



# A Canadian River Ice Database from the 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 midwinter and spring break-up events. Reports and associated data of 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, midwinter 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-bc13-48eedfcf2f4> (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/>, last access: 20 July 2020) has been quite active and productive since the 1970s (Beltaos, 2012a), during which time the study of river ice processes and hydraulics has 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 a growing number of publications on river ice processes that focus on specific locations or river reaches and that look 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 multisite river ice database. It is not commonly known by the wider hydrology research community that a valuable source of 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), and several Canadian provinces and territories, operates a current network of more than 2800 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, was not published up until the turn of the 21st 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 0 °C isotherm, differentiating between ice-induced and open-water flood-generating mechanisms (Prowse et al., 2001). A study from 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), and correlations of ice event occurrence with both the 0 °C 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, b), 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, b) 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, b) 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, 2019). Peters et al. (2006) examined the maximum extent of flooding of ice jam versus open-water flood events in this delta. Other well-studied Canadian locations include, to mention but a few, Hay River (De Coste et al., 2017), Red River (Wazney and Clark, 2015) and Chaudiere River (De Munck et al., 2017).

Expanding beyond Canada, Newton et al. (2017) reported on hydro-climatic drivers on midwinter 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 since the year 1780. 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) data set (Vuglinsky, 2000). These databases have been used for assessments of river ice conditions (e.g. Smith, 2000; Vuglinsky, 2006), with selected on-site updates up 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), which includes time series of freeze, thaw, and break-up dates and descriptions of ice cover for 237 rivers. A compilation and analysis of Norwegian river 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 the 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 broadscale 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 that assesses the magnitude and timing of specific dynamic river ice variables during the fall freeze-up, midwinter, 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 efforts 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 a description of the data availability and data disclaimers and a conclusion.

## 2 Study area and hydrometric monitoring sites

The locations and characteristics of the near 8400 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](https://wateroffice.ec.gc.ca/station_metadata/reference_index_e.html) (20 July 2020). 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 Canadian 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<sup>2</sup> and that are located north of the mean annual 0 °C 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,

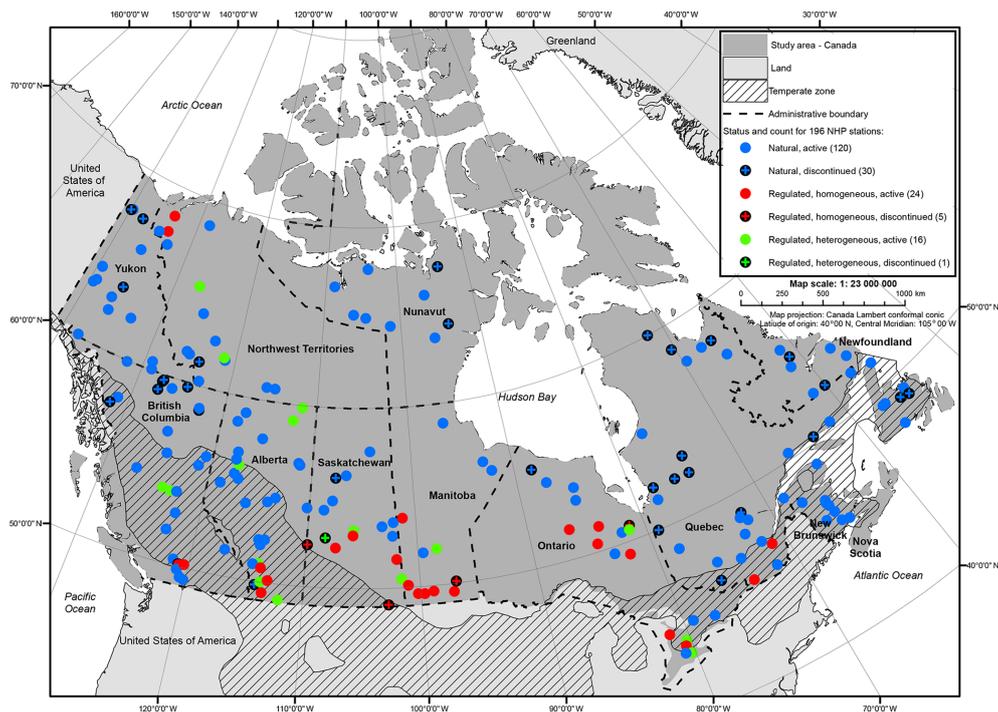
the geographic criterion was expanded south into a “temperate zone” (Newton et al., 2017) and the drainage area threshold was removed. A review of literature and correspondence with WSC staff and provincial flood authorities identified an additional 60 southern sites prone to midwinter break-up events. Inclusion of these sites resulted in a network of 196 sites, with drainage areas ranging from 20.4 km<sup>2</sup> to 1.68 × 10<sup>6</sup> km<sup>2</sup>, 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 or abstraction. The majority of natural sites (120) were in operation up to the end of the study period of 31 December 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 and 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 have resumed operation since their shutdown in the mid-1990s (Fig. 2). After removing the combined 1012 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 the start and end dates and station type. Specific CRID locations within this paper are referenced by gauging site name followed by the NHP alphanumeric identifier in 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 ca. 2000) during the freeze-up, midwinter break-up (if applicable), and spring break-up periods; (2) digital files (after ca. 2000) with water level data at discrete 5 to 15 to 60 min intervals, some including minimum and maximum instantaneous water level for an 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 (ca. 2003–



**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), whether they are active (in operation up to end of 2015) or discontinued, and if the flow condition is homogeneous (always regulated) or heterogeneous (regulated during specific period of operation).

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 handwritten 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 2 years while the 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 and 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 “rivière” in their name) prior to ~ 1997 were limited to the first water level recording of the day, and thereafter summaries of 15 min 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](https://wateroffice.ec.gc.ca/index_e.html) (last access: 20 July 2020) and <http://www.cehq.gouv.qc.ca/hydrometrie/index-en.htm> (last access: 20 July 2020). Finally, note that 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 as NHP had not yet screened these data.

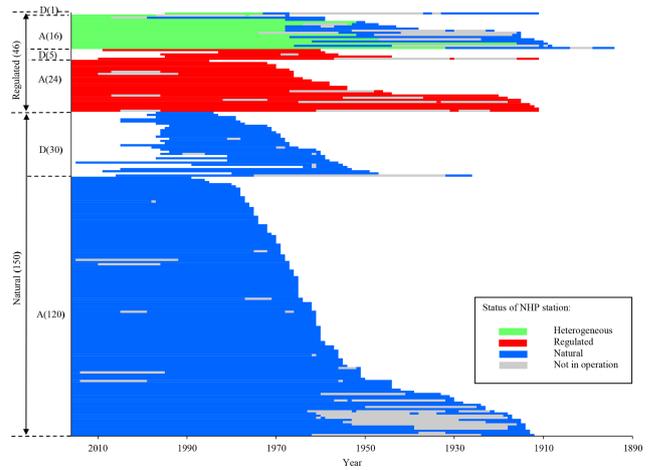
The evolution of the CRID was comprised of six data collection campaigns undertaken since the year 2000 (Table 1). Major data archival efforts in the years 2000–2001 and 2010–2011 required a team of two to three people visiting up to eight WSC regional offices, with each visit lasting up to 2 weeks,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

### 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 and the associated date and time. These instantaneous values correspond

**Table 1.** List of the six data collection campaigns during 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 and 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, Yellowknife, Regina, Winnipeg, Burlington, St. Johns, Corner brook; 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, b)
2007	spring break-up	Mackenzie River delta	14	2002–2006	2	up to 1 week	Yellowknife, Inuvik	Goulding (2008), Goulding et al. (2009a, b)
2008–2009	spring break-up	Northern Canada	136	2002–2006	–	–	Transfer of digital information from eight regional offices and three provincial agencies	von de Wall et al. (2009, 2010), von de Wall (2011)
2010–2011	fall freeze-up, midwinter and spring break-up	Canada	196	up to 2008	7	up to 2 weeks	Vancouver, Calgary, Yellowknife, Regina, Winnipeg, Burlington, Fredericton; digital information from three provincial agencies	Brooks (2012), Brooks et al. (2013), Newton et al. (2017), Newton (2018)
2017–2018	fall freeze-up, midwinter and spring break-up	Canada	196	2009–2015	–	–	Transfer of digital information from seven regional offices and three provincial agencies	de Rham et al. (2018, 2019)



**Figure 2.** Bar chart showing the operational history of the 196 National Hydrometric Program (NHP) stations included in the Canadian River Ice Database. Stations are categorized by flow condition (natural or regulated), operational status (active, A, or discontinued, D) and flow condition (homogeneous or heterogeneous). The number in each subcategory is shown brackets.

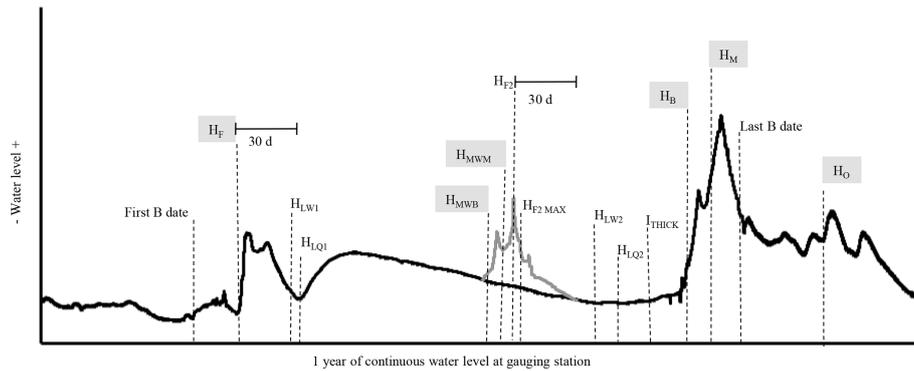
with the water level at the initiation and maximum flood level for ice-specific and open-water conditions during each calendar year. The procedure for extracting river ice data follows the guidelines of Beltaos (1990) and primarily involves visual examination of water level records. Hence, identification 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 variables based on instantaneous (Table 2, grey shading), mean daily water level or mean daily discharge ( $H_{LQ1}$ ,  $H_{LQ2}$ ), 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 in Table 3.

### 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 and other publications, in addition to experiences during the development of this database. This background information is considered to be of high value to users when interpreting spatial and temporal characteristics of river ice data.

**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 that denotes an attempt to identify instantaneous water level events. Data quality rating was applied to the data in bold.

Season	Variable	Symbol	Description	Data resolution: instantaneous (I), daily (D), no extraction (-)	Data quality rating (0-1-2)	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	Freeze-over water level	H <sub>F</sub>	Channel-wide ice cover; daily water level at H <sub>F</sub> and the following 29 d	<b>I or D</b>	D	<b>I or D</b>	Y
Ice cover	First minimum winter water level	H <sub>LW1</sub>	Minimum daily water level between H <sub>F</sub> and H <sub>B</sub>	<b>D</b>	D	D	Y
Ice cover	First minimum winter discharge	H <sub>LQ1</sub>	Minimum daily discharge between H <sub>F</sub> and H <sub>B</sub>	D	<b>D</b>	D	Y
Ice cover	Midwinter break-up initiation	H <sub>MWB</sub>	Initiation of midwinter break-up event	<b>I</b>	D	I	Y
Ice cover	Maximum midwinter break-up water level	H <sub>MWM</sub>	Maximum midwinter break-up event water level	<b>I or D</b>	D	<b>I or D</b>	Y
Ice cover	Maximum winter water level	H <sub>F2</sub>	Freeze-up after H <sub>MWM</sub> . If there is no midwinter event, the first day of the 7 d average if it exceeds the H <sub>F</sub> 7 d average	<b>D</b>	D	D	Y
Ice cover	Maximum winter water level 7 d	H <sub>F2MAX</sub>	Maximum daily water level within the first 7 d following H <sub>F2</sub>	<b>D</b>	D	D	Y
Ice cover	Second minimum winter water level	H <sub>LW2</sub>	Minimum daily water level between H <sub>F2</sub> and H <sub>B</sub> if H <sub>LW1</sub> is before H <sub>F2</sub>	<b>D</b>	D	D	Y
Ice cover	Second minimum winter discharge	H <sub>LQ2</sub>	Minimum daily discharge between H <sub>F2</sub> and H <sub>B</sub> if H <sub>LQ1</sub> is before H <sub>F2</sub>	D	<b>D</b>	D	Y
Ice cover	River ice thickness	TRHICK	Average channel ice thickness prior to spring break-up	-	-	D	N
Break-up	Spring break-up initiation	H <sub>B</sub>	Beginning of spring break-up event	<b>I</b>	D	I	Y
Break-up	Maximum spring break-up water level	H <sub>M</sub>	Maximum spring break-up water level event	<b>I or D</b>	D	<b>I or D</b>	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 <sub>O</sub>	Maximum water level occurring outside the first B date to last B date range	<b>I or D</b>	<b>I or D</b>	<b>I or D</b>	Y



**Figure 3.** Conceptual schematic of a continuous river water level hydrograph (black line) spanning 1 September to 31 August. The period of ice-affected flow is constrained by the first B date and last B date. A possible midwinter break-up event is shown as a grey line at the approximate centre of the hydrograph. Symbols for the 15 variables that 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 the x axis and vertical exaggeration of the y axis accentuate the water level changes observed during ice conditions. The relative magnitudes of variables and water level pathology should not be considered as typical.

**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 that there is no gap in the recorded hydrometric data, fragmented means that there are some gaps over the period of review and sporadic indicates that only limited data are available. This was a qualitative expert-judgement-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

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 relocation of the station due to a loss of a 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 that lead 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 forms (Poyser et

al., 1999). The data user, therefore, has to be aware of these possibilities when using “B” dates as a metric for river ice conditions. In reference to S–Q relationships under ice, Environment Canada (1980) makes the following statement:

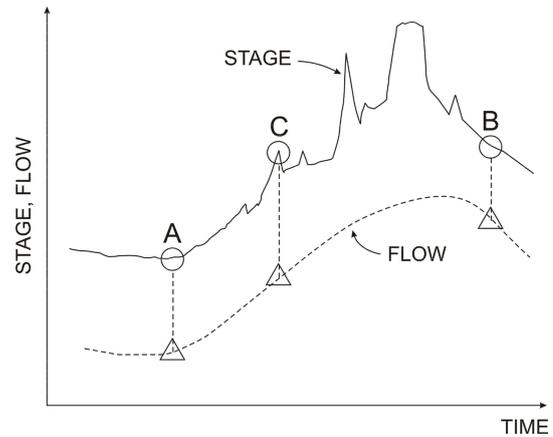
Because of the many variable factors involved, no single standard procedure is suggested for the computation of daily discharges during periods when the stage–discharge relation is affected by the presence of ice. Several methods of computing discharges under ice conditions are available and it is suggested that the Regional Offices use the method that best suits each individual station.

The CRID, with data sourced from regional offices and partner organizations across the country, inherits this discharge calculation legacy for the 11 reported on-site ice-affected discharge time series (Table 2: discharge in the data resolution column). Cold-region hydrometric programs have to contend with measurement problems and uncertainties of under-ice flows (Pelletier, 1990). The accuracy of measurements 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 complicates 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 follows: “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 “computa-

tion 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](https://wateroffice.ec.gc.ca/report/historical_e.html?stn=07KC001), last access: 20 July 2020) the WSC informs users that “data quality during spring break-up [is] considered poor and [quality during the] remaining ice period [is] 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; therefore, 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 generated by runoff. 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, and 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.

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. Cunderlik and Ouarda, 2009; Burn and Whitfield, 2015). More discussion on these issues is needed to inform the water community of the challenges related to cold-region 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.



**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. Figure taken from Beltaos (© Crown Copyright, 2012b; published by NRC Research Press).

### 3.4 CRID variables

The following subsections, 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 freeware Environment Canada Data Explorer ([https://wateroffice.ec.gc.ca/mainmenu/tools\\_and\\_downloads\\_index\\_e.html](https://wateroffice.ec.gc.ca/mainmenu/tools_and_downloads_index_e.html), last access: 20 July 2020). The first occurrence of this flag, the first B date, marks the beginning of the 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 the nearby presence of significant anchor ice build-up on the riverbed. 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 10 October, but open-water sections appear on 14 October and even 1 month later on 7 November. Only the 12 November image shows 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 as-

sumed 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/>, last access: 20 July 2020) 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 the 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, the NHP first B date was used.

Formation of a channel-wide ice cover is the culmination of various processes that include frazil ice growth and ice pan development, juxtaposition, and upstream progression. 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 rated as “1”. Review of daily meteorological data at proximal climate stations can help the interpretation by showing that air temperatures remained below  $0^\circ\text{C}$  and the observed spike was not a result of rainfall in the region (Beltaos, 1990). Meteorological data review was accomplished using the “Search by Proximity” function from: [https://climate.weather.gc.ca/historical\\_data/search\\_historic\\_data\\_e.html](https://climate.weather.gc.ca/historical_data/search_historic_data_e.html) (last access: 20 July 2020). 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 tends to occur when temperatures dropped to  $-10^\circ\text{C}$ . 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

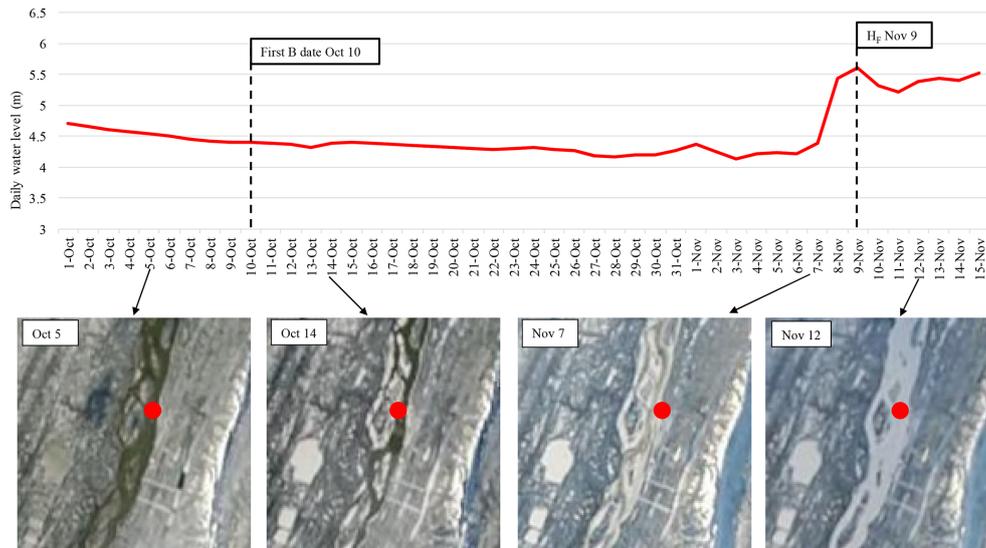
as the average water level for 1 week after formation of a complete ice cover (Beltaos, 1997). Following this methodology, the CRID includes all available daily water levels at  $H_F$  and the following 29 d to (1) allow for calculation of a 7 d average to parameterize a water level threshold of exceedance for the ice to detach from channel banks at break-up (Beltaos, 1997) and (2) tabulate the 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 kilometres upstream (e.g. Prowse and Carter, 2002; Beltaos, 2009) and (3) allows for the application of peak factors concept (Zhang et al., 2005) as the ratio between instantaneous and mean daily water level to aid in the design of river structures.

### 3.4.2 Ice cover: $H_{LW1}$ , $H_{LQ1}$

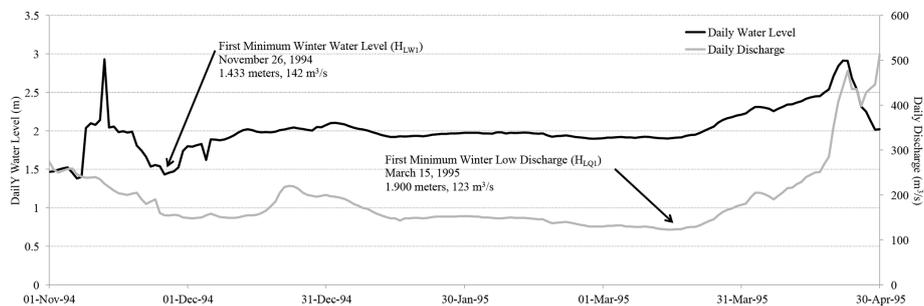
Along with the drainage of surface water storage, a primary source of flow in unregulated rivers during the winter ice cover period is groundwater. The gradual drawdown of these contributions over the ice cover season leads to a reduction in river flow, with the water level eventually reaching a corresponding 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 3 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 with 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).

### 3.4.3 Ice cover: $H_{MWB}$ , $H_{MWM}$

Rapidly warming air temperatures (above  $0^\circ\text{C}$ ) and associated rain-on-snow events during the ice cover season are the main causes of midwinter 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 midwinter ice jams, elevated



**Figure 5.** Daily mean water level hydrograph for 1 October to 15 November 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/>, last access: 20 July 2020). The station location is indicated by red circle. The width of the channel is approximately 1300 m and includes numerous islands. Flow is from bottom to top. The first B date is 10 October, while the freeze-over water level ( $H_F$ ) occurred on 9 November and these images were obscured by clouds. River channel open water is green and ice cover is white on these true-colour images.



**Figure 6.** Daily reported water level and discharge for the Athabasca River below Fort McMurray (07DA001) for the ice-affected (B flagged) period spanning 1 November 1994 to 30 April 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).

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 us if temperatures exceed  $0^{\circ}\text{C}$  and associated rainfall occurred. During data extraction it was often observed that midwinter break-up occurrence corresponded with tens of centimetres of 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 when station visit re-

marks were available days before or after the “winter peak”, alluding to the channel ice condition or whether 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 midwinter breakup event is



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

followed by a dramatically cold period during which frazil generation is significant. The result may be very thick ice accumulations, more ice-jamming or 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 judgement of whether these daily maximums likely represented a midwinter break-up. On occasion, a rudimentary internet search was used to find alternative verification. Midwinter 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 midwinter 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 midwinter break-up events, a closer examination of the CRID time series and comparison to nearby hydrometric stations may be required before pursuing further analysis.

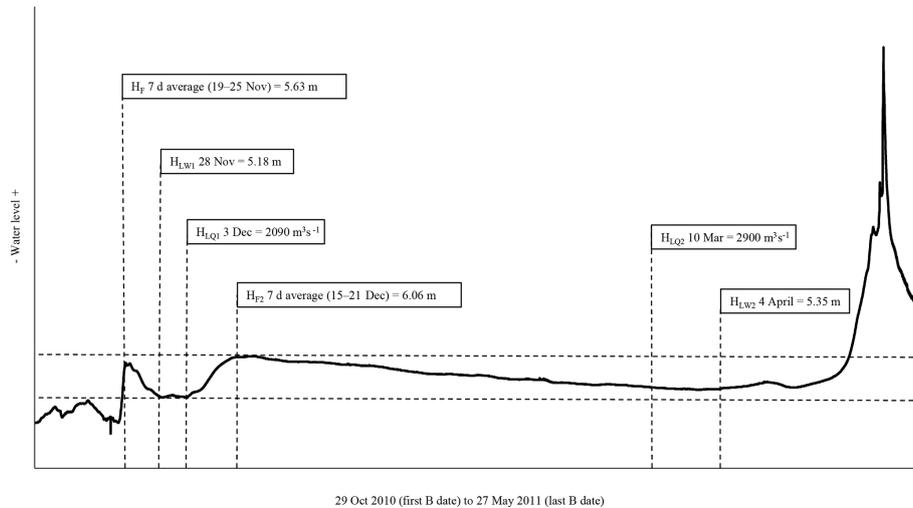
#### 3.4.4 Ice cover: $H_{F2}$ , $H_{F2MAX}$ , $H_{LW2}$ , $H_{LQ2}$

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 midwinter break-up event, an attempt was made to extract the first 7 d 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) that extend far beyond the  $H_{MWM}$  event. Examination of more recent continuous digi-

tal water level records reveals that after midwinter break-up, limited “stage up”, synonymous with  $H_F$ , 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 midwinter break-up generally reveal a pattern of steadily declining daily water levels. Notably, this pattern is likely typical on relatively flat river channels, while on steep river sections, progressive frazil accumulation produced in newly open sections 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 the “B” data flag appeared again. As with the first freeze-up events,  $H_{F2}$  and the following 29 d of daily water level were recorded. Water levels within the first 7 d after  $H_{F2}$  were also assessed to extract a maximum ( $H_{F2MAX}$ ) 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 midwinter break-up event. In this situation, the 7 d average water level beginning at  $H_{F2}$  exceeds that commencing from  $H_F$ . This may correspond with a secondary stage during extreme cold events described by Hamilton (2003), with Fig. 8 depicting 1 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 station at Peace Point (07KC001), when midwinter 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.

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

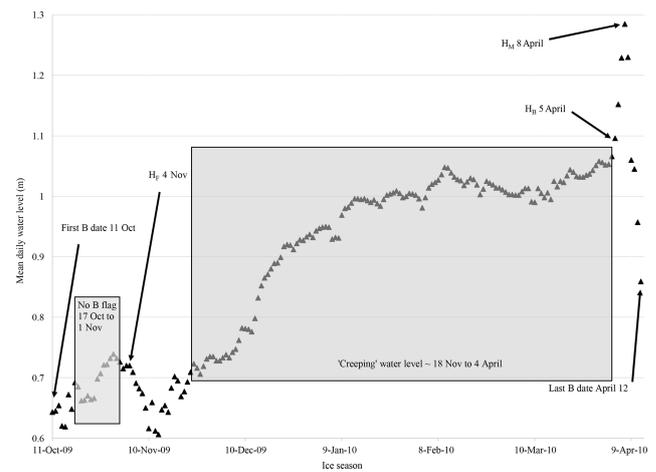


**Figure 8.** Continuous water level record for Mackenzie River at Norman Wells during the 2010–2011 ice-affected flow period. Note the occurrence of a higher magnitude 7 d average following  $H_{F2}$  in comparison to  $H_F$  and the corresponding second winter minimums ( $H_{LW2}$  and  $H_{LQ2}$ )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

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: $I_{THICK}$

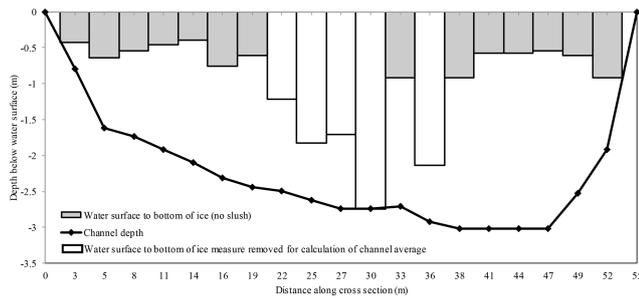
Hydrometric technicians visit gauging stations for velocity, water depth, discharge, and water level measurements and instrument maintenance approximately six to eight times per year, which includes both open-water and ice-covered conditions. During the latter, a measure related to the solid portion 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 in 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  $\sim 1995$  are generally limited to water surface elevation to bottom of ice cover and thus may underestimate the actual thickness of the ice cover as 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 these 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



**Figure 9.** Daily water level from first B date to last B date at Pembina River station at Jarvie (07BC002) during the 2009–2010 ice-affected flow season that depict “creeping” water level. There are no B data flags from 17 October to 1 November and daily average water levels creeping upwards throughout the ice cover period.

include slush (see caption for Fig. 10). The remaining measurements were used to calculate the average river ice thickness ( $I_{THICK}$ ).

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 d) time window. In addition to data collection timing, incomplete archiving and scanning for the database may also be a reason for missing or wide



**Figure 10.** A bar plot of the 19 water surface to bottom of ice thickness measurements collected on 28 March 1978 at Nashwaak River below Durham Bridge (01AL002). The hydrometric survey note indicates that the measurement, at 30 m river cross section distance is slush to bottom. Visual examination of this plot reveals 4 other measurements (shown with white fill) that likely include slush. These 5 measurements are removed when calculating average river ice thickness.

ranges in time series. Thus, any time series analysis of  $I_{\text{THICK}}$  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.

#### 3.4.6 Break-up: $H_B$ , $H_M$ , last B date

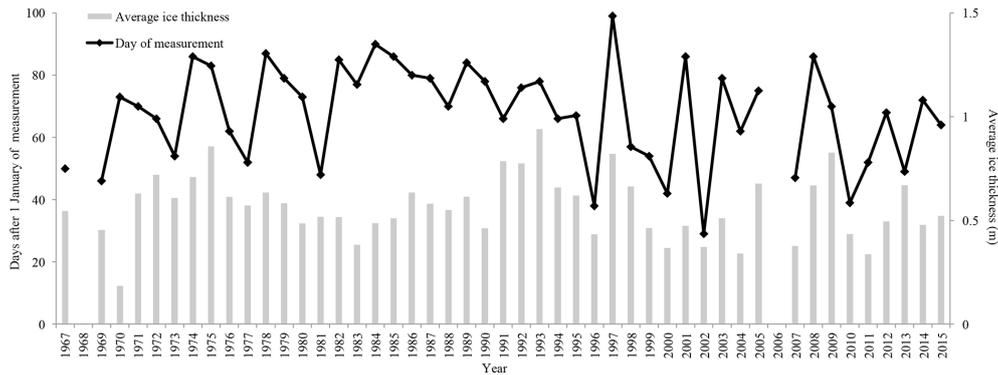
The end of the river ice season progresses through a continuum of spring break-up initiation ( $H_B$ ), maximum spring break-up water level ( $H_M$ ) and the last day of ice-affected flow (last B date).  $H_B$  occurs at the initial downstream movement of river ice cover. The associated decrease in resistance 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 the 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 gauge can also have 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 midwinter thaws accompanied by intense rain-on-snow runoff events (Deslauriers, 1968). It is likely that much of the CRID midwinter 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 station near Hay River (07OB001). Unfortunately, images at the extracted CRID timings of  $H_B$  and  $H_M$  are not available; however, images 5 min later are illustrative. The night-time image (24 April, 04:30 UTC) shows a large chunk of ice along the left channel bank, indicating fracture of the ice cover and initiation of break-up. An hour later, the near-open-channel condition (24 April, 05:30 UTC) highlights the downstream forces involved in flushing of in-channel ice. The image on 25 April at 15:30 UTC shows stranded ice fragments on the channel banks, 5 min after  $H_M$  (25 April, 15:25 UTC). 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



**Figure 11.** Plot showing average ice thickness (grey bars) day of measurement (black line) at site Nashwaak River below Durham Bridge (01AL002). Measurement dates input to CRID represent a range of 72 d from 29 January (2002) to 9 April (1997). Initiation of break-up at this location ranges from 27 February (2010) to 13 April (2001) with the average being 25 March (84 d after 1 January).

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 provide 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 by solely identifying the last B date.

### 3.4.7 Open-water: $H_O$

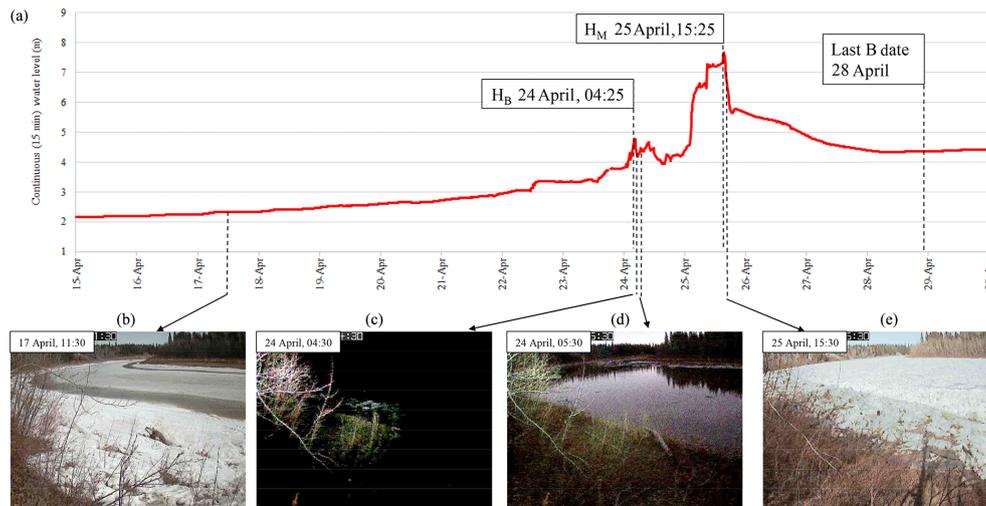
The CRID includes the magnitude and timing of the annual maximum open-water level ( $H_O$ ) and the associated discharge value at each station, along with data quality rating. These data are extracted from the hydrometric archives and are easily verified, as NHP web pages generally report both daily 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 level versus open-water level on the Peace River. These types of analyses inform the hydrological community of the importance of looking at ice effects as the likely causes of maximum annual flood for nearly 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 processes (snowmelt, rain-on-snow, rainfall) and their seasonality is 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 two decimal places for the pre-1978 data (given in feet) and three decimal places for the post-1978 data (in metres) was possible based on visual inspection of the continuous (i.e. analogue) water level recording charts (pre ~ 2000). All imperial data in feet were converted to metres using factor of 0.3048 and are reported to three decimal places in the CRID database. Although a lot of the water level records are continuous, the visual extraction method often limited the associated timing of an event to a 15 min resolution. Instantaneous timing at finer resolution within the CRID was usually obtained from alternative archival documents (e.g. annual water level page, station analysis or published online summaries). The widespread use of digital water level recording instrumentation after ca. 2000 decreased the temporal resolution (i.e. accuracy) of water level records as data collection interval varied from 5 to 15 to 60 min. Some data loggers also recorded hourly to sub-hourly maxima and minima, 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 on-site station observers that 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 publica-



**Figure 12.** Continuous 15 min interval water level hydrograph for 15 to 30 April 2010 at the National Hydrometric Program Hay River gauging station near Hay River (070B001), along with images courtesy of the Alberta Research Group. **(b)** Image looking upstream taken 7 d prior to spring break-up initiation ( $H_B$ ) of 24 April 2010, 04:25 UTC. Channel width of approximately 63 m. Panel **(c)** is a night-time image 5 min after  $H_B$  and shows evidence of fragmented ice in the channel. Panel **(d)** was taken 65 min after  $H_B$  and shows the channel nearly clear of ice. Panel **(e)** was taken 5 min after the maximum spring break-up water level on 25 April 2010, 15:25 UTC. Stranded ice on channel banks indicates higher water levels. The last B date was 28 April 2010.

tions (Table 1). CRID station data were initially compiled as single-station Excel files that include all extracted water levels; discharges; date, time, and accuracy ratings; average ice thicknesses; and time series plots for visual identification of outliers. A separate station Excel file contains all available ice thickness measurements and average calculations. All finalized station data were compiled in to a single .csv file (118 columns  $\times$  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 midwinter associated discharge had the highest input error at 16 %. This higher percentage of error is a likely a remnant of the multiple rounds of revisions to midwinter 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 or entry error. The CRID initiation of break-up ( $H_B$ ) time series at the Red River site near Lockport (050J010) was provided to Becket (2020) who reported that, 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 h too early and another was 2 d 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](http://data.ec.gc.ca/data/water/scientificknowledge/canadian-river-ice-database/CRID_BDCGF_Versioning_EN_FR.txt), last access: 20 July 2020).

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 1-year period at a single station was about 1 h. 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 dams in the channels; open water leads at, upstream, or downstream of the gauge; percentage of ice cover at gauge; water flowing between the ice layers; and anchor

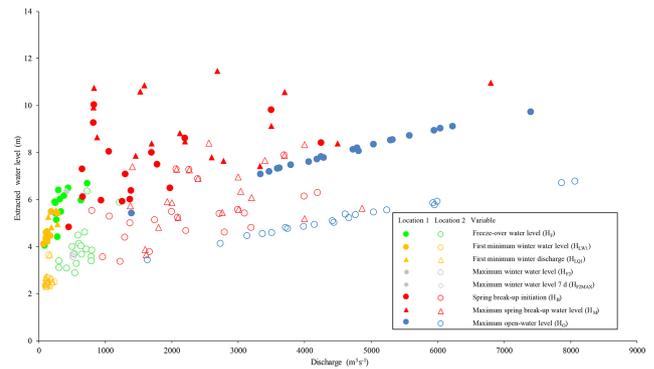
ice at a cross section. While these types of observations are not part the CRID, users should be aware of such factors that add further complexity to wintertime water level interpretation. Furthermore, collection of data using a stilling well (von de Wall, 2011) could also affect resultant water level 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 that can result in wintertime cross section measurements taken metres 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 is a necessary next step. For example, Fig. 13 shows all Albany River CRID data on a stage–discharge plot. The WSC website informs us 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 that are not directly comparable for many types of analysis.

## 4 Discussion

### 4.1 The CRID

Nearly 2 decades of data collection efforts and study have culminated in the CRID, which covers a network of 196 hydrometric stations with data up to 31 December 2015 that collectively 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, and discharge-based metrics and provide a comprehensive baseline data set for research purposes. The CRID is available for download at <https://doi.org/10.18164/c21e1852-ba8e-44af-bc13-48eedfcf2f4> (de Rham et al., 2020).



**Figure 13.** A stage–discharge plot of Canadian River Ice Database variables for the Albany River site 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 29 September 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.

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 6094 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 9705 (94 %) of the 10 378 active station years. Similarly, the 8933 (9240) first (last) day with backwater due to ice (B dates) and 8178 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 midwinter break-up occurrence includes 467 maximum midwinter break-up water level and 362 associated midwinter break-up initiation events. The data quality rating presented in Table 4 confirms that the NHP archive 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 nearly 2800 active and 5500 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

**Table 4.** Total number of variables that populate the Canadian River Ice Database and their data quality ratings. Grey shading indicates that an attempt was made to extract the instantaneous water level. Also included are column totals per river type: natural versus regulated, active versus discontinued and homogeneous versus heterogeneous.

Season	Variable	Symbol	Total number of variables	Data quality rating			Number of variables by station type			
				0	1	2	Natural		Regulated	
							active	discontinued	Homo-geneous, active	Hetero-geneous, discontinued
Freeze-up	First day with backwater due to ice	First B date	8933	No data quality rating	5754	806	1204	130	1022	16
Freeze-up	Freeze-over water level	H <sub>F</sub>	6547	4794	1592	161	4142	466	881	3
Ice cover	First minimum winter water level	H <sub>1W1</sub>	4767	4557	193	17	2861	214	766	0
Ice cover	First minimum winter discharge	H <sub>1Q1</sub>	8178	8114	62	2	5301	764	925	0
Ice cover	Midwinter break-up initiation	H <sub>MWB</sub>	362	359	3	0	249	11	40	0
Ice cover	Maximum midwinter break-up water level	H <sub>MWM</sub>	467	392	70	5	308	22	51	0
Ice cover	Maximum winter water level	H <sub>P2</sub>	1954	1816	39	99	1180	104	325	0
Ice cover	Maximum winter water level 7 d	H <sub>P2MAX</sub>	1952	1849	27	78	1180	104	325	0
Ice cover	Second minimum winter water level	H <sub>LW2</sub>	798	794	4	0	407	39	159	0
Ice cover	Second minimum winter discharge	H <sub>LQ2</sub>	709	709	0	0	325	37	171	0
Ice cover	River ice thickness	ITHICK	6094	No data quality rating	4163	416	762	59	669	25
Break-up	Spring break-up initiation	H <sub>B</sub>	5534	5070	333	131	3541	323	641	23
Break-up	Maximum spring break-up water level	H <sub>M</sub>	7355	5428	1571	356	4483	503	914	44
Break-up	Last day with backwater due to ice	Last B date	9240	No data quality rating	5816	788	1380	186	1024	46
Open-water	Maximum open-water level	H <sub>O</sub>	9705	5705	3728	271	6121	826	1119	47
	Column total		72 595	39 587	7622	1122	45 831	5423	9032	204

of operation up until 31 December 2015. Regulated locations are also split into homogeneous and heterogeneous depending on when the regulation began during the measurement timeline. Active station 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 a particular year, or loss of information during the CRID archival and scanning process.

#### 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 changed 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-mtgn/ndmp/fldpln-mppng-en.aspx>, last access: 20 July 2020).

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 hydraulic research initiatives (e.g. NSERC FloodNet, 2015, and 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, 2015). 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 the thickness and strength of pre-break-up ice covers, the 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 and 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 or 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-region 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 hydraulic (Lindenschmidt, 2017) modelling efforts, and ground truth observations for remote sensing applications (Pavelsky and Smith, 2004; Yang et al., 2020).

## 5 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-bc13-48eedfcf2f4> (de Rham et al., 2020). A 0.5 Terabyte digital archive of all available scanned and digital hydrometric archives, which contains around 30 000 folders and over 100 000 files, is stored on the ECCC server and is available up request.

## 6 Conclusions

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 worth of data from a select subset of 196 sta-

tions, 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 that are 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 31 December 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 is needed to formalize whether this task would be completed by the same group or undertaken by others. It is fortunate that much of the task of data acquisition discussed above could be automated using the Aquarius platform currently in use by NHP partner organizations (Stuart Hamilton, personal communication, 25 June 2019). 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 2 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-region river systems.

## Appendix A

**Table A1.** List of the 196 National Hydrometric Program stations that comprise the Canadian River Ice Database. Data extraction time period are shown in the “start” and “end” columns. Locations with “rivière” in the name of the water course are in Quebec. The “type” column is the regime type, defined as follows: 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	Station number	Start	End	Type	Water course	Station number	Start	End	Type	Water course
01AL002	1961	2015	NA	Nashwaak River at Durham Bridge	04JG001	1966	2015	RHOA	Kenogami River near Mammamattawa	07NB001	1921	2015	RHEA	Slave River at Fitzgerald (Alberta)
01AN002	1974	2015	NA	Salmon River at Castaway	04LD001	1920	2015	RHOA	Groundhog River at Fauquier	07OB001	1921	2015	NA	Hay River near Hay River
01AP004	1961	2015	NA	Kennebecasis River at Apohaqui	04LG002	1959	1982	RHOD	Moose River at Moose River	07OB003	1974	2015	NA	Hay River near Meander River
01BC001	1962	2015	NA	Restigouche River below Kedgwick River	04LJ001	1959	2015	NA	Missinaibi River at Mattice	07OC001	1969	2015	NA	Chinchaga River near High Level
01BH005	1970	2015	NA	Dartmouth (Rivière) en Amont du Ruisseau du Pas de Dame	04LM001	1972	2015	NA	Missinaibi River below Waboose River	07PA001	1968	2015	NA	Buffalo River at Highway no. 5
01BO001	1918	2015	NA	Southwest Miramichi River at Blackville	04ME003	1959	2015	RHEA	Abitibi River at Onakawana	08AB001	1974	2015	NA	Alsek River above Bates River
01BP001	1951	2015	NA	Little Southwest Miramichi River at Lyttleton	04NA001	1924	2015	NA	Harricana (Rivière) 3.1 km en aval du Pont-Route 111 a Amos	08CE001	1954	2015	NA	Stikine river at Telegraph Creek
01BQ001	1961	2015	NA	Northwest Miramichi River at Trout Brook	04NB001	1967	2004	ND	Turgeon (Rivière) en Amont de la Rivière Harricana	08CF001	1971	1995	ND	Stikine River above Butterfly Creek
01BV006	1964	2015	NA	Point Wolfe River at Fundy National Park	05AA023	1949	2008	ND	Oldman River near Waldron's Corner	08EE004	1930	2015	NA	Bulkley River at Quick
02EC002	1913	2015	NA	Black River near Washago	05AB021	1908	2015	RHEA	Willow Creek near Claresholm	08JC001	1915	2015	RHEA	Nechako River at Vanderhoof
02FC001	1911	2015	RHOA	Saugeen River near Port Elgin	05AC003	1918	2015	RHOA	Little Bow River at Carmangay	08JC002	1950	2015	RHEA	Nechako River at Isle Pierre
02GA014	1947	2015	RHEA	Grand River near Marsville	05AD028	1966	2015	RHOA	Waterton River near Glenwood	08KB001	1950	2015	NA	Fraser River at Shelley
02GA034	1967	2015	RHOA	Grand River at West Montrose	05BJ001	1894	2015	RHEA	Elbow River below Glenmore Dam	08KH006	1939	2015	NA	Quesnel River near Quesnel
02GB001	1912	2015	RHEA	Grand River at Brantford	05BJ004	1923	2015	NA	Elbow River at Bragg Creek	08LF051	1951	2015	NA	Thompson River near Spences Bridge
02GD021	1978	2015	NA	Thames River at Inkerkip	05BL024	1970	2015	RHOA	Highwood River near the mouth	08LG007	1911	2009	RHOD	Nicola River near Merritt
02HL005	1965	2015	NA	Moirs River near Deloro	05CB001	1960	2015	NA	Little Red Deer River near the mouth	08LG010	1911	2015	RHOA	Coldwater River at Merritt
02LG005	1972	2015	NA	Gatineau (Rivière) aux Rapides Ceizur	05CC001	1912	2015	NA	Blindman River near Blackfalds	08LG048	1965	2015	NA	Coldwater River near Brookmere
02LH004	1926	2005	ND	Picanoc (Rivière) pres de Wright	05CC007	1962	2015	NA	Medicine River near Eckville	08LG049	1915	2015	RHOA	Nicola River above Nicola Lake
02NE011	1965	2015	NA	Croche (Rivière) à 2.6 km en aval du Ruisseau Changy	05FF001	1911	1994	RHED	Battle River at Battleford	08MB005	1970	2015	NA	Chilcotin River below Big Creek
02NF003	1931	2015	NA	Matawin (Rivière) a Saint-Michel-des-Saints	05GA007	1944	1994	RHOD	Eyehill Creek near Macklin	08NB005	1944	2015	NA	Columbia River at Donald

Table A1. Continued.

Station number	Start	End	Type	Water course	Station number	Start	End	Type	Water course	Station number	Start	End	Type	Water course
02OA054	1970	2015	RHOA	Chateauguay (Rivière) à 2 km en amont du Pont-Route 132	05GC006	1962	2015	RHOA	Eagle Creek near Environ	08NL007	1914	2015	NA	Similkameen River at Princeton
02OE027	1956	2015	NA	Eaton (Rivière) pres de la Rivière Saint-Francois-3	05GG001	1910	2015	RHEA	North Saskatchewan River at Prince Albert	08NL038	1914	2015	NA	Similkameen River near Hedley
02PB006	1965	2015	NA	Sainte-Anne (Rivière) (bras du Nord de la) en Amont	05HH001	1958	2015	RHOA	South Saskatchewan River at St. Louis	09AE003	1956	2015	NA	Swift River near Swift River
02PJ005	1915	2015	RHOA	Chaudiere (Rivière) au Pont-Route 218 à Saint-Lambert-De-Lauzon	05JM001	1915	2015	RHEA	Qu'Appelle near Welby	09AH001	1951	2015	NA	Yukon River at Carmacks
02QA002	1962	2015	NA	Rimouski (Rivière) à 3.7 km en amont du Pont-Route 132	05KC001	1955	2015	NA	Carrot River near Smoky Burn	09BC001	1951	2015	NA	Pelly River at Pelly Crossing
02RD002	1953	2004	ND	Mistassibi (Rivière)	05KH007	1965	2015	NA	Carrot River near Turnberry	09BC004	1970	2015	NA	Pelly River below Vangorda Creek
02RF001	1915	2015	NA	Ashuapmushuan (Rivière) à la tête de la chute aux Saumons	05KJ001	1913	2015	RHOA	Saskatchewan at the Pas	09CD001	1956	2015	NA	Yukon River above White River
02RG005	1964	2015	NA	Metabetchouane (Rivière) en amont de la Centrale SRPC	05LC001	1914	2015	NA	Red Deer River near Erwood	09DC002	1947	1979	ND	Stewart River at Mayo
02UC002	1965	2015	NA	Moisie (Rivière) à 5.1 km en amont du pont du QNSLR	05LH005	1923	2015	NA	Waterhen River near Waterhen	09DD003	1951	2015	NA	Stewart River at the mouth
02VC001	1956	2014	ND	Romaine (Rivière) au pont de la QIT	05LM006	1967	2015	RHEA	Dauphin River near Dauphin River	09EA003	1965	2015	NA	Klondike River above Bonanza Creek
02WB003	1980	2015	NA	Natashquan (Rivière) à 0.6 km en aval de la décharge du Lac Alieste	05MD004	1944	2015	RHOA	Assiniboine River at Kamsack	09EB001	1944	2015	NA	Yukon River at Dawson
02XA003	1979	2015	NA	Little Mecatina River above Lac Fourmont	05ME006	1954	2015	RHOA	Assiniboine near Miniota	09FB001	1965	1995	ND	Porcupine River below Bell River
02XA004	1979	1996	ND	Rivière Joir near the provincial boundary	05MH005	1954	2015	RHOA	Assiniboine near Holland	09FC001	1976	2015	NA	Old Crow River near the mouth
02XC001	1967	2015	NA	Saint-Paul (Rivière) à 0.5 km du Ruisseau Chanion	05NB009	1956	1995	RHOD	Souris River near Roche Percee	09FD001	1961	1995	ND	Porcupine River at Old Crow
02YA002	1986	2015	NA	Bartletts River near St. Anthony	05NG001	1912	2015	RHOA	Souris River at Wawanesa	10AA001	1960	2015	NA	Liard River at Upper Crossing
02YK008	1985	2015	NA	Boot Brook at Trans-Canada Highway	05NG021	1946	2015	RHOA	Souris River at Souris	10AB001	1962	2015	NA	Frances River near Watson Lake
02YL001	1928	2015	NA	Upper Humber River near Reidville	05OC012	1958	2015	RHOA	Red River near Ste. Agathe	10BB001	1960	1995	ND	Kechika River at the mouth
02YO007	1984	1996	ND	Leech Brook near Grand Falls	05OJ010	1960	2008	RHOD	Red River near Lockport	10BB002	1967	1994	ND	Kechika River above Boya Creek
02YQ012	1989	2015	NA	Southwest Brook at Lewisporte	06AD001	1933	2015	NA	Beaver River near Dorintosh	10BE001	1944	2015	NA	Liard River at Lower Crossing
02YQ004	1983	1998	ND	Northwest Gander River near Gander Lake	06AD006	1955	2015	NA	Beaver River at Cold Lake Reserve	10BE005	1968	1995	ND	Liard River above Beaver River
02ZD002	1969	2015	NA	Grey River near Grey River	06AG001	1971	2015	NA	Beaver River below Waterhen River	10BE006	1969	1995	ND	Liard River above Kechika River

Table A1. Continued.

Station number	Start	End	Type	Water course	Station number	Start	End	Type	Water course	Station number	Start	End	Type	Water course
03BF001	1975	2015	NA	Pontax (Rivière) à 60.4 km de l'Embouchure	06BC001	1970	1995	ND	Mudjatik River near Forcier Lake	10CC002	1978	2004	ND	Fort Nelson River above Muskwa River
03CB001	1959	1980	ND	Eastmain (Rivière) en aval de la Rivière a l'Eau Claire	06BD001	1966	2015	NA	Haultain River above Norbert River	10CD001	1944	2015	NA	Muskwa River near Fort Nelson
03CB004	1979	2004	ND	Eastmain (Rivière) a la tete de la Gorge Prosper	06DA004	1966	2015	NA	Geikie River below Wheeler River	10EA003	1960	2015	NA	Flat River near the mouth
03CC001	1958	1980	ND	Eastmain (Rivière) a la tete de la Gorge de Basile	06GD001	1955	2015	NA	Seal River below Great Island	10EB001	1960	2015	NA	South Nahanni River above Virginia Falls
03DD002	1960	1993	ND	De Pontois (Rivière) en amont de la Rivière Sakami	06JC002	1965	2015	NA	Thelon River above Beverly Lake	10EC001	1959	1996	ND	South Nahanni River above Clausen Creek
03ED001	1961	2015	NA	Baleine (Grande Rivière de la) en amont de la Rivière Denys-1	06LC001	1960	2015	NA	Kazan River above Kazan Falls	10ED001	1942	2015	NA	Liard River at Fort Liard
03HA001	1954	1963	ND	Arnaud (Payne) (Rivière) en amont de la Rivière Hamelin-1	06MB001	1969	1996	ND	Quoich River above St. Clair Falls	10ED002	1972	2015	NA	Liard River near the mouth
03JB001	1955	1988	ND	Feuilles (Rivière aux) en aval de la Rivière Peladeau	07AE001	1960	2015	NA	Athabasca River near Windfall	10GB006	1974	2015	NA	Willowlake River above Metahdali Creek
03KC004	1965	2015	NA	Melezes (Rivière aux) à 7.6 km en amont de la confluence avec la Koksoak	07BC002	1957	2015	NA	Pembina River at Jarvie	10GC001	1938	2015	RHEA	Mackenzie River at Fort Simpson
03MB002	1956	2015	NA	Baleine (Rivière a la) à 40.2 km de l'Embouchure	07BE001	1913	2015	NA	Athabasca River at Athabasca	10HB005	1975	2015	NA	Redstone River 63 km above the mouth
03MC001	1972	1993	ND	Tunlic (Rivière) pres de l'Embouchure	07CD001	1930	2015	NA	Clearwater River at Draper	10KA001	1943	2015	RHEA	Mackenzie River at Norman Wells
03MD001	1975	2015	NA	George (Rivière) à la sortie du Lac de la Hutte Sauvage	07DA001	1957	2015	NA	Athabasca River below Fort McMurray	10LA002	1968	2015	NA	Arctic Red River near the mouth
03NF001	1978	2015	NA	Ugjoktok River below Harp Lake	07EA005	1978	2015	NA	Finlay River above Akie River	10LC002	1972	2015	RHOA	Mackenzie (East Channel) at Inuvik
03NG001	1977	1996	ND	Kanairiktok River below Snegamook Lake	07EC002	1975	2015	NA	Omineca River above Osilinka River	10LC014	1985	2015	RHOA	Mackenzie River at Arctic Red River
03PB002	1977	2015	NA	Naskaupi River below Naskaupi Lake	07FB001	1961	2015	NA	Pine River at East Pine	10MA001	1961	2015	NA	Peel River above Canyon Creek
03QC001	1966	2015	NA	Eagle River above Falls	07FC001	1917	2015	NA	Beatton River near Fort St. John	10MC002	1969	2015	NA	Peel River above Fort McPherson
03QC002	1978	2015	NA	Alexis River near Port Hope Simpson	07GE001	1917	2015	NA	Wapiti River near Grande Prairie	10NC001	1969	2015	NA	Anderson River below Carnwath River
04AB001	1972	2015	NA	Hayes River below Gods River	07GH002	1959	2015	NA	Little Smoky River near Guy	10QC001	1976	2015	NA	Burnside River near the mouth
04AD002	1967	2015	NA	Gods River near Shamattawa	07GJ001	1915	2015	NA	Smoky River at Watino	10QD001	1969	2015	NA	Ellice River near the mouth
04CC001	1968	1995	ND	Seyvern River at Limestone Rapids	07HA001	1915	2015	RHEA	Peace River at Peace River	10RA001	1977	2015	NA	Back River below Beechy Lake
04DC001	1965	2015	NA	Winisk River below Asheweig River tributary	07HA005	1967	2015	NA	Whitemud River near Dixonville	10RA002	1977	2015	NA	Baillie River near the mouth

**Table A1.** Continued.

Station number	Start	End	Type	Water course	Station number	Start	End	Type	Water course	Station number	Start	End	Type	Water course
04EA001	1967	2015	NA	Ekwan River below North Washagami River	07HC001	1961	2015	NA	Notikewin River at Manning	10RC001	1960	2015	NA	Back River above Hermann River
04FC001	1968	2015	NA	Attawapiskat River below Muketei River	07JD002	1970	2015	NA	Wabasca River at Highway no. 88	10SB001	1971	1994	ND	Hayes River above Chantrey Inlet
04GD001	1966	2015	RHOA	Albany River above Nottik Island	07KC001	1959	2015	RHEA	Peace River at Peace Point (Alberta)	11AA005	1909	2015	RHEA	Milk River at Milk River
04HA001	1964	2015	RHOA	Albany River near Hat Island										

**Author contributions.** LdR coordinated this study, completing data extraction, data entry, and quality control and also wrote the manuscript. YD supervised this study as principal investigator since 2017 and reviewed the manuscript. SB conceptualized the extraction of river-ice-related data from hydrometric records in 1990, provided technical guidance throughout the study and reviewed the manuscript. DP provided technical input in the data extraction, data quality, and ecological and flood aspects and also reviewed the manuscript. BB advised on river regulation, hydroclimatic regions, and time series uncertainties and also reviewed the manuscript. TP, ECCC Emeritus Scientist since 2017, initiated this study as a principle investigator in the late 1990s.

**Competing interests.** The authors declare that they have no conflict of interest.

**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 their processing and management. Furthermore, the material or any data derived using the data are 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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