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 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 season-specific 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 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, 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)

1 Introduction

River ice is an intrinsic component of cold climate watersheds. 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. 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. 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 estimating channel 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 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 CRIPE 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 196 sites with drainage areas ranging from 20.4 km^2 to 1.68 x 10^6 km^2, 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 (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 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.

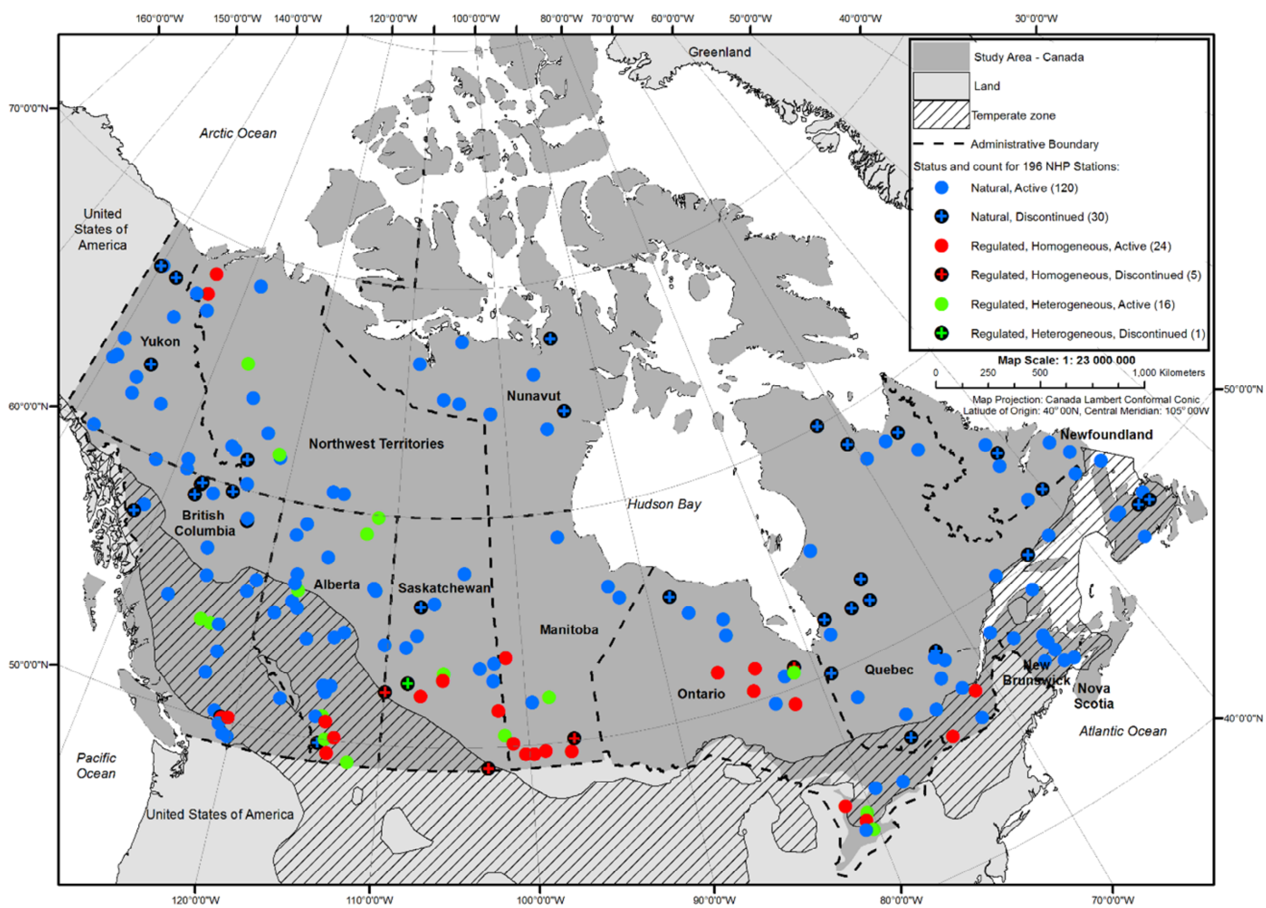

Figure 1. Location of the 196 National Hydrometric Program (NHP) hydrometric gauging stations included in the Canadian

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).

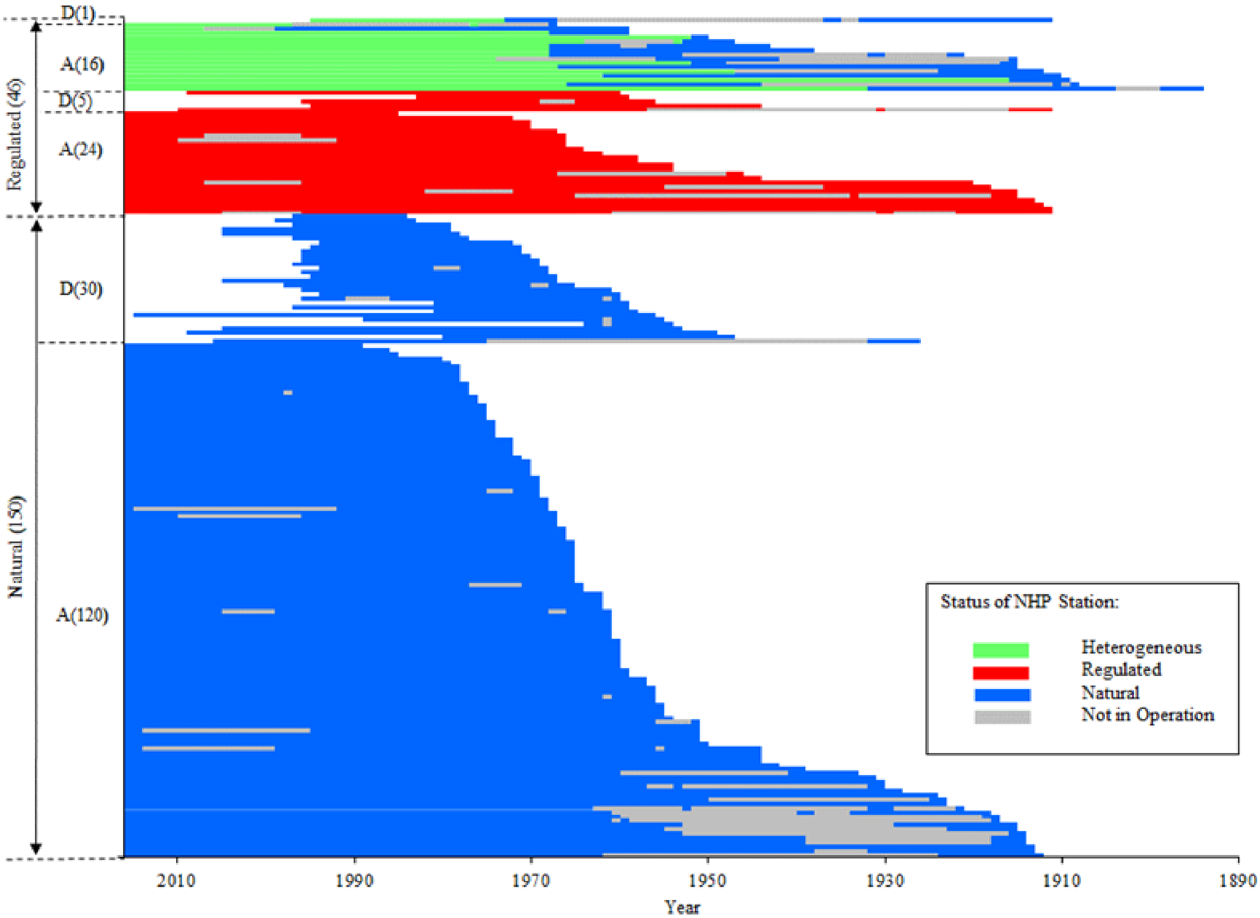

Figure 2. Bar chart showing the operational history of the 196 National Hydrometric Program (NHP) included in the Canadian River Ice Database. Stations are categorized by flow conditions (Natural or Regulated), operational status (Active (A) or Discontinued (D) and flow condition as homogeneous (always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

3 Methodology

3.1 National Hydrometric Program Archives

The various 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 year 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. 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 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 agency of the National Hydrometric Program (NHP), which also includes provincial and territorial agencies.

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 affected metrics is plotted in Fig. 3. The CRID includes up to 15 variables that cover the water year (Table 2). These variables are categorized as occurring during one of four seasons: freeze-up, ice cover, break-up, or open-water. 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. 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 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 resolution (Table 3). Under some circumstances, judgement was applied to rate data quality higher or lower depending 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.

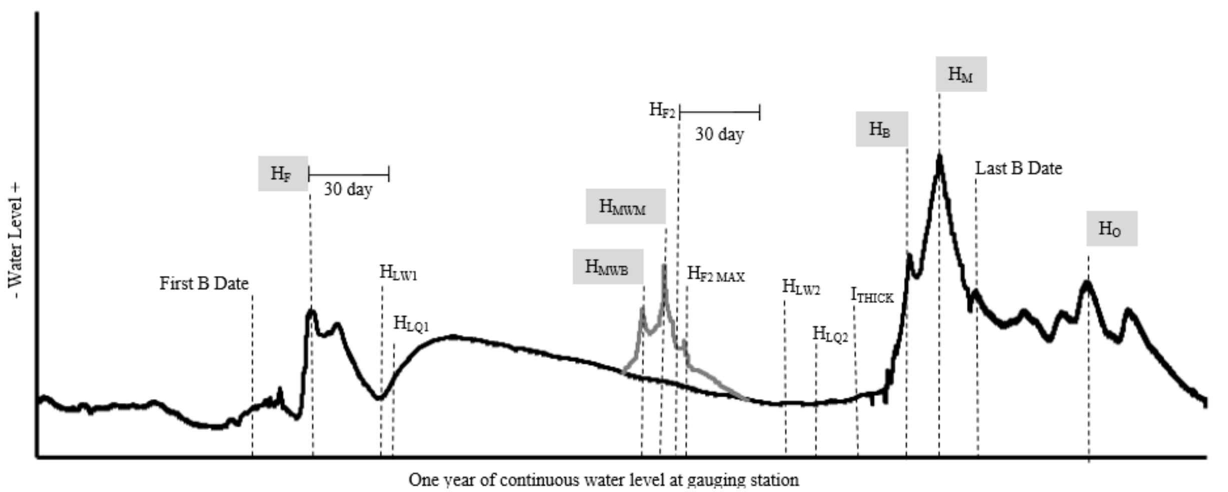

Figure 3. Conceptual schematic of continuous river water level hydrograph (black line) spanning September 1 to August 31. Period of ice affected flow is constrained by First B Date to Last B Date. A possible mid-winter break up event is shown as grey line, at approximate centre of hydrograph. Symbols 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.

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

				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

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 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). 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"*. An example schematic showing the ice affected condition is provided in Fig. 4, 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.

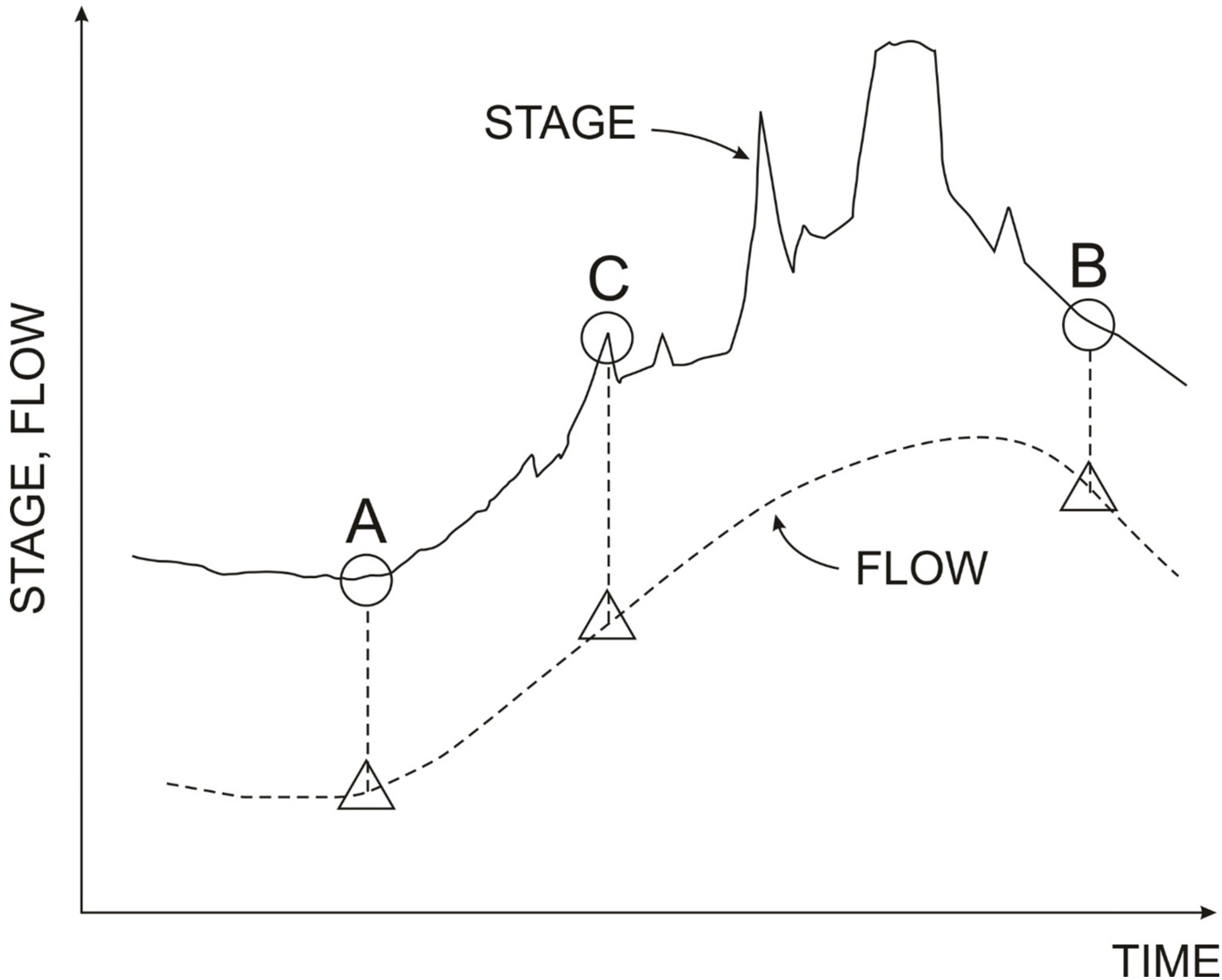

Figure 4. Schematic illustration of typical stage (i.e. water level) and flow (i.e. discharge) variations during the early phase of the spring runoff event. From Beltaos (2012b); Crown Copyright; Published by NRC Research Press.

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.

3.4 CRID Variables

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.

3.4.1 Freeze-up: First B Date, H_F

As mentioned above, the NHP daily discharge values include a 'B' 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.

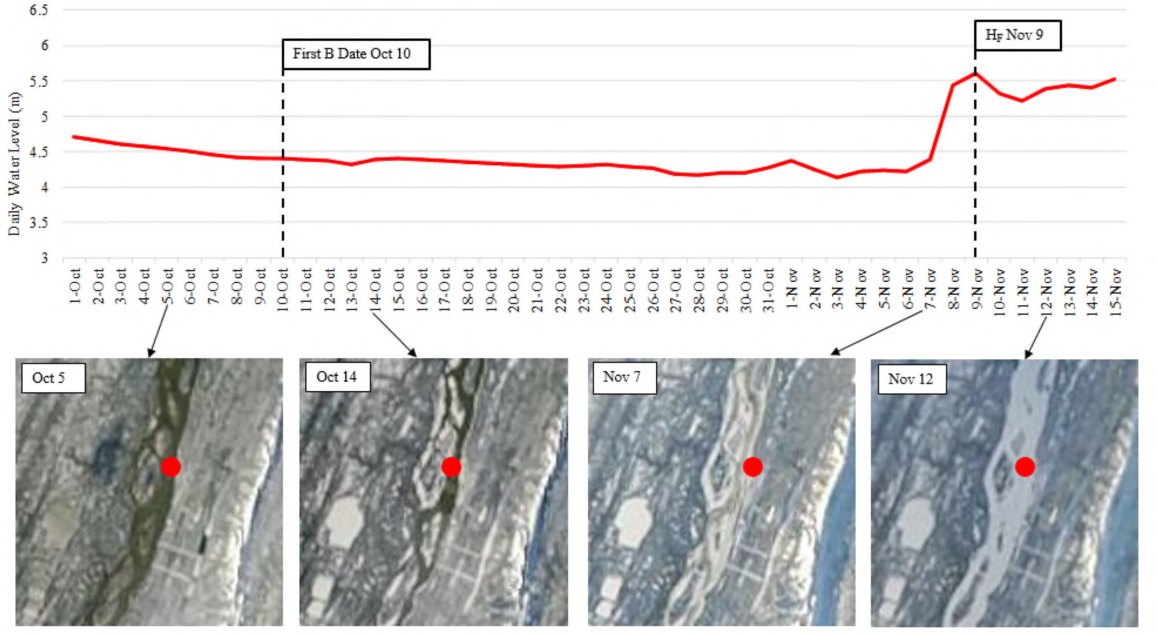

Figure 5. Daily mean water level hydrograph for October 1 to November 15, 2000 at National Hydrometric Program gauging station Mackenzie River at Norman Wells (10KA001) along with MODIS time-lapse satellite images (accessed at: https://worldview.earthdata.nasa.gov/). Station location indicated by red 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 (H_F) 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.

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 will cause a gradual increase to a maximum in the water level chart and is depicted as H_F (freeze-over water level) in Fig. 3. The CRID includes transcription of the 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 0ºC 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 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 to: (1) allow for calculation of a 7-day average to parameterize 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 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 analyses (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).

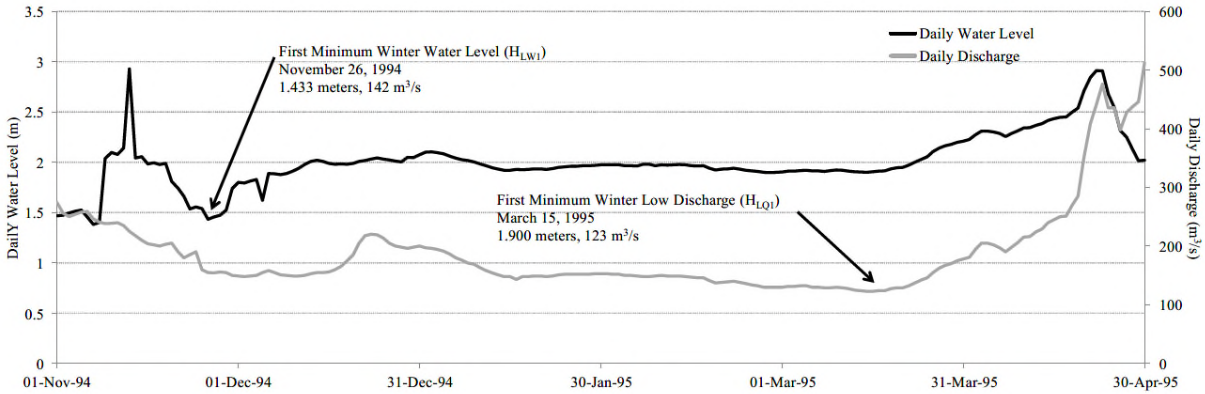

Figure 6. Daily reported water level and discharge for the Athabasca River below Fort McMurray (07DA001) for ice affected (B flagged) period spanning November 1, 1994 to April 30, 1995. Note that an increase in water level does not necessarily result in more discharge due to the varying hydraulic effects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

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

Rapidly warming air temperatures (above 0ºC) 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., 2017). The possibility of mid-winter ice jams, elevated water levels, 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 0ºC 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 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 closer examination of the CRID time series and comparison to nearby hydrometric stations may be required before pursing further analysis.

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 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.

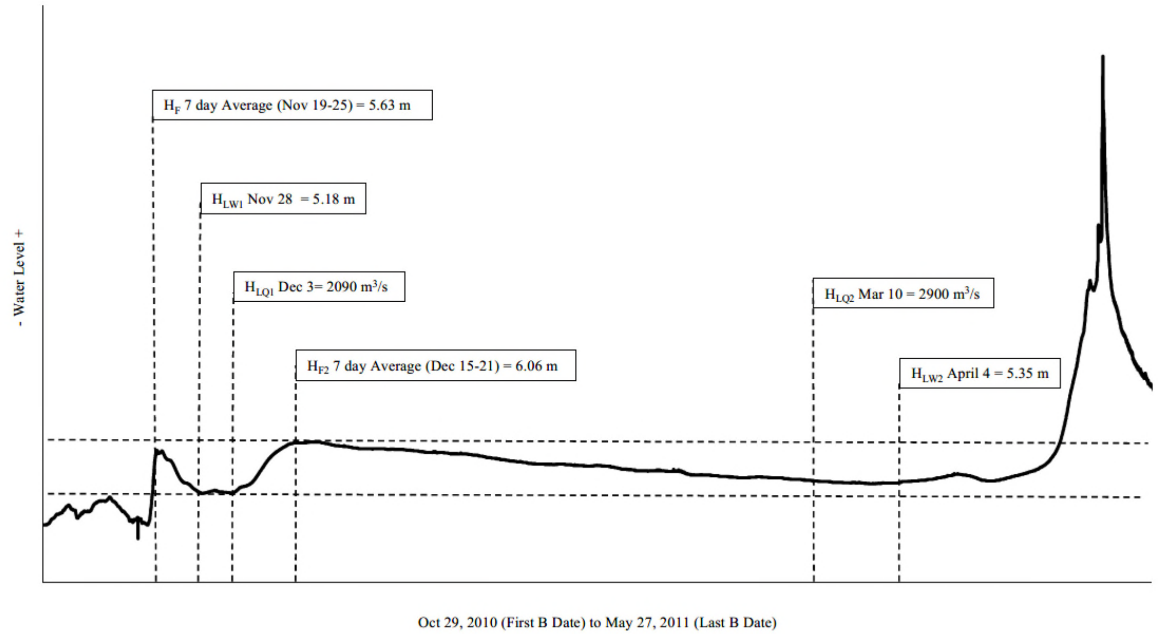

Figure 8. Continuous water level record at Mackenzie River at Norman wells during 2010-2011 ice affected flow period. Note the occurrence of a higher magnitude 7 day average following H_{F2} in comparison to H_F and the corresponding second winter minimums (H_{LW2} and H_{LQ2}) in addition to the first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

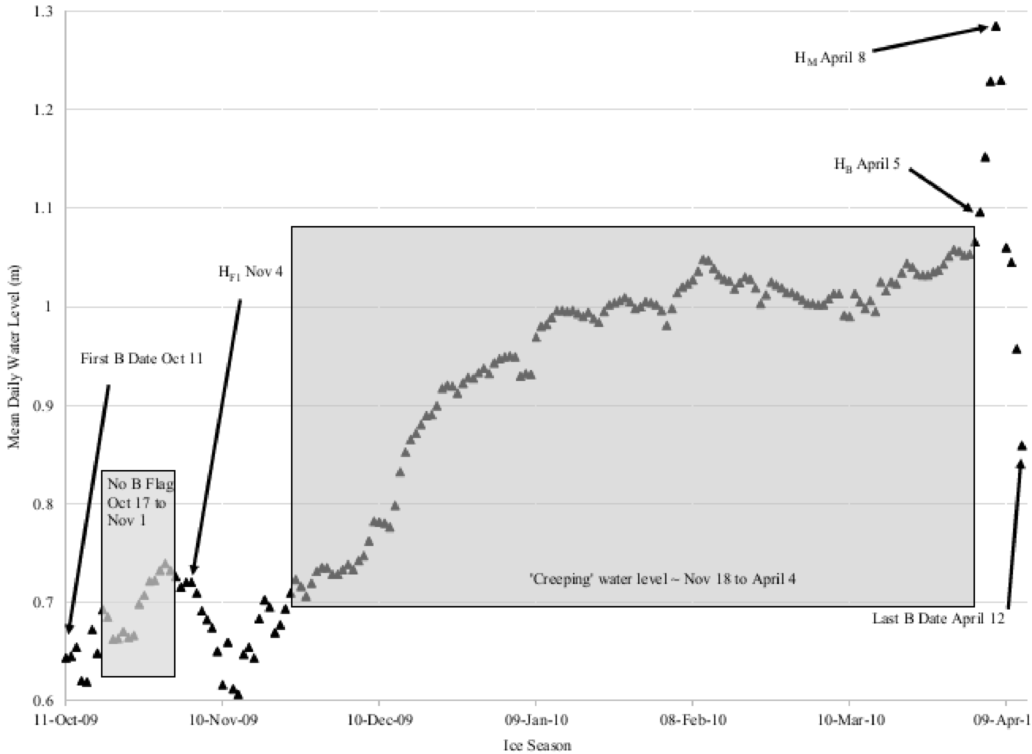

Figure 9. Daily water level from First B to Last B date at Pembina River at Jarvie (07BC002) during the 2009-2010 ice affected flow season that depict 'Creeping' water level. There are no B data flags from Oct 17 to Nov 1 and daily average water levels 'Creeping' upwards throughout the ice cover period.

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. 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 specific gravity of river ice is commonly taken as 0.92. Nevertheless, these measurements are assumed to represent the actual ice cover thickness. 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}).

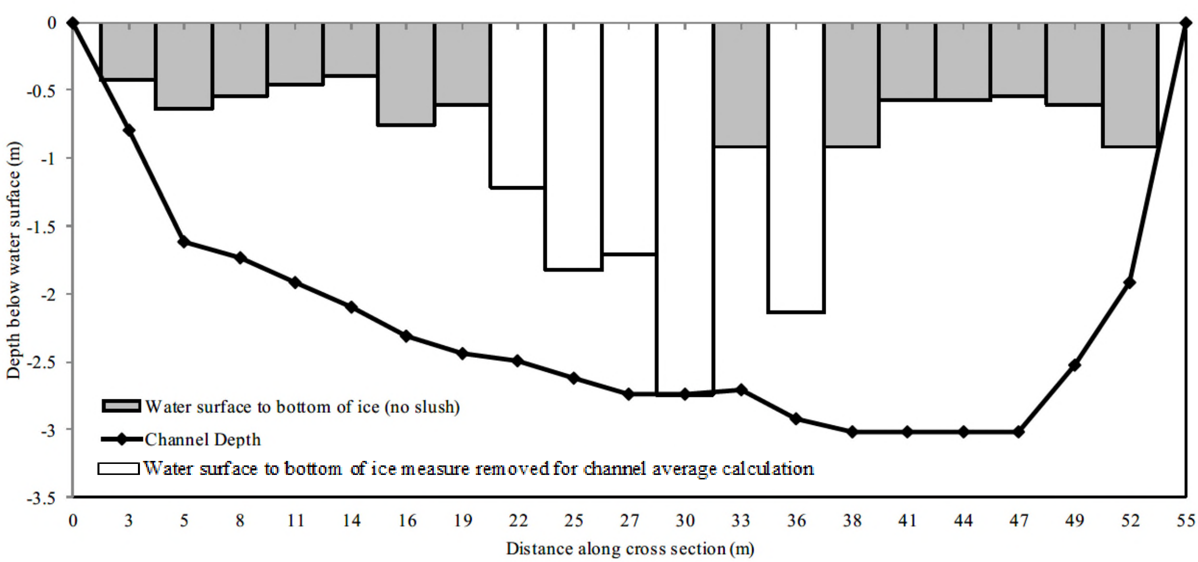

Figure 10. A bar plot of the 19 water survey to bottom of ice thickness measurements collected on March 28, 1978 at Nashwaak River below Durham Bridge (01AL002). The hydrometric survey note indicates measurement at river cross section distance 30 m is Slush To Bottom. Visual examination of this plot 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. 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 establish if this measurement was collected prior to the ice cover beginning to melt.

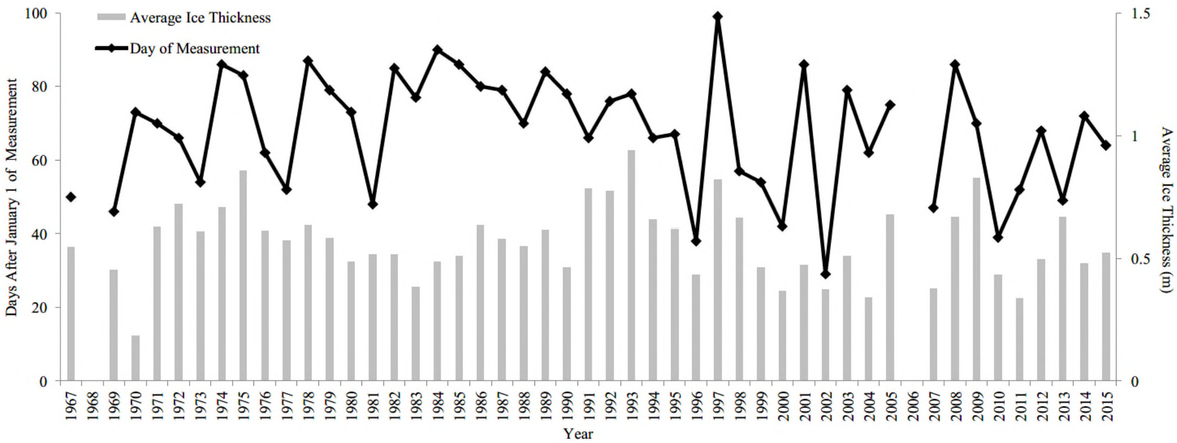

Figure 11. Plot showing average ice thickness (grey bars) day of measurement (black line) and at site Nashwaak River below Durham Bridge (01AL002). Measurement dates input to CRID represent a range of 72 days from a minimum Jan 29 (2002) to April 9 (1997). Initiation of break-up at this location ranges 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 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 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 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 (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 another dynamic mechanism that can generate the identified H_M 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 less obvious "spiking" of water levels. An example water level with this 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.

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 chunk 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 Last B Date 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 Last B Date 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 Last B Date.

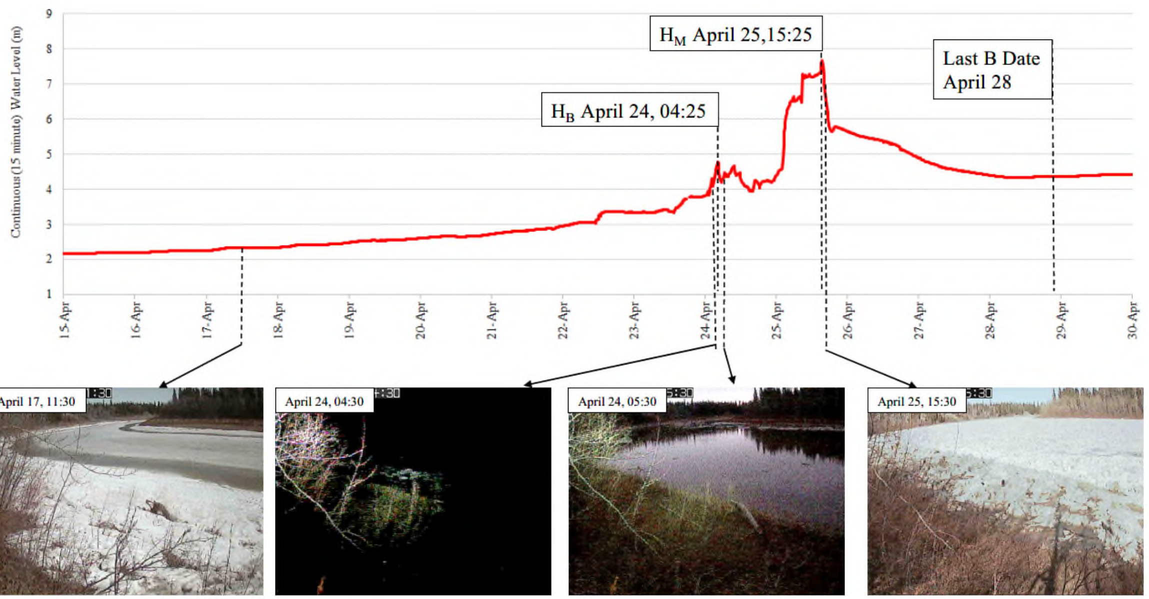

Figure 12: Continuous 15 minute interval water level hydrograph for April 15 to 30, 2010 at National Hydrometric Program gauging station Hay River near Hay River (07OB001) along with images courtesy of Alberta Research Group. Left: Image looking upstream taken 7 days prior to spring break-up initiation (H_B) of April 24, 2010, 004:25. 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 indicates higher water levels. Last B Date was April 28, 2010.

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 estimate the associated water level. Gerard and Karpuk (1979) provided one of the earlier examples of comparing maximum ice affected 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). 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 is as follows. For the six 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 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. 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 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 an accounting for these factors towards assessments of station homogeneity are a necessary next step. For example, Fig. 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 maximum open-water level magnitudes (blue circles) plots as two separate populations which are not directly comparable for many types of analysis.

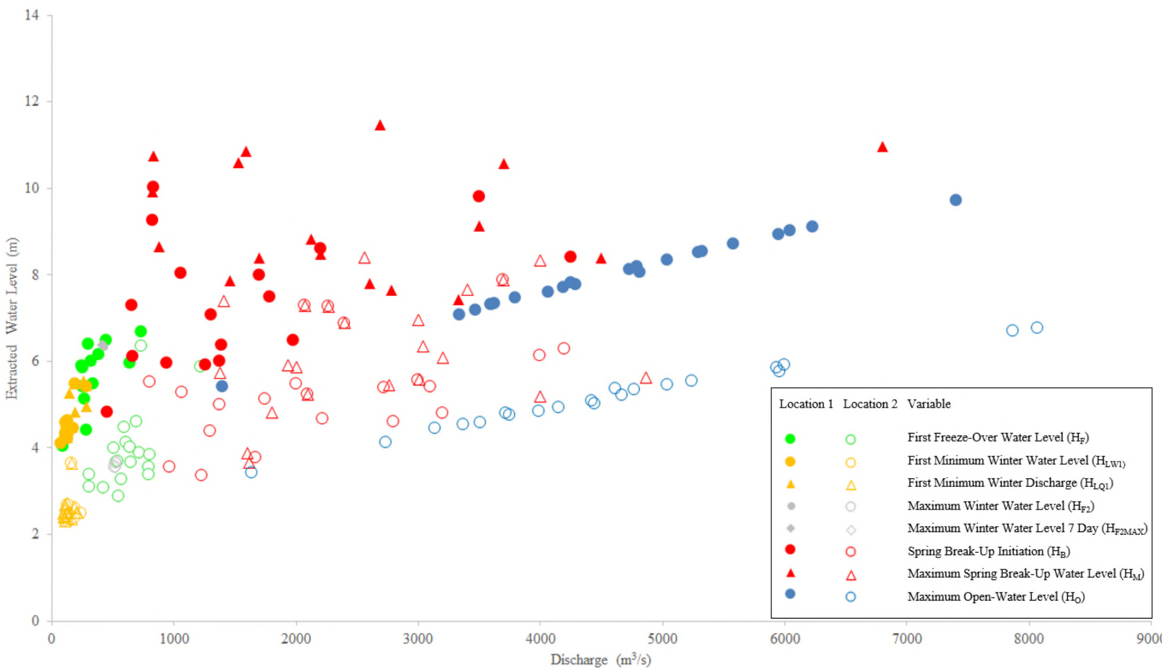

Figure 13. A stage-discharge plot of Canadian River Ice Database variables for site Albany River near Hat Island (04HA001). Time series (1964-2015) symbols are separated into Location 1 and Location 2 to illustrate the effect of the gauge being moved approximately 3.5 km downstream on Sept 29, 1988. 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.

4 Discussion

4.1 The CRID

Nearly two decades of data collection effort and study 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 spread over different stages of the 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) first (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 First and Last B Date. 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	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 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 often the result of ice processes and jamming (Beltaos, 1984; von de Wall, 2009) with water levels exceeding those occurring under open-water conditions (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 should, when applicable, be considered for use in future hydrological initiatives and flood assessments. 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 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. 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 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, 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.. 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, 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, 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 , 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	1913	2015	NA	BLACK RIVER NEAR WASHAGO
02FC001	1911	2015	RHOA	SAUGEEN RIVER NEAR PORT ELGIN
02GA014	1947	2015	RHEA	GRAND RIVER NEAR MARSVILLE
02GA034	1967	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	1926	2005	ND	PICANOC (RIVIERE) PRES DE WRIGHT
02NE011	1965	2015	NA	CROCHE (RIVIERE) À 2,6 KM EN AVAL DU RUISSEAU CHANGY
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	1956	2015	NA	EATON (RIVIERE) PRES DE LA RIVIERE SAINT-FRANCOIS-3
02PB006	1965	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
02RD002	1953	2004	ND	MISTASSIBI (RIVIERE)
02RF001	1915	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	1965	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 ALIESTE
02XA003	1979	2015	NA	LITTLE MECATINA RIVER ABOVE LAC FOURMONT
02XA004	1979	1996	ND	RIVIERE JOIR NEAR PROVINCIAL BOUNDARY
02XC001	1967	2015	NA	SAINT-PAUL (RIVIERE) À 0,5 KM DU RUISSEAU CHANION
02YA002	1986	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	1983	1998	ND	NORTHWEST GANDER RIVER NEAR GANDER LAKE
02ZD002	1969	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	1993	ND	DE PONTOIS (RIVIERE) EN AMONT DE LA RIVIERE SAKAMI
03ED001	1961	2015	NA	BALEINE (GRANDE RIVIERE DE LA) EN AMONT DE LA RIVIERE DENYS-1
03HA001	1954	1963	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	1965	2015	NA	MELEZES (RIVIERE AUX) À 7,6 KM EN AMONT DE LA CONFLUENCE AVEC LA KOKSOAK
03MB002	1956	2015	NA	BALEINE (RIVIERE A LA) À 40,2 KM DE L'EMBOUCHURE
03MC001	1972	1993	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
04GD001	1966	2015	RHOA	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	1924	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	1894	2015	RHEA	ELBOW RIVER BELOW GLENMORE DAM
05BJ004	1923	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	1958	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
05KH007	1965	2015	NA	CARROT RIVER NEAR TURNBERRY
05KJ001	1913	2015	RHOA	SASKATCHEWAN RIVER AT THE PAS
05LC001	1914	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	1954	2015	RHOA	ASSINIBOINE RIVER NEAR HOLLAND
05NB009	1956	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	1933	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	1955	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	1969	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
07HA005	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
09AE003	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	1947	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	1965	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	1975	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	RHOA	MACKENZIE RIVER (EAST CHANNEL) AT INUVIK
10LC014	1985	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	1976	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

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