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-bc13-48eeedfcf2f4 (de Rham et al., 2020).

1 Introduction

River ice is an intrinsic component of cold climate watersheds. The Committee on River Ice Processes and the Environment (CRIPE; http://www.cripe.ca/, 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 Chaudière 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 (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 km² 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 km² to 1.68 × 10⁶ km², 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–
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 (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.

| Study focus | Collection Location | Number of Archival and WSC regional sites | Duration of WSC regional office visits | WSC regional office visit locations and NHP partners | Publications |
|-------------|---------------------|------------------------------------------|--------------------------------------|--------------------------------------------------|--------------|
| 2000–2001 spring break-up | northern Canada | 143 | up to 2 weeks | Vancouver, Calgary, Yellowknife, Regina, Winnipeg, Burlington, Prowse and Lacroix (2001), Inuvik, Fort Simpson, Calgary | L. de Rham et al. (2000a, b) |
| 2003 spring break-up | Mackenzie River basin | 29 | 5 up to 1 week | Inuvik, Fort Simpson, Calgary, Yellowknife, Inuvik, Peace River | de Rham et al. (2006), de Rham et al. (2008a, b) |
| 2007 spring break-up | Mackenzie River delta | 14 | 2 up to 1 week | Yellowknife, Inuvik, Peace River | Goulding et al. (2008a, b) |
| 2008–2009 spring break-up | Northern Canada | 136 | 7 up to 2 weeks | Vancouver, Calgary, Yellowknife, Regina, Winnipeg, Burlington, Prowse and Lacroix (2001), Inuvik, Fort Simpson, Calgary | Newton et al. (2017), Newton (2018) |
| 2010–2011 fall freeze-up | Canada | 196 | up to 2 weeks | Yellowknife, Inuvik, Peace River | de Rham et al. (2012), Brooks et al. (2013), Gouding et al. (2008), Newton et al. (2017), Newton (2018) |
| 2017–2018 fall freeze-up | Canada | 196 | 7 up to 2 weeks | Vancouver, Calgary, Yellowknife, Regina, Winnipeg, Burlington, Prowse and Lacroix (2001), Inuvik, Fort Simpson, Calgary | 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. |
|------------------------------------------------------|
| Data resolution: instantaneous (I), Data quality rating: daily (D), no extraction (–) |

| Season | Variable Description | Symbol | Data Quality Rating | Data Resolution |
|--------|-----------------------|--------|---------------------|----------------|
| Fall-Winter | Maximum water level reached last day of freeze-up | H_max | – | I |
| Winter-Spring | First day freeze-up | D | I |
| Winter-Spring | Maximum water level reached first day of freeze-up | H_min | – | I |
| Winter-Spring | Maximum water level reached last day of freeze-up | H_max | – | I |
| Winter-Spring | First day freeze-up | D | I |
| Winter-Spring | Minimum water level between H_min and H_max | H_l | D | D |
| Winter-Spring | Maximum water level reached last day of freeze-up | H_max | – | I |
| Winter-Spring | First day freeze-up | D | I |
| Winter-Spring | Maximum water level reached first day of freeze-up | H_max | – | I |
| Winter-Spring | Minimum water level between H_min and H_max | H_l | D | D |
| Winter-Spring | Maximum water level reached last day of freeze-up | H_max | – | I |
| Winter-Spring | First day freeze-up | D | I |
| Winter-Spring | Maximum water level reached first day of freeze-up | H_max | – | I |
| Winter-Spring | Minimum water level between H_min and H_max | H_l | D | D |
| Winter-Spring | Maximum water level reached last day of freeze-up | H_max | – | I |
| Winter-Spring | First day freeze-up | D | I |
| Winter-Spring | Maximum water level reached first day of freeze-up | H_max | – | I |
| Winter-Spring | Minimum water level between H_min and H_max | H_l | D | D |
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                          | 0                | 1                | 2                |
|-------------------------------|------------------|------------------|------------------|
| Instantaneous water level      | Continuous       | Fragmented       | Fragmented       |
| 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 the 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, 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 breakup 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, 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-
 assumed to be a channel-wide ice cover condition. Though extraction of CRID variables did not use alternative means of verification, using satellite images from the WorldView interface (accessed at https://worldview.earthdata.nasa.gov/, 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\textsubscript{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°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 (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 $-10^\circ$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\textsubscript{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\textsubscript{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\textsubscript{LW1}, H\textsubscript{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\textsubscript{LW1}) and estimated first minimum winter discharge (H\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{MWB}, H\textsubscript{MWM}

Rapidly warming air temperatures (above 0°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<sub>F</sub>) 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°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<sub>WMWB</sub> 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<sub>WMWM</sub>. For some stations, H<sub>WMWB</sub> and H<sub>WMWM</sub> can occur more than once during a single ice season (e.g. Beltaos, 2002). In such cases, only the first H<sub>WMWB</sub> and the highest H<sub>WMWM</sub> are included in the CRID. In some cases, a midwinter breakup event is
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\textsubscript{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\textsubscript{F2}, H\textsubscript{F2 MAX}, H\textsubscript{LW2}, H\textsubscript{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\textsubscript{F2}) after the event. As with H\textsubscript{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\textsubscript{F2} since the CRID archive does not have historical pen recorder charts (Sect. 3.2) that extend far beyond the H\textsubscript{MWM} event. Examination of more recent continuous digital water level records reveals that after midwinter break-up, limited “stage up”, synonymous with H\textsubscript{F}, was usually observed. This may be due to the lack of complete ice flush down the channel after H\textsubscript{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\textsubscript{MWM} was followed by days with no “B” data flag, H\textsubscript{F2} was restricted to days when the “B” data flag appeared again. As with the first freeze-up events, H\textsubscript{F2} and the following 29 d of daily water level were recorded. Water levels within the first 7 d after H\textsubscript{F2} were also assessed to extract a maximum (H\textsubscript{F2 MAX}) daily water level exceeding H\textsubscript{F2}. This variable may more closely match the instantaneous processes resulting in the H\textsubscript{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\textsubscript{F2} exceeds that commencing from H\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{F} for most of the ice season (Fig. 9). In such cases, it was not possible to establish H\textsubscript{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\textsubscript{F2} variable was identified, the ice cover period was examined for a second winter-low water level (H\textsubscript{LW2}) and discharge (H\textsubscript{LQ2}) event. These data were only added to the CRID if H\textsubscript{LW1} or H\textsubscript{LQ1} were before H\textsubscript{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 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 \sim100\text{m} from this location. Image taken from Rebello (2013).
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\textsubscript{F2} in comparison to H\textsubscript{F} and the corresponding second winter minimums (H\textsubscript{LW2} and H\textsubscript{LQ2}) in addition to the first occurrence (H\textsubscript{LW1} and H\textsubscript{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\textsubscript{THICK}

Hydrometric technicians visit gauging stations for velocity, water depth, 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 ∼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 include slush (see caption for Fig. 10). The remaining measurements were used to calculate the average river ice thickness (I\textsubscript{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
ranges in time series. Thus, any time series analysis of I\textsubscript{THICK} needs to account for the 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\textsubscript{B}, H\textsubscript{M}, last B date

The end of the river ice season progresses through a continuum of spring break-up initiation (H\textsubscript{B}), maximum spring break-up water level (H\textsubscript{M}) and the last day of ice-affected flow (last B date). H\textsubscript{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\textsubscript{B} from a record of mean daily water level. Therefore, the timing and magnitude of H\textsubscript{B} may be less accurate than H\textsubscript{M}, the maximum instantaneous or daily water level established following H\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{B} and H\textsubscript{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\textsubscript{B} and H\textsubscript{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\textsubscript{M} (25 April, 15:25 UTC). The peak water levels at H\textsubscript{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

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**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.
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 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

The CRID includes the magnitude and timing of the annual maximum open-water level (H) 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 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, H, H, H, H, H), 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 (07OB001), 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.

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 × 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 (05OJ010) 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.

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, up-steam, 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-bc13-48eeedfcf2f4 (de Rham et al., 2020).

In total, the CRID holds 72 595 recorded variables with more than 460 000 data entries of water level, discharge, date, time and data quality rating based on the review of over 100 000 hydrometric archive files. Tabulation of the 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 population 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.

| Number of variables by station type | Data quality rating | Natural | Homogenously, active | Homogenously, discontinued | Heterogenously, active | Heterogenously, discontinued |
|-----------------------------------|---------------------|---------|----------------------|---------------------------|-----------------------|-----------------------------|
| Total number geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneous, geneo...
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 (Linden-schmidt, 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-bc13-48eedf6ef24 (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 upon 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 stations, covering a range of stream types and climatic regions, to identify and extract recorded data corresponding to 15 variables comprising water levels, discharges, timings, ice thickness and data quality ratings. Close to 73,000 records of river ice variables are now available to the water research community. For sites 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.
### 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, 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   | 04QG001        | 1966  | 2015  | RHOA  | Kenogami River near Mammatawawa  | 07NB001        | 1921  | 2015  | RHEA  | Slave River at Fitzgerald (Alberta) |
| 01AN002        | 1974  | 2015  | NA    | Salmon River at Castaway          | 04LD001        | 1920  | 2015  | RHOA  | Groundhog River at Faquier       | 07OB003        | 1921  | 2015  | NA    | Hay River near Hay River          |
| 01AP004        | 1961  | 1982  | RHOD  | Moose River at Moose River        | 07DB003        | 1974  | 2015  | NA    | Hay River near Meander River      |                |       |       |       |                                   |
| 01BC001        | 1962  | 1959  | NA    | Restigouche River below Redpike   | 04LJ001        | 1959  | 2015  | NA    | Missinabik 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    | Missinabik River below Waboo River | 07PA003        | 1968  | 2015  | NA    | Buffalo River at Highway no. 5     |
| 01BO001        | 1951  | 2015  | NA    | Little Southwest Miramichi River at Blackville | 04ME003        | 1959  | 2015  | RHEA  | Abitibi River at On-akawana       | 08AB001        | 1974  | 2015  | NA    | Alsek River above Bates River      |
| 01BP001        | 1951  | 2015  | NA    | Little Southwest Miramichi River at Lyndes | 04NA001        | 1924  | 2015  | NA    | Huriciana (Rivière) (3.1 km en aval du Pont-Route 111 a Amos) | 08CE001        | 1954  | 2015  | NA    | Stikine river at Telegraph Creek   |
| 01BQ001        | 1961  | 2004  | ND    | Missouri River at Trout Brook     | 04NB001        | 1967  | 2004  | ND    | Turgeon (Rivière) en Amont de la Rivière | 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    | Baikley 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  | Saugerm River near Port Elgin      | 05AC003        | 1918  | 2015  | RHOA  | Little Bow River at Carmangay     | 08JC002        | 1950  | 2015  | RHOA  | Nechako River at Isle Pierre      |
| 02GA014        | 1947  | 2015  | RHEA  | Grand River near Mansville        | 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       | 05BH001        | 1984  | 2015  | RHEA  | Elbow River below Glenmore Dam    | 08KB006        | 1939  | 2015  | NA    | Quesnel River near Quesnel         |
| 02GB001        | 1912  | 2015  | RHEA  | Grand River at Brantford          | 05BH004        | 1923  | 2015  | NA    | Elbow River at Bragg Creek        | 08LF051        | 1951  | 2015  | NA    | Thompson River near Spences Bridge |
| 02GD021        | 1978  | 2015  | NA    | Thames River at Inverkirk         | 05BL024        | 1970  | 2015  | RHOA  | Highwood River near the mouth     | 08LG007        | 1911  | 2009  | RHOD  | Nicola River near Merritt         |
| 02HL005        | 1965  | 2015  | NA    | Mist River near Deloros           | 05CB001        | 1960  | 2015  | NA    | Little Red Deer River near the mouth | 08LG010        | 1911  | 2015  | RHOD  | Coldwater River near Merritt       |
| 02LG005        | 1972  | 2015  | NA    | Gatineau (Rivière) aux Rapides Ceziur | 05CC001        | 1912  | 2015  | NA    | Blindman River near Blackfalds    | 08LG048        | 1965  | 2015  | NA    | Coldwater River near Brokmere      |
| 02LH004        | 1926  | 2005  | ND    | Picanoc (Rivière) pres de Wright  | 05CC007        | 1962  | 2015  | NA    | Medicine River near Eckville      | 08LG049        | 1915  | 2015  | RHOD  | Nicola River above Nicola Lake     |
| 02NE011        | 1965  | 2015  | NA    | Croche (Rivière) à 2.6 km en aval du Ruisseau Changey | 05FF001        | 1911  | 1994  | RHOD  | Battle River at Battleford        | 08MB005        | 1970  | 2015  | NA    | Chilkoot River below Big Creek     |
| 02NP003        | 1931  | 2015  | NA    | Matawin (Rivière) a Saint-Michel-des-Saints | 05GJ007        | 1944  | 1994  | RHOD  | Eyehill Creek near Macklin         | 08NB005        | 1944  | 2015  | NA    | Columbia River at Donald           |

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| Station number/Year | Start/End | Type | Water course | Station number/Year | Start/End | Type | Water course |
|---------------------|-----------|------|--------------|---------------------|-----------|------|--------------|
| 02DA054             | 1970-2015 | RHOA | Chateauguay   | 05GC006             | 1962-2015 | RHOA | Eagle Creek  |
|                     |           |      | (Rivière) à 2 km en amont du Pont-Route 132 |                     |           |      | near Embrun  |
| 02DR027             | 1956-2015 | NA   | Eaton (Rivière) près de la Rivière Saint-François-3 | 05GJ001             | 1910-2015 | RHEA | North Saskatchewan River at Prince Albert |
|                     |           |      |              |                     |           |      |              |
| 02PB006             | 1965-2015 | NA   | Sainte-Anne (Rivière) bras du Nord de la en Amont | 05HI001             | 1958-2015 | RHOA | South Saskatchewan River at St. Louis |
|                     |           |      |              |                     |           |      |              |
| 02PB005             | 1915-2015 | RHOA | Chaudiere (Rivière) au Pont-Route 218 à Saint-Lambert-De-Lauzon | 05IM001             | 1915-2015 | RHEA | Qu’Appelle near Wey |
| 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  | Madjutik River near Fortier Lake | 10CC002       | 1978   | 2004  | ND  | Fort Nelson River above Muska River |
| 03CB001       | 1959   | 1980  | ND   | Eastmain (Rivière) en aval de la Rivière à l’Eau Claire | 06BD001       | 1966   | 2015  | NA  | Hautlait River above Norbert River | 10CD001       | 1944   | 2015  | NA  | Muskwa River near Fort Nelson |
| 03CB004       | 1979   | 2004  | ND   | Eastmain (Rivière à la tête de la Gorge Prosper) | 06DA004       | 1966   | 2015  | NA  | Gekie River below Wheeler River | 10EA003       | 1960   | 2015  | NA  | Flat River near the mouth |
| 03CC001       | 1958   | 1980  | ND   | Eastmain (Rivière) à la tête de la Gorge de Basle | 06GD001       | 1955   | 2015  | NA  | Seal River below Great Island | 10EB001       | 1960   | 2015  | NA  | South Nahanni River above Virginia Falls |
| 03DD002       | 1960   | 1993  | De Pontois (Rivière) en amont de la Rivière Sakamik | 06EC002       | 1965   | 2015  | NA  | Thelon River above Beverly Lake | 10EC001       | 1959   | 1996  | ND  | South Nahanni River above Chasen 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   | Amsal (Paysse) (Rivière) en amont de la Rivière Hamelin-1 | 06MB001       | 1969   | 1996  | ND  | Quoch 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 Peladou | 07AE001       | 1960   | 2015  | NA  | Athabasca River near Wunifdall | 10GB006       | 1974   | 2015  | NA  | Willow Lake River above Metabah Creek |
| 03KC004       | 1965   | 2015  | NA   | Melreaux (Rivière aux) à 7.6 km en amont de la confluence avec la Koksook | 07BC002       | 1957   | 2015  | NA  | Pembina River at Jarvie | 10GC001       | 1938   | 2015  | RHEA | Mackenzie River at Fort Simpson |
| 03MB002       | 1956   | 2015  | NA   | Baleine (Rivière à la) à 40.2 km de l’Embouchure | 07BE001       | 1913   | 2015  | NA  | Athabasca River at Athabaska | 10HB005       | 1975   | 2015  | NA  | Redstone River 63 km above the mouth |
| 03MC001       | 1972   | 1993  | ND   | Tumalic (Rivière) près 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 Sauvant | 07DA001       | 1957   | 2015  | NA  | Athabasca River below Fort McMurray | 10LA002       | 1968   | 2015  | NA  | Arctic Red River near the mouth |
| 03NF001       | 1978   | 2015  | NA   | Ujgoistik River below Harp Lake | 07EA005       | 1978   | 2015  | NA  | Finlay River below Aksie River | 10LC002       | 1972   | 2015  | RHEOA | Mackenzie River (East Channel) at Inuvik |
| 03NG001       | 1977   | 1996  | ND   | Kavanaktuk River below Snagamook Lake | 07EC002       | 1975   | 2015  | NA  | Omistea River below Ominkka River | 10LC014       | 1985   | 2015  | RHEOA | 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  | Beaton River near Fort St. John | 10MC002       | 1969   | 2015  | NA  | Peel River above Fort McPherson |
| 03QC002       | 1978   | 2015  | NA   | Alexis River near Port Hope Simpson | 07GB001       | 1917   | 2015  | NA  | Wapiti River near Grande Prairie | 10NC001       | 1969   | 2015  | NA  | Anderson River below Cameron River |
| 04AB001       | 1972   | 2015  | NA   | Hayes River near Port Hope Simpson | 07GH002       | 1959   | 2015  | NA  | Little Smoky River near Gay | 10Q0001       | 1976   | 2015  | NA  | Burns River near the mouth |
| 04AD002       | 1967   | 2015  | NA   | Gods River near Shoemattawa | 07GI001       | 1915   | 2015  | NA  | Smoky River at Watino | 10Q0001       | 1969   | 2015  | NA  | Ellese River near the mouth |
| 04CC001       | 1968   | 1995  | ND   | Severe River at Limestone Rapids | 07HA001       | 1915   | 2015  | RHEA | Peace River at Peace River | 10RA001       | 1977   | 2015  | NA  | Back River below Beechey Lake |
| 04DC001       | 1965   | 2015  | NA   | Winisk River below Ashweig River tributary | 07HA005       | 1967   | 2015  | NA  | White Mud River near Dixonville | 10RA002       | 1977   | 2015  | NA  | Baillie River near the mouth |
| 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 Muketi 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 Notik 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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