of the cold climate hydrological cycle. The annual succession… ”

RC1: Line 18-19: Not sure why this sentence is here. There has been papers focusing on many sites and many rivers. In turn, there is a reason why specific reports try to address local issues. In both cases, the Canadian data base would be useful

AR1: With this statement, we are stating the fact that, other than few studies that assessed B dates, river ice studies based on many sites and many rivers are not common in the river ice literature. We wanted to indicate that such studies were not common since there was no Canada wide river ice data base, and we are now trying to fill that gap by compiling the CRID.

Action1: Page 1, Line 20-21: revise to say “Reports and associated data on river ice occurrence are often limited to single locations or regional assessments, are season-specific and use readily available data.”

RC1: Line 36: Why not saying: River ice processes are an intrinsic component of cold climate watersheds.

AR1: Agree.

Action1: Page 2, Line 37: revise sentence to “River ice is an intrinsic component of cold climate watersheds”

RC1: Lines 37-41: The authors could refer to CRIPE at this point in the introduction. This Canadian research group on river ice has been quite active and productive since the1980.

AR1: Agree. We note that CRIPE active since 1970s’ and revise text as:

Action1: Page 2, Line 42-45: Revised to say “The Committee on River Ice Processes and the Environment (CRIPE; http://www.cripe.ca/) has been quite active and productive since the 1970s (Beltaos, 2012a) as the study of river-ice processes and hydraulics emerged as an important research area (Hicks, 2008), while the past decade includes a renewed focus on its ecological aspects (e.g., Peters et al., 2016; Lindenschmidt et al., 2018).

Add to reference:

Beltaos, S. Canadian Geophysical Union Hydrology Section Committee on River Ice Processes and the Environment: Brief History. Journal of Cold Regions Engineering, 26(3), 71–78, 2012a

Action1: additional Beltaos 2012 requires ‘b’ to be added to this ref and appropriate ref in text at Figure 4
Beltaos, S.: Mackenzie Delta flow during spring breakup: Uncertainties and potential improvements. Canadian Journal of Civil Engineering, 39, 5, 579-588, https://doi.org/10.1139/l2012-033, 2012b

RC1: Line 42: Following the general comment #1, I am not sure why this sentence starts with "However"

AR1: Agree.

Action1: Page 2, Line 47-50: Revised to start with “While there are growing number of publications on river ice processes focusing on specific locations or river reaches and looking at a specific part of the ice period, such as the spring break-up, there are only few large-scale (countrywide) studies on the complete river ice season because of the absence of a comprehensive and multi-site river ice database.”

RC1: Lines 43-44: This is not necessarily true. Researchers have been extractting the data that they needed, most of the time. It has just not been done in a consistent way.

AR1: Revise to incorporate ‘wider hydrology research community’

Action 1: Page 2, Line 51-52: Revise to say: “It is not commonly known by the wider hydrology research community that a valuable source on river ice information can be extracted from the archives of hydrometric networks”

RC1: Line 50: "calculating" could be "estimating". Using "calculation" may insinuate that the result is exact, which is not the case.

AR1: Agree.

Action1: Page 2, Line 58: revise to say: “…for estimating channel discharge.”
Action 1: Page 2, line 59: revise to say: “… when producing discharge estimates.”

RC1: Line 50-52: This is the main point of the paper.

AR1: Agree.

No Action1

RC1: Lines 69-77: Note that these examples are all from the Mackenzie basin, and then, the following paragraph is about outside Canada. Should there be a short mention of river ice studies in other watersheds in Canada before initiating the following paragraph?

AR1: The examples provided here focus towards studies that specifically used CRID data. We have now added a few more examples of river ice studies in other watersheds in Canada:

Action1: Page 3, line 87-89: Added sentence: “Other well studied Canadian locations include, to mention but a few, the Hay River (De Coste et al., 2017); Red River (Wazney and Clark, 2015) and Chaudiere River (De Munck et al., 2016).”

And added following to reference list:
De Coste, M., She, Y., Blackburn, J. : Incorporating the effects of upstream ice jam releases in the prediction of flood levels in the Hay River delta, Canada, Canadian Journal of Civil Engineering, 44(8) 643-651, https://doi.org/10.1139/cjce-2017-0123, 2017

Wazney, L., and Clark, S.P.: The 2009 flood event in the Red River Basin: Causes, assessment and damages, Canadian Water Resources Journal, 41(1-2), 56-64, https://doi.org/10.1080/07011784.2015.1009949, 2015

De Munck, S., Gauthier, Y., Bernier, M., Chokmani, K., Légaré, S.: River predisposition to ice jams: a simplified geospatial model. Natural Hazards and Earth System Sciences Discussions, 17(7), 1033-1047, https://doi.org/10.5194/nhess-17-1033-2017, 2016

RC1: Lines 90-93: This comes back to Canada. Scandinavia is not mentioned in this paragraph. They must have done similar work, and if not, it could be mentioned.

AR1: Agreed. We have included reference to Scandinavia study:

Action1: Page 3, line 102-103: Added sentence: "A compilation and analysis of Norwegian rivers ice was described by Gebre and Alfredsen (2011)"

And added following to reference list:
Gebre, S.B, and Alfredson, K.T.: Investigation of river ice regimes in some Norwegian water courses, in Proceeding of the 15th Workshop on the Hydraulics of Ice Covered Rivers, Winnipeg, Manitoba, Canada. http://www.cripe.ca/publications/proceedings/16, 2011

RC1: Lines 99-101: Indeed, no one has ever done an extraction of all river ice variables on so many Canadian rivers. This should not be expressed as a weakness from the literature, but as a strength of this research to support other research and development. This paper is strong enough to avoid falling on the classic message about the need to fill obvious gaps in the literature.

AR1: We agree with the reviewer's point. Here we are referring to Beltaos and Prowse (2009) and it may be unclear. We have revised to make link to these authors more obvious.

Action1: Page 3, Line 111: revise to say: "Specifically, these authors noted that broad scale…"

RC1: Line 168: Can you please double-check that Groudin is not Grondin (a more common name)? Also in Table 1. You may very well be correct.

AR1: confirmed it is Groudin

No Action1

RC1: Line 194: Is "potential" the right word here? My understanding of potential is what can be reached or achieved at a site or station, as opposed to the fine-scale maximum at a station for any given year.

AR1: agreed and removed word "potential"

Action1: Page 10, line 214-216: Revised to say: "These instantaneous values correspond with the water level at the initiation and maximum flood level for ice specific and open water conditions during each calendar year."

RC1: Line 197: Should "daily" be "daily-averaged"?

AR1: WSC site reports values a "daily" time step. We opt to use: mean daily

Action1: Page 11, Line 220: Revise to say: "mean daily water level or mean daily discharge"

RC1: Line 199: Should "depends" be "depending"?

AR1: agreed

Action1: Page 11, Line 222: Revise to say “depending”

RC1: Figure 3: You could clarify this figure by adding the duration of the ice season. I am not sure that the title of the X axis is accurate. This cannot be a complete year, at least not if the scale is constant. Last B date is quite low compared with HM. Is this a typical behavior? I like that HO is significantly lower that HM, but again, is this typical? It just seems that so much water has been flowing during breakup and that the freshet is almost over by then. I understand that this may be representative of a specific river, but is this largely applicable / representative of Canadian River?

AR1:
-This ‘conceptual schematic’ was created by using Sept 1 to Aug 31 water level hydrograph from Mackenzie River at Norman Wells with mid-winter event superimposed over top. With the schematic, we are only trying to show spikes and rising water levels we look for when extracting data with some vertical exaggeration and we did not make any mention of relative differences in magnitude between events. We have revised caption to further clarify the conceptual diagram

Action1: Page 12, Line 247-254: Figure 3 caption revised to say:
“Figure 3. Conceptual schematic of continuous river water level hydrograph (black line) spanning September 1 to August 31. Period of ice affected flow is constrained by First B Date to Last B Date. A possible mid-winter break up event is shown as grey line, at approximate centre of hydrograph. Symbols for the 15 variables which populate the Canadian River Ice Database are shown in the figure (see Table 2 for additional information). The variables shaded in grey show the instantaneous water level and associated time when the event occurred Compression of x-axis and vertical exaggeration of y-axis accentuates the water level changes observed during ice conditions. The relative magnitudes of variables and water level pathology should not be considered as typical.”

RC1: Figure 3: The peak to and from HM is intriguing to me. It is a relatively gradual rise, which does not suggest the formation of an ice jam. Then, the water level drop does suggest the gradual thermal melting of an ice jam. Also, in my mind, Last B date should be at higher level than HB, but I may be wrong.

AR1: Figure 3 is simply a schematic presentation of ice affected river water level and largely aims to visually define the various parameters that are extracted for CRID; its appearance can change from site to site and from year to year as can the relative magnitudes of variables. To address this concern have added statement to caption

Action1: Page 12, Line 253: added statement: “The relative magnitudes of variables and water level pathology should not be considered as typical”

RC1: Not sure if this is well positioned in Fig. 3. It seems that after freeze-up, thermal thickening or thermal erosion should follow. Therefore, I do not see why this first minimum Q would occur during the subsequent rise in water level. I may be wrong and you may have seen this at some stations.

AR1: What we are trying to show here is the possibility of different dates of minimum daily water level and minimum daily discharge. This is because open water stage discharge relationship is invalid during ice conditions.

Action1: Have moved HLQ1 closet to HLW1.

Action1: Page 12, Line 253: added statement: "The relative magnitudes of variables and water level pathology should not be considered as typical"

RC1: Table 2: First B date (and last B date): Has this been re-analyzed or indicated B dates were just adopted as they appeared in reports? My understanding is that B dates are often off by a few days and this can be checked with some temperature and hydrological indicators. It can have a significant impact when preparing flood maps that distinguish different flooding processes.

AR1: First B date and Last B date – input to CRID as they appear in the published NHP data and this is detailed in methodology. We gave full description of B date, applicable hydrometric manual references and some caveats.

No Action1

RC1: HF: This is quite obvious when the ice cover forms by frontal progression, but the gradual formation of border ice followed by ice congestion in a relatively narrow open water channel may not generate a clear signal. That being said, there would most probably always be a "maximum freeze-up level", and this may be a more appropriate name for this parameter. (I am unsure how you would differentiate that from a small runoff event taking place during freeze-up and generating or not, a freeze-up jam.). I appreciate the explanation provided at lines 362-368.

AR1: It is stated in paper that on occasion water levels crept up through the winter period as a result 'maximum' was removed from this variable name.

No Action1

RC1: HF2: Could change the name of this variable to "water level at second freeze-up"

AR1: A second freeze-up is only exclusive to a mid-winter break-up event. In case of water level creeping through the winter we observed maximums when assumed no break-up and refreezing of the river ice cover, so opted for a name that does not imply a process.

No Action1

RC1: Line 258: Drifting ice is part of the flow, it is not stagnant ice, and it should not generate bacwater if the surface concentration remains low. Same comment for flowing ice chunks.

AR1: This information is verbatim from Poyser et al, 1999. We are making a point that using B date alone does not tell much about specific river ice condition.

No Action1

RC1:Line 284: I am unsure why point C is not at the first spike that seem to be sharp enough to represent a local ice movement, possibly a downstream partial breakup that would reduce backwater at the station.

AR1: This figure is schematic published in Beltaos 2012. Point C was selected for illustrative purposes. That another spike was not selected is a good example of the 'judgement/art/subjective' aspect or extracting river ice information. Notably, Beltaos has mentioned numerous time that Point C (synonymous to HB) is not the best metric.

No Action1

RC1: Lines 290-291: I believe that hydrological simulation, comparison with other stations, or judgment can still provide some kind or error margin (it can hardly be more than one order of magnitude, at least).

AR1: Thank you for paying attention to this. Suggestions on how to better estimate flow during this time are outside scope of this paper. To reduce confusion "error margin" is removed from text.

Action1: Page 17, Line 322-323: Revised sentence to say: "Consequently, it is not possible to assign reliable flow estimates during this period, leading to the aforementioned "poor" characterization since there is no way at this time to quantify the reliability of these data."

RC1: Lines 307-311: Not sure if this paragraph invites CRID users to report on possible errors that could justify specific re-analyses. I believe that it should be the case, but it depends on how ECCC will want to maintain and update the CRID.

AR1: We have revised the paragraph for more clarity with respect to data maintenance and updates. This aspect of CRID was also brought up by other reviewers. We address database errors and corrections at a later section.

Action1: Page 19, Line 349-351: Remove text : "As a corollary, the water level interpretation toward the CRID research data set also required a high level of expert judgement with this subjective attribute inherent to the reported variables"

Action1: Page 19, Line 340 – 343: Revise to say "National assessments that analyze flow data often make no mention of the uncertainties associated with the collection and interpretation of hydrometric data during ice conditions (e.g. Cunderlink and Ouarda; 2009; Burn and Whitfield, 2016). More discussion on this issues are needed to inform the water community of the challenges related to cold-regions hydrometric data collection (Hamilton, 2003) and caution when interpreting study results"

Action1: Page 38, Line 720-723 : add sentence: "As is indicated on the Open Data Portal where the CRID can be downloaded, ongoing work with the CRID may include error checking and corrections, so users should use the latest version of the CRID by referring to the version number that appears in the .csv file name (http://data.ec.gc.ca/data/water/scientificknowledge/canadian-river-ice-database/CRID_BDCGF_Versioning_EN_FR.txt).

Action1: Page 44 Line 857-861: add section: ". It is recommended that periodic updates be made to this database since a longer time series record is of more value. Based on the 160 locations in operation up to Dec 31, 2015 (Table A1), a 5 year update of CRID time series (2016-2020) would require 800 person-hours of work. Evaluation of future research priorities are needed to formalize whether this task would be completed by the same group or undertaken by others."

RC1: Line 327: The authors could confirm if this first B date on Oct 10 was the result of a rise in water level that trigger the decision to initiate B condition. More generally, the authors could confirm the information (cameras?) or signs (rise in water level after X degree-days of freezing) that are usually considered to initiate B conditions.

AR1: B date is decided by NHP and is an indication of ice affected flow. The example is used to illustrate that a channel wide, bank to bank ice cover is not present at gauge on the given B date. Our goal is not to validate First B, rather provide other less 'readily available' metrics of river ice which have some physical/process rationale. Page 18, Line 372 we did state "NHP reports"

No Action1

RC1: Figure 5: Adding the water level signal to this figure would be of interest, but it does represent some work.

AR1: Agreed and water level plot is added. This comment has also prompted a revision of the similar Figure 12 to include water level signal

Action1: Page 21-22: Figure has been revised to include water level signal. In addition remote sensing images perspective has been changed to overhead rather than oblique to aid visualization. Location of station now indicated with red circle. Figure caption has been revised to: "Figure 5. Daily mean water level hydrograph for October 1 to November 15, 2000 at National Hydrometric Program gauging station Mackenzie River at Norman Wells (10KA001) along with MODIS time-lapse satellite images (accessed at: https://worldview.earthdata.nasa.gov/). Date of images corresponds with black arrow. Station location indicated by red circle. Width of the channel is approximately 1,300 meters and includes numerous islands. Flow is from bottom to top. First B Date is October 10 while freeze-over water level (HF) occurred November 9 and these images were obscured by clouds. River channel open water is green and ice cover is white on these true colour images.."

RC1: Lines 351-352: The authors could mention something about peak factors (instantaneous divided by daily-averaged) here. For freeze-up, peak factors can be in the order of 1.1 or 2.0, depending on freeze-up dynamics... This would just be a reminder that using a 1 for design may be unsafe.

AR1: This is a good point and peak factors could be calculated from the CRID as it records both instantaneous and daily values at freeze-up whenever available. Statement has been added with reference to peak factors at lines 365-368

Action1: Page 22, Line 428-429: revised to say: and (3) allow for calculation of peak factors (as a ratio between instantaneous and mean daily as described Zhang et al., 2005) to aid in design of river structures.

Have added the following reference:

Zhang, X., Buchberger, S.G., van Zyl, J.E. A Theoretical Explanation for Peaking Factors. World Water and Environmental Resources Congress. ASCE Library. https://ascelibrary.org/doi/10.1061/40792%28173%2951, 2005

RC1: Line 367: The authors could mention that this can take place over a distance of several hundred km upstream.

AR1: Agreed

Action1: Page 22, Line 427: Revise to say: “This process can take place over a distance of several hundred km upstream (e.g.”

RC1: Line 371: "...snow and..." First time I see this expression. In some regions, there is snow, but no ice cover because there is too much heat (downstream of lakes or reservoirs, or maybe downstream of cities and industries). Still, the word "snow" here may create confusion since this paper is about the ice cover period.

AR1: removed “snow”

Action1: Page 23, Line 433 – revise to say: “during the winter ice cover”

RC1: Lines 377-379: It could be mentioned that this is common and mostly caused by the thicker ice cover at the end of winter that generates a higher water level despite this being the actual winter min Q.

AR1: Agreed

Action1: Page 23, Line 440-441: Add statement:” This example illustrates how a thick, late winter ice cover would raise water levels due to reductions in channel cross sectional area.”

RC1: Line 383: "analysis" is probable "analyses" (plural)

AR1: OK

Action1: Page 23, Line 445: change to “analyses”

RC1: Line 396: "risk" and "threats": The risk cannot be a threat. Consider rephrasing this considering that the risk is a combination of consequence and probability (or possibility) of a hazard and that a threat is in this case a hazard.

AR1: Thank you for the clarification. Have removed word “risk”.

Action1: Page 24, line 458 Revise to say: “elevated water levels, and in extreme cases”

RC1: Lines 400-401: There are also records from nearby hydrometric stations.

AR1: This study did not evaluate nearby hydrometric station records. This watershed continuum or watershed analog method would be a good way to verify if identification of perceived mid winter events was correct (Beltaos 1990, interpretation of these ‘winter peaks’ is a challenge). CRID sites were treated independent for data extraction.

Action1: Page 25, Line 483-485: Changed to say: “Due to these inherent challenges of interpreting mid-winter break-up events, a closer examination of the CRID time series and comparison to nearby hydrometric stations may be required before pursing further analysis. “

RC1: Line 407: Not sure if a sudden drop in water level can be considered as a "spike". Also, depending on where the station is located and about the intensity of the winter runoff events, the water level signal can be a drop (local breakup) , a gradual rise (ice cover is lifted), a sudden rise (ice jam formation), or a combination of the above.

AR1: The spike occurs as water levels increase above threshold for ice to become detached from banks and entrained in flow, resulting in reduction in hydraulic resistance. This is the characteristic “spike”. We found the spike method to consistently appear on the rising water level limb at many sites. The drops in water level related to very thermal events which are not overly common in the CRID.

No Action1

RC1: Line 411: In areas where multiple mid-winter breakup events occur, they can be hard to distinguish from freeze-up chaos. First question: Does a mid-winter runoff event only qualifies after a complete ice cover has formed? Second question: why not using the highest mid-winter peak instead of the first one? Third question: How would you consider a massive breakup event at the end of February like it happened in 1981 in southern and central Quebec? Would that be a mid-winter breakup followed by no more winter, or would that be the spring breakup event? I am curious, but understand that we may not have to start a conversation about this.

AR1: First Question Response: mid-winter runoff is assumed to have occurred after formation of ice cover. Second Question Response: We use highest mid winter peak (HMWM) but first initiation of mid winter breakup (HMWB). Third Question Response. We came across this issue in earlier work of Newton et al 2017 comparing Doyle 1984 mid-winter break-up events to earlier iteration of CRID. An event that we categorized as spring break-up event, Doyle categorized as a mid winter break-up event. This type of categorizing is a challenge since river ice is continuum.

No Action1

RC1: Lines 414-415: I am not too familiar with WSC’s practice, but I would be very careful to remove a B in the middle of winter following a mid-winter breakup event. This may occur in NE, NB, southern QC and ON as well as in West-southern BC, but in most of Canada, after a complete mid-winter breakup, the presence of shear walls would prevent the removal of the B until the flow has receded significantly and this is when a cold spell may have already created border ice.

AR1: We agree that the text may be misleading so:

Action1: Page 25, Line 482: revise to say: “extracting the mid-winter variables”

RC1: Line 431: "mark": I would say "may mark" as this is not the case for all types of rivers.

AR1: agreed

Action1: Page 26, Line 499: Revise to say “may mark”

RC1: Line 435: Depends where: In some cases, a mid-winter breakup event is followed by a dramatically cold period during which frazil generation is significant. The result may be a very thick ice accumulations, with inflated ice jams and new anchor ice cycles.

AR1: Thank you description of process. This is more appropriate to observation of multiple HMWB so added to previous section

Action1: Page 25, Line 475-477 :add "In some cases, a mid-winter breakup event is followed by a dramatically cold period during which frazil generation is significant. The result may be a very thick ice accumulations, more ice jamming and new anchor ice cycles".

RC1: Line 436: Of course, daily-averaged levels may appear smooth enough. At specific locations, the water level could remain high or even increase even though the discharge drops. This would be caused by progressive frazil accumulation produced in a newly open (steep) reach exposed to cold air. Hydrometric stations are usually not located in reaches affected by this type of process. I am just providing this information in case it would seem appropriate to adapt the text (and this applies to many other comments).

AR1: Thank you for description of process. We modify text as follows

Action1: Page 26, Line 504: revise to say "…generally reveal"
Action1: Page 26, Line 505-507: add sentence: "Notably, this patterns is likely typical on relatively flat river channels, while on steep river sections, progressive frazil accumulation produced in newly open section exposed to cold could increase water levels even during receding flows"

RC1: Lines 450-452: A hanging dam can form several km downstream of an open reach. It all depends on the river gradient and profile. In the case of anchor ice, it can hardly remain in place for several months. It will either contribute to the formation of a complete surface ice cover, or will melt away during mild spells and come back during cold spells. I suggest that this creeping signal is mostly associated with frazil acaccumulation.

AR1: hanging dams are very stable features and can remain in place for many months. We modify text as follows

Action1: Page 27, line 522: Add sentence: "However, anchor ice formations are not known to remain in place for several months"

RC1: Lines 452-453: But wouldn't it still deplete during the winter time? I see that you have a reference at the end of the sentence but does that reference suggest that?

AR1: We have no definitive information on how rapidly the depletion is for swamps and muskegs at this site.

Action1: Page 27, Line 524-525: "though this assumes no depletion over the period of ice cover."

RC1: Figures 8 and 9: A superposed air temperature graph would be of interest.

AR1: We opted to not include air temperature data plots since reader may imply that a detailed evaluation of temperatures was part of this study. Temperature use was limited primarily to aid interpreting freeze-up (temps less than -10^{o}C) and mid winter events (positive temps and rain).

No Action1

RC1: Line 471: Please update Figure #

AR1: Thank-you

Action1: Page 30, line 547: change to “Fig. 8”

RC1: Line 485: "Impure ice": Is this common? Should you explain what this means in brackets? Should you also add this to the previous sentence that refers to snow load, for consistency?

AR1: remove word ‘impure’ and ‘snow load’ from text and revise to say:

Action1: Page 31, Line 559-561: Revise to say: “since the specific gravity of river ice is commonly taken as 0.92. Nevertheless, these measurements are assumed to represent the actual ice cover thickness”

RC1: Lines 504-506: You may suggest that readers could take the measured thickness and associated date, evaluate the corresponding cumulated degree-days of freezing (or a cumulated sophisticated heat budget), and create a relationship between both parameters. Step 2 would simply be to apply this relationship to the maximum degree-days of freezing of each winter to obtain an estimate of the maximum ice thickness (if no midwinter breakup occurred between ice thickness measurement and actual max freezing degree-days).

AR1: Specific method of ice growth prediction is not within scope of paper so leave text as is.

No Action1

RC1: Lines 517-518: Actually, the station may start "feeling" some stage instabilities that come from upstream (these would actually be discharge instabilities induced by upstream ice movement), and it would still mean that breakup has initiated. How do we know that this is taking place downstream, especially when looking at daily-average stage data?

AR1: If only daily data, cannot determine HB. For clarity:

Action1: Page 34, Line 600: replace “in the absence of a continuous water level record.” with “from a record of mean daily water level”

RC1: Line 518: Same comment as before: a reduction in roughness would generate a sudden drop of the instantaneous stage signal. In turn, a jave would be a spike and a sudden raise would be the formation of an ice jam downstream.

AR1: Agree that a drop in water level, however, the method of pen chart reading assumes that water level rises, the ice cover detaches/ entrains, and then drops. Jave is mentioned at line 535.

No Action1

RC1: Line 529: I am not sure that there is a need to state "quickly" here. First, it applies to both time and distance traveled. Second, quickly is relative and I have seen large ice slabs (especially those that were part of a hanging dam or a snowmobile crossing) remaining fairly large several days or km after breakup.

AR1: Agree

Action1: Page 34, line 610: remove work “quickly”

RC1: Line 532: Should there be an example of a case study reporting X meters above the rating curve? This would illustrate the meaning of "far exceed"

AR1: Agree

Action1: Page 34, Line 614 -617. Revise to say: “open-water flow conditions (von de Wall et al, 2009, 2010; von de Wall, 2011) For example at Liard River near the Mouth (10ED001) the 25 year return period for ice affected water level was 16.11 m versus 9.69 m for the open water event (de Rham et al, 2008a) “

RC1: Lines 534-535: This is not exact: They can also cause a measurable stage (actual discharge) depressions for several hours before reaching an equilibrium. The jave is much more sharp, especially in steep channels and when the released jam was not too far upstream from the station.

AR1: Agree

Action1: Page 34, Line 618-622. Revise to say: “. A jam lodged upstream of a guage can also have a measurable stage (actual discharge) depressions for several hours before reaching an equilibrium. The release of a jam can generate a sharp wave called a ‘jave’ (Beltaos, 2013) yet another dynamic mechanism that can generate the identified HM water level on instantaneous water level recordings).”

RC1: Lines 535: It should be stated that 1. Javes can only be adequately documented using instantaneous data. 2. Javes have probably been removed from discharge records (at least in Quebec) as they were considered to be ice jams that had nothing to do with a discharge signal. It is also possible that javes and ice jams have been removed from some records because they were peceived as instrument pathologies. If there is enough evidence of this practice in some offices, the authors should mention it in the discussion.

AR1: agreed with point 1. Point 2. and 3. are suited to future work that exclusively examines CRID time series for jave. Author recollection is that extreme spikes on water level recording charts were generally not filtered out by NHP and thus reported as instantaneous events.

Action1: Page 34, line 622: add statement “on instantaneous water level recordings”

RC1: Line 541: Could be completed by "... where the stage gradually returns to the stage discharge relationship as the discharge slowly increases"

AR1: agreed. The overall sentence has been revised

Action1: Page 35, Line 625-628: change to: “The less common “overmature” break-up sequence was observed at some CRID stations with no less obvious “spiking” of water levels. An example water level of with this occurrence characteristic on the Peace River in 1982 (Fonstad, 1982) is included in Beltaos (1990) where minor water level perturbations are followed by a generally smooth reduction to open channel conditions. . In some cases the HB and HM were interpreted to occur at the same time.”

RC1: Line 550: Should the authors state that the last B date could likely be off by a few days? It is not to criticize the work done by different offices, but to warn users about this possible limitation. The last B date is specially difficult to confirm during thermal breakup years or when post-break ice runs from far upstream still occur after a complete local wash.

AR1: We are not attempting to quality control Last B date, rather inform the CRID includes alternative variables to the readily available last B date.

No Action1

RC1: Figure 12: Second image is very dark. Is there a way to tweak this?

AR1: Thanks you for the prompt.

Action1: Page 36, Figure 12: tweaked brightness and contrast of 2nd and 3rd image. Also took Reviewer recommendation on Figure 5 to add water level record. Thus, the Figure caption has been revised to: “Figure 12: Continuous 15 minute interval water level hydrography for April 15 to 30, 2010 at National Hydrometric Program gauging station Hay River near Hay River (07OB001) along with images courtesy of Alberta Research Group. Left: Image looking upstream taken 7 days prior to spring break-up initiation (HB) of April 24, 2010, 04:25. Channel width of approximately 63 meters. Centre, left is a night time image 5 minutes after HB and shows evidence of fragmented ice in the channel. Centre, right is 65 minutes after HB and shows channel nearly clear of ice. Right image is 5 minutes after maximum spring break-up water level on April 25, 2010, 15:25. Stranded ice on channel banks indicates higher water levels. Last B date was April 28, 2010.”

RC1: Line 575: Should the authors mention that Ho may actually occur in mid-summer (e.g., Saguenay event in Quebec, 1996) or during the fall, and therefore may not be associated with the spring freshet, especially in Eastern Canada?

AR1: Agreed

Action1: Page 35, Line 670-671: Add sentence “A Canadian perspective on flood process (snowmelt, rain-on-snow, rainfall) and their seasonality are detailed in Buttle et al., (2016).”

RC1: Line 577-578: Just to complete the idea, i would suggest: "...for a large ratio of hydrometric stations in Canada, and most probably for an equal ratio of unmonitored sites."

AR1: Agreed though use word “portion” instead of “ratio”

Action1: Page 37, Line 670: Add “for near one third of hydrometric stations in Canada (e.g. von de Wall 2009) and most probably for a similar proportion of unmonitored sites”

RC1: Line 584: "five" should probably be "six"

AR1: thank-you

Action1: Page 37, Line 678. Change to “six”

RC1: Line 605: Should the author specific what defines an error or what it the calculation behind this %?

AR1: OK. This section has comments from all reviews so revising text for clarity.

Action1: Page 38, Line 699-708: “ A quantification of human error in transcribing CRID data was undertaken using automated scripts to extract and compare the CRID daily discharge and First and Last B Date to those published by the NHP. Daily discharge was incorrectly transcribed on 4.7% to 7.8% of the time series depending on the variable while mid-winter associated discharge had the highest input error at 16%. This higher percentage of error is a likely remnant to the multiple rounds of revisions to mid-winter time series and confusion that arises when examining non-consecutive events that can occur across calendar years. For ice seasons when both a First and Last B Date were available, dates were incorrectly transcribed on 7.5% of time series. All erroneous daily discharge and First and Last B Date values were replaced. The remaining CRID data entries are not amendable to automated quality control since they were manually extracted.”

RC1: Lines 606-607: It is unclear to me if indicated B dates are considered true and other parameters are corrected consequently, or the opposite.

AR1: OK. Text revised for clarity:

Action1: Page 38; Line 705-706. Revise to say: “For ice seasons when both a First and Last B Date were available, an input error ofdates were incorrectly transcribed on 7.5% was found.of time series

RC1: Lines 613-614: As asked earlier, would the authors also commit to present updated versions of the CRID with corrections?

AR1: Thank you for reiterating

Action1: Page 38, Line 720-723: added statement “As is indicated on the Open Data Portal where the CRID can be downloaded, ongoing work with the CRID may include error checking and corrections, so users should use the latest version of the CRID by referring to the version number that appears in the .csv file name (http://data.ec.gc.ca/data/water/scientificknowledge/canadian-river-ice-database/CRID_BDCGF_Versioning_EN_FR.txt).

RC1: Lines 623 vs. Line 634: If I had to choose, I would say that ice processes are site specific.

AR1: Agreed

Action1: Page 39, Line 733 change to “are”

RC1: Line 628-629: (e.g. promoting a thicker ice cover in the deck shadow and promoting ice jamming against abutment or pillars)

AR1: Thank you for this addition. Use word piers instead of pillars.

Action1: Page 39, Line 739: Add to end of sentence: "such as promoting a thicker ice cover in the deck shadow and promoting ice jamming against abutment or piers"

RC1: Figure 13: The legend in this graph could include variable acronyms for clarity. Also, it would have been useful to separate the two populations with different icons / colors. The only obvious difference is the two populations is blue circles.

AR1: Agreed. Revise figure and associated text as follows:

Action1: Page 40, Figure 13: Figure has been modified following suggestion, the caption has been revised

Action1: Page 39, Line 745: added: "towards assessments of station homogeneity are a necessary next step"

Action1: Page 39, Line 747: added: "this rudimentary visualization of data towards confirming non-homogeneity reveals the"

RC1: Table 4: There may not be enough space, but the authors could consider adding a column with the variable acronym.

AR1: Agreed and there is enough space

Action1: Page 42, added added column 'Symbol' to table

RC1: Line 694: "Very often" Do we have an updated number about that? If not, I hope that the CRID will be used by researchers to update the one third presented by Beltaos years ago.

AR1: von de Wall (2009) is most recent and has been added to this statement.

Action1: Page 43, Line 814-815: Revise to say "It has been established that extreme flooding in ~ 30% of Canadian rivers is often the result of ice processes and jamming (Beltaos, 1984; von de Wall, 2009)"

RC1: Line 694-695: I am not sure that I agree with this interpretation. It can be said that ice jams produce higher water levels at similar high flows (quite logical), and it can be said that at some sites, the main flooding process is caused by ice processes. In turn, the highest discharge in rivers most often occur in the absence of ice. There should be a more efficient way to express this.

AR1: As written it reference to Gerard 1989 and statement is revised to address reviewer concern:

Action1: Page 43, Line 816-817: Revise to say "At these locations stream discharge cannot be used to quantify flood level since the stage-discharge relationship is invalid during ice conditions"

RC1: Line 696: "eg." should be "e.g.". I take note that FloodNET is only one example. Other groups have completely ignored river ice processes in their flood research.

AR1: Agree with change. Don't have specific ref for Ouranos and Global Water Futures, but the groups are mentioned in Turcotte et al, 2019 will revise

Action1: Page 43, Line 820-821, revise to say: "(e.g. NSERC FloodNet, 2015, other groups mentioned by Turcotte et al., 2019), likely as a result of the limited, long term field"

RC1: Line 700: "could likely" should be "should, when applicable,"

AR1: agreed

Action1: Page 43, Line 825: Revise to "should, when applicable,"

RC1: Line 701: For sites that are not included in the CRID and where winter water level information is available, the CRID can represent a template to extract pertinent information for various purposes, including flood mapping and hydraulic structure design.

AR1: Thank-you for this. Have revised text.

Action1: Page 44, Line 856-857. Add sentence "For sites not included, the CRID can represent a template to extract pertinent information for various purposes including flood mapping and hydraulic structure design"

RC1: Line 742: A last sentence could be: "Maintaining funding and constantly improving hydrological estimation and measurements approaches is needed to maintain an adequate level of knowledge and to update the CRID in the future."

AR1: Since CRID was completed using public service tax dollars not appropriate to make call for additional funding. Hydrological estimation and measurement approaches are outside the scope of this data description paper of the CRID. From earlier reviewer comments a statement was added about updates (page 44, line 858 to 861): "Based on the 160 locations in operation up to Dec 31, 2015 (Table A1), a 5 year update of CRID time series (2016-2020) would require 800 person-hours of work. Evaluation of future research priorities are needed to formalize whether this task would be completed by the same group or undertaken by others". We do agree that associating last sentence to CRID and river ice science is a good idea so have added :

Action1: Page 45, Line 872-873: The CRID supports continued research on river ice processes and the extreme water level fluctuations common to many cold regions river systems.

RC1: Lines 1042-1044: I do not see this paper referred to in the paper and it should removed from the reference.

AR1: Apologies on the oversight. This paper (Turcotte et al., 2019) is now referenced in text

Action1: Referenced page 42, line 839 "…other groups mentioned by Turcotte et al, 2019),…"

Title: A Canadian River Ice Database from National Hydrometric Program Archives

Author(s): Laurent de Rham, Yonas Dibike, Spyros Beltaos, Daniel Peters, Barrie Bonsal, Terry Prowse

MS No.: essd-2020-29

RC2 General Comments:

The manuscript introduces the newly developed Canadian River Ice Database (CRID). Such a database is very welcomed in the river ice science and practitioner community and will promote studies to address a variety of research questions and practical issues. It is tremendous efforts to go through the large amount of historical data and collect the variables related to specific key ice events. Several of these variables can be very challenging to identify and require extensive expertise in river ice engineering, which is offered by the author team. The team's experience and expertise are also reflected in the selection of the variables, detailed description of their physical importance, quality control of the ice data, and uncertainty assessment. In this regard, the manuscript provides an important reference document for the use of the CRID. I will definitely be using the database and would like to see it being updated regularly as new information becomes available.

AR2: Thank you for this overview and positive feedback on the work. The note about 'uncertainty' has initiated authors to undertake the following:

Action2: Page 9, Line 191-193. Added sentence: "A final note: the vast majority of historical annual water levels (item (8)) are reported by NHP as preliminary since these values were never published. Similarly, some recent digital water level files (item (2)) were also preliminary since NHP had not yet screened these data."

Action2: Page 37, Line 675: have added "Uncertainty" to the section title.

Action2: Page 37, line 687-690: added sentence: "The vast majority of mean daily water level pages and some of the more recent digital water level recordings were deemed "Preliminary" by NHP. Different methods of collecting requisite information for mean daily water level have existed over the archive from at site station observers who viewed a staff gauge once daily to the more modern arithmetic averages determined from continuous water levels."

Specific comments:

RC2 Line 87: select to selected

AR2: Agreed

Action1: Page 3, Line 100. Change to "selected"

RC2 Line 115-126: It seems that with minimum 20-year record, no minimum drainage area and including both north of 0deg isotherm and southern temperate zone would result in much more than 196 stations. Am I missing any additional selection criteria used here?

AR2: line 122 authors state ‘subset’ and Line 128/129 ‘sites prone to mid-winter break-up events’. The text references (Prowse and Lacroix, 2001) from which the initital subset was selected.

Action2: Page 4, Line 129: have added “the near 8,400 active and discontinued”
Action2: Page 4, Line 132. Changed sentence to being with: “These select”
Action2, Page 4:, Line 139: add statement: “Inclusion of these sites resulted in a network of”

RC2 Line 135: foci to forcing

AR2. Foci is s common term in ecology, though other reviews mentioned confusion with “foci”. For clarification:

Action: Page 3, line 150: change “foci” to “focus”

RC2 Line 139: listing to list

AR2: agreed

Action2: Page 5, line 154 change to “list”

RC2 Line 191: There are actually more than 15 variables as several of the ones listed in Table 2 include both water level and discharge and they probably should be counted as 2 variables.

AR2: We use ‘variable’ in a multidimensional sense to include all data types associated with each variable: water level, discharge, date, time, rating.

No Action2

RC2 Figure 3: I am not sure if this figure is based on actual gauge record or purely conceptual. It may worth to show a water level hydrograph where the key ice events are less obvious (less “spiky”) and explain how the different variables are identified.

AR2: As the caption states, the figure is conceptual schematic. It was based on actual water level record in the Mackenzie River at Arctic Red and we added a mid winter section. Questions about this figure were also brought up by the other two reviewers. Given all of these comments, Figure 3 caption was revised.

Action2: Page 12, Figure 3, line 247-254. Caption has been revised to address these concerns and was described in Reviewer 1 comments

RC2 Table 2: does the wording “data accuracy” best represent what this indicator really means? It may lead reader/user to think the published data is accurate while it is less likely in case of ice affected discharge data.

AR2: Good comment. Data resolution is better representation

Action2: Page 11, Line 218: change accuracy to “resolution”
Page 11, Line 221: change accuracy to “resolution”
Page 15, Line 257: Table 2 caption: change Accuracy to “Resolution”
Page 17, Line 296: add “(Table 2: “Discharge” under column “Data Resolution”). ”

Page 34, Line 602: change accuracy to “resolution
Remainder of MS has been checked and confirm no other changes required

RC2 Section 3.3 What are the methods used to compute discharges under ice conditions? Can the authors briefly describe some common ones? This is important information for users of the published discharge data. Additionally, my understanding is that different methods and techniques have been used when deciding when to start and end the B symbol. Maybe the authors can provide some information on this as well?

AR2: Section 3.3, Page 16, Line 276-278 states:
“This section highlights challenges related to data collection during the ice season through excerpts from hydrometric program operational manuals, other publications and experience in developing this database. This background information is considered of high value to users when interpreting spatial and temporal characteristics of river ice.”
We are only attempting to provide background information rather than explain the intricacies of under ice discharge estimates and B dates. We included references and appropriate statements so readers can inform themselves:
Line 289: Poyser et al (1999) is referenced and have listed the types of river ice conditions that can result in B date.

Here is reference:
Poyser, B., Leblanc, R., and Kirk, D: Lesson Package No. 20 – Computation of Daily Discharge (Ice Conditions), The Water Survey of Canada, Hydrometric Career Development Program, 1999.

Line 291: verbatim statement of Environment Canada 1980 with several methods to compute discharge under ice. Reader can look at reference for specifics on how discharge is calculated.

Here is reference:
Environment Canada: Manual of Hydrometric Data Computation and Publication Procedures, Fifth Edition, Inland Waters Directorate, Internal Report, Ottawa, 1980.

No Action2

RC2 Line 278: repetitive quotation marks

AR2: OK

Action2: Page 17, Line 310: Revise to say: “

RC2 Page 12: Section goes from 3.3 to 3.4.1, missing 3.4

AR2: OK. Thank you for picking up this missed detail

Action2: Page 19, Line 357 add section: “3.4 CRID Variables”

RC2:Line 345-348: It may not be accurate to say the initial ice cover progression past a gauge is always a spike in the water level chart. In many cases, the “stage up” caused by an ice cover approaching from downstream and passing a gauge is a gradual water level increase. How is HF decided in a case like this?

AR2: Since we had access instantaneous water level recording we examine for rise and maximum in water level to indicate possible start of bank to bank ice cover. We do state at page 12, line 421 “Beltaos (1990) discussed the unlikelihood that a complete ice cover forms at the instant of HF.” We acknowledge the use of work ‘spike’ is not a good describer so revise text as follows:

Action2: Page 22, Line 406. Revise to say “This initial ice cover progression upstream past the gauge can cause a gradual increase to a maximum in the water level chart and is depicted as HF (freeze-over water level) in Fig. 3.”

Action2: Page 22, Line 418: delete “freeze-up spikes” and change to “maximum freeze-over water level”

RC2 Line 483: maybe add “approximately” before 0.92 as ice density can be affected by many factors.

AR2: Review 1 also brought up this item and text was revised.

Action2: change text page 30, line 559 to “since the specific gravity of river ice is commonly taken as 0.92”

RC2 Line 501 Fig. 10 should be Fig. 11

AR2: thank-you

Action2: Page 33, Line 579 change to “Fig. 11”

RC2 Line 517-518: this statement about the spike on the water level hydrograph indicating the onset of breakup seems to be conflicting with line 539-541. In the case of thermal breakup, how is HB determined?

AR2: Agreed this needs clarification. The following revisions to text are detailed below:

Action2: Page 35, line 625-626 change no obvious to “less obvious”
Action2: Page 35, Line 627-628: added “where minor water level perturbations are followed by a generally smooth reduction to open channel conditions. In some cases the HB and HM were interpreted to occur at the same time.”

RC2 Line 529-531: ice jams can form at morphologically conducive locations even without intact ice cover stopping the ice run.

AR2: Unknown occurrence to authors so revise as

Action2: Page34, Line 612-613: Added sentence “According to an anonymous reviewer, ice jams can also form at morphologically conducive locations even without an intact ice cover stopping the ice run”

RC2 Line 534-535: Jams formed upstream of a gauge may also choke the flow. It also depends on its vicinity to the gauge.

AR2: RC1 had similar comment

Action2: Page 34, line 618-622: added sentence: “A jam lodged upstream of a guage can also have a measurable stage (actual discharge) depressions for several hours before reaching an equilibrium. The release of a jam can generate a sharp wave called a ‘jave’ (Beltaos, 2013) another dynamic mechanism that can generate the identified HM water level on instantaneous water level recordings.”

RC2 Line 545 chuck -> chunk

AR2: OK

Action2: Page 35, line 632: Revise to say: “chunk”

RC2 Line 553-556: I wouldn’t say the last B date is always used as a surrogate/index, and less accurate than the CRID data to analyze spring breakup timing. They just represent different stage of the breakup.

AR2: We said the last B date is **sometimes** used not **always** used. In any case, the Last B date is final day that ice affects channel flow condition at the gauge, however, there may be no actual ice at gauge, and rather, the flow condition is affected by backwater from ice downstream. In general the sequence and processes associated with ice break-up all occur prior to the Last B date. However, this would depend on specific river flushing and clearance characteristics at the gauge. Users of data should view Poyser et al 1999 which is WSC publication describing discharge estimates under ice.

No Action2

RC2 Line 573-575: how can one calculate the water level using rating curve when instrumentation is damaged or not functioning?

AR2: Only discharge values are estimated, generally by interpolation and indicated with “E” by NHP to indicate that it is an estimate. Word calculate is misleading so:

Action2: Page 37, line 666: remove calculate and replace with “estimate”

RC2 Line 603-607 unclear to me how the percentage error are calculated.

AR2: Human input error versus NHP reported value as extracted by automated script. This section was also unclear to other reviewer so revised section.

Action2: Page 38, Line 699-708 as follows:

“A quantification of human error in transcribing CRID data was undertaken using automated scripts to extract and compare the CRID daily discharge and First and Last B Date to those published by the NHP. Daily discharge was incorrectly transcribed on 4.7% to 7.8% of the time series depending on the variable while mid-winter associated discharge had the highest input error at 16%. This higher percentage of error is a likely remnant to the multiple rounds of revisions to mid-winter time series and confusion that arises when examining non-consecutive events that can occur across calendar years. For ice seasons when both a First and Last B Date were available, dates were incorrectly transcribed on 7.5% of time series. All erroneous daily discharge and First and Last B Date values were replaced. The remaining CRID data entries are not amendable to automated quality control since they were manually extracted”

RC2 Line 635 Fig 12 should be Fig. 13

AR2: OK

Action2: Page 39, line 745: change to “13”

Interactive comment on “A Canadian River Ice Database from National Hydrometric Program Archives” by Laurent de Rham et al.
Zoe Li (Referee)
zoeli@mcmaster.ca
Received and published: 30 April 2020
RC3: Comments to the Editor:
The authors developed a Canadian River Ice Database using the Canadian National Hydrometric Program hydrometric records. River ice related events, especially ice jam flooding, are of great importance to the watershed management in many cold regions around the world, including Canada. This database provides a significant amount of valuable data to support river ice research and applications. I can definitely see myself and my colleagues using this database. This paper is well organized and well written. I only have some minor concerns as indicated in the comments to the authors. I suggest a minor revision.

RC3: We thank Dr.Li for her comment and valuable review. It is encouraging that she highlighted the importance of river ice for watershed management and the CRID data as presented is valuable for research and applications.

3

RC3: Detailed Comments to the Authors:

RC3:- Line 24: “73,000 variables” should be changed to “73,000 records”.

AR3: This a useful comment. Rather than change to records, which will not be consistent with remainder of paper, for clarification we change to:

Action3: Page 1, line 25: change text to “73,000 recorded variables”

RC3:- Line 28: “a time series of up to 15 variables” should be changed to “time series of up to 15 variables”.

AR3: agreed

Action3: Page 1, line 29: revise to say “time series of up to 15 variables”

RC3:- Lines 119-126: It is not clear how the 196 sites in this database were selected. Does it include any of the additional 60 southern sites? Or is it the same 196 gauging stations as in the NHP archives?

AR3: The paragraph describes the evolution of this subset of 196 NHP gauging locations and similar questions came up from RC2. Paragraph has been modified to quantify total number of active and discontinued NHP stations and highlight “These select monitoring sites”. Have added following statement for clarity:

Action3: Page 5, Line 139: Have modified final sentence to “Inclusion of these sites resulted in a network of 196 sites with drainage areas ranging from 20.4 km2 to 1.68 x 106 km2, including both natural and regulated flow conditions, with the latter distributed throughout this range.”

RC3:- Line 135: Typo: “hydro-ecological foci”.

AR3: This is terminology is used in hydo-ecological studies but since other reviewers also commented the text is now revised:

Action3: Page 5, Line 150. Change from “hydro-ecological foci” to “hydro-ecological focus”

RC3- Figure 2: Consider removing the border lines and using a different color for stations not in operation.

AR3: OK

Action3: Page 8, Figure 2: border line has been removed and color when station are not in operation has been made darker

RC3- - Table 1: Add bottom border.

AR3: OK

Action3: Page 10, Table 1. Added bottom border

RC3:- Figure 3: Add a legend for the grey line to show it is the water level during mid-winter breakup.

AR3: Grey line is described in the caption so does not need to be shown as a legend item.

No Action3

RC3:- Line 265: It’s not clear which 12 discharge time series the authors meant.

AR3: OK. In addressing this comment it was determined that this number should be 11. We also clarified in text by referring to location on Table 2.

Action3: Page 17 Line 295-296: revised to say: “for the 11 reported at-site ice affected discharge time series. (Table 2: “Discharge” under column “Data Resolution”)”

RC3:- Line 315: The subtitle of section 3.4 is missing.

AR3: OK. Addressed for RC2

Action3: Page 19, Line 357 added “3.4 CRID Variables”

RC3:- Line 325 & Figure 5: Consider defining the colors in the MODIS images for readers who are not familiar with satellite images.

AR3: OK. These images are true colour.

Action3: Page 22, Line 399-400 added sentence: “River channel open water is green and ice cover is white on these true colour images”

RC3:- Line 333: An extra space in “Sect. 3.4.4)”.

AR3: OK.

Action3: Page 20, Line 380 remove extra space

RC3:- Line 365: “parameterizes” should be changed to “parameterize”.

AR3: OK.

Action3: Page 22, Line 424 change to “parameterize”

RC3:- Line 466: An extra space in “level .”

AR3: OK

Action3: Page 30, line 542. Change to “level.”

RC3:- Line 496: No need to provide the abbreviation S.T.B. if it is used only once in the manuscript.

AR3: OK

Action3: Page 32, Line 575. Remove “S.T.B”

RC3:- Line 512: An extra space in “(84 days after January 1) .”

AR3: OK

Action3: Page 34, Line 592 remove extra space

RC3:- Line 618: An extra space in “about 1 hour .”

AR3: OK

Action3: Page 39, Line 728 remove space

RC3:- Table 2: Change “2000-01” to “2000-2001”.

AR3: OK

Action3: Page 10, Table 1: Revise to say: “2000-2001”

RC3:- Tables 2 and 3: The column heads need to be re-formatted.

AR3: OK

Action3: Page 14 and 15: Remove line gaps on column head for Table 2 and 3. Also add Line at bottom of these tables.

RC3:- Lines 365-368: It is not quite clear why the length of water level data was determined to be 30 days.

AR3: OK

Action3: Page 22, Line 425-426. Revise to say: “tabulates water level for 1 month as”

RC3:- Line 412: What about HMWB? How was it determined when there are no continuous water level records?

AR3: Cannot determine HMWB in absence of instantaneous records. This is good observation and have removed “D” (Daily) from Water level and Time column in Table 2

Action3: Page 25, Line 472. Added sentence: “This variable cannot be determined from mean daily summaries of water level records.”

RC3:- In Section 3.4, the variables were classified into 7 groups (7 subsections). Reasoning for the classification should be provided and reflected in the subtitles.

AR3: Thank-you.

Action3: Page 19, line 359-361. Moved sentence from above paragraph to below heading ‘3.4 CRID Variables: and state: “The following sub sections, corresponding to the four seasons of occurrence (Table 2) provide the background, extraction details and justifications for the selected CRID variables. For ease of reference the ice cover season is divided into three subsections that describe a maximum of four variables.”

RC3:- A brief data management plan, particularly the current database maintenance and update plan, should be provided.

AR3: Thank-you. This is common theme from all reviews. It has been addressed as follows: conclusion:

Action3: Page 38, Line 720-723. Added sentence. “As is indicated on the Open Data Portal where the CRID can be downloaded, ongoing work with the CRID may include error checking and corrections, so users should use the latest version of the CRID by referring to the version number that appears in the .csv file name (http://data.ec.gc.ca/data/water/scientificknowledge/canadian-river-ice-database/CRID_BDCGF_Versioning_EN_FR.txt).”

Action3: Page 44, Line 857-861: “It is recommended that periodic updates be made to this database since a longer time series record is of more value. Based on the 160 locations in operation up to Dec 31, 2015 (Table A1), a 5 year update of CRID time series (2016-2020) would require 800 person-hours of work. Evaluation of future research priorities are needed to formalize whether this task would be completed by the same group or undertaken by others.”

RC3:- There are some minor formatting errors in the references section. For example, the format of doi is not consistent. All references should be provided in the same format.

AR3: We have gone through the reference section and made formatting corrections to maintain consistency. Final formatting corrections will be made by the journal at the final editing stage.

Action3: went through references to ensure all doi format begins with http or https

A Canadian River Ice Database from National Hydrometric Program Archives

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Abstract

River ice, like open water conditions, is an integral component of the cold climate hydrological cycle. The annual succession ~~River ice is a common occurrence in cold climate hydrological systems. The annual cycle~~ of river ice formation, growth, decay and clearance can include low flows and ice jams, as well as mid-winter and spring break-up events. Reports and associated data on river ice occurrence are often limited to single locations or regional assessments, are ~~te~~ ~~and~~ season-specific ~~studies~~and use readily available data. Within Canada, the National Hydrometric Program (NHP) operates a network of gauging stations with water level as the primary measured variable to derive discharge. In the late 1990s, the Water Science and Technology Directorate of Environment and Climate Change Canada initiated a long-term effort to compile, archive and extract river ice related information from NHP hydrometric records. This data article describes the original research data set produced by this near 20-year effort: the Canadian River Ice Database (CRID). The CRID holds almost 73,000 recorded variables from a ~~network~~ subset of 196 NHP stations throughout Canada that were in operation within the period 1894 to 2015. Over 100,000 paper and digital files were reviewed representing 10,378 station-years of active operation. The task of compiling this database involved manual extraction and input of more than 460,000 data entries on water level, discharge, ice thickness, date, time and data quality rating. Guidelines on the data extraction, rating procedure and challenges are provided. At each location, ~~a~~ time series of up to 15 variables specific to the occurrence of freeze-up and winter-low events, mid-winter break-up, ice thickness, spring break-up and maximum open-water level were compiled. This database follows up on several earlier efforts to compile information on river ice, which are summarized herein, and expands the scope and detail for use in Canadian river ice research and applications. Following the Government of Canada Open Data initiative, this original river ice data set is available at: https://doi.org/10.18164/c21e1852-ba8e-44af-bc13-48eeedfcf2f4 (de Rham et al., 2020)

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1 Introduction

River ice is an intrinsic component of cold climate watersheds. ~~River ice and ice-related events are a common feature throughout cold-climate regions. However, the hydrological and hydraulic effects of ice receive considerably less attention than open-water river conditions. In the past decade, the study of river-ice processes and hydraulics emerged as an important research area (Hicks, 2008) with a renewed focus on ecological aspects (e.g. Peters et al., 2016; Lindenschmidt et al., 2018).~~ The Committee on River Ice Processes and the Environment (CRIPE; http://www.cripe.ca/) has been quite active and productive since the 1970s (Beltaos, 2012a) while the study of river-ice processes and hydraulics emerged as an important research area (Hicks, 2008). The past decade includes a renewed focus on its ecological aspects (e.g., Peters et al., 2016; Lindenschmidt et al., 2018). Given recent rapid changes to the cryosphere, there is a need to better understand river ice processes and hydraulics as they relate to a warming climate (Derksen et al., 2019). Advances in river ice process science are largely driven by observation and collection of field data supplemented by hydraulic modelling. While there are growing number of publications on river ice processes focusing on specific locations or river reaches and looking at a specific part of the ice period, such as the spring break-up, there are only few large-scale (countrywide) studies on the complete river ice season because of the absence of a comprehensive and multi-site river ice database.~~However, most studies have been limited to a specific location or river reach and focused on a particular part of the ice period, such as the spring break-up.~~ It is not commonly known by the wider hydrology research community that a ~~well known by the hydrologic research community that a~~ valuable source on river ice information can be extracted from the archives of hydrometric networks. In Canada, the National Hydrometric Program (NHP), in partnership with the Water Survey of Canada (WSC), provinces and territories, operates a current network of more than 2,800 hydrometric stations covering a broad range of hydroclimatic and hydrologic conditions, thus providing a good cross-section of the various river ice types and regimes. Historically, the primary mandate of the NHP was to provide water quantity information published as a time series of river discharge. The associated water level data, a requisite for ~~calculation~~ estimating channel~~of~~ discharge, has not been published up until the turn of this century. Importantly, the NHP accounts for the hydraulic effects of ice on river channels when ~~calculating~~ producing discharge estimates. Archival data used to compute discharge values in the form of field site visit notes, occasional ice thickness measurements, and continuous water level records, are a valuable source of information for the scientific, engineering and water management communities.

The ~~Committee on River Ice Processes and the Environment (~~CRIPE ~~; http://www.cripe.ca/)~~ sponsored report *Working Group on River Ice Jams - - Field Studies and Research Needs* by Beltaos et al., (1990) includes a chapter with detailed guidelines on the extraction of river ice data from hydrometric archives. Although field observations and data can be imperfect, with evidence of ice recorded only to improve the hydrometric program's discharge estimates, the archives cover a range of locations and are accessible upon request. Based on these beneficial attributes, efforts towards the creation of a database of river ice parameters were recommended (Beltaos, 1990) and a compilation of the hydrometric archives for a pan-Canadian river ice database began in the late 1990s. Prowse and Lacroix (2001) reported on the extraction of spring break-up extreme events at a subset of 143 NHP gauging sites up to the year 1999, covering major drainage basins and ecological zones in Canada. This work was followed by a preliminary analysis on 111 sites proximal and north of the annual 0ºC isotherm, differentiating between ice-induced and open-water flood generating mechanisms (Prowse et al., 2001). von de Wall et al., (2009, 2010) also used NHP sites north of the temperate ice zone, covering the years 1913 to 2006, for analysis of the spring break-up period. These works reported on the geographical distribution and statistical analysis of physical controls on flood generating mechanisms, a trend analysis (1969-2006), as well as correlations of ice event occurrence to both the 0ºC isotherm and various atmospheric teleconnection patterns.

More common in Canada are watershed and reach-scale studies of river ice processes. Examples include the work of de Rham et al., (2008a, 2008b) who examined spatial and temporal characteristics of the timing and magnitude of the spring break-up period from 1913 to 2002 throughout the Mackenzie River Basin. Downstream in the Mackenzie River Delta, Goulding et al., (2009a, 2009b) assessed spring break-up and ice jam water level event timing and magnitude to provide insights on hydro climatic controls of the break-up sequence over the 1974-2006 period. For the upstream Peace watershed, Beltaos (2003a, 2003b) and Beltaos and Carter (2009) utilized field based data and hydraulic modelling to examine the effects of hydroelectric reservoir operation on fall freeze-up and spring break-up flows and levels in the lower Peace River; the objective was to address the question of declining ice-jam flooding of the Peace-Athabasca Delta (Beltaos, 2018), while Peters et al., (2006) examined the maximum extent of flooding of ice-jam vs open-water flood events in this delta. Other well studied Canadian locations include, to mention but a few, the Hay River (De Coste et al., 2017); Red River (Wazney and Clark, 2015) and Chaudiere River (De Munck et al., 2016).

Expanding beyond Canada, Newton et al., (2017) reported on hydro-climatic drivers on mid-winter break-up occurrence derived from NHP hydrometric records for western Canada and the Cold Regions Research and Engineering Laboratory Ice Jam Database (IJDB) for Alaska (1950-2014). The IJDB (Carr et al., 2015) includes the timing and magnitude of ice-jam events across the United States for the period 1780 to present. While data sources are wide in scope, the initial creation of the IJDB during the 1990s drew largely from the United States Geological Survey (USGS) gauging station data, including peak backwater level events (White, 1996). Outside of North America, efforts to compile river ice information from hydrometric data have included work to assess river break-up dates (1893-1991) in Russia (Soldatova, 1993). The National Snow and Ice Data Centre (NSIDC) provides online access to Russian River Ice Thickness and Duration (1917-1992) dataset (Vuglinsky, 2000). These databases have been used for assessments of river ice conditions (e.g. Smith, 2000; Vuglinsky, 2006), with selected at-site updates to the year 2012 (Shiklomanov and Lammers, 2014). The NSIDC also provides access to The Global Lake and River Ice Phenology Database, Version 1 (Benson et al., 2000) that includes time series of freeze, thaw/break-up dates and description of ice cover for 237 rivers. A compilation and analysis of Norwegian rivers ice was described by Gebre and Alfredsen (2011). Although not specific to river ice processes, the national scale Canadian Ice Database (CID; Lenormand et al., 2002) also compiled visual observations of freeze-up and break-up dates along with measurements of ice thickness at

288 rivers across Canada. Brooks et al., (2013) used the data from the CID, along with international and NHP archives to quantify freshwater ice characteristics in the Northern Hemisphere.

Beltaos and Prowse (2009) presented a comprehensive review of global changes in river ice processes. While overall results indicated a shortening ice season, the authors noted that the majority of published studies assessed freeze-up and break-up dates, which can be more readily obtained from hydrometric agencies, rather than the more difficult to obtain daily and instantaneous ice-affected water levels. Specifically, these authors noted that broad-scale studies assessing river ice data extracted directly from hydrometric archives are yet to be completed. Thus, only a limited body of published research is available assessing the magnitude and timing of specific, dynamic river ice variables during the fall freeze-up, mid-winter, winter-low and spring break-up periods.

This paper expands upon the brief overview of the Canadian River Ice Database (CRID) presented at CRIPE (de Rham et al., 2019) and aims to provide a comprehensive reference document to accompany the publication of the CRID on the Government of Canada Open Data Portal. The main objectives are to: 1) describe the NHP archives and data collection history of this study; 2) present the 15 variables identified from the NHP archives recordings outlining the data extraction procedure while providing justification and relevant references for process based understanding; 3) report on challenges, assumptions and uncertainties encountered in the extraction of river ice information from hydrometric archives; and 4) identify resource requirements if others elect to undertake similar effort and highlight potential uses for this river ice database. The paper begins by describing the Study Area and Hydrometric Monitoring Sites followed by the Methodology covering details of the data extraction procedure. The Discussion section summarizes the data and highlights database utility and future research needs. The paper ends with sections on Data Availability, Data Disclaimer and Conclusion.

2 Study Area and Hydrometric Monitoring Sites

The locations and characteristics of the near 8,400 active and discontinued NHP stations, including their operation and regulation history, are available (in downloadable .csv format) at: https://wateroffice.ec.gc.ca/station_metadata/reference_index_e.html. The CRID includes data on river ice affected water level, associated channel flows and timing at a subset of 196 gauging stations across Canada (Fig. 1). These select monitoring sites are located within 11 of the 13 provinces and territories, and extend over 10 of the 11 Canadian climate regions (Gullet et al., 1992). In the beginning, the database focused on 143 stations with a minimum 20-year record, drainage area greater than 10,000 km^2, and located north of the mean annual 0ºC isotherm (Prowse and Lacroix, 2001). Thereafter, an examination of spring break-up at 136 northern gauging sites was reported (von de Wall, 2011). For the current study, the geographic criterion was expanded south into a “temperate zone” (Newton et al., 2017) and the drainage area threshold was removed. A review of literature and correspondence with WSC staff and provincial flood authorities identified an additional 60 southern sites prone to mid-winter break-up events. Inclusion of these sites resulted in a network of ~~The database now includes~~ 196 sites with drainage areas ranging from 20.4 km^2 to 1.68 x 10^6 km^2, ~~includes~~including both natural and regulated flow conditions, with the latter distributed throughout this range.

The flow regime at the 150 natural sites has not been affected by any significant upstream waterworks. At the remaining 46 regulated gauging stations, predominantly in southern Canada (Fig. 1), flows were affected by instream waterworks, such as weirs, dams and water diversion/abstraction. The majority of natural sites (120) were in operation up to the end of the study period of Dec 31, 2015, while most of the discontinued (30) stations ceased operating in the mid 1990s (Fig. 2). This late 20th century reduction in the monitoring network has also been reported by others (Lenormand et al., 2002; Lacroix et al., 2005). The regulated sites include 29 homogeneous (entire period of operation regulated) and 17 heterogeneous (natural then regulated flow during period of operation) hydraulic conditions (Fig. 2). The Peace River system, an example of a heterogeneous hydrometric archive, is affected by both climate and regulation and a system of hydro-ecological focus ~~foci~~ (e.g. Hall et al., 2018; Timoney et al., 2018; Beltaos, 2019). A large number of the older stations have periods of inactive operation during 1920 to 1960. A few inactive stations resumed operation since shutdown in the mid-1990s (Fig. 2). After removing the 1,012 years of inactive status, the 196 NHP sites considered represent 10,378 station-years of data prior to 2016. Appendix A1 provides a list~~ing~~ of all the stations selected for the CRID, including start and end dates and type. Specific CRID locations within this paper are referenced by gauging site name followed by the NHP alpha-numeric identifier in brackets.

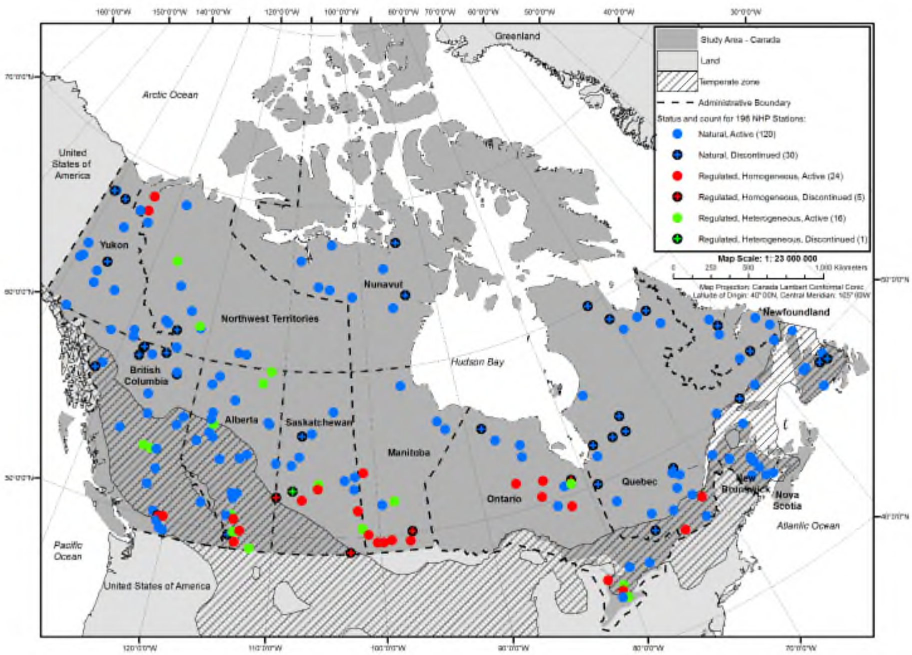
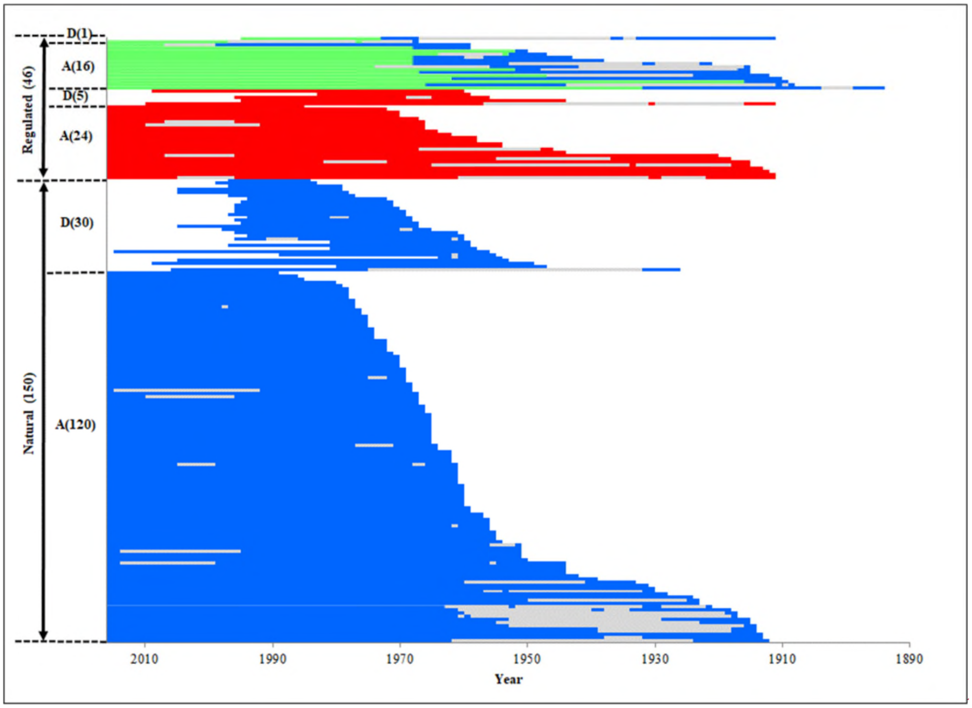


Figure 1. Location of the 196 National Hydrometric Program (NHP) hydrometric gauging stations included in the Canadian River Ice Database. Status and count for the stations are based on flow condition (Natural or Regulated), Active (in operation up to end of 2015) or Discontinued and if flow condition is homogeneous (always regulated) or heterogeneous (regulated during specific period of operation).


D(1)
A(16)
D(5)
A(24)
Regulated (46)
D(30)
A(120)
Natural (150)
2010
1990
1970
1950
1930
1910
1890
Year

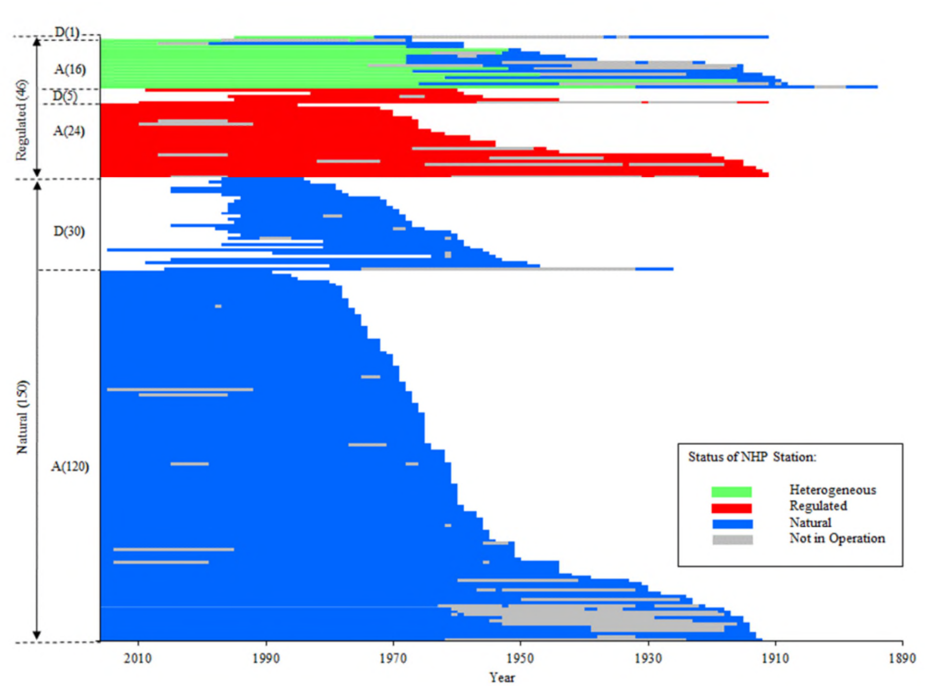


Figure 2. Bar chart showing the operational history of the 196 National Hydrometric Program (NHP) included in the Canadian River Ice Database. Stations are categorized by flow conditions (Natural or Regulated), operational status (Active (A) or Discontinued (D) and ~~homogeneity in~~ flow condition~~ns~~ ~~(homogeneous or~~ as homogeneous (always regulated) or heterogeneous (regulated during specific period of operation)~~s)~~, ~~and operational status (Active (A) or Discontinued (D)).~~ The number in each sub-category is shown brackets.

3 Methodology

3.1 National Hydrometric Program Archives

The ~~specific~~ various ~~paper~~ documents and digital hydrometric archives compiled and reviewed for this study include: (1) continuous water-level pen recorder charts (before year ca. 2000) during the freeze-up, mid-winter break-up (if applicable) and spring break-up periods; (2) digital files (after year ca. 2000 onwards) with water level data at discrete 5- to 15- to 60-minute interval, some including minimum and maximum instantaneous water level for entire annual period; (3) station descriptions; (4) site visit survey notes, including ice thickness summary files; (5) gauge and benchmark history; (6) stage-discharge (S-Q) relationship tables; (7) annual station analyses; (8) annual water level tables; (9) discharge measurement summaries; and (10) yearly station summary files (year ca. 2003-2009). Archives since 2009 are primarily in digital format extracted from the Aquarius water data management platform, which simplified the data extraction, as compared to reading hand-written notes and pen charts for prior years. The last ~~end~~ year ~~2015~~ ~~was selected for the~~of the CRID is 2015 as finalized NHP archival data can be delayed by up to two years while data control protocol is followed. The NHP works with provincial governments and partner organizations at some network stations; therefore~~–~~ archives also include those provided by the governments of Alberta, Saskatchewan, as well as the Centre d'Expertise Hydrique du Quebec (CEHQ). An earlier report (Groudin, 2001) included baseline break-up and open-water river information for 16 Quebec sites. Supplementary digital daily water level data for Quebec stations (Table A1; stations with "RIVIERE" in name) prior to ~ 1997 were limited to first water level recording of the day and, thereafter, summaries of 15 minute and daily average water level were provided. Information on discharge and river ice data qualifiers (such as the B dates, discussed below) were gleaned from the following WSC and CEHQ internet sites: https://wateroffice.ec.gc.ca/index_e.html and http://www.cehq.gouv.qc.ca/hydrometrie/index-en.htm. ~~and~~. A final note: the vast majority of historical annual water levels (item (8)) are reported by NHP as preliminary since these values were never published. Similarly, some recent digital water level files (item (2)) were also preliminary since NHP had not yet screened these data.

The evolution of the CRID was comprised of six data collection campaigns since 2000 (Table 1). Major data archival efforts in the years 2000-2001 and 2010-2011 required a team of two to three people visiting up to 8 WSC regional offices, with each visit lasting up to 2 weeks to photocopy and/or scan hydrometric archives. Following that, all paper based information, except for Quebec stations, was digitally scanned and filed to a central electronic repository. This 0.5 Terabyte digital data ~~entity~~ consists of over 30,000 folders and 100,000 files that is currently stored on a secure Environment and Climate Change Canada server. The CRID digital archive is available on request.

Table 1. List of the six data collection campaigns towards the development of the Canadian River Ice Database. The Water Survey of Canada (WSC) is the federal ~~part~~ agency of the National Hydrometric Program (NHP), which also includes provincial and territorial agencies.

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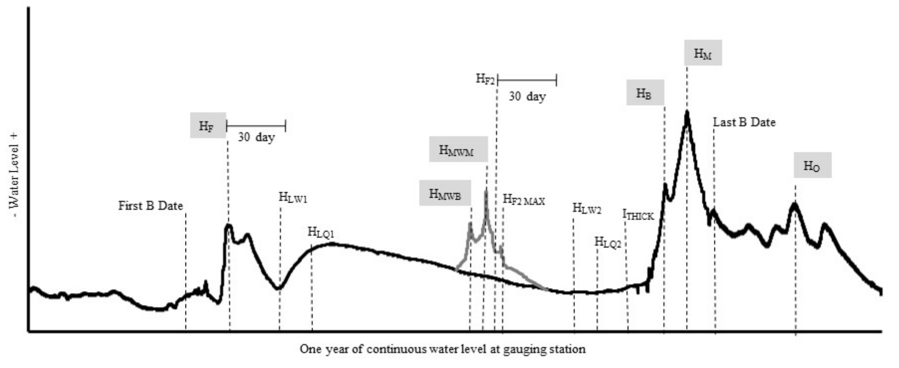
Data Collection Campaign	Study Focus	Location of NHP Sites	Number of NHP sites	NHP site Archival & Extraction	WSC Regional Office Visits	Duration of Office Visit	WSC Regional Office Locations and NHP partners	Publications
2000-01	spring break-up	Northern Canada	143	up to 2001	8	up to 2 weeks	Vancouver, Calgary, Yellowkinfe, Regina, Winnipeg, Burlington, St. Johns, Comerbrook; Groudin (2001) report on Quebec sites	Prowse and Lacroix 2001; Prowse et al., 2001
2003	spring break-up	Mackenzie River Basin	29	2002	5	up to 1 week	Inuvik, Fort Simpson, Calgary , Inuvik, Peace River	de Rham 2006; de Rham et al., 2008a, 2008b
2007	spring break-up	Mackenzie River Delta	14	2002-2006	2	up to 1 week	Yellowknife, Inuvik	Goulding 2008; Goudling et al., 2009a, 2009b
2008-2009	spring break-up	Northern Canada	136	2002-2006	-	-	transfer of digital information from 8 regional offices and 3 provincial agencies	von de Wall et al., 2009, 2010; von de Wall 2011,
2010-2011	fall freeze-up, mid-winter and spring break-up	Canada	196	up to 2008	7	up to 2 weeks	Vancouver, Calgary, Yellowkinfe, Regina, Winnipeg, Burlington, Fredericton; digital information from 3 provincial agencies	Brooks, 2012; Brooks et al., 2013, Newton et al, 2017; Newton, 2018
2017-2018	fall freeze-up, mid-winter and spring break-up	Canada	196	2009 - 2015	-	-	transfer of digital information from 7 regional offices and 3 provincial agencies	de Rham et al., 2018, de Rham et al., 2019

Data Collection Campaign	Study Focus	Location of NHP Sites	Number of NHP sites	NHP site Archival & Extraction	WSC Regional Office Visits	Duration of Office Visit	WSC Regional Office Locations and NHP partners	Publications
2000-2001	spring break-up	Northern Canada	143	up to 2001	8	up to 2 weeks	Vancouver, Calgary, Yellowkinfe, Regina, Winnipeg, Burlington, St. Johns, Comerbrook; Groudin (2001) report on Quebec sites	Prowse and Lacroix 2001; Prowse et al., 2001
2003	spring break-up	Mackenzie River Basin	29	2002	5	up to 1 week	Inuvik, Fort Simpson, Calgary , Inuvik, Peace River	de Rham 2006; de Rham et al., 2008a, 2008b
2007	spring break-up	Mackenzie River Delta	14	2002-2006	2	up to 1 week	Yellowknife, Inuvik	Goulding 2008; Goudling et al., 2009a, 2009b
2008-2009	spring break-up	Northern Canada	136	2002-2006	-	-	transfer of digital information from 8 regional offices and 3 provincial agencies	von de Wall et al., 2009, 2010; von de Wall 2011,
2010-2011	fall freeze-up, mid-winter and spring break-up	Canada	196	up to 2008	7	up to 2 weeks	Vancouver, Calgary, Yellowkinfe, Regina, Winnipeg, Burlington, Fredericton; digital information from 3 provincial agencies	Brooks, 2012; Brooks et al., 2013, Newton et al, 2017; Newton, 2018
2017-2018	fall freeze-up, mid-winter and spring break-up	Canada	196	2009 - 2015	-	-	transfer of digital information from 7 regional offices and 3 provincial agencies	de Rham et al., 2018, de Rham et al., 2019

3.2 Data Extraction and Quality Rating

A conceptual schematic of a water level hydrograph showing all typical ice aeffected metrics is plotted in Fig. 3. The CRID includes up to 15 variables ~~extracted from NHP recorded archives~~ that cover the water year (Table 2). These variables are categorized as occurring during one of four seasons ~~the~~: freeze-up, ice cover, break-up, or open-water ~~season~~. For the variables shaded in grey, the objective was to record data on instantaneous water level, associated date and time. These instantaneous values correspond with the water level at the initiation and maximum flood level for ice specific and open water conditions during each calendar year. ~~These instantaneous values reflect the maximum flood potential.~~ The procedure for extracting river ice data follows the guidelines of Beltaos (1990), and primarily involves visual examination of water level records. Hence, identification and extraction of river ice data is a subjective process and the ~~accuracy~~ resolution to which water level, discharge and event timings were registered is included in Table 2. Depending on the possibility of extracting instantaneous (Table 2, grey shading), mean daily water level or mean daily discharge (H_{LQ1}, H_{LQ2}) based variable, a data quality rating scheme with values of 0, 1 and 2 was used to quantify the continuum of higher to lower data ~~accuracy~~ resolution (Table 3). Under some circumstances, judgement was applied to rate data quality higher or lower depending~~s~~ on various circumstances, such as termination of a continuous water level record during the spring break-up season where ice movement, synonymous with variable spring break-up initiation (Sect. 3.4.6) damaged the recording instrument. Such data would rate as 0 even though data from the fragmented record rates as 1 on Table 3.



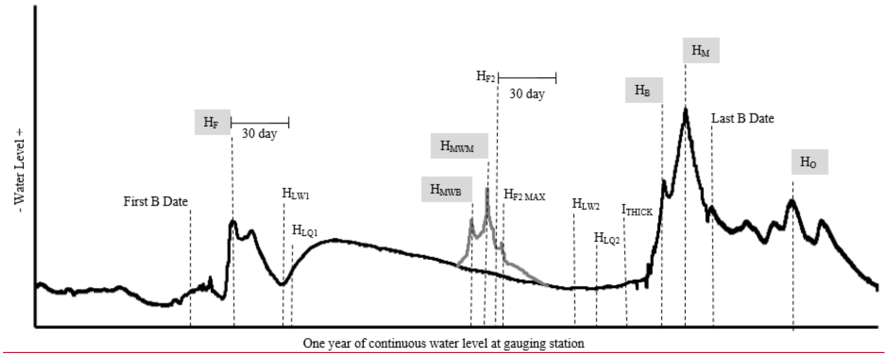


Figure 3. Conceptual schematic of continuous river water level hydrograph (black line) spanning September 1 to August 31. ~~.~~ Period of ice affected flow is constrained by First B Date to Last B Date. A possible~~Possible~~ mid-winter break up event is shown as grey line, at approximate cent~~er~~e of hydrograph. Symbols for the 15 variables which populate the Canadian River Ice Database are shown in the figure (see Table 2 for additional information). ~~F~~ The variables shaded in grey show the instantaneous water level and associated time when the event occurred ~~or the variables shaded in grey, the objective was to record the instantaneous water level and associated time when the event occurred.~~ Compression of x-axis and vertical exaggeration of y-axis accentuates the water level changes observed during ice conditions

. The relative magnitudes of variables and water level pathology should not be considered as typical.

Table 2. The 15 variables extracted from the National Hydrometric Program archives and input to the Canadian River Ice Database (CRID). The CRID includes the date of all variables classified by season. The ~~accuracy to which the~~resolution of

the water level or discharge record ~~was~~ examined is summarized with grey shading denoting attempt to identify instantaneous water level events. Data quality rating was applied to the underlined data.

				Data Accuracy: Instantaneous (I), Daily (D), No Extraction (-)			Data Quality Rating (0-1-2)
Season	**Variable**	**Symbol**	**Description**	**Water Level**	**Discharge**	**Time**	**Yes (Y) or No (N)**
Freeze-up	First Day With Backwater Due To Ice	First B Date	First day that ice affects channel flow conditions	-	-	D	N
Freeze-up	First Freeze-Over Water Level	H_F	Channel wide ice cover; daily water level at H_F and following 29 days	I or D	D	I or D	Y
Ice cover	First Minimum Winter Water Level	H_{LW1}	Minimum daily water level between H_F and H_B	D	D	D	Y
Ice cover	First Minimum Winter Discharge	H_{LQ1}	Minimum daily discharge between H_F and H_B	D	D	D	Y
Ice cover	Mid-Winter Break-Up Initiation	H_{MWB}	Initiation of mid-winter break-up event	I or D	D	I or D	Y
Ice cover	Maximum Mid-Winter Break-Up Water Level	H_{MWM}	Maximum mid-winter break-up event water level	I or D	D	I or D	Y
Ice cover	Maximum Winter Water Level	H_{F2}	Freeze-up after H_{MWM}. If no Mid-winter event, first day of 7 day average if exceeds H_F 7 day average	D	D	D	Y
Ice cover	Maximum Winter Water Level 7 Day	$H_{F2\,MAX}$	Maximum daily water level within first 7 days following H_{F2}	D	D	D	Y
Ice cover	Second MinumumWinter Water Level	H_{LW2}	Minimum daily water level between H_{F2} and H_B if H_{LW1} before H_{F2}	D	D	D	Y
Ice cover	Second Minimum Winter Discharge	H_{LQ2}	Minimum daily discharge between H_{F2} and H_B if H_{LQ1} before H_{F2}	D	D	D	Y
Ice cover	River Ice Thickness	I_{THICK}	Average channel ice thickness prior to spring break up	-	-	D	N
Break-up	Spring Break-Up Initiation	H_B	Beginining of spring break up event	I or D	D	I or D	Y
Break-up	Maximum Spring Break -Up Water Level	H_M	Maximum spring break-up water level event	I or D	D	I or D	Y
Break-up	Last Day With Backwater Due To Ice	Last B Date	Final day that ice affects channel flow conditions	-	-	D	N
Open-Water	Maximum Open-Water Level	H_O	Maximum water level occuring outside First B date to Last B date	I or D	I or D	I or D	Y

				Data Resolution: Instantaneous (I), Daily (D), No Extraction (-)			Data Quality Rating (0-1-2)
Season	Variable	Symbol	Description	Water Level	Discharge	Time	Yes (Y) or No (N)
Freeze-up	First Day With Backwater Due To Ice	First B Date	First day that ice affects channel flow conditions	-	-	D	N
Freeze-up	First Freeze-Over Water Level	H_F	Channel wide ice cover; daily water level at H_F and following 29 days	I or D	D	I or D	Y
Ice cover	First Minimum Winter Water Level	H_{LW1}	Minimum daily water level between H_F and H_B	D	D	D	Y
Ice cover	First Minimum Winter Discharge	H_{LQ1}	Minimum daily discharge between H_F and H_B	D	D	D	Y
Ice cover	Mid-Winter Break-Up Initiation	H_{MWB}	Initiation of mid-winter break-up event	I	D	I	Y
Ice cover	Maximum Mid-Winter Break-Up Water Level	H_{MWM}	Maximum mid-winter break-up event water level	I or D	D	I or D	Y
Ice cover	Maximum Winter Water Level	H_{F2}	Freeze-up after H_{MWM}. If no Mid-winter event, first day of 7 day average if exceeds H_F 7 day average	D	D	D	Y
Ice cover	Maximum Winter Water Level 7 Day	$H_{F2\,MAX}$	Maximum daily water level within first 7 days following H_{F2}	D	D	D	Y
Ice cover	Second MinumumWinter Water Level	H_{LW2}	Minimum daily water level between H_{F2} and H_B if H_{LW1} before H_{F2}	D	D	D	Y
Ice cover	Second Minimum Winter Discharge	H_{LQ2}	Minimum daily discharge between H_{F2} and H_B if H_{LQ1} before H_{F2}	D	D	D	Y
Ice cover	River Ice Thickness	I_{THICK}	Average channel ice thickness prior to spring break up	-	-	D	N
Break-up	Spring Break-Up Initiation	H_B	Beginining of spring break up event	I	D	I	Y
Break-up	Maximum Spring Break -Up Water Level	H_M	Maximum spring break-up water level event	I or D	D	I or D	Y
Break-up	Last Day With Backwater Due To Ice	Last B Date	Final day that ice affects channel flow conditions	-	-	D	N
Open-Water	Maximum Open-Water Level	H_O	Maximum water level occuring outside First B date to Last B date	I or D	I or D	I or D	Y

Table 3. The data quality rating for water level or discharge associated with 12 of the 15 variables in the Canadian River Ice Database. Continuous indicates no gap in the recorded hydrometric data, fragmented means there are some gaps over the period of review, and sporadic indicates limited data available. This was a qualitative, expert judgment-based rating**.**

Data	Data Quality Rating		
	0	1	2
Instantaneous Water Level	continuous	fragmented, continuous daily	fragmented daily
Daily Water Level or Discharge	continuous	fragmented	sporadic

Data	Data Quality Rating		
	0	1	2
Instantaneous Water Level	continuous	fragmented, continuous daily	fragmented daily
Daily Water Level or Discharge	continuous	fragmented	sporadic

3.3. Ice Affected Stage-Discharge Relationship and B Dates

This section highlights challenges related to data collection during the ice season through excerpts from hydrometric program operational manuals, other publications and experience in developing this database. This background information is considered of high value to users when interpreting spatial and temporal characteristics of river ice data.

A fundamental concept in hydrometry is the stage – discharge (S-Q) relationship. At each NHP monitoring location, a reach-specific relationship is established via field surveys. Each year, hydrometric staff complete multiple site visits to measure in situ stream velocity and flow area to calculate discharge for a given water level. This work is ongoing with occasional refinement and adjustment of the S-Q relationship to account for changes in channel morphology and bed roughness – in some cases requiring relocations of station due to loss of stable control section in response to natural and/or anthropogenic impacts. Besides, the open water S-Q relationship is not valid during river ice conditions due to well-known hydraulic effects of ice on flow conveyance. In Canada, ice-influenced flows are identified with a "B" flag to inform the user that the water level is affected by 'Backwater' conditions leading to a higher water level associated with a given discharge on the S-Q curve. The specific river ice condition can take different forms, such as frazil and slush ice, anchor ice, partial ice cover, complete ice cover, ice jams, flowing ice chunks or a mix of these (Poyser et al., 1999). The data user, therefore, has to be aware of these possibilities when using 'B' dates as metric for river ice conditions. In reference to S-Q relationships under ice, Environment Canada (1980) states: "*Because of the many variable factors involved, no single standard procedure is suggested for the* *computation of daily discharges during periods when the stage-discharge relation is affected by the presence of ice. Several methods of computing discharges under ice conditions are available and it is suggested that the Regional Offices use the method that best suits each individual station*”. The CRID, with data sourcing from regional offices and partner organizations across the country, inherits this discharge calculation legacy for the ~~12~~ 11 reported at-site ice affected discharge time series (Table 2: “Discharge” under column “Data Resolution”). Cold-region hydrometric programs have to contend with measurement problems and uncertainties of under-ice flows (Pelletier, 1990). Accurate measurement receives continued attention since water resource managers, dam operators and the flooding research community seek to reduce data uncertainty for ice affected periods (e.g. Healy and Hicks, 2004; Fulton et al., 2018). ~~for ice affected periods.~~ The apparently chaotic flow condition during the freeze-up and break-up periods along with Kennedy’s (1975) observation that: *“an ice-jammed river is among the most deranged of hydraulic phenomena”* further complicate discharge estimation. The WSC Lesson Package No. 20 – Computation of Daily Discharge (Ice Conditions) (Poyser et al., 1999) reiterated freeze-up and break-up as: “*two periods are often the most difficult ones for which to produce reliable discharge estimates, even for seasoned hydrometrists, who must use ingenuity, experience, and a knowledge of the characteristic traits that indicate transition”* and that “*Computation under ice conditions involves a high level of personal judgement on the part of the technician in the interpretation of the available data”.*

Thus, interpretation of ice affected conditions remains a challenge for hydrometric programs. For example, at a gauge station along the Peace River (https://wateroffice.ec.gc.ca/report/historical_e.html?stn=07KC001) the WSC informs users that ““*Data quality during spring break-up considered poor and remaining ice period considered fair”*. ~~Background for this~~An example schematic showing the ice affected condition ~~assessment~~ is provided in ~~by~~ Fig. 4, ~~in which the~~where the latest time when ice-covered flow can be estimated with a fair degree of confidence is at point A. Under conditions of a stable ice cover, hydrometric staff can apply site-specific methods to estimate the applicable discharge, based in part on sporadic flow measurements during the winter period. Point B in Fig. 4 denotes the last day of backwater, so that after that time discharge can be estimated with very good confidence using the gauge-specific S-Q relationship that applies to open-water conditions. Point C in Fig. 4 approximately delineates the periods of pre-breakup (sheet ice cover, possibly subjected to hinge and transverse cracking) and actual breakup when various events such as ice jams and ice runs generate repeated increases and decreases in the water level that are too sharp to be runoff-generated. For the breakup period, hydrometric staff estimate daily flows by taking into account the general trend of the water level hydrograph, prevailing weather conditions, flows at upstream gauges and tributaries, as well as any in-situ visual observations that may be available. Once the ice cover is fractured, mobilized, and broken up, flow measurement is inhibited by problematic access and safety considerations. Consequently, it is not possible to assign reliable flow estimates during the break-up period, leading to the aforementioned “poor” characterization since there is no way at this time to quantify the reliability of these data. ~~Consequently, it is not possible to assign error margins to associated flow estimates, leading to the aforementioned “poor” characterization.~~

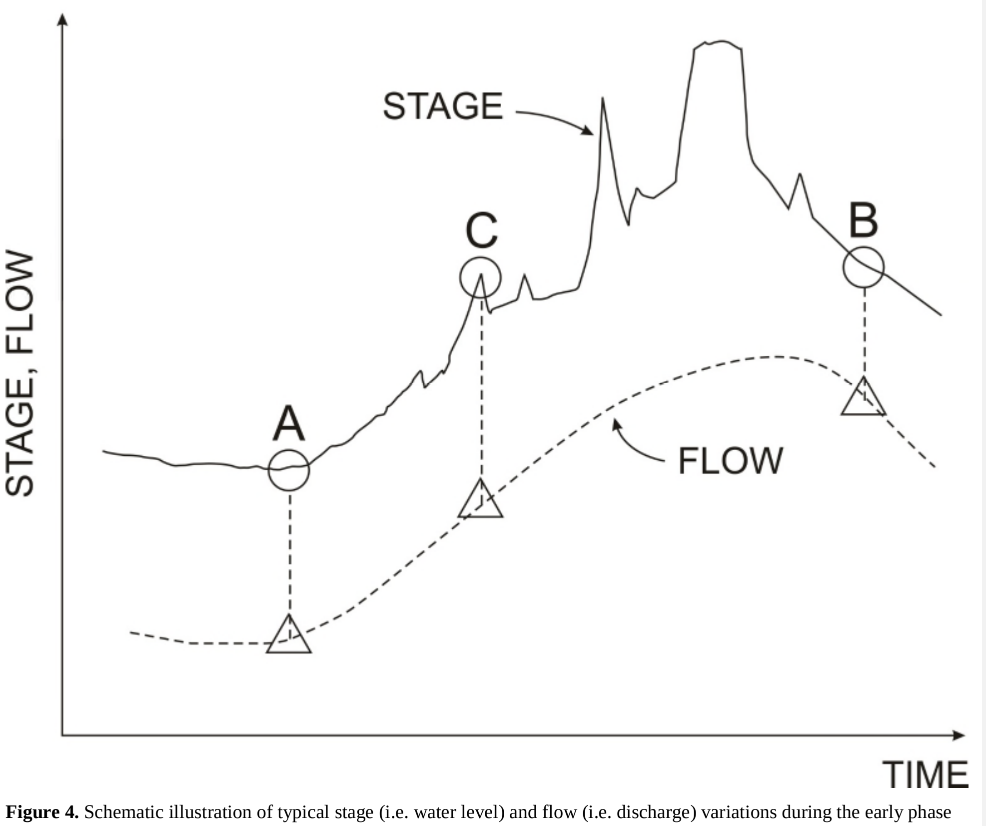


Figure 4. Schematic illustration of typical stage (i.e. water level) and flow (i.e. discharge) variations during the early phase of the spring runoff event. From Beltaos (2012b); Crown Copyright; Published by NRC Research Press.

~~The first ever published analysis of WSC 'B' dates was completed by Brimley and Freeman (1997) who examined trends in the Atlantic region. Their observations on station locations and the dynamic ice conditions *"that the data on river ice should only be considered valid at the gauging station site and may not be transferable to the entire watershed"* are applicable to the CRID product.~~

National assessments that analyze flow data often make no mention of the uncertainties associated with the collection and interpretation of hydrometric data during ice conditions (e.g. Cunderlink and Ouarda; 2009; Burn and Whitfield, 2016). More discussion on this issues are needed to inform the water community of the challenges related to cold-regions hydrometric data collection (Hamilton, 2003) and caution when interpreting study results. The first ever published analysis of WSC 'B' dates was completed by Brimley and Freeman (1997) who examined trends in the Atlantic region. Their observations on station locations and the dynamic ice conditions *"that the data on river ice should only be considered valid at the gauging station site and may not be transferable to the entire watershed"* are applicable to the CRID product. ~~Users of ice-affected discharge estimates are encouraged to actively report the data uncertainties inherent to the ice period and how station location and hydraulic conditions can affect the ice and flow regimes. This practice informs the water community on a unique characteristic of cold-regions hydrometry and caution in interpreting study results. As a corollary, the water level interpretation toward the CRID research data set also required a high level of expert judgement with this subjective attribute inherent to the reported variables.~~

~~The following sub sections, corresponding to the season of occurrence (Table 2) aims to provide the background, extraction details and literature justifications for the CRID variables.~~

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3.4 CRID Variables

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The following sub sections, corresponding to the four seasons of occurrence (Table 2) ~~aims to~~ provide the background, extraction details and ~~literature~~ justifications for the selected CRID variables. For ease of reference the ice cover season is divided into three subsections that describe a maximum of four variables.

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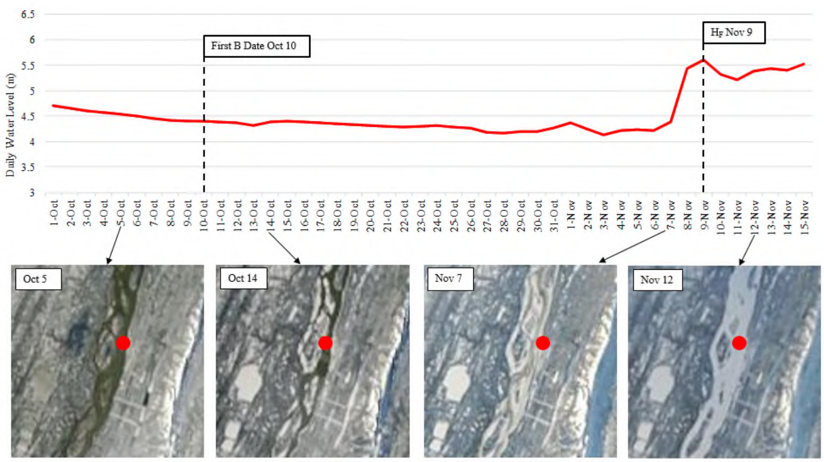
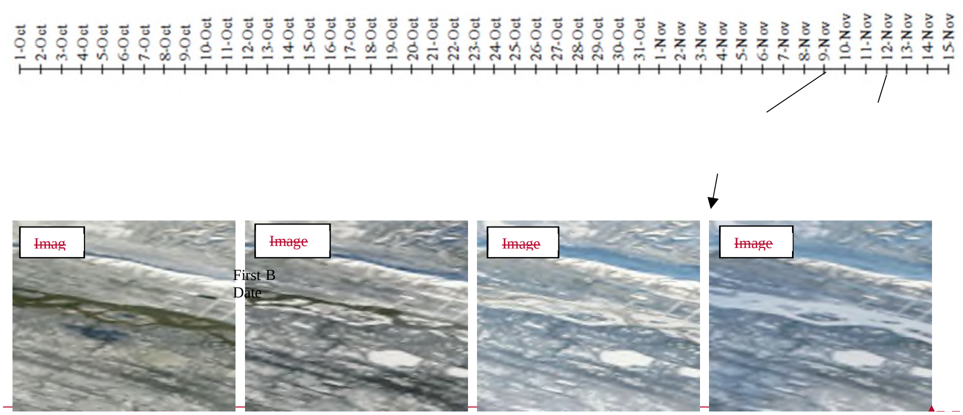
3.4.1 Freeze-up: First B Date, H_F

As mentioned above, the NHP daily discharge values include a 'B' ~~date~~ flag to inform users of discharge estimates that consider the ice "Backwater" effect in the stream reach (Environment Canada, 2012). Users can access these data in the online archive and/or downloadable HYDAT database with the Environment Canada Data Explorer freeware (https://wateroffice.ec.gc.ca/mainmenu/tools_and_downloads_index_e.html). The first occurrence of this flag, the First B

Date, marks the beginning of ice affected channel flow condition and has been used to investigate changes in the timing of river freeze-up (Zhang et al., 2001; Peters et al., 2014). However, the First B Date does not indicate the presence of an ice cover at a hydrometric gauge since the backwater effect may be a result of ice conditions far downstream of the station or nearby presence of significant anchor ice build-up on the river bed. The MODIS time-lapse satellite images in Fig. 5 illustrate the freeze-up and ice cover conditions on a reach of the Mackenzie River in the fall of 2000. For that year, NHP reports a First B Date of Oct 10, but open water sections appear on Oct 14 and even one month later on Nov 7. Only the Nov 12 image shows the ice cover over the entire river channel with no open water sections apparent. The First B Date in the CRID therefore only marks the beginning of ice effects on a river reach and cannot be assumed to be a channel wide ice cover condition. Though extraction of CRID variables did not use alternative means of verification, using satellite images from the WorldView interface (accessed at: https://worldview.earthdata.nasa.gov/) in this example is a simple way to view time series of changing ice cover conditions since the year 2000. For locations with several freeze-up and break-up cycles, such as the temperate zone locations (Fig. 1) or gauges with associated intermittent daily B data flags (depicted on Fig. 9, Sect. 3.4.4), the first B occurrence was recorded as First B Date. For CEHQ stations in Quebec, the data qualifier R was assumed synonymous to B and in the very few situations where the date did not match, NHP First B Date was used.





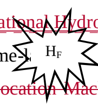


Figure 5. Daily mean water level hydrograph for October 1 to November 15, 2000 at National Hydrometric Program gauging station Mackenzie River at N [illegible] Wells (10KA001) along with ~~Year 2000~~ MODIS time-[illegible]ite images (accessed at: https://worldview.earthdata[illegible]) ~~at the National Hydrometric Program gauge location Mackenzie River at Norman Wells (10KA001). Station is located near centre of the images~~ Station location indicated by red circle. ~~-~~ Width of the channel

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is approximately 1,300 meters and includes numerous islands. Flow is from ~~right to left~~bottom to top. First B Date is October 10 while freeze-over water level (H_F) occurred November 9 and these images were obscured by clouds. ~~and~~ River channel open water is green and ice cover is white on these true colour images.~~open water appears during the freeze-up season.~~ ~~Images on First B date and H_F were obscured by clouds.~~

Formation of a channel-wide ice cover is the culmination of various processes that include frazil ice growth, ice pan development, juxtaposition and upstream progression taking place. When the ice cover ‘bridges’ or is present ‘bank to bank’ across the river channel the increasing frictional resistance causes a rise in the water level. This initial ice cover progression upstream past the gauge ~~is~~ will cause a gradual increase to a maximum ~~observed as a spike~~ in the water level chart and is depicted as H_F (freeze-over water level) in Fig. 3. The CRID includes transcription of t~~T~~he NHP recorded instantaneous water level, up to the minute timing, date and associated daily discharge, as available are manually extracted and given a ‘0’ rating. Instantaneous discharge during ice conditions is not a NHP data product since the open water S-Q relationship is invalid. If no instantaneous record was available, the lower-resolution daily water levels are used to identify the maximum water level occurring after the First B Date with the data quality was rated as ‘1’. Review of daily meteorological data at proximal climate stations can help the interpretation by knowing that air temperatures remained below 0^{o}C and the observed spike was not a result of rainfall in the region (Beltaos, 1990). Meteorological data review was accomplished using the ‘Search by Proximity’ function from: https://climate.weather.gc.ca/historical_data/search_historic_data_e.html. Southern locations generally have a climate station within a 10 km radius; while at some northern locations, it was necessary to assume a representative meteorological site beyond a 200 km radius. The archived hydrometric station analysis (item 7, Sect. 3.1) often includes reference to a nearby meteorological site with: “*Rainfall or temperature records used for estimating the missing periods or the ice affected periods*”. It was generally observed, though not recorded, that ~~freeze-up spikes~~ maximum freeze-over water level tend to occur when temperatures dropped to -10 °C. While ice jamming at freeze-up is a known occurrence (e.g. Jasek, 1999), there was no attempt to distinguish these events in the current exercise due to the complex hydrological and hydraulic conditions affecting these processes. Beltaos (1990) discussed the unlikelihood that a complete ice cover forms at the instant of H_F. A later recommendation was to define the freeze-up water level as the average water level for one week after formation of a complete ice cover (Beltaos, 1997). Following this methodology, the CRID includes all available daily water level at H_F and the following 29 days ~~for the two following reasons~~to: (1) allow for calculation of a 7-day average to parameterize~~s~~ a water level threshold of exceedance for the ice to detach from channel banks at break-up (Beltaos, 1997) and (2) tabulates water level for 1 month as liquid water goes into hydraulic storage and ice formation, temporarily reducing the discharge at the gauge. This process can take place over a distance of several hundred km upstream (e.g. Prowse and Carter, 2002; Beltaos 2009) and (3) allow for calculation of peak factors (as a ratio between instantaneous and mean daily as described in Zhang et al., (2005)) to aid in design of river structures.

3.4.2 Ice Cover: H_{LW1}, H_{LQ1}

Along with the drainage of surface water storage, a primary source of flow in unregulated rivers during the winter ~~snow and~~ ice cover period is groundwater. The gradual drawdown of these contributions over the ice cover season leads to a reduction in river flow with the water level eventually reaching a corresponding minimum value. In small streams, the minimum flow of the year may occur just after the first extremely cold period (United States Geological Survey, 1977). Since the open water S-Q relationship does not hold under ice, the NHP daily reported first minimum winter water level (H_{LW1}) and estimated first minimum winter discharge (H_{LQ1}) over the ice period may not occur on the same day. For example, Fig. 6 depicts more than three months of separation between the two on the lower Athabasca River where the higher reported water level in March has a smaller discharge compared to the November minimum water level event~~. –~~. This example illustrates how a thick, late winter ice cover would raise water levels due to reductions in channel cross sectional area. The H_{LQ1} is one of several water quality and aquatic habitat indicators in ice affected rivers (Beltaos and Prowse, 2009; Peters et al., 2014), while an occurrence synonymous to the first minimum winter water level (H_{LW1}) was recently highlighted as a determining factor for navigation within the Mississippi watershed (Giovando and Daly, 2019). These data on under-ice minimum magnitude and occurrence are to inform regional low flow analyse~~i~~s (Beltaos and Prowse, 2009), environmental flow need assessments, water intake elevations, water withdrawal guidelines and cross-sectional habitat reductions during ice conditions (e.g., Peters et al., 2014).

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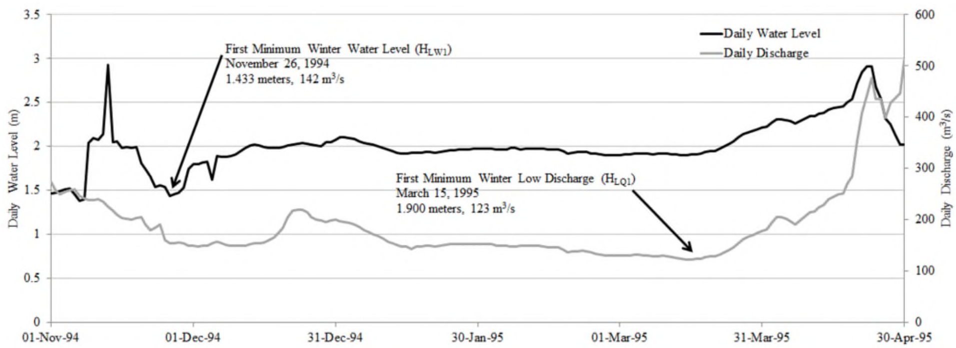


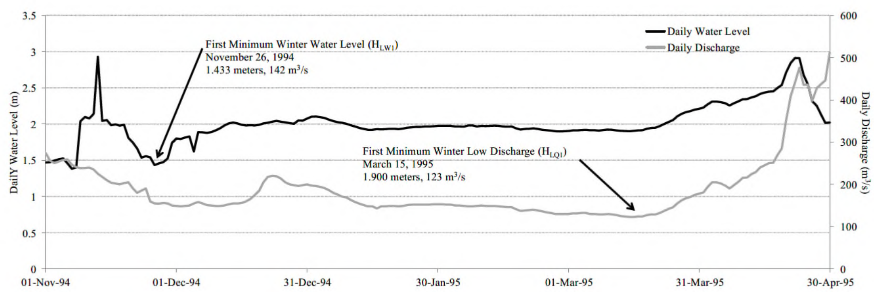


Figure 6. Daily reported water level and discharge for the Athabasca River below Fort McMurray (07DA001) for ice affected (B flagged) period spanning November 1, 1994 to April 30, 1995. Note that an increase in water level does not necessarily result in more discharge due to the varying hydraulic effects of ice. Figure adapted from de Rham et al., (2019).

3.4.3 Ice Cover: H_{MWB}, H_{MWM}

Rapidly warming air temperatures (above 0°C) and associated rain on snow events during the ice cover season are the main causes of mid-winter break-up events depicted as the water level trace in grey on Fig. 3. These events occur on both regulated (Picco et al., 2003) and unregulated rivers (Newton et al., ~~2016~~2017). The possibility of mid-winter ice jams, elevated water levels ~~risk~~, and in extreme cases, the freezing of overbank floodwaters as shown in Fig. 7, are major threats to riverside communities and infrastructure (e.g. Beltaos, 2002; Beltaos et al., 2003; Curi et al., 2019). Interpretation of these "winter peaks" from water level records to determine if they are results of ice cover break-up is a challenge (Beltaos, 1990), especially in the absence of other supporting evidence (e.g. site observations, new reports, flood summaries). Similar to freeze-over interpretation (Sect. 3.4.1),~~–~~ the review of daily climate data from nearby stations informs if temperatures exceed $0^{o}C$ and associated rainfall occurred. During data extraction it was often observed that mid-winter break-up occurrence corresponded with 10's of cm reductions in daily snow on ground for day(s) prior to the event. A review of the discharge measurement summary (item 9, Sect. 3.1) also increased interpretation confidence towards when station visit remarks were available days before or after the "winter peak" alluding to channel ice condition or if discharge measurements were collected from the ice cover or wading.

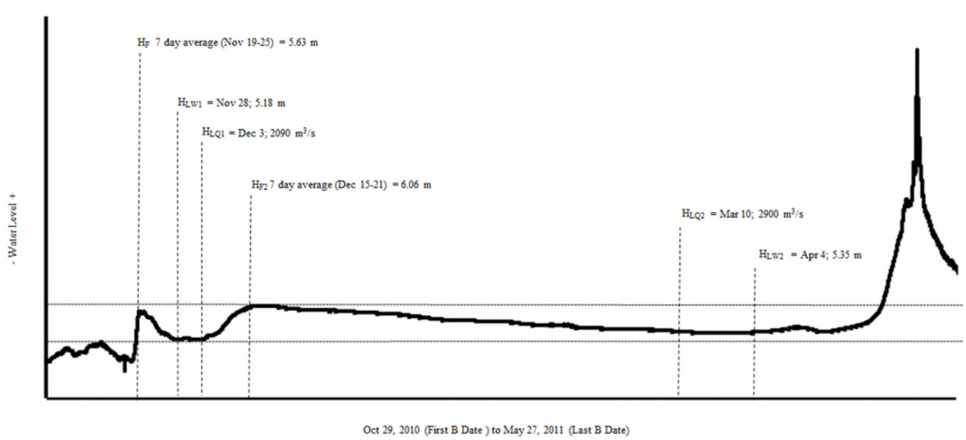
The instantaneous H_{MWB} represents the onset of ice cover movement at a site during the winter season and is identified as a spike on the rising limb of the water level record. The cause of this spike is a rapid decrease in hydraulic resistance as the ice cover breaks and starts moving downstream. This variable cannot be determined from mean daily summaries of water levels. Following the initial break-up event, the water level will typically continue to rise until it reaches a maximum value represented by instantaneous H_{MWM}. For some stations, H_{MWB} and H_{MWM} can occur more than once during a single ice season (e.g. Beltaos, 2002). In such cases, only the first H_{MWB} and the highest H_{MWM} are included in the CRID. In some cases, a mid-winter breakup event is followed by a dramatically cold period during which frazil generation is significant. The result may be a very thick ice accumulations, more ice jamming and new anchor ice cycles. For years with no continuous water level records, daily summaries (item 8, Sect. 3.1) were examined for a presence of a H_{MWM}. NHP notations in the other archival documents (Sect. 3.1) and meteorological data review assisted judgment on whether these daily maximums likely represented a mid-winter break-up. On occasion, a rudimentary internet search was used to find alternative verification. Mid-winter break-up sites usually occurred in the temperate zone where B date flags can be intermittent, leading to complexity and additional interpretation in extracting the mid-winter~~is~~ variables. For instance, a few winter break-up events were interpreted to occur during non-B dates because of the extreme water level magnitudes reported. Due to these inherent challenges of interpreting mid-winter break-up events, a c~~C~~loser examination of the CRID time series and ~~of these events for~~comparison to nearby hydrometric stations may be required before pursing further analysis. ~~future studies is recommended.~~

Figure 7. Frozen water after mid-winter break-up and over-bank flooding on the Exploits River. Image was taken on February 9, 2013 on Beothuck Street property in Badger, Newfoundland. Ring of frozen ice around the tree trunk indicates the highest water level. Hydrometric station Exploits River at Badger (02YO013), not a CRID station, is ~ 100 m from this location. Image from Rebello (2013).

3.4.4 Ice Cover: H_{F2}, $H_{F2\,MAX}$, H_{LW2}, H_{LQ2}

The occurrence of ice cover season maximum water levels, not associated with the freeze-up or break-up of the ice cover were identified from the hydrometric archive and input to the CRID. If there was mid-winter break-up event, an attempt was made to extract the first of the 7-day maximum average winter water level (H_{F2}) after the event. As with H_F (Sect. 3.4.1), these data may mark important parameters for the onset of break-up prediction. No attempt was made to identify an instantaneous H_{F2} since the CRID archive does not have historical pen recorder charts (Sect. 3.2) much beyond the H_{MWM} event. Examination of more recent continuous digital water level records reveals that after mid-winter break-up, limited 'stage up', synonymous to H_F was usually observed. This may be due to the lack of complete ice flush down the channel after H_{MWM}. Since large, fragmented ice blocks likely remain in the channel, the hydraulic resistance and refreezing of the ice cover is probably a less dynamic event.- Daily water level values after mid-winter break-up ~~revealed~~ generally reveal a pattern of steadily declining daily water levels. Notably, this patterns is likely typical on relatively flat river channels, while on steep river sections, progressive frazil accumulation produced in newly open section exposed to cold could increase water levels even during receding flows. If H_{MWM} was followed by days with no 'B' data flag, H_{F2} was restricted to days when 'B' data flag appear again. As with the first freeze-up events, H_{F2} and the following 29 days of daily water level were recorded. Water levels within the first 7 days after H_{F2} were also assessed to extract a maximum ($H_{F2\ MAX}$) daily water level exceeding H_{F2}. This variable may more closely match the instantaneous processes resulting in the H_F occurrence.

Maximum winter water level was also recorded at select locations with no mid-winter break-up event. In this situation, the 7 day average water level beginning at H_{F2} exceeds that commencing of H_F. This may correspond with a secondary stage up during extreme cold events described by (Hamilton, 2003) with Fig. 8 depicting one month between the two peak stages. It is possible that rising water levels after H_F are caused by secondary consolidation events (Andres, 1999, Andres et al., 2003, Wazney et al, 2018) however, the daily resolution may be too coarse to capture this short-lived occurrence. An H_{F2} is also reported (Beltaos, unpublished data) to occasionally occur on the regulated Peace River at Peace Point (07KC001) when mid-winter flow releases cause increasing water levels but the ice cover remains stable. Some CRID stations reveal 'creeping' water levels exceeding H_F for most of the ice season (Fig. 9). In such cases, it was not possible to establish H_{F2} and their occurrences are not included in the CRID. This continuous wintertime increase in water levels could be caused by the development of anchor ice or continuous build-up of a hanging dam by frazil ice, although both cases require open water at or upstream of the gauging location. However anchor ice formations are not known to remain in place for several months. Another possible explanation may be that in the case of Fig. 9, the Pembina drainage area contains many swamps and muskegs with a water table at or near the surface (Farvolden, 1961) though this assumes no depletion of the water table during the period of ice cover.



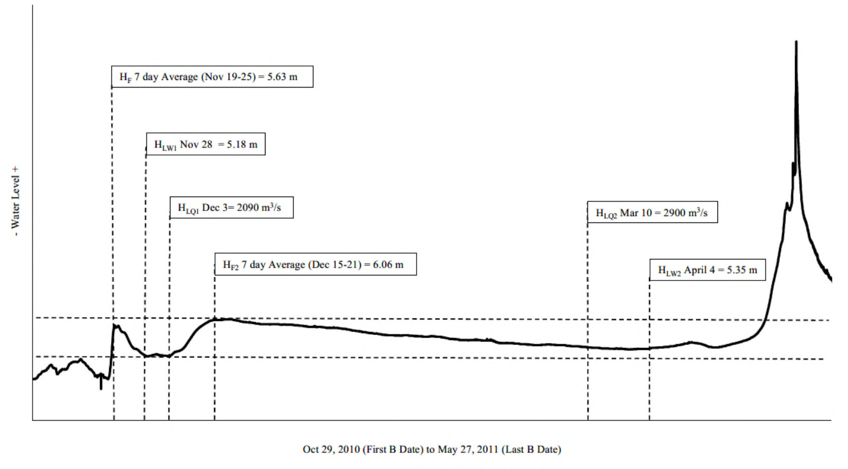
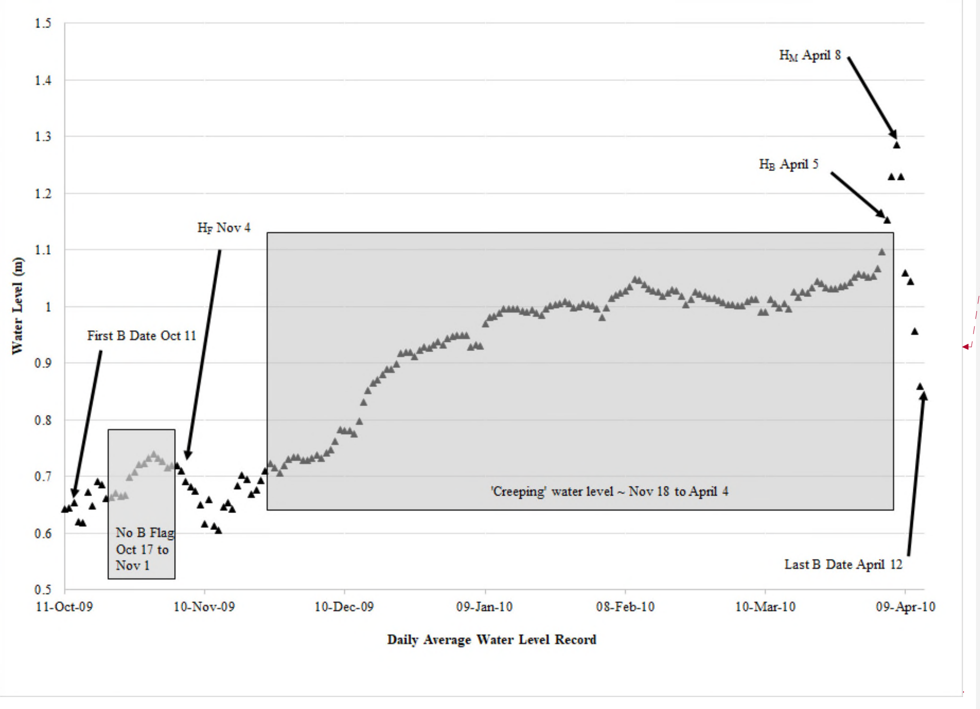


Figure 8. Continuous water level record at Mackenzie River at Norman wells during 2010-2011 ice affected flow period. Note the occurrence of a higher magnitude 7 day average following H_{F2} in comparison to H_F and the corresponding second winter minimums (H_{LW2} and H_{LQ2}) in addition to the first occurrence (H_{LW1} and H_{LQ1}).



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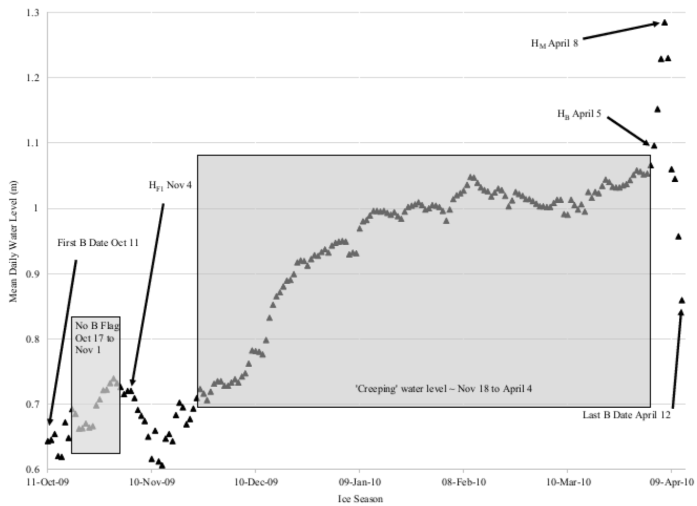
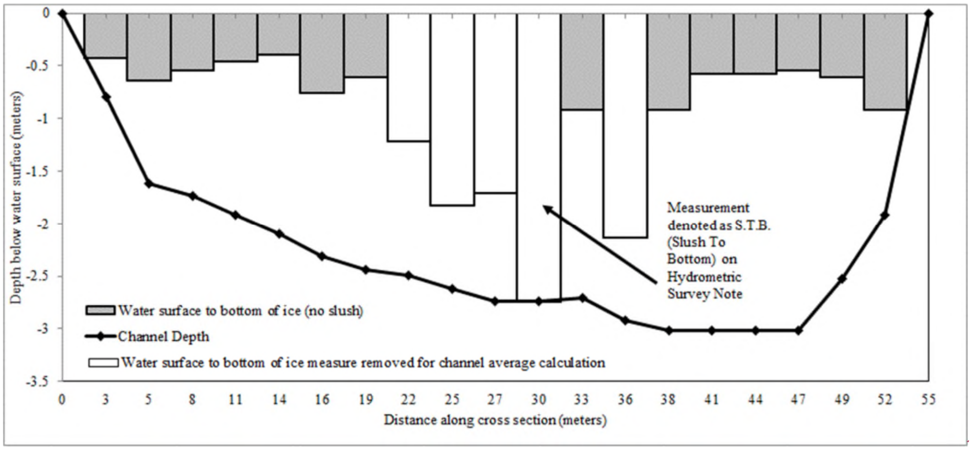


Figure 9. Daily water level from First B to Last B date at Pembina River at Jarvie (07BC002) during the ~~-~~2009-2010 ice affected flow season that depict 'Creeping' water level~~-~~. There are no B data flags from Oct 17 to Nov 1 and daily average water levels 'Creeping' upwards throughout the ice cover period.

Whenever an H_{F2} variable was identified, the ice cover period was examined for a second winter-low water level (H_{LW2}) and discharge (H_{LQ2}) event. These data were only added to the CRID if H_{LW1} or H_{LQ1} were before H_{F2}. At some locations, several months may have lapsed between the first and second occurrences of winter-low events as shown in Fig. ~~7~~8. The incident of a second winter-low is probably one of the most understudied events in ice covered channels, while it can have all the water quality and navigation related implications as that of the first winter-low events described in Sect. 3.4.2 above.

3.4.5 Ice Cover: I_{THICK}

Hydrometric technicians visit gauging stations for velocity, water depth, discharge, and water level measurements and instrument maintenance approximately six to eight times per year, which include both open-water and ice-covered conditions. During the latter, a measure related to the solid portion of the ice cover thickness is recorded on the site survey note (item 4, Sect. 3.1). End of ice cover season measurements quantify ice thickness prior to the spring break-up and some cases this may represent a pre-melt ice thickness, a relevant factor in break-up initiation and potential severity (Beltaos, 1997). Measurements prior to ~1995 are generally limited to water surface elevation to bottom of ice cover, thus may underestimate the actual thickness of the ice cover since the ~~density of solid ice is~~specific gravity of river ice is commonly taken as 0.92~~ that of water and part of the ice cover may float above the water line depending on the snow loading~~. Nevertheless, these measurements are assumed to represent the actual ice cover thickness~~ considering the likely presence of impure ice and snow loads~~. WSC Regional office and provincial partner protocols for collection and summary of this ancillary ice thickness data differ, while some of the more recent digital data archives may have actual ice thickness measurements. Figure 10 shows 19 channel depth and water surface to bottom of ice measurements. Some hydrometric survey notes report the presence of slush that results in an overestimate of channel ice depth. For the CRID, all cross-sectional ice thickness measurements were reviewed for the reporting of slush conditions, while all data were plotted to aid in visual identification and removal of measurements that include slush (see caption for Fig. 10). The remaining measurements were used to calculate the average river ice thickness (I_{THICK}).



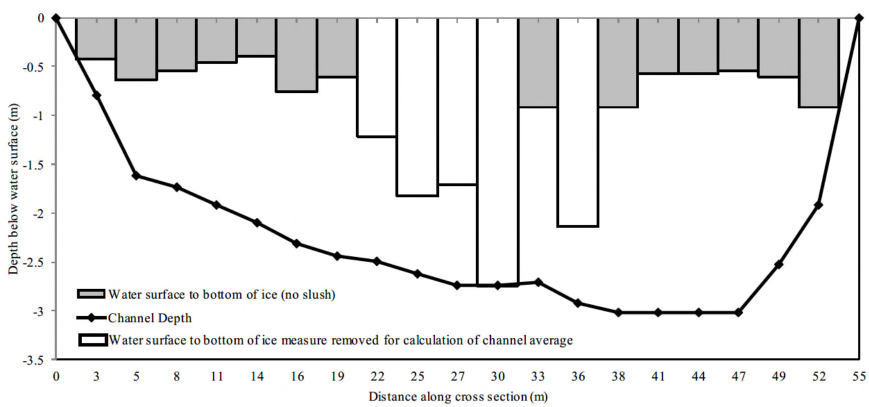
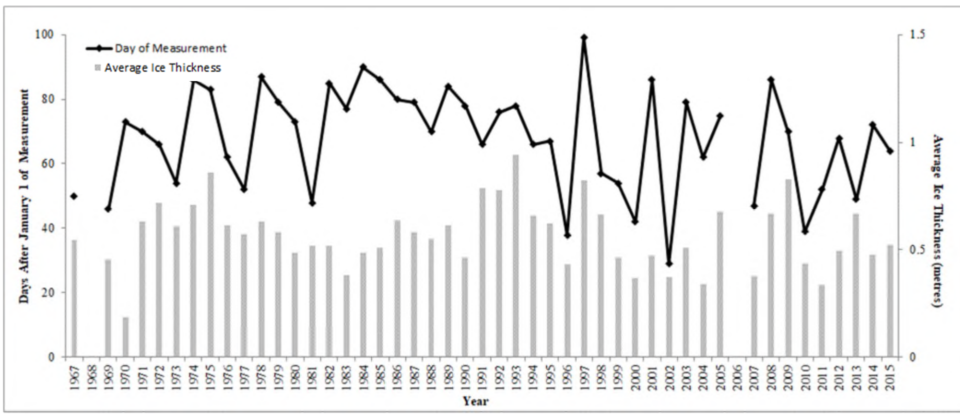


Figure 10. A bar plot of the 19 water survey to bottom of ice thickness measurements collected on March 28, 1978 at Nashwaak River below Durham Bridge (01AL002). The hydrometric survey note indicates measurement at river cross section distance 30 m is ~~S.T.B. (Slush To Bottom~~Slush To Bottom.~~).~~ Visual examination of this plot reveals four other measurements (shown with white fill) which likely include slush. These five measurements are removed when calculating average river ice thickness.

In some years, visits and data collection at hydrometric stations were hampered by weather conditions, logistics or on-ice safety considerations. As an example, Fig. ~~10~~ 11 shows a time series of 47 average ice thickness data points at one CRID location. Over the time series, the measurement dates range over a 10-week (72 day) time window. In addition to data collection timing, incomplete archival and scanning for the database may also be a reason for missing or wide ranges in time series. Thus, any time series analysis of I_{THICK} needs to account for this year-to-year sample date variability. While an attempt was made to compile the time series of final (season's end) ice thickness measurements, ~~a more detailed climatological analysis will be required to~~a more detailed climatological analysis will be required to ~~ ~~establish if this measurement was collected prior to the ice cover beginning to melt.



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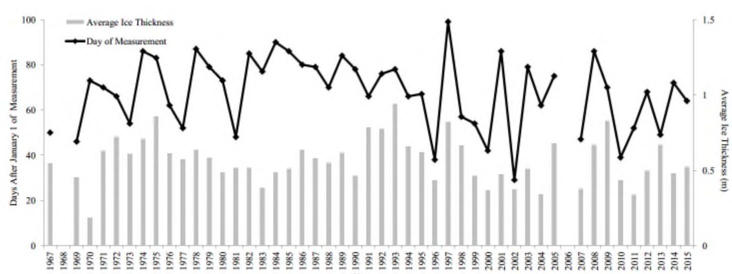

Figure 11. Plot showing average ice thickness (grey bars) day of measurement (black line) and at site Nashwaak River below Durham Bridge (01AL002). Measurement dates input to CRID represent a range of 72 days from a minimum Jan 29 (2002) to

April 9 (1997). Initiation of break-up at this location ranges from Feb 27 (2010) to April 13 (2001) with average of March 25 (84 days after January 1)~~-~~.

3.4.6 Break-up: H_B, H_M, Last B Date

The end of the river ice season progresses through a continuum of spring break-up initiation (H_B), maximum spring break-up water level (H_M) and the last day of ice affected flow (Last B Date). H_B occurs at the initial downstream movement of river ice cover. The associated decrease in resistance to flow registers as a spike on the rising limb of the water level hydrograph (see Fig. 3). Beltaos (1990) indicated that identification of break-up initiation can be uncertain and that it is not possible to establish H_B ~~in the absence of a continuous water level record~~from a record of mean daily water level. Therefore, the timing and magnitude of H_B may be less accurate than H_M, the maximum instantaneous or daily water level established following H_B. Data ratings are provided to indicate the ~~accuracy~~ resolution of these events. The Last B Date was the final day with a B data flag (R data flag for CEHQ sites).

The break-up period can be characterized as either thermal (overmature) or mechanical (dynamic) (Gray and Prowse, 1993; Beltaos, 2003). In the case of a thermal event, increasing air temperatures and solar radiation inputs during early spring cause the ice cover to decay. A slow increase in channel flow will prolong the decay period and resulting water levels do not reach magnitudes much beyond those with similar flow indicated by the open water S-Q relationship. Conversely, a mechanical break-up is characterized by limited reduction in the mechanical strength of the ice cover and rapid increase in channel flow. As the rising flow eventually overcomes the resistance of the ice cover, the latter is mobilized in dynamic fashion and ~~quickly~~ breaks down into slabs and blocks, which eventually are arrested by still-intact ice cover to form ice jams, typically at morphologically conducive locations such as constrictions and abrupt slope reductions. According to an anonymous reviewer, ice jams can also form at morphologically conducive locations even without an intact ice cover stopping the ice run.~~-~~ Earlier analysis reports indicated that H_M can far exceed water levels that occur under similar open-water flow conditions (~~de Rham et al., 2008a;~~ von de Wall et al., 2009, 2010; von de Wall, 2011). For example at Liard River near the Mouth (10ED001) the 25 year return period magnitude for ice affected water level was 16.11 m versus 9.69 m for the open water event (de Rham et al, 2008a). Depending on their location and persistence, ice jams lodged at or below the gauge site affect the local water levels to a varying degree. A jam lodged upstream of a guage can also have a measurable stage (actual discharge) depressions for several hours before reaching an equilibrium. The release of a jam can generate a sharp wave called a ‘jave’ (Beltaos, 2013) yet ~~. Jams lodged upstream of the gauge only affect the local water level upon their release, which generates a sharp wave (called jave for short, Beltaos, 2013). A jave is yet~~ another dynamic mechanism that can generate the identified H_M ~~water level~~on instantaneous water level recordings. ~~.~~ Highly dynamic events, initiated with minimal or negligible ice cover decay, are sometimes referred to as “premature” and typically result from mid-winter thaws accompanied by intense rain-on-snow runoff events (Deslauriers, 1968). It is likely that much of the CRID mid-winter data described above in Sect. 3.4.3 are these highly dynamic events. The less common “overmature” break-up sequence was observed at some CRID stations with ~~no~~ less obvious “spiking” of water levels. An example water level ~~of~~ with this ~~occurrence~~ characteristic on the Peace River in 1982 (Fonstad, 1982) is included in Beltaos (1990) where minor water level perturbations are followed by a generally smooth reduction to open channel conditions. ~~-~~In some cases the H_B and H_M were interpreted to occur at the same time.

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Figure 12 shows an example timeline, with images of changing ice conditions for the year 2010 break-up sequence at Hay River near Hay River (07OB001). Unfortunately, images at the extracted CRID timings of H_B and H_M are not available; however, images 5 minutes later are illustrative: The night time image (April 24, 04:30) shows a large chun~~e~~k of ice along the left channel bank indicating fracture of the ice cover and initiation of break-up. One hour later, the near open channel condition (April 24, 05:30) highlights the downstream forces involved in flushing of in-channel ice. The image on April 25 at 15:30 shows stranded ice fragments on the channel banks, 5 minutes after H_M (April 25, 15:25). The peak water levels at H_M and subsequent water level drop would raft and settle the ice fragments outside the channel. While no Last B Date image is available, it is notable that the river ice break-up processes described occur prior to this date. While spring break-up peak water level magnitude and timing in the CRID have high degree of accuracy, classification of events as ice jam or not, was not pursued as this would require local observations and/or photos. The L~~l~~ast B Da~~da~~te is sometimes used to represent break-up for time series analysis (e.g. Zhang et al., 2001; Chen and She, 2019) and a recent publication used B dates and discharge to assess trends in ice jam flooding events (Rokaya et al., 2018). Unlike using the L~~l~~ast B D~~d~~ate as a surrogate and/or index, the water-level based data in the CRID provides the science community with a direct and thus more accurate data set towards analysis of spring break-up timing, magnitude and processes. For instance, the identification of H_M provides the means to assess change in the flow magnitude driving spring breakup flooding, which would not be possible with discharge analysis alone and/or solely identifying the L~~l~~ast B D~~d~~ate.

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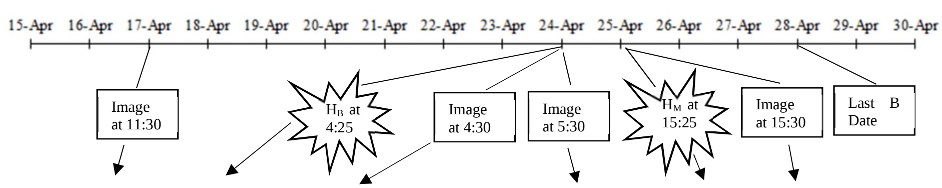

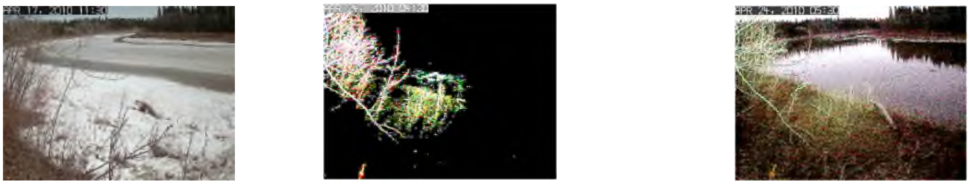

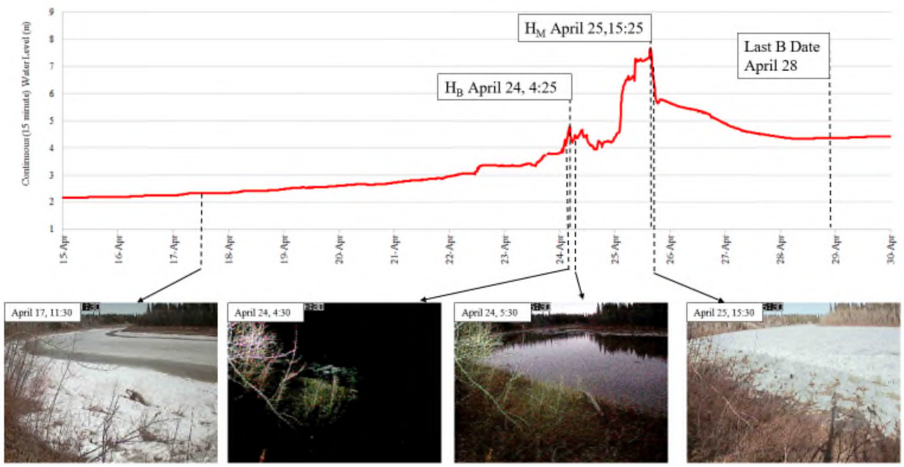

Figure 12:~~;~~ Continuous 15 minute interval water level hydrograph for April 15 to 30, 2010 at National Hydrometric Program gauging station Hay River near Hay River (07OB001) along with images courtesy of Alberta Research Group. Left: Image looking upstream taken 7 days prior to spring break-up initiation (H_B) of April 24, 2010, 004:25~~ at location Hay River near Hay River (07OB001)~~. Channel width of approximately 63 meters. Centre, left is a night time image ~~-~~5 minutes after H_B and shows evidence of fragmented ice in the channel. Centre, right is 65 minutes after H_B and shows channel nearly clear of ice. Right image is 5 minutes after maximum spring break-up water level on April 25, 2010, 15:25. Stranded ice on channel banks

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indicates higher water levels. Last B ~~date~~ Date was April 28, 2010. ~~Images courtesy of University of Alberta River Ice Research Group.~~

3.4.7 Open-Water: H_O

The CRID includes the magnitude and timing of the annual maximum open-water level (H_O) and the associated discharge value at each station along with data quality rating. These data are extracted from the hydrometric archives and are easily verified as NHP web pages generally report both daily and instantaneous maximum annual discharge and timing. In the event of damaged or non-functioning instrumentation, NHP or CEHQ may estimate (data flagged with E) daily discharge values. The S-Q relationship (Sect. 3.1) can be used to ~~calculate~~ estimate the associated water level. Gerard and Karpuk (1979) provided one of the earlier examples of comparing maximum ice affected ~~to~~ versus open water levels on the Peace River. These types of analysis inform the hydrological community on the importance of looking at ice effects as the likely causes of maximum annual flood for near one third of hydrometric stations in Canada (e.g. von de Wall 2009) and most probably for a similar proportion of unmonitored sites. A Canadian perspective on flood process (snowmelt, rain-on-snow, rainfall) and their seasonality are detailed in Buttle et al., (2016). ~~levels (e.g. de Rham et al., 2008a).~~ Visual examination of H_O time series on a stage-discharge plot is a cursory method to identify station movements, benchmark or datum shifts, or changes to the stage-discharge relationship. This is discussed in more detail below.

3.5 Data Accuracy and Precision, Uncertainty, Quality Control and Interpretation

The accuracy and precision of extracting water level, discharge and timing of the CRID variables ~~was~~ is as follows. For the six~~five~~ grey shaded instantaneous variables in Table 2 (H_F, H_{MWB}, H_{MWM}, H_B, H_M, H_O), extraction precision of up to 2 decimals for the pre-1978 (data in feet) and 3 decimals for the post-1978 (data in meters) was possible based on visual inspection of the continuous (i.e. analog) water level recording charts (pre ~ 2000). All imperial data in feet were converted to metres using factor of 0.3048 and are reported to 3 decimals in the CRID database. Although much of the water level records are continuous, the visual extraction method often limited the associated timing of an event to a 15-minute resolution. Instantaneous timing at finer resolution within the CRID were usually obtained from alternative archival documents (e.g. Annual Water Level Page, Station Analysis or published online summaries). The wide-spread use of digital water level recording instrumentation after the year ca. 2000 decreased the temporal resolution (i.e., accuracy) of water level records as data collection interval varied from 5 to 15 to 60 minutes. Some data loggers also recorded hourly to sub-hourly maximum and minimums, which increased the accuracy towards instantaneous events, though selection does require judgement. The vast majority of mean daily water level pages and some of the more recent digital water level recordings were deemed "Preliminary" by NHP. Different methods of collecting requisite information for mean daily water level have existed over the archive from at site station observers who viewed a staff gauge once daily to the more modern arithmetic averages determined from continuous water levels.

Quality Control (QC) for the CRID has included preliminary data analysis and peer review of associated publications (Table 1). CRID station data were initially compiled as single station Excel files which include all extracted water level, discharge, date and time and accuracy rating, average ice thickness along with time series plots for visual identification of outliers. A separate station Excel file contains all available ice thickness measurements and averages calculation. All finalized station data were compiled in to a single .csv file (118 columns x 22,736 rows with 464,891 cell entries) for further QC. This single spreadsheet was examined for data entry errors using the filter and count capabilities inherent to Excel.

A quantification of human error in transcribing CRID data was undertaken~~A quantification of data interpretation and input errors was undertaken~~ using a~~. A~~utomated scripts ~~were used~~ to extract and compare the CRID ~~associated~~ daily discharge and ~~values along with~~ First and Last B D~~d~~ate to those published by the ~~from a bulk download of all available~~ NHP. ~~daily flow data.~~ Daily d~~D~~ischarge ~~values input to the CRID~~ was~~ere~~ ~~found to be~~incorrectly transcribed on ~~between~~ 4.7% to 7.8% of the time series depending on the variable while~~.~~ ~~Mid~~mid-winter associated ~~events~~ discharge had the highest input error at 16%. This higher percentage of error is a likely remnant to the multiple rounds of revisions to mid-winter time series and confusion that arises when examining non-consecutive events that can occur across calendar years. For ice seasons when both a First and Last B Date were available, ~~an input error of~~dates were incorrectly transcribed on 7.5% ~~was found.~~of time series. All erroneous daily discharge and First and Last B Date values were replaced. The remaining CRID data entries are not amendable to automated quality control since they were manually extracted. ~~The CRID initiation of break-up (H_B) time series at site Red River near Lockport (05OJ010) was provided to Becket (2020) who reported: of the 34 years, 3 years of timing were revised based on evidence in newspapers (an ancillary evidence source not included in the CRID), while 2 years were found to be incorrectly interpreted and input to the CRID. One year was 12:00 hours too early and one year 2 days too early.~~ Based on these QC activities the CRID likely has a 5-10% data interpretation/entry error. The CRID initiation of break-up (H_B) time series at site Red River near Lockport (05OJ010) was provided to Becket (2020) who reported: of the 34 years, 3 years of timing were revised based on evidence in newspapers (an ancillary evidence source not included in the CRID), while 2 years were found to be incorrectly interpreted and input to the CRID. One year was 12:00 hours too early and one year 2 days too early. While it would be impractical to review the entire database for errors, users are encouraged to undertake their own QC activities and review the data disclaimer in Sect. 7. The data quality ratings should not replace the professional responsibility of engineers and geoscientists for the conception of flood maps and for the design of hydraulic structures. Original archival documents can be requested from the authors. Upload of this archive to a more convenient format may be pursued in the future. As is indicated on the Open Data Portal where the CRID can be downloaded, ongoing work with the CRID may include error checking and corrections, so users should use the latest version of the CRID by referring to the version number that appears in the .csv file name (http://data.ec.gc.ca/data/water/scientificknowledge/canadian-river-ice-database/CRID_BDCGF_Versioning_EN_FR.txt).

Extraction of river ice data from hydrometric records is a time consuming and detail-oriented task. The average time needed by an experienced investigator to identify and input data associated with the 15 CRID variables for a one-year period at a single station was about 1 hour. Besides the laborious nature of this work, additional uncertainties are caused by site-specific phenomena that can have varying effects on water level. The NHP archives include field observations of beaver dam in channel, open water leads at, upstream or downstream of the gauge, percentage of ice cover at gauge, water flowing between the ice layers and anchor ice at a cross section. While these types of observations are not part the CRID, users should be aware of such factors that add further complexity to wintertime water level interpretation. Furthermore, collection of data using a stilling well (von de Wall, 2011) also could affect resultant water level interpretation. Since river ice processes ~~can be~~are site specific users should be aware of possible spatial discrepancy in location of gauge site versus where ice thickness and flow measurements are collected. Access to ice cover and worker safety are field based considerations which can result in a wintertime cross section measurements taken meters or kilometres upstream or downstream from the actual gauge. Another consideration is that many gauges are located near a bridge, which provides a safe platform from which water velocity measurements can be performed. Bridge pilings would change the hydraulics and very likely the ice condition on a river channel such as promoting a thicker ice cover in the deck shadow and promoting ice jamming against abutment or piers. Finally, changes to watershed characteristics such as urbanization and agriculture likely have effects on river ice hydrology.

CRID users should also bear in mind that all variables were transcribed directly as recorded in the NHP archive. There is no tabulation of: at-station movements, benchmark or datum shifts, or changes to the stage-discharge relationship. Since river ice processes are site specific, prior to time series analysis of phenology or water level data ~~needs to~~an accounting for these ~~three~~ factors towards assessments of station homogeneity are a necessary next step. For example, Fig. ~~12~~ 13 shows all Albany River CRID data on a stage-discharge plot. The WSC website informs that the station was relocated in 1988 with a new gauge height, and as a result this rudimentary visualization of data towards confirming non-homogeneity reveals the ~~e~~ maximum open-water level magnitudes (blue circles) plots as two separate populations which are not directly comparable for many types of analysis.

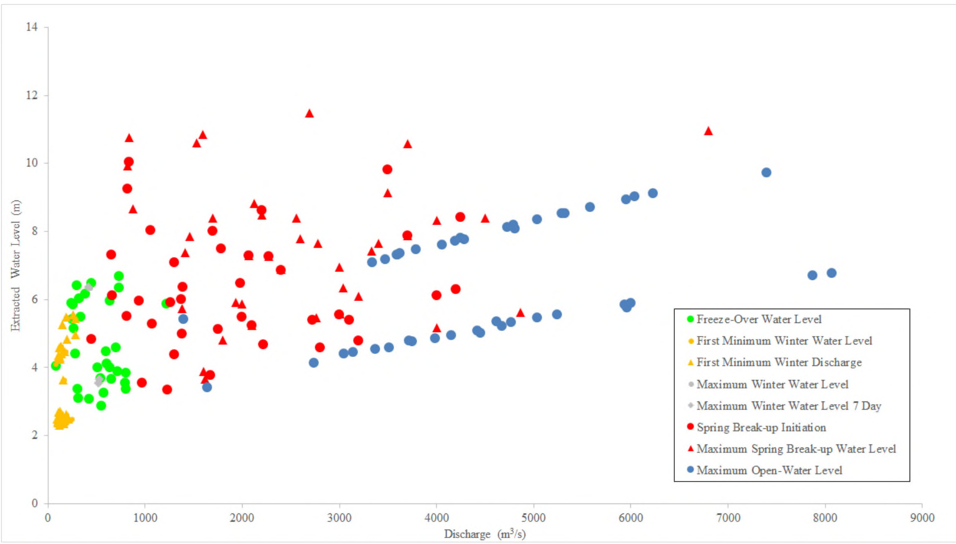

Figure 13. A stage-discharge plot of Canadian River Ice Database variables for site Albany River near Hat Island (04HA001). -Time series (1964-2015) symbols -are separated into Location 1 and Location 2 to illustrate the effect of the gauge being

moved approximately 3.5 km downstream on Sept 29, 1988. Since the stage-discharge relationship is invalid during ice conditions visual inspection of river ice variables reveals considerable scatter. The blue open-water time series (H_O) illustrate a shift caused by a station movement and the two separate data populations.~~for Maximum Open-Water Level (blue circles) plot as 2 separate populations. This gauge was relocated approximately 3.5 km downstream on Sept 29, 1988.~~

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4 Discussion

4.1 The CRID

~~A two-decade~~Nearly two decades of data collection effort and study ~~effort~~ has culminated in the CRID which covers a network of 196 hydrometric stations with data up to Dec 31, 2015 that represent 10,378 station-years of active operation. During the first decade, the work focused primarily on the spring break-up season, while for the past decade it was expanded to include the entire period of ice-affected flow. The 15 variables are ~~occur at~~spread over different stages of the ~~season~~ annual period (Table 4) and include minimum daily and maximum instantaneous water level events, ice thickness along with discharge-based metrics and provide a comprehensive baseline dataset for research purposes. The CRID is available for download at: https://doi.org/10.18164/c21e1852-ba8e-44af-bc13-48eeedfcf2f4 (de Rham et al., 2020)

In total, the CRID holds 72,595 recorded variables with more than 460,000 data entries of water level, discharge, date, time and data quality rating based on the review of over 100,000 hydrometric archive files. Tabulation of the 6,094 ice thickness measurements required examination on the order of 100,000 cross-sectional measurements and removal of slush affected data. In terms of data completeness, extraction of maximum open-water level (H_o) was the most successful covering 9,705 (94%) of the 10,378 active station years. Similarly, the 8,933 (9,240) f~~f~~irst (last) day with backwater due to ice (B dates) and 8,178 first minimum winter discharge populate the majority of active station-years and attest to the NHP historical mandate to publish discharge information. Freeze-over water level and maximum spring break-up water level were extracted from 72% and 80% of those years reporting F~~f~~irst and L~~l~~ast B D~~d~~ate. This first known attempt to centralize data on mid-winter break-up occurrence includes 467 maximum mid-winter break-up water level and 362 associated mid-winter break-up initiation events. The data quality rating presented in Table 4 confirms that the NHP archives is a high quality source of river ice information with 82% of data rated as ‘0’. Although some of the data have lower quality ratings, their inclusion increases the population size and helps provide a more complete spatial and temporal coverage over Canada.

While the CRID represents the largest existing effort to extract river ice variables from hydrometric archives, it does not provide a complete time series of ice events at the near 2,800 active and 5,500 discontinued hydrometric stations in Canada. However, it covers a representative sample with six station types (Table 4), including natural and regulated sites along with their status as active, or discontinued during time of operation up until Dec 31, 2015. Regulated locations are also split into homogeneous and heterogeneous depending on when the regulation began during the measurement timeline. Active stations data comprise over 90% of the CRID. Discontinued stations provide additional information and help increase the density of the network. Reasons for less than complete at-station time series include seasonal operation, damage to water level recording instrumentation, no available hydrometric archive for particular year, or loss of information during the CRID archival and scanning process.

Table 4. Total number of variables that populate the Canadian River Ice Database and their Data Quality Ratings. Grey shading indicates an attempt was made to extract the instantaneous water level. Also included are column totals per river type: Natural/Regulated, Active/Discontinued, Homogeneous/Heterogeneous.

			Data Quality Rating			Number of Variables by Station Type					
						Natural		Regulated			
Season	Variable	Total Number of Variables	0	1	2	Active	Discontinued	Homogeneous, Active	Homogeneous, Discontinued	Heterogeneous, Active	Heterogeneous, Discontinued
Freeze-up	First Day With Backwater Due To Ice	8,933	no Data Quality rating			5,754	806	1,204	130	1,022	16
Freeze-up	Freeze-Over Water Level	6,547	4,794	1,592	161	4,142	466	949	106	881	3
Ice cover	First Minimum Winter Water Level	4,767	4,557	193	17	2,861	214	823	103	766	0
Ice cover	First Minimum Winter Discharge	8,178	8,114	62	2	5,301	764	1,077	111	925	0
Ice cover	Mid-Winter Break-Up Initiation	362	359	3	0	249	11	54	8	40	0
Ice cover	Maximum Mid-Winter Break-Up Water Level	467	392	70	5	308	22	77	9	51	0
Ice cover	Maximum Winter Water Level	1,954	1,816	39	99	1,180	104	329	16	325	0
Ice cover	Maximum Winter Water Level 7 Day	1,952	1,849	27	78	1,180	104	329	16	325	0
Ice cover	Second MinumumWinter Water Level	798	794	4	0	407	39	186	7	159	0
Ice cover	Second Minimum Winter Discharge	709	709	0	0	325	37	172	4	171	0
Ice cover	River Ice Thickness	6,094	no Data Quality rating			4,163	416	762	59	669	25
Break-up	Spring Break-Up Initiation	5,534	5,070	333	131	3,541	323	885	121	641	23
Break-up	Maximum Spring Break -Up Water Level	7,355	5,428	1,571	356	4,483	503	1,216	168	914	44
Break-up	Last Day With Backwater Due To Ice	9,240	no Data Quality rating			5,816	788	1,380	186	1,024	46
Open-Water	Maximum Open-Water Level	9,705	5,705	3,728	271	6,121	826	1,408	184	1,119	47
	Column Total:	**72,595**	**39,587**	**7,622**	**1,122**	**45,831**	**5,423**	**10,851**	**1,228**	**9,032**	**204**

				Data Quality Rating			Number of Variables by Station Type					
							Natural		Regulated			
Season	Variable	Symbol	Total Number of Variables	0	1	2	Active	Discontinued	Homogeneous, Active	Homogeneous, Discontinued	Heterogeneous, Active	Heterogeneous, Discontinued
Freeze-up	First Day With Backwater Due To Ice	First B Date	8,933	no Data Quality rating			5,754	806	1,204	130	1,022	16
Freeze-up	Freeze-Over Water Level	H_F	6,547	4,794	1,592	161	4,142	466	949	106	881	3
Ice cover	First Minimum Winter Water Level	H_{LW1}	4,767	4,557	193	17	2,861	214	823	103	766	0
Ice cover	First Minimum Winter Discharge	H_{LQ1}	8,178	8,114	62	2	5,301	764	1,077	111	925	0
Ice cover	Mid-Winter Break-Up Initiation	H_{MWB}	362	359	3	0	249	11	54	8	40	0
Ice cover	Maximum Mid-Winter Break-Up Water Level	H_{MWM}	467	392	70	5	308	22	77	9	51	0
Ice cover	Maximum Winter Water Level	H_{F2}	1,954	1,816	39	99	1,180	104	329	16	325	0
Ice cover	Maximum Winter Water Level 7 Day	H_{F2MAX}	1,952	1,849	27	78	1,180	104	329	16	325	0
Ice cover	Second MinumumWinter Water Level	H_{LW2}	798	794	4	0	407	39	186	7	159	0
Ice cover	Second Minimum Winter Discharge	H_{LQ2}	709	709	0	0	325	37	172	4	171	0
Ice cover	River Ice Thickness	I_{THICK}	6,094	no Data Quality rating			4,163	416	762	59	669	25
Break-up	Spring Break-Up Initiation	H_B	5,534	5,070	333	131	3,541	323	885	121	641	23
Break-up	Maximum Spring Break -Up Water Level	H_M	7,355	5,428	1,571	356	4,483	503	1,216	168	914	44
Break-up	Last Day With Backwater Due To Ice	Last B Date	9,240	no Data Quality rating			5,816	788	1,380	186	1,024	46
Open-Water	Maximum Open-Water Level	H_O	9,705	5,705	3,728	271	6,121	826	1,408	184	1,119	47
	Column Total:		**72,595**	**39,587**	**7,622**	**1,122**	**45,831**	**5,423**	**10,851**	**1,228**	**9,032**	**204**

4.2 Utility of the Database and Research Needs

The CRID can be used for the study of river ice processes and the key characteristics of different ice regimes that are encountered within Canada and how these characteristics may have been changing over time. From a practical standpoint, there are many flood-prone sites across Canada, and various municipalities often commission engineering studies to assess open-water and ice-jam flood risk. If a site happens to be included in the database, much effort could be saved by, for example, having a readily available historical record of maximum ice-influenced levels and related flows, their time of occurrence, and the thickness of the winter ice cover. Maximum ice affected water levels in the CRID are a good candidate ~~to populate~~ for inclusion to the National Ice Jam Database (Muise et al., 2019), a Natural Resources Canada contribution to the Federal Floodplain Mapping Guidelines (https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/dsstr-prvntn-mtgtn/ndmp/fldpln-mppng-en.aspx).

It has been established that extreme flooding in ~30% of Canadian rivers ~~is very~~is often the result of ice ~~jams,~~ processes and jamming (Beltaos, 1984; von de Wall, 2009) with water levels exceeding those occurring under open-water conditions ~~at much higher discharges~~ (e.g. Gerard, 1989). At these locations stream discharge cannot be used to quantify flood level since the open-water stage-discharge relationship is invalid during ice conditions. Some classification schemes have been proposed to help educate current and future hydrological practitioners on the types and significance of river ice processes and ice jams (IAHR Working Group on River Ice Hydraulics 1986; Turcotte and Morse, 2013). However, river ice is generally omitted from major Canadian hydrological and hydraulics research initiatives (e.g. NSERC FloodNet, 2015, other groups mentioned by Turcotte et al., 2019), likely as a result of the limited, long term field data representing these complex and sometimes chaotic events of ice formation, growth and decay. Many national-scale assessments of flooding make little mention of river ice conditions, their implications to extreme water levels and the inherent challenges encountered in the estimation and reporting of discharge under ice (e.g.~~,~~ Cunderlink and Ouarda; 2009; Burn and Whitfield, 2016). Variables from the CRID ~~could likely~~should, when applicable, be ~~incorporated~~ considered for use in future hydrological initiatives and flood assessments.

~~Some classification schemes have been proposed to help educate current and future hydrological practitioners on the types and significance of river ice processes and ice jams (IAHR Working Group on River Ice Hydraulics 1986; Turcotte and Morse, 2013).~~ Beltaos and Prowse (2009) also made numerous research recommendations towards the study of river ice conditions. Examples include: calculation of trends in the frequency and magnitude of ice jams and thickness and strength of pre break-up ice covers and evaluation of climate-induced changes on river ice hydrology and quantification of intervals between major river ice events. The CRID provides the necessary baseline data for a complete national assessment of river ice conditions and can help identify rivers/regions where climate change adaptation may be of high priority.

There are a variety of other research questions that can be addressed using the CRID. Many were detailed in CRIPE 2019 proceedings (de Rham et al., 2019) and are reiterated/updated here such as: application of site-specific break-up forecast methodologies (e.g., Beltaos, 1997; Beltaos et al., 2003); flood studies and their relations with regional climate (Buttle et al., 2016); evaluation of locations using the global river ice classification model (Turcotte and Morse, 2013); cold-regions ecological assessments (e.g. Peters et al., 2014; 2016); baseline information for under-ice sediment transportation studies (as reviewed by Turcotte et al., 2011) and riverine habitats stressors (as reviewed by Prowse and Culp, 2008); calibration and validation of river ice hydrology (Morales-Marin et al., 2019) and hydraulics (Lindenschmidt, 2017) modelling efforts; and ground truth observations for remote sensing applications (Pavelsky and Smith, 2004; Yang et al., 2020).

5 Conclusion

The Watershed Hydrology and Ecology Research Division of Environment and Climate Change Canada has compiled the CRID for public access through the Government of Canada open data portal. This effort follows the recommendation of the 1990 CRIPE sponsored report *Working Group on River Ice Jams*, specifically *Chapter 2: Guideline for Extraction of Ice-Break-Up Data From Hydrometric Station Records* (Beltaos, 1990). National Hydrometric Program gauge records proved to be very valuable sources of field data for parameterization of ice related hydrologic events on Canadian rivers. This work involved reviewing over 10,000 station years of data from a select ~~network~~ subset of 196 stations, covering a range of stream types and climatic regions, to identify and extract recorded data corresponding to 15 variables comprising water levels, discharges, timings, ice thickness, and data quality ratings. Close to 73,000 records of river ice variables are now available to the water research community. ~~While many research avenues are possible, it is recommended that periodic updates be made to this database since a longer time series record is of more value.~~ For sites not included, the CRID can represent a template to extract pertinent information for various purposes including flood mapping and hydraulic structure design. It is recommended that periodic updates be made to this database since a longer time series record is of more value. Based on the 160 locations in operation up to Dec 31, 2015 (Table A1), a 5 year update of CRID time series (2016-2020) would require 800 person-hours of work. Evaluation of future research priorities are needed to formalize whether this task would be completed by the same group or undertaken by others. It is fortunate that much of the data acquisition tasks, discussed above could be automated using the Aquarius platform currently in use by NHP partner organizations (S. Hamilton, pers. comm). It is also recommended that a tabulation of station movements, benchmark or datum shifts, and changes to the stage-discharge relationship be compiled to rectify the site-specific nature of river ice conditions and non-homogeneous time series. Lastly, the CRID follows on several other notable national and international efforts to compile river ice information. The Global Lake and River Ice Phenology Database (Benson et al., 2000), the Canadian Ice Database (Lenormand et al., 2002), CRREL Ice Jam Database (Carr et al., 2015), and Russian River Ice Thickness and Duration database (updated by Shiklomanov and Lammers, 2014) represent major open data contributions to river ice science over the past two decades. The CRID expands on the number of variables considered, as well as, the temporal and spatial scope of these earlier databases for stations in Canada. The work highlights the excellence of NHP agencies in the collection and dissemination of hydrometric data, adds value to the NHP archive and delivers on Environment and Climate Change Canada's commitment to making water science knowledge and data openly available to the scientific community and the general public. The CRID supports continued research on river ice processes and the extreme water level fluctuations common to many cold regions river systems.

6 Data Availability

The CRID is available for download as a single .csv format file on the Government of Canada Open Data portal at: https://doi.org/10.18164/c21e1852-ba8e-44af-bc13-48eeedfcf2f4 (de Rham et al., 2020). A 0.5 Terabyte digital archive of all available scanned and digital hydrometric archives contains around 30,000 folders and over 100,000 files is stored on ECCC server and ~~. This archive~~ is available up request.

7 Data Disclaimer

Environment and Climate Change Canada employs every reasonable effort whenever feasible, to ensure the currency, accuracy and precision of the information provided. However, there are some limitations due to the sources of the data and the technology used in its processing and management. Furthermore, the material or any data derived using the data is subject to interpretation. Users are responsible for verifying that the supplied material is appropriate for the use or application for which they wish to employ it.

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9 Author Roles

LD coordinated this study completing data extraction, data entry, and quality control and wrote this manuscript (MS). YD supervised this study as PI since 2017 and reviewed the MS. SB conceptualized extraction of river ice related data from hydrometric records in 1990, provided technical guidance throughout the study and reviewed the MS. DP provided technical input towards data extraction, data quality, ecological and flood aspects and reviewed the MS. BB advised on river regulation, hydroclimatic regions, time series uncertainties and reviewed the MS. TP, ECCC Emeritus Scientist since 2017, initiated this study as a PI in the late 1990s.

10 References

Andres, D.D.: The effect of freezing on the stability of a juxtaposed ice cover, in: Proceedings of the 10th Workshop on the Hydraulics of Ice Covered Rivers, Winnipeg, Canada, http://www.cripe.ca/publications/proceedings/10, 1999.

Andres, D.D., Van Der Vinne, G., Johnson. B., Fonstad, G.: Ice consolidation on the Peace River: release patterns and downstream surge characteristics, in: Proceedings of the 12th Workshop on the Hydraulics of Ice Covered Rivers, Edmonton, Canada, http://www.cripe.ca/publications/proceedings/12, 2003

Becket, M. Investigation of the Occurrence of Ice Jams on the Lower Red River in Manitoba, M.Sc. thesis, Department of Civil Engineering, University of Manitoba, Winnipeg, Canada, 2020.

Beltaos, S.: Guidelines for extraction of ice break-up data from hydrometric station records, in: Working Group on River Ice Jams - Field Studies and Research Needs, edited by: Beltaos, S., Gerard, R., Petryk, S., and Prowse, T.D., NHRI Science Report No. 2. National Hydrology Research Institute. Environment Canada, Saskatoon, Saskatchewan, 37-70, 1990.

Beltaos, S.: Onset of river ice break-up, Cold Regions Science and Technology, 25, 3, 183-196, https://doi.org/10.1016/S0165-232X(96)00011-0, 1997.

Beltaos, S.: Effects of climate on mid-winter ice jams, Hydrological Processes, 16, 4, 789-804, https://doi.org/10.1002/hyp.370, 2002.

Beltaos, S: Reply to Discussions by Timoney et al (2018) and Hall et al (2018) on “Frequency of ice-jam flooding of Peace-Athabasca Delta”. Canadian Journal of Civil Engineering, 46, 3, 243-248, https://doi.org/10.1139/cjce-2018-0724, 2019.

Beltaos, S.: Numerical modelling of ice-jam flooding on the Peace–Athabasca delta, Hydrological Processes, 17, 18, 3685-3702, https://doi.org/10.1002/hyp.1355, 2003a.

Beltaos, S.: Threshold between mechanical and thermal breakup of river ice cover, Cold Regions Science and Technology, 37, 1, 1-13, https://doi.org/10.1016/S0165-232X(03)00010-7, 2003b

Beltaos, S.: River flow abstraction due to hydraulic storage at freezeup. Canadian Journal of Civil Engineering, 36, 3, 519-523, https://doi.org/10.1139/L08-128, 2009

Beltaos, S. Canadian Geophysical Union Hydrology Section Committee on River Ice Processes and the Environment: Brief History. Journal of Cold Regions Engineering, 26(3), 71–78, https://doi.org/10.1061/(ASCE)CR.1943-5495.0000046, 2012a

Beltaos, S.: Mackenzie Delta flow during spring breakup: Uncertainties and potential improvements. Canadian Journal of Civil Engineering, 39, 5, 579-588, https://doi.org/10.1139/l2012-033, 2012b

Beltaos, S.: Hydrodynamic characteristics and effects of river waves cause by ice jam releases, Cold Regions Science and Technology 85, 42-55, https://doi.org/10.1016/j.coldregions.2012.08.003, 2013.

Beltaos, S., and Carter, T.: Field studies of ice breakup and jamming in lower Peace River, Canada, Cold Regions Science and Technology, 56, 2-3, 102-114, https://doi.org/10.1016/j.coldregions.2008.11.002, 2009.

Beltaos, S., and Prowse T.: River-ice hydrology in a shrinking cryosphere. Hydrological Processes, 23, 1,~~–~~ 122-144, https://doi.org/10.1002/hyp.7165, 2009.

Beltaos, S., Gerard, R., Petryk, S., and Prowse, T.D.: Working Group on River Ice Jams - Field Studies and Research Needs, NHRI Science Report No. 2. National Hydrology Research Institute. Environment Canada, Saskatoon, Saskatchewan, 1990.

Beltaos, S., Ismail, S., and Burrell, B.C.: Midwinter breakup and jamming on the upper Saint John River: a case study, Canadian Journal of Civil Engineering, 30, 1, 77-88, http://dx.doi.org/10.1139/l02-062, 2003.

Benson, B., Magnuson, J., and Sharma, S.: updated 2013. Global Lake and River Ice Phenology Database, Version 1, National Snow and Ice Data Center, ~~. doi:~~ https://doi.org/10.7265/N5W66HP8, 2013.

Brimley, W.A., Freeman, C.N.: Trends in River ice cover in Atlantic Canada, in: Proceedings 9th Workshop on the Hydraulics of Ice Covered Rivers, Fredericton, Canada, http://cripe.ca/publications/proceedings/9, 1997.

Brooks, R.N.: Quantifying peak freshwater ice across the Northern Hemisphere using a regionally defined degree-day ice-growth model, M.Sc. thesis, Department of Geography, University of Victoria, Victoria, Canada, http://hdl.handle.net/1828/4035,2011, 2012.

Brooks, R.N., Prowse, T.D., O'Connell, I.J.: .Quantifying Northern Hemisphere freshwater ice, Geophysical Research Letters, 40, 5, 1128-1131, https://doi.org/10.1002/grl.50238, 2013.

Burn, D.H., and Whitfield, P.H.: Changes in floods and flood regimes in Canada, Canadian Water Resources Journal, 41: 1-2, 139-150, https://doi.org/10.1080/07011784.2015.1026844, 2015.

Buttle, J.M., Allen, D.M., Cassie, D. , Davison, B., Hayashi, M., Peters, D.L., , Pomeroy, J.W., Simonovic, S., St-Hilaire, A., and Whitfield, P.H.: Flood processes in Canada, regional and special aspects, Canadian Water Resources Journal, 41, 1-2, 7-30, https://doi.org/10.1080/07011784.2015.1131629, 2016.

Cunderlik, J.M., Ouardra, T.B.M.J.: Trends in the timing and magnitude of floods in Canada. Journal of Hydrology 375, 3-4, 471-480. https://doi.org/10.1016/j.jhydrol.2009.06.050, 2009.

Carr, M.L., Gaughan, S.P., George, C.R., and Mason,J.G. : CRREL'S Ice Jam Database: Improvement and Updates, in: Proceedings of the 18th Workshop on the Hydraulics of Ice Covered Rivers, Quebec City, Canada, 18-20 http://cripe.ca/publications/proceedings/18 , 2015.

Chen, Y., and She, Y.: Temporal and Spatial Variation of River Ice Breakup Timing across Canada, in: Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Canada, http://cripe.ca/publications/proceedings/20, 2019.

Curi, F., Boyd, D., Carson, R., and Rungis, G.: Brantford 2018 Ice Jam, in: Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Canada, http://cripe.ca/publications/proceedings/20, 2019.

De Coste, M., She, Y., Blackburn, J. : Incorporating the effects of upstream ice jam releases in the prediction of flood levels in the Hay River delta, Canada, Canadian Journal of Civil Engineering, 44(8) 643-651, https://doi.org/10.1139/cjce-2017-0123, 2017.

De Munck, S., Gauthier, Y., Bernier, M., Chokmani, K., Légaré, S.: River predisposition to ice jams: a simplified geospatial model. Natural Hazards and Earth System Sciences Discussions, 17(7), 1033-1047, https://doi.org/10.5194/nhess-17-1033-2017, 2016.

de Rham, L.P.: Spatial and Temporal Variations of River-ice Break-up, Mackenzie River Basin, Canada, M.Sc. thesis, Department of Geography, University of Victoria, Victoria, Canada, http://hdl.handle.net/1828/1609, 2006.

de Rham, L.P, Prowse, T.D., Beltaos, S., and Lacroix, M.P.: Assessment of annual high-water events for the Mackenzie River basin, Canada, Hydrological Processes, 22, 18, 3864-3880, https://doi.org/10.1002/hyp.7016, 2008a

de Rham, L.P., Prowse, T.D., and Bonsal, B.R.: Temporal variations in river-ice break-up over the Mackenzie River Basin, Canada. Journal of Hydrology, 349, 3-4, 441-454, https://doi.org/10.1016/j.jhydrol.2007.11.018, 2008b.

de Rham L, Prowse T, Dibike Y:. Progress towards the development of a Canadian River-ice Database, poster at: 71st Canadian Water Resources Association National Conference, Victoria, Canada, 2 May -June 1, 2018, 2018.

de Rham, L., Dibike, Y., Prowse, T.D., and Beltaos, S.: Overview of a Canadian River Ice Database Derived from Water Survey of Canada Hydrometric Archives, in: Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Canada, http://cripe.ca/publications/proceedings/20, 2019.

de Rham, L., Dibike, Y., Beltaos, S., Peters, D. Bonsal, B. Prowse, T. Canadian River Ice Database. https://doi.org/10.18164/c21e1852-ba8e-44af-bc13-48eeedfcf2f4, 2020

Derksen, D., Burgress, D., Duguay, D., Howell, S., Mudryk, L., Smith, S., Thackeray., C., and Kirchmeier-Young, M.: Chapter 5: Changes in Snow, Ice and Permafrost Across Canada. In Canada's Change Climate Report, https://changingclimate.ca/CCCR2019, 2019

Deslauriers, C.E.: Ice break-up in rivers, in Proceedings of the Conference on Ice Pressures against Structures, NRC Technical Memorandum No. 92, 217-229, 1968.

Environment Canada: Manual of Hydrometric Data Computation and Publication Procedures, Fifth Edition, Inland Waters Directorate, Internal Report, Ottawa, 1980.

Environment Canada: Hydrometric Manual - Data Computations. Prepared by Water Survey of Canada, http://www.wmo.int/mwg-internal/de5fs23hu73ds/progress?id=P6BercOrrSLFozHtZTDbPpEh5a4ZZdcjVQrBImv0vKw, 2012.

Farvolden, R.N.: Groundwater Resource Pembina Area, Alberta. Research Council of Alberta, Preliminary Report 61-4, https://ags.aer.ca/document/ESR/ESR_1961_04.pdf. 1961

Fonstad, G.D.: Peace river 1981/92 ice observation report, River Engineering Branch, Alberta Environment, Edmonton, Alberta, 61. Pp. 1982.

Fulton, J.W., Henneberg, M.F., Mills, T.J., Kohn, M.S., Epstien, B., Hittle, E.A., Damshen, W.C., Laveau, C.D., Lambrecht, J.M. and Farmer, W.H. Computing under-ice discharge: A proof-of-concept using hydro acoustics and the Probability Concept, Journal of Hydrology, 562, 733-748, https://doi.org/10.1016/j.jhydrol.2018.04.073, 2018.

Gebre, S.B, and Alfredson, K.T.: Investigation of river ice regimes in some Norwegian water courses, in Proceeding of the 15th Workshop on the Hydraulics of Ice Covered Rivers, Winnipeg, Manitoba, Canada. http://www.cripe.ca/publications/proceedings/16, 2011.

Gerard, R.,~~ 1989:~~ Chapter 10: Ice jam floods, in: Hydrology of Floods in Canada (editor-in-chief: W.E. Watt), National Research Council of Canada, Ottawa, Canada, 169-184, 1989.~~.~~

Gerard, R., and Karpuk, E.: Probability analysis of historical flood data, Journal of the Hydraulics Division, ASCE, 105(HY9), 1153-1165, 1979.

Giovando, J., Daly, S.: Mississippi River Ice Bite, in: Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, ~~-~~Canada, http://cripe.ca/publications/proceedings/20, 2019.

Goulding, H.L.: Spatial and temporal patterns and hydroclimatic controls of river ice break-up in the Mackenzie Delta, NWT, M.Sc. thesis, Department of Geography, University of Victoria, Victoria, Canada, http://hdl.handle.net/1828/1285, 2008.

Goulding, H.L., Prowse, T.D., and Beltaos, S.: Spatial and temporal patterns of break-up and jam flooding in the Mackenzie Delta, NWT, Hydrological Processes, 23, 18, 2654-2670, https://doi.org/10.1002/hyp.7251, 2009a.

Goulding, H.L., Prowse, T.D., and Bonsal, B.: Hydroclimatic controls on the occurrence of break-up and ice-jam flooding in the Mackenzie Delta, NWT, Canada, Journal of Hydrology, 379, 3-4, 251-267, https://doi.org/10.1016/j.jhydrol.2009.10.006, 2009b.

Gray, D.M., and Prowse, T.D.: Snow and floating ice, in Handbook of Hydrology, edited by Maidment, D., McGraw-Hill: New York, 7.1-7.58, 1993.

Groudin, D.: Summary Reports of maximum water levels under open-water and ice affected conditions at 16 hydrometric sites in Quebec, Environment Canada contract KW504-000117, 2011.

Gullet, D.W., Skinner, W.R., and Vincent, L.: Development of an historical Canadian climate database for temperature and other climate elements, Climatological Bulletin, 26, 125-131, 1992.

Hall, R.I., Wolfe, B.B., and Wiklund, J.A.: Discussion of "Frequency of ice-jam flooding of Peace-Athabasca Delta". Canadian Journal of Civil Engineering, 45, 1, 71-75, http://dx.doi.org/10.1139/cjce-2017-0434, 2018.

Hamilton, S. 2003. Winter Hydrometry. Real-time data issues, in: Proceedings of the 12th Workshop on the Hydraulics of Ice Covered Rivers, Edmonton, Canada, http://www.cripe.ca/publications/proceedings/12, 1999.

Healy, D., and Hicks, F.: Index velocity methods for winter discharge measurement, Canadian Journal of Civil Engineering, 31, 3, 407-419, https://doi.org/10.1139/l04-00, 2004.

Hicks, F.: An overview of river ice problems: CRIPE07 guest editorial. Cold Regions Science and Technology, 55, 175–185. https://doi.org/10.1016/j.coldregions.2008.09.006, 2008.

IAHR Working Group on River Ice Hydraulics: River ice jams: a state of the art report. Proceedings, IAHR International Ice Symposium, Iowa City, U.S.A., III, 561-594, 1986.

Jasek, M.J.: 1998 break-up and flood on the Yukon River at Dawson Did El Nino and Climate change play in role?, in: Ice in Surface Waters, edited by Shen, H.T., Balkema, Rotterdam, 761-768, 1999.

Kennedy, J.F. 1975. Ice-jam mechanics, in Proceedings of the 3rd IAHR international Symposium on Ice Problems, Hanover, New Hampshire, 143-164.

Lacroix, M., Prowse, T.D., Bonsal, B., Duguay, C. and Menard, P. River Ice Trends in Canada, in: Proceedings of the 13th Workshop on Hydraulics of Ice Covered Rivers, Hanover, USA, http://cripe.ca/publications/proceedings/13, 2005.

Lenormand, F., Duguay, C.R., and Gauthier, R.: Development of a historical ice database for the study of climate change in Canada, Hydrological Processes, 16, 18, 3707-3722, https://doi.org/10.1002/hyp.1235, 2002.

Lindenschmidt, K.E.: RIVICE – A Non-Proprietary, Open-Source, One-Dimensional River-Ice Model, Water, 9, 314, https://doi.org/10.3390/w9050314, 2017.

Lindenschmidt, K-E., Baulch, H.M., and Cavalier, E.: River and Lake Ice Processes – Impacts of Freshwater Ice on Aquatic Ecosystems in a Changing Globe. Water. 10, 11, 1586: https://doi.org/10.3390/w10111586, 2018.

Morales-Marin, L.A., Sanyal, P.R., Kadowaki, H., Li, X., Royaka, P., and Lindenschmidt, K.E.: A hydrological and water temperature modelling framework to simulate the timing of river freeze-up and ice-cover breakup in large-scale catchments. Environmental Modelling & Software, 114, 49-63, https://doi.org/10.1016/j.envsoft.2019.01.009, 2019.

Muise, P., Tolszczuk-Leclerc, S., and Gauthier, Y.: Proposal for a National River Ice Database Model and Integration with NRCan Observer, NRCan's CGI Mobile Application. poster at: Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Canada, http://cripe.ca/publications/proceedings/20, 2019.

Newton, B.W.: An evaluation of winter hydroclimatic variables conducive to snowmelt and the generation of extreme hydrologic events in western Canada, Ph.D. thesis, Department of Geography,, University of Victoria, Victoria, Canada, https://dspace.library.uvic.ca//handle/1828/9965, 2018.

Newton, B.W., Prowse T.D., and de Rham, L.P.: Hydro-climate drivers of mid-winter break-up of river ice in western Canada and Alaska, Hydrology Research 48, 4, 945-956, https://doi.org/10.2166/nh.2016.358, 2017.

NSERC FloodNet: NSERC Canadian Strategic Network for Enhancing Flood Forecasting and Management Capacity in Canada. McMaster University, Hamilton, ON, 41 pp, 2015.

Pavelsky, T.M., and Smith, L.C.: Spatial and temporal patterns in Arctic river ice breakup observed with MODIS and AVHRR time series. Remote Sensing of Environment, 93, 3 328-338, https://doi.org/10.1016/j.rse.2004.07.018, 2004.

Pelletier, P.M. A Review of Techniques used by Canada and other Northern Countries for Measurement and Computation of Streamflow under Ice Conditions: Paper presented at the 8th Northern Res. Basins Symposium/Workshop (Abisko, Sweden, March 1990), Hydrology Research, 21, 4, 317-340, https://doi.org/10.2166/nh.1990.0023, 1990.

Peters, D.L., Prowse, T.D., Pietroniro, A., and Leconte, R.: Flood Hydrology of the Peace-Athabasca Delta, Northern Canada, Hydrological Processes, 20, 19, 4073-4096, https://doi.org/10.1002/hyp.6420, 2006.

Peters, D.L., Monk, W.A., and Baird, D.J.: Cold-regions Hydrological Indicators of Changes (CHIC) for ecological flow needs assessments. Hydrological Sciences Journal 59, 502-516, https://doi.org/10.1080/02626667.2013.835489, 2014.

Peters, D.L., Cassie, D., Monk, W.A., Rood, S.B., and St-Hilaire, A.: An ecological perspective on floods in Canada. Canadian Water Resources Journal, 41, 1, 2, 288-306, https://doi.org/10.1080/07011784.2015.1070694, 2016.

Picco, R., Ali Khan, A., and Rollings, K.: Badger Flood 2003 Situation Report. Newfoundland Department of Environment, Water Resources Division, https://www.mae.gov.nl.ca/waterres/flooding/badger.html, 2003.

Poyser, B., Leblanc, R., and Kirk, D: Lesson Package No. 20 – Computation of Daily Discharge (Ice Conditions), The Water Survey of Canada, Hydrometric Career Development Program, 1999.

Prowse, T.D., and Carter, T. Signification of ice-induced storage to spring runoff: a case study of the Mackenzie River, Hydrological Processes 14, 4, 779-788, https://doi.org/10.1002/hyp.371, 2002.

Prowse, T.D., and Culp, J.M.: River ice breakup: a neglected factor in river ecology, in River ice breakup edited by Beltaos, S., Water Resources Publications, Highlands Ranch, Colorado, USA, 2008.

Prowse, T.D., and Lacroix, M.: Hydrologic Extremes on Arctic Flowing Rivers: Analysis and Recovery Summary Data Archive Report, Climate Change Action Fund Project S99-13-13, 6pp. + Appendices, 2001.

Prowse, T.D., Lacroix, M.P. and Beltaos, S. 2001: Flood frequencies on cold-regions rivers, in: abstracts of the 27th Scientific Meeting of the Canadian Geophysical Union, Ottawa, Canada, 14-17 May 2001, 2001.

Rebello, K.: Badger Flood Event – Field Report Februrary 2013, Government of Newfoundland and Labrador, https://www.mae.gov.nl.ca/waterres/flooding/badger.html, 2013.

Rokaya, P., Budhathoki, S., and Lindenschmidt, K-E.: Trends in the Timing and Magnitude of Ice-Jam Floods in Canada, Nature Science Reports, 8, 1-9, https://doi.org/10.1038/s41598-018-24057-z~~doi:10.1038/s41598-018-24057-z~~, 2018.

Shiklomona, A., and Lammers, R.B.: River ice responses to a warming Arctic – recent evidence from Russian rivers. Environmental Research Letters, 9, 3, 1-0, https://iopscience.iop.org/article/10.1088/1748-9326/9/3/035008~~doi:10.1088/1748-9326/9/3/03500~~, 2014.

Soldatova, I.I.: Secular variation in river break-up dates and their relationship with climate variation Russian Meteorology and Hydrology, 9, 70-76, 1996.

Timoney, K., Smith, J.D., Lamontagne. J.R., Jasek, M.: Discussion of “Frequency of ice-jam flooding of Peace-Athabasca Delta”. Canadian Journal of Civil Engineering, 46, 3, 1-4, http://dx.doi.org/10.1139/cjce-2018-0409, 2018.

Turcotte, B., and Morse, B.: A global river ice classification model, Journal of Hydrology, 507, 134-148, https://doi.org/10.1016/j.jhydrol.2013.10.032, 2013.

Turcotte, B., Morse, B., Bergeron, N.E., and Roy, A.G.: Sediment transport in ice affected rivers, Journal of Hydrology, 409, 561-577, https://doi.org/10.1016/j.jhydrol.2011.08.009, 2011.

Turcotte, B., Burrell, B.C., Beltaos, S., She, Y. : The Impact of Climate Change on Breakup Ice Jams in Canada: State of knowledge and research approached, in: Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Canada, http://cripe.ca/publications/proceedings/20, 2019.

United States Geological Survey: National Handbook of Recommended Methods for Water Data Acquisition. Office of Water Data Coordination, Reston, VA, 1977.

von de Wall, S.J.: An Assessment of the river ice break-up season in Canada, M.Sc. thesis, Department of Geography, University of Victoria, Victoria, Canada, http://hdl.handle.net/1828/3752, 2011.

von de Wall, S.J., de Rham, L.P., and Prowse, T.D. :Open water and ice-induced extreme water levels on Canadian rivers, in: 17th International Northern Research Basins Symposium and Workshop, Iqaluit-Pangnirtung-Kuujjuaq, Canada, 12 -18 August 2009, 2009.

von de Wall, S.J., de Rham, L.P., and Prowse, T.D.: The river ice break-up season in Canada: variations in water levels and timing. 67th Eastern Snow Conference, Jiminy Peak Mountain Resort, Hancock, MA, USA, 8-10 June 2010, 2010.

Vuglinsky, V.: Russian River Ice Thickness and Duration, Version 1, National Snow and Ice Data Center, doi: https://doi.org/10.7265/N5J10129.

Vuglinsky,V.S.: Ice regime in the rivers of Russia, its dynamics during last decades and possible future changes, in: 18th IAHR International Symposium on Ice, Sapporo, Japan, 1, 93-98, 2006.

Wazney, L., and Clark, S.P.: The 2009 flood event in the Red River Basin: Causes, assessment and damages, Canadian Water Resources Journal, 41(1-2), 56-64, https://doi.org/10.1080/07011784.2015.1009949, 2015

Wazney, L., Clark, S.P, and Wall, A.J.: Field monitoring of secondary consolidation events and ice cover progression during freeze-up on the Lower Dauphin River, Manitoba, Cold Regions Science and Technology, 148, 159-171, https://doi.org/10.1016/j.coldregions.2018.01.014, 2018

White, K.D.: A New Ice Jam Database, Journal of the American Water Resources Association 32, 341-348, https://doi.org/10.1111/j.1752-1688.1996.tb03456.x, 1996.

Yang, X., Pavelsky, T.M., and Allen, G.H. The past and future of global River Ice. Nature. 577, 69–73, https://doi.org/10.1038/s41586-019-1848-1 ~~doi:10.1038/s41586-019-1848-1~~, 2020.

Zhang, X., Buchberger, S.G., van Zyl, J.E. A Theoretical Explanation for Peaking Factors. World Water and Environmental Resources Congress. ASCE Library. https://ascelibrary.org/doi/10.1061/40792%28173%2951, 2005

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R.: Trends in Canadian streamflow. Water Resources Research, 37, 4, 987-998, https://doi.org/10.1029/2000WR900357, 2001.

Appendix

Table A1: List of the 196 National Hydrometric Program stations which comprise the Canadian River Ice Database. Data extraction time period are shown in column 'Start' and 'End'. Location with (RIVIERE) in water course are in Quebec. Column 'Type' is the regime as Natural, Active (NA); Natural, Discontinued (ND); Regulated, Heterogeneous, Active (RHEA); Regulated, Heterogeneous, Discontinued (RHED); Regulated, Homogeneous, Active (RHOA) Regulated, Homogeneous Discontinued (RHOD)

Station Number	Start	End	Type	Water Course
01AL002	1961	2015	NA	NASHWAAK RIVER AT DURHAM BRIDGE
01AN002	1974	2015	NA	SALMON RIVER AT CASTAWAY
01AP004	1961	2015	NA	KENNEBECASIS RIVER AT APOHAQUI
01BC001	1962	2015	NA	RESTIGOUCHE RIVER BELOW KEDGWICK RIVER
01BH005	1970	2015	NA	DARTMOUTH (RIVIERE) EN AMONT DU RUISSEAU DU PAS DE DAME
01BO001	1918	2015	NA	SOUTHWEST MIRAMICHI RIVER AT BLACKVILLE
01BP001	1951	2015	NA	LITTLE SOUTHWEST MIRAMICHI RIVER AT LYTTLETON
01BQ001	1961	2015	NA	NORTHWEST MIRAMICHI RIVER AT TROUT BROOK
01BV006	1964	2015	NA	POINT WOLFE RIVER AT FUNDY NATIONAL PARK
02EC002	1915	2015	NA	BLACK RIVER NEAR WASHAGO
02FC001	1911	2015	RHOA	SAUGEEN RIVER NEAR PORT ELGIN
02GA014	1947	2015	RHEA	GRAND RIVER NEAR MARSVILLE
02GA034	1987	2015	RHOA	GRAND RIVER AT WEST MONTROSE
02GB001	1912	2015	RHEA	GRAND RIVER AT BRANTFORD
02GD021	1978	2015	NA	THAMES RIVER AT INNERKIP
02HL005	1965	2015	NA	MOIRA RIVER NEAR DELORO
02LG005	1972	2015	NA	GATINEAU (RIVIERE) AUX RAPIDES CEIZUR
02LH004	1928	2005	ND	PICANOC (RIVIERE) PRES DE WRIGHT
02NE011	1960	2015	NA	CROCHE (RIVIERE) À 2,6 KM EN AVAL DU RUISSEAU CHANDY
02NF003	1931	2015	NA	MATAWIN (RIVIERE) A SAINT-MICHEL-DES-SAINTS
02OA054	1970	2015	RHOA	CHATEAUGUAY (RIVIERE) À 2 KM EN AMONT DU PONT-ROUTE 132
02OE027	1930	2015	NA	EATON (RIVIERE) PRES DE LA RIVIERE SAINT-FRANCOIS-3
02PB006	1963	2015	NA	SAINTE-ANNE (RIVIERE) (BRAS DU NORD DE LA) EN AMONT
02PJ005	1915	2015	RHOA	CHAUDIERE (RIVIERE) AU PONT-ROUTE 218 À SAINT-LAMBERT-DE-LAUZON
02QA002	1962	2015	NA	RIMOUSKI (RIVIERE) À 3,7 KM EN AMONT DU PONT-ROUTE 132
02RD003	1953	2006	ND	MISTASSIBI (RIVIERE)
02RF001	1963	2015	NA	ASHUAPMUSHUAN (RIVIERE) À LA TÊTE DE LA CHUTE AUX SAUMONS
02RG005	1964	2015	NA	METABETCHOUANE (RIVIERE) EN AMONT DE LA CENTRALE S.R.P.C.
02UC002	1960	2015	NA	MOISIE (RIVIERE) À 5,1 KM EN AMONT DU PONT DU Q.N.S.L.R.
02VC001	1956	2014	ND	ROMAINE (RIVIERE) AU PONT DE LA Q.I.T.
02WB003	1980	2015	NA	NATASHQUAN (RIVIERE) À 0,6 KM EN AVAL DE LA DÉCHARGE DU LAC ALLESTE
02XA003	1979	2015	NA	LITTLE MECATINA RIVER ABOVE LAC FOURMONT
02XA004	1979	1986	ND	RIVIERE JOIR NEAR PROVINCIAL BOUNDARY
02XC001	1967	2015	NA	SAINT-PAUL (RIVIERE) À 0,3 KM DU RUISSEAU CHANION
02YA002	1988	2015	NA	BARTLETTS RIVER NEAR ST. ANTHONY
02YK008	1985	2015	NA	BOOT BROOK AT TRANS-CANADA HIGHWAY
02YL001	1928	2015	NA	UPPER HUMBER RIVER NEAR REIDVILLE
02YO007	1984	1996	ND	LEECH BROOK NEAR GRAND FALLS
02YO012	1989	2015	NA	SOUTHWEST BROOK AT LEWISPORTE
02YQ004	1985	1998	ND	NORTHWEST GANDER RIVER NEAR GANDER LAKE
02ZD002	1989	2015	NA	GREY RIVER NEAR GREY RIVER
03BF001	1975	2015	NA	PONTAX (RIVIERE) À 60,4 KM DE L'EMBOUCHURE
03CB001	1959	1980	ND	EASTMAIN (RIVIERE) EN AVAL DE LA RIVIERE A L'EAU CLAIRE
03CB004	1979	2004	ND	EASTMAIN (RIVIERE) A LA TETE DE LA GORGE PROSPER
03CC001	1958	1980	ND	EASTMAIN (RIVIERE) A LA TETE DE LA GORGE DE BASILE
03DD002	1960	1995	ND	DE POSTOIS (RIVIERE) EN AMONT DE LA RIVIERE SAKAMI
03ED001	1961	2015	NA	BALEINE (GRANDE RIVIERE DE LA) EN AMONT DE LA RIVIERE DENYS-1
03HA001	1956	1960	ND	ARNAUD (PAYNE)(RIVIERE) EN AMONT DE LA RIVIERE HAMELIN-1
03JB001	1955	1988	ND	FEUILLES (RIVIERE AUX) EN AVAL DE LA RIVIERE PELADEAU
03KC004	1960	2015	NA	MELEZES (RIVIERE AUX) À 7,6 KM EN AMONT DE LA CONFLUENCE AVEC LA KOKSOAK
03MB002	1930	2015	NA	BALEINE (RIVIERE A LA) À 40,2 KM DE L'EMBOUCHURE
03MC001	1972	1990	ND	TUNULIC (RIVIERE) PRES DE L'EMBOUCHURE
03MD001	1975	2015	NA	GEORGE (RIVIERE) À LA SORTIE DU LAC DE LA HUTTE SAUVAGE
03NF001	1978	2015	NA	UGJOKTOK RIVER BELOW HARP LAKE
03NG001	1977	1996	ND	KANAIRIKTOK RIVER BELOW SNEGAMOOK LAKE
03PB002	1977	2015	NA	NASKAUPI RIVER BELOW NASKAUPI LAKE
03QC001	1966	2015	NA	EAGLE RIVER ABOVE FALLS
03QC002	1978	2015	NA	ALEXIS RIVER NEAR PORT HOPE SIMPSON
04AB001	1972	2015	NA	HAYES RIVER BELOW GODS RIVER
04AD002	1967	2015	NA	GODS RIVER NEAR SHAMATTAWA
04CC001	1968	1995	ND	SEVERN RIVER AT LIMESTONE RAPIDS
04DC001	1965	2015	NA	WINISK RIVER BELOW ASHEWEIG RIVER TRIBUTARY
04EA001	1967	2015	NA	EKWAN RIVER BELOW NORTH WASHAGAMI RIVER
04FC001	1968	2015	NA	ATTAWAPISKAT RIVER BELOW MUKETEI RIVER
04HA001	1966	2015	RHEA	ALBANY RIVER ABOVE NOTTIK ISLAND
04JG001	1966	2015	RHOA	KENOGAMI RIVER NEAR MAMMAMATTAWA
04LD001	1920	2015	RHOA	GROUNDHOG RIVER AT FAUQUIER
04LG002	1959	1982	RHOD	MOOSE RIVER AT MOOSE RIVER
04LJ001	1959	2015	NA	MISSINAIBI RIVER AT MATTICE
04LM001	1972	2015	NA	MISSINAIBI RIVER BELOW WABOOSE RIVER
04ME003	1959	2015	RHEA	ABITIBI RIVER AT ONAKAWANA
04NA001	1934	2015	NA	HARRICANA (RIVIERE) 3,1 KM EN AVAL DU PONT-ROUTE 111 A AMOS
04NB001	1967	2004	ND	TURGEON (RIVIERE) EN AMONT DE LA RIVIERE HARRICANA
05AA023	1949	2008	ND	OLDMAN RIVER NEAR WALDRON'S CORNER
05AB021	1908	2015	RHEA	WILLOW CREEK NEAR CLARESHOLM
05AC003	1918	2015	RHOA	LITTLE BOW RIVER AT CARMANGAY
05AD028	1966	2015	RHOA	WATERTON RIVER NEAR GLENWOOD
05BJ001	1896	2015	RHEA	ELBOW RIVER BELOW GLENMORE DAM
05BJ004	1935	2015	NA	ELBOW RIVER AT BRAGG CREEK
05BL024	1970	2015	RHOA	HIGHWOOD RIVER NEAR THE MOUTH
05CB001	1960	2015	NA	LITTLE RED DEER RIVER NEAR THE MOUTH
05CC001	1912	2015	NA	BLINDMAN RIVER NEAR BLACKFALDS
05CC007	1962	2015	NA	MEDICINE RIVER NEAR ECKVILLE
05FF001	1911	1994	RHED	BATTLE RIVER AT BATTLEFORD
05GA007	1944	1994	RHOD	EYEHILL CREEK NEAR MACKLIN
05GC006	1962	2015	RHOA	EAGLE CREEK NEAR ENVIRON
05GG001	1910	2015	RHEA	NORTH SASKATCHEWAN RIVER AT PRINCE ALBERT
05HH001	1938	2015	RHOA	SOUTH SASKATCHEWAN RIVER AT ST. LOUIS
05JM001	1915	2015	RHEA	QU'APPELLE RIVER NEAR WELBY
05KC001	1955	2015	NA	CARROT RIVER NEAR SMOKY BURN
05KD007	1961	2015	NA	CARROT RIVER NEAR TURNBERRY
05KJ001	1913	2015	RHOA	SASKATCHEWAN RIVER AT THE PAS
05LC001	1916	2015	NA	RED DEER RIVER NEAR ERWOOD
05LH005	1923	2015	NA	WATERHEN RIVER NEAR WATERHEN
05LM006	1967	2015	RHEA	DAUPHIN RIVER NEAR DAUPHIN RIVER
05MD004	1944	2015	RHOA	ASSINIBOINE RIVER AT KAMSACK
05ME006	1954	2015	RHOA	ASSINIBOINE RIVER NEAR MINIOTA
05MH005	1914	2015	RHOA	ASSINIBOINE RIVER NEAR HOLLAND
05NB009	1916	1995	RHOD	SOURIS RIVER NEAR ROCHE PERCEE
05NG001	1912	2015	RHOA	SOURIS RIVER AT WAWANESA
05NG021	1946	2015	RHOA	SOURIS RIVER AT SOURIS
05OC012	1958	2015	RHOA	RED RIVER NEAR STE. AGATHE
05OJ010	1960	2008	RHOD	RED RIVER NEAR LOCKPORT
06AD001	1955	2015	NA	BEAVER RIVER NEAR DORINTOSH
06AD006	1955	2015	NA	BEAVER RIVER AT COLD LAKE RESERVE
06AG001	1971	2015	NA	BEAVER RIVER BELOW WATERHEN RIVER
06BC001	1970	1995	ND	MUDJATIK RIVER NEAR FORCIER LAKE
06BD001	1966	2015	NA	HAULTAIN RIVER ABOVE NORBERT RIVER
06DA004	1966	2015	NA	GEIKIE RIVER BELOW WHEELER RIVER
06GD001	1965	2015	NA	SEAL RIVER BELOW GREAT ISLAND
06JC002	1965	2015	NA	THELON RIVER ABOVE BEVERLY LAKE
06LC001	1960	2015	NA	KAZAN RIVER ABOVE KAZAN FALLS
06MB001	1960	1996	ND	QUOICH RIVER ABOVE ST. CLAIR FALLS
07AE001	1960	2015	NA	ATHABASCA RIVER NEAR WINDFALL
07BC002	1957	2015	NA	PEMBINA RIVER AT JARVIE
07BE001	1913	2015	NA	ATHABASCA RIVER AT ATHABASCA
07CD001	1930	2015	NA	CLEARWATER RIVER AT DRAPER
07DA001	1957	2015	NA	ATHABASCA RIVER BELOW FORT MCMURRAY
07EA005	1978	2015	NA	FINLAY RIVER ABOVE AKIE RIVER
07EC002	1975	2015	NA	OMINECA RIVER ABOVE OSILINKA RIVER
07FB001	1961	2015	NA	PINE RIVER AT EAST PINE
07FC001	1917	2015	NA	BEATTON RIVER NEAR FORT ST. JOHN
07GE001	1917	2015	NA	WAPITI RIVER NEAR GRANDE PRAIRIE
07GH002	1959	2015	NA	LITTLE SMOKY RIVER NEAR GUY
07GJ001	1915	2015	NA	SMOKY RIVER AT WATINO
07HA001	1915	2015	RHEA	PEACE RIVER AT PEACE RIVER
07HA003	1967	2015	NA	WHITEMUD RIVER NEAR DIXONVILLE
07HC001	1961	2015	NA	NOTIKEWIN RIVER AT MANNING
07JD002	1970	2015	NA	WABASCA RIVER AT HIGHWAY NO. 88
07KC001	1959	2015	RHEA	PEACE RIVER AT PEACE POINT (ALBERTA)
07NB001	1921	2015	RHEA	SLAVE RIVER AT FITZGERALD (ALBERTA)
07OB001	1921	2015	NA	HAY RIVER NEAR HAY RIVER
07OB003	1974	2015	NA	HAY RIVER NEAR MEANDER RIVER
07OC001	1969	2015	NA	CHINCHAGA RIVER NEAR HIGH LEVEL
07PA001	1968	2015	NA	BUFFALO RIVER AT HIGHWAY NO. 5
08AB001	1974	2015	NA	ALSEK RIVER ABOVE BATES RIVER
08CE001	1954	2015	NA	STIKINE RIVER AT TELEGRAPH CREEK
08CF001	1971	1995	ND	STIKINE RIVER ABOVE BUTTERFLY CREEK
08EE004	1930	2015	NA	BULKLEY RIVER AT QUICK
08JC001	1915	2015	RHEA	NECHAKO RIVER AT VANDERHOOF
08JC002	1950	2015	RHEA	NECHAKO RIVER AT ISLE PIERRE
08KB001	1950	2015	NA	FRASER RIVER AT SHELLEY
08KH006	1939	2015	NA	QUESNEL RIVER NEAR QUESNEL
08LF051	1951	2015	NA	THOMPSON RIVER NEAR SPENCES BRIDGE
08LG007	1911	2009	RHOD	NICOLA RIVER NEAR MERRITT
08LG010	1911	2015	RHOA	COLDWATER RIVER AT MERRITT
08LG048	1965	2015	NA	COLDWATER RIVER NEAR BROOKMERE
08LG049	1915	2015	RHOA	NICOLA RIVER ABOVE NICOLA LAKE
08MB005	1970	2015	NA	CHILCOTIN RIVER BELOW BIG CREEK
08NB005	1944	2015	NA	COLUMBIA RIVER AT DONALD
08NL007	1914	2015	NA	SIMILKAMEEN RIVER AT PRINCETON
08NL038	1914	2015	NA	SIMILKAMEEN RIVER NEAR HEDLEY
09AE005	1956	2015	NA	SWIFT RIVER NEAR SWIFT RIVER
09AH001	1951	2015	NA	YUKON RIVER AT CARMACKS
09BC001	1951	2015	NA	PELLY RIVER AT PELLY CROSSING
09BC004	1970	2015	NA	PELLY RIVER BELOW VANGORDA CREEK
09CD001	1956	2015	NA	YUKON RIVER ABOVE WHITE RIVER
09DC002	1967	1979	ND	STEWART RIVER AT MAYO
09DD003	1951	2015	NA	STEWART RIVER AT THE MOUTH
09EA003	1965	2015	NA	KLONDIKE RIVER ABOVE BONANZA CREEK
09EB001	1944	2015	NA	YUKON RIVER AT DAWSON
09FB001	1962	1995	ND	PORCUPINE RIVER BELOW BELL RIVER
09FC001	1976	2015	NA	OLD CROW RIVER NEAR THE MOUTH
09FD001	1961	1995	ND	PORCUPINE RIVER AT OLD CROW
10AA001	1960	2015	NA	LIARD RIVER AT UPPER CROSSING
10AB001	1962	2015	NA	FRANCES RIVER NEAR WATSON LAKE
10BB001	1960	1995	ND	KECHIKA RIVER AT THE MOUTH
10BB002	1967	1994	ND	KECHIKA RIVER ABOVE BOYA CREEK
10BE001	1944	2015	NA	LIARD RIVER AT LOWER CROSSING
10BE005	1968	1995	ND	LIARD RIVER ABOVE BEAVER RIVER
10BE006	1969	1995	ND	LIARD RIVER ABOVE KECHIKA RIVER
10CC002	1978	2004	ND	FORT NELSON RIVER ABOVE MUSKWA RIVER
10CD001	1944	2015	NA	MUSKWA RIVER NEAR FORT NELSON
10EA003	1960	2015	NA	FLAT RIVER NEAR THE MOUTH
10EB001	1960	2015	NA	SOUTH NAHANNI RIVER ABOVE VIRGINIA FALLS
10EC001	1959	1996	ND	SOUTH NAHANNI RIVER ABOVE CLAUSEN CREEK
10ED001	1942	2015	NA	LIARD RIVER AT FORT LIARD
10ED002	1972	2015	NA	LIARD RIVER NEAR THE MOUTH
10GB006	1974	2015	NA	WILLOWLAKE RIVER ABOVE METAHDALI CREEK
10GC001	1938	2015	RHEA	MACKENZIE RIVER AT FORT SIMPSON
10HB005	1973	2015	NA	REDSTONE RIVER 63 KM ABOVE THE MOUTH
10KA001	1943	2015	RHEA	MACKENZIE RIVER AT NORMAN WELLS
10LA002	1968	2015	NA	ARCTIC RED RIVER NEAR THE MOUTH
10LC002	1972	2015	RHEA	MACKENZIE RIVER (EAST CHANNEL) AT INUVIK
10LC014	1965	2015	RHOA	MACKENZIE RIVER AT ARCTIC RED RIVER
10MA001	1961	2015	NA	PEEL RIVER ABOVE CANYON CREEK
10MC002	1969	2015	NA	PEEL RIVER ABOVE FORT MCPHERSON
10NC001	1969	2015	NA	ANDERSON RIVER BELOW CARNWATH RIVER
10QC001	1970	2015	NA	BURNSIDE RIVER NEAR THE MOUTH
10QD001	1969	2015	NA	ELLICE RIVER NEAR THE MOUTH
10RA001	1977	2015	NA	BACK RIVER BELOW BEECHY LAKE
10RA002	1977	2015	NA	BAILLIE RIVER NEAR THE MOUTH
10RC001	1960	2015	NA	BACK RIVER ABOVE HERMANN RIVER
10SB001	1971	1994	ND	HAYES RIVER ABOVE CHANTREY INLET
11AA005	1909	2015	RHEA	MILK RIVER AT MILK RIVER