Cold-regions Hydrological Indicators of Change (CHIC) for ecological flow needs assessment

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Abstract Ecological flow needs (EFN) frameworks incorporate a range of ecologically-relevant hydrological variables based on prior knowledge of river regime characteristics. However, when applied in cold regions, these approaches have largely ignored the influence of winter ice cover and the spring freshet on hydrological regimes: key components of river systems in cold regions with important direct effects on water quality, aquatic habitat and ecology. Here, we combine a review of the published literature on cold-regions hydrology and hydro-ecology with available hydrometric information for sites across Canada, a major cold-region country, to explore phenomena unique to these systems. We identify several ecologically-relevant hydrological measures (i.e. annual ice on/off dates, ice-cover duration, spring freshet initiation, peak water level during river ice break-up), pairing these with established metrics for incorporation into an enhanced suite of indicators specifically designed for cold regions. This paper presents the Cold-regions Hydrological Indicators of Change (CHIC), which can provide the basis for the assessment of EFN and climate change assessments in cold-region river ecosystems.

Key words ecological flow needs assessment; cold-regions hydrology; hydro-ecology; indices

Indicateurs hydrologiques du changement pour une évaluation du débit écologique nécessaire dans les régions froides

Résumé Le débit écologique a besoin d’un cadre intégrant toute une gamme de variables hydrologiques écologiquement pertinentes fondée sur la connaissance préalable des caractéristiques du régime de la rivière. Toutefois, lorsqu’elles ont été appliquées dans les régions froides, ces approches ont largement ignoré l’influence sur les régimes hydrologiques de la couverture de glace hivernale et de la crue printanière, qui sont les composantes fondamentales des systèmes fluviaux des régions froides avec des effets directs importants sur la qualité de l’eau, l’habitat aquatique et l’écologie. Nous combinons ici une revue de la littérature publiée sur l’hydrologie et l’hydro-écologie des régions froides avec l’information hydrométrique disponible pour des sites du Canada, un grand pays de régions froides, afin d’explorer les phénomènes propres à ces systèmes. Nous avons identifié plusieurs mesures hydrologiques écologiquement pertinentes (durée et dates du débit et de la fin de l’englacement, date du début de la crue de printemps, niveau d’eau maximum pendant la débâcle), et associé celles-ci avec les métriques habituelles pour les incorporer dans un ensemble amélioré d’indicateurs spécialement conçus pour les régions froides. Cet article présente les indicateurs hydrologiques de changement, qui peuvent servir de base à l’évaluation des débits écologiques nécessaires et à l’évaluation des changements climatiques dans les écosystèmes fluviaux des régions froides.

Mots clefs débit écologique ; évaluation des besoins ; hydrologie des régions froides ; hydro-écologie ; indices

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INTRODUCTION

Landscape alterations and instream flow modifications, such as deforestation, irrigation, diversion and hydroelectric dams, alter the flow regime of rivers in terms of the quantity, variability and timing of streamflow. This in turn causes alterations in sediment transport, water quality and habitat quality in aquatic ecosystems, e.g. the south Saskatchewan River Basin in western Canada (Clipperton et al. 2003) and the Colorado River in the western USA (Pennisi 2004). In response to river system degradation, instream flow-needs guidelines (also known as ecological or environmental flow needs; see Acreman and Dunbar 2004 for definitions) have been developed towards protecting and sustaining aquatic ecosystems across the world. Since the 1990s, instream flow-needs research has increasingly focused on the protection goal of maintaining all components of the river ecosystem, such as those that are influenced by extreme temporal variation in instream flow (Richter et al. 1996, Poff et al. 1997, Lytle and Poff 2004). This is particularly true in cold-climate countries, such as Canada, where the majority of flow regimes are characterized by winter low flows and high spring/summer flow periods (Leclerc et al. 2003, Monk et al. 2011).

The natural flow paradigm proposed by Poff et al. (1997) emphasizes the importance of maintaining the range of intra- and inter-annual variation of the daily and seasonal flows to protect aquatic ecosystems. Ecologically relevant components of the hydrological regime can be expressed as hydrological variables, such as the 33 variables employed in the Indicators of Hydrological Alteration (IHA) method (TNC 2007). Through an exploration of flow–ecology relationships, numerous studies have demonstrated that several of these hydrological variables can explain observed ecological variability in riverine communities (e.g. Monk et al. 2006, Monk and Wood 2008, Armanini et al. 2011, 2012). Hydro-ecological variables, such as the IHA, typically quantify five facets of the hydrological regime: the magnitude, frequency, timing, duration and rate of change of events. With a large number of available hydrological indices presented in the literature (currently >200), Olden and Poff (2003) produced a comprehensive review to explore the potential statistical redundancy, and identified a subset of variables that could be used to explain statistical variation in critical attributes of flow regimes. Beveridge et al. (2012) extended this analysis northward to the Canadian prairies. Despite the obvious influence of low winter temperatures on flow regimes and habitat conditions in North America, no explicit cold-region relevant hydrological indices are found in the above redundancy assessments.

Recent developments in establishing ecological flow needs (EFN) frameworks have incorporated a range of ecologically-relevant hydrological variables (e.g. Poff et al. 2010, Peters et al. 2012a). However, these approaches often fail to explicitly characterize the influence of winter ice cover and the spring freshet—key components of river systems in cold regions—on hydrological regimes and the associated water quality, aquatic habitat and ecology. Based on a review of the published literature and the available hydrometric information for Canadian rivers, we have identified several ecologically-relevant hydrological measures (i.e. annual ice on/off dates, ice cover duration, spring freshet initiation) paired with established hydrological metrics for incorporation into a comprehensive suite of indicators specifically designed for regions of the world that experience annual winter snowpack and ice cover. This paper introduces the Cold-regions Hydrological Indicators of Change (CHIC) using case study samples from the Mackenzie River Basin, a cold-region watershed currently experiencing multiple hydro-ecological stresses from climate variability/change, land-use change, flow regulation and water abstraction.

COLD-REGIONS HYDROLOGY AND ECOLOGY

A large portion of the northern hemisphere experiences air temperatures sufficiently cold (i.e. <0°C) for precipitation to fall as snow and accumulate on the landscape, or to form ice cover on river, lake and wetland systems. Figure 1 presents the world map of the main Köppen-Geiger climate classification for snow and polar climates of the world. In the Northern Hemisphere these two broad air temperature- and precipitation-based classifications (see Kottek et al. 2006 for details) cover the bulk of the continental areas north of 50°N latitude, and extend farther south in several areas, such as elevated mountain regions. Seasonal ice cover can develop as far south as 33°N in North America and 26°N in Eurasia, affecting about half of the world’s 15 largest river and lake systems (Prowse 2005).

The hydrology of watersheds in cold regions is governed by a number of temperature-controlled
processes that influence the timing, duration and magnitude of flow and water levels related to the formation, growth and ablation of the annual snow and ice cover (Ashton 1986, Gray and Prowse 1993). Prowse et al. (2001a, 2001b) provide a synthesis of river-ice ecology with a focus on the major hydrological event of the year—spring break-up of river ice (Beltaos 1995, Prowse and Culp 2003). According to Hicks (2008), the study of river ice processes and hydraulics is an emerging research area, as is the winter dynamics of stream ecosystems (Huusko et al. 2007). In this paper, we focus on highlighting the in-channel hydraulic effects of ice processes and snowmelt on flow and water levels that are important to riverine aquatic ecology and to the identification and/or development of hydrological indices of change to incorporate in EFNs for cold regions of the world.

For most of Canada and other cold regions, winter is a period during which ice cover coincides with an annual low-flow period (e.g. Fig. 2 representing flow in a headwater tributary of the Mackenzie River Basin, western Canada; location in Fig. 3). Even before ice begins to form, the biological system must begin to adjust to declining flows and also to reducing solar radiation (i.e. shortening of day length) and cooling waters (Prowse 2001a). Winter conditions present a substantial challenge to the
survival of aquatic species, and are considered a critical stage for stream-dwelling fish, because reduced winter flows and associated ice formation will reduce the availability of habitat (Cunjak 1996, Cunjak et al. 1998). Adaptive changes in behaviour and distribution of animals are expected in such regions with dramatic seasonal environmental changes (Chapman 1966). An example of typical seasonal variation in surface water conditions is shown in Fig. 4 for stream reaches in the Mackenzie River Basin, typifying changes from the early autumn open water through late autumn freeze-up to stable winter ice cover, and ultimately followed by river ice break-up in the spring. Floating ice is thus a key component of cold-regions freshwater systems, as it creates and controls aquatic habitats and related biological productivity and diversity.

The first step of river ice-cover formation is cooling of surface waters to 0°C and below, leading to the development of ice crystals that are kept in suspension by fluid turbulence, and formation of border ice along the river banks where both flow velocity and turbulence are negligible (Hicks 2008). The so-called frazil slush ice particles will grow and reach a size at which they become buoyant, accumulating to form floating pans that flow downstream, freeze together and collect along border ice. Low flows can increase the incidence of frazil and anchor ice as more water is exposed to cold air, especially over riffle areas where cold air is entrained by turbulence (Simkins and Hubert 2000). In certain conditions, fish that inhabit pools may be buffered from low flows (Dare et al. 2002); however, the accumulation of frazil ice in pools can be significant, forcing fish to exit these habitats (Komandian-Douthwright et al. 1997). Frazil ice entrained within the main flow can cause physical and physiological damage to fish species through gill abrasion and plugging (Brown et al. 1994).

As the surface concentration of ice approaches 80–90%, the congestion of ice floes and the resulting

**Fig. 3** Map of Mackenzie River Basin in western Canada. Headwater tributaries, the Peace and Athabasca rivers, as well as the Peace-Athabasca Delta (1), the WAC Bennett Dam (2), the Slave River Delta (3) and the Mackenzie Delta (4), are highlighted.
cessation of their movement downstream can occur at tight bends or at narrowing of the channel. Once bridging of the ice cover occurs, incoming ice floes may accumulate edge to edge and lead to upstream progression of the ice front by juxtaposition, or may be swept under the existing ice cover, resulting in hydraulic ice thickening at that point. The hydraulic properties defining fish habitat may also be affected by frazil ice particles that adhere to bed material to form anchor ice. Anchor ice can alter flow conditions by artificially raising the riverbed, creating backwaters with reduced water velocities, which may result in water diversion into other parts of the channel and/or into the floodplain (Prowse and Gridley 1993, Stickler and Alfredsen 2005). Eythorsson and Sigtryggsson (1971) reported that flow in the lowland reaches of an Iceland river was reduced to 6% of normal by the rapid formation and damming effects of anchor and frazil ice in its headwaters. Biota, particularly fish eggs and embryos developing within gravel beds, in addition to macroinvertebrates utilizing the interstitial spaces as refugia, may be affected by freezing of the bed material, and also by the elimination of substrate inflow (e.g. Walsh and Calkins 1986, Calkins 1989, Power et al. 1993). Macroinvertebrate communities, a key source of food for overwintering fish, are also affected by ice and freezing conditions, with anchor ice found to be implicated in winter-long declines in invertebrate abundance (Martin et al. 2001).

The establishment of ice cover on a river channel decreases the flow conveyance by reducing channel cross-sectional area, reducing flow velocity and increasing flow resistance due to the presence of an enlarged wetted perimeter. This may influence upstream water levels through backwater increase with the displacement of water into channel storage behind the ice cover (Prowse 2001a, Hicks 2008). For instance, the relative rise in stage for an ice cover with similar roughness as the bed is about 30% higher than for comparable open-water flow conditions (Prowse 1994). Winter stage increases have been found to be important for supplying water to aquatic habitats located along channel margins and the floodplain (Paschke and Coleman 1986, Burn 1993), providing preferred side-channel and off-channel pond habitat for some fish species (e.g. Komadina-Douthwright et al. 1997), whereas restricted access to bank habitat and overwintering survival of fish was found in a region with low winter flows not influenced by the hydraulic effects of an ice cover (Mitro et al. 2003). On a large river system, water abstraction from flow to feed ice growth and hydraulic storage upstream behind the accumulating ice can substantially decrease the water flow downstream (Moore et al. 2002, Prowse and Carter 2002). For example, a pronounced dip in the hydrograph during the freeze-up period in the headwaters of the Mackenzie River Basin resulted in the lowest historical daily mean flow observed in 2001 on the lower Athabasca River (e.g. also seen in Fig. 2).

Low-gradient, larger rivers are characterized by a stable ice cover with ice-free openings in riffles. In contrast, smaller, steeper rivers can undergo an extended period of dynamic ice formation due to turbulent flow before stabilizing (Tesaker 1994, Stickler and Alfredsen 2005). Growth of the ice cover over the winter months can occur from both above and below. In the absence of an insulating snow cover, the ice cover grows down from the bottom as a result of thermal heat loss through the ice cover, halting when the depth of any snow equals...
about half the ice thickness (Prowse 1994, Hicks 2008). An additional ice layer may form on top of an ice cover when the overlying snow mass is sufficient to depress the top of the floating ice below the water level, causing water to overflow and saturate the lower snowpack and subsequently freeze as white ice (Hicks 2008).

Lower velocities associated with receding flows can result in lower hyporheic flow and an increased presence of lower dissolved oxygen groundwater, which can cause mortality of incubating eggs and larvae (Bradford and Heinonen 2008). In addition, the restriction of re-aeration due to ice cover and oxidation of organic material may further increase rates of dissolved oxygen depletion over the long winter period (Chambers et al. 1997). Continued ice growth during the winter period can lead to an increasing portion of the river channel margins (and other shallow locations) completely freezing to the bed. In shallow streams or connecting channels, such as in deltaic environments, ice growth can lead to the concentration of flow within only the deepest and/or highest velocity portions of the channel, and complete freezing of small streams can occur unless there is enough winter flow from lakes and ponds or recharge from groundwater (Prowse 2001a). Complete or partial freezing to the bed can be beneficial to connected lake systems by preventing drainage during the winter period (e.g. Pohl et al. 2009, Lesack and Marsh 2010). In Nordic regions, streamflow in small streams may cease completely during the winter, due to the freezing of soil down to the permafrost, preventing subsurface flow from reaching the channel (Woo 1986).

In temperate climates, river ice can go through a series of freeze-up/break-up cycles, whereas in colder climates break-up is typically a spring event (Beltaos et al. 2003). Changing ice conditions have been cited as a major reason for in-stream movement of some fish species throughout the winter (e.g. Cunjak and Randall 1993). The movement of gravel beds in association with ice formation, ice break-ups and high flows may also negatively impact fish eggs by washing them out, subjecting them to mechanical abrasion, or by decreasing wetted area and thereby exposing the eggs to desiccation or freezing. Ice processes thus need to be taken into consideration in the design of fish-stream habitat enhancement (Linnansaari et al. 2009).

Another major change event in cold-regions river hydrology, the late winter/early spring freshet, occurs when air temperatures increase above 0°C causing melting of the snowpack and initiating significant runoff to the river systems. The interaction of a large flood wave with an intact and mechanically strong ice cover can result in dynamic river ice break-up and ice jamming. These may present significant resistance and/or obstruction to the intense freshet flow, leading to extremely high river stage and occasional over-banking of channel water. In contrast, moderate increases in flow and a thermally deteriorated ice cover (thermal break-up) together pose little resistance to the passage of flow (Gray and Prowse 1993). Figure 5 illustrates the dramatic effect of dynamic break-up processes on river stage as compared to open-water flow conditions for a Mackenzie River headwater tributary (Peace River); the presence of ice jams produced backwater levels several metres higher than those for the same discharge under open water conditions.

The ice-influenced flood mechanism has been shown to be essential for periodic replenishing of water to perched lake and wetland basins of cold-regions deltas in the Mackenzie River Basin (Peters et al. 2006, Lesack and Marsh 2010). A study by de Rham et al. (2008a) demonstrated that about half of the tributaries of this basin, for which the Peace and Athabasca rivers form the headwater tributaries, are dominated by annual extreme peak water levels generated under river ice (spring) break-up conditions. Nationally, an estimated 40% of the floods in Canada over the years 1983–1987 were caused by ice-jam events (Beltaos 1995). The analyses of flood recurrences in cold regions of the world cannot be solely based on discharge records, but should also consider the occurrence of backwater level conditions produced by ice jamming. The severity of extreme events is dependent on the prevailing climate, and may be affected by activities in the watershed, such as hydroelectric power generation and/or water abstractions. Moreover, their frequency and intensity are likely to be significantly altered under climate warming scenarios (Beltaos et al. 2006).

**ECOLOGICAL FLOW ASSESSMENT FOR COLD REGIONS**

The emergence of hydrology-based EFN frameworks (Richter et al. 1996, Arthington et al. 2006, Poff et al. 2010) has led to increasing interest in the use of hydrological indices by riverine ecologists and water resources managers. However, concern has been raised regarding the large number of hydrological predictors available and the potential for
significant redundancy (multicollinearity) between variables (Olden and Poff 2003). For instance, Olden and Poff (2003) identified 171 hydrograph indicators from the literature and applied them to 420 hydrometric stations across the continental USA to select a statistically reduced set of variables that could be used to quantify the hydrological variability within the flow regimes. Beveridge et al. (2012) extended the analysis northward to more than 200 Canadian prairie streams using a subset of 131 of the hydrological variables, with the goal of statistically deriving a small, independent subset of hydrograph indicators that will lead to more effective EFN decisions. However, Monk et al. (2007) demonstrated that statistically identified dominant sources of hydrological variability may not select variables of true ecological significance. As seen in Fig. 1, extensive areas of the continental USA and Canada are influenced by cold-region processes described in the previous section; yet, no hydrological indicators that explicitly describe key cold-regions riverine phenomena are contained in the lists of indicators presented in Olden and Poff (2003) and Beveridge et al. (2012). Cold-region specific hydrological indicators are found in the literature (e.g. climate change assessments in Canada). However, their omission in EFN frameworks and assessments is important since the suite of indicators selected should reflect the characteristics of the region being studied. More specifically, this could be achieved through characterization in terms of hydrograph variables likely to be important in shaping ecological processes in a river that are sensitive to various forms of anthropogenic disturbance.

Bradford and Heinonen (2008) stated that standard setting and hydrological methods can provide EFN recommendations for winter months, but their efficacy in protecting aquatic biota is still unknown through lack of supporting study. For instance, 25% of the mean annual flow (MAF), a minimum flow level required to maintain aquatic habitats, was a method historically used for the evaluation of EFN in Atlantic Canada (Caisse et al. 2007). Across the country, a percent reduction from natural flow recommendations (e.g. 0–15% of instantaneous flows, with a cutoff flow for the 80% exceedence natural flow based on a weekly or monthly time step) has been proposed for fish habitat protection in Alberta streams, western Canada (Locke and Paul 2011). The importance of explicitly assessing the winter flow period was further supported with a recent workshop and literature review-based project for the assessment and development of winter flow requirements for the protection of fish in streams of the neighbouring province of British Columbia, Canada (Hatfield 2012).

More elaborate habitat modelling can be used, but it is unclear whether the abundance of appropriate physical habitat in winter is limiting fish relative to other factors such as ice formation. A review of

![Fig. 5 Annual peak water level vs discharge under break-up conditions in the lower Peace River at Peace Point hydrometric station 70 km upstream of Delta, headwaters of the Mackenzie River Basin, northern Alberta (updated from Peters et al. 2006). Data are presented for the pre-regulation (1962–1967), filling of Williston Reservoir (1968–1971), and post-regulation (1972–2008) periods.](image-url)
The development of hydro-ecological models that incorporate winter habitat for fish, and include the hydraulic complexities of ice formation and the effects of ice on flows, is under way in Norway (Alfredsen and Tesaker 2002) and Canada (Katopodis and Ghamry 2007, Ohlson et al. 2010). According to Bradford and Heinonen (2008), the complexity of such models currently precludes their routine use in stream assessments. Thus, while river managers await the development of elaborate, high-tiered EFN methodologies that incorporate the mechanisms by which winter flows and conditions affect the performance and survival of biota, it is sensible and timely that first-level assessment tools, such as the widely used IHA approach, be upgraded with cold-region specific indicators of hydrological change that are ecologically relevant for the geographic areas shown in Fig. 1. Monk et al. (2012) initially explored and used additional flow-based cold-region specific indices relevant to the Athabasca River and downstream delta environments. This paper advances the work of Monk et al. (2012) to be used in the EFN Framework proposed by Peters et al. (2012a), which explicitly combines a “hydrological standard” with an “ecological performance indicator” to assess hydro-ecological deviations from a reference state for Canadian riverine systems.

COLD-REGIONS HYDROLOGICAL INDICATORS OF CHANGE

The 33 annual hydrological variables that form the Indicators of Hydrologic Alteration (IHA; TNC 2007) suite of variables that characterize intra- and inter-annual variability in flow conditions based on the work of Richter et al. (1996, 1997) are described and summarized in TNC (2007) and Monk et al. (2012). To some extent, the IHA framework does provide information relevant to cold-regions hydrology, e.g. mean/median monthly flows during the months of November to April. However, as pointed out above, and also seen in Figs 2 and 6, low and high water conditions can occur during both ice and open-water seasons in cold regions. It may thus be important to focus not only on the annual low-flow event that typically occurs during the late autumn/winter time, but also on the summer low flow that may coincide with the annual high water temperature, producing a high stress event that may be harmful to aquatic habitat under these extreme combinations. In other regions, peak water levels may be generated during both the open-water (discharge dependent) and ice-influenced (i.e. discharge and ice condition dependent, such as an ice jam) seasons. An important first modification to the IHA approach is to identify the period of the year affected by both ice-influenced and open-water conditions.

Hydrometric data in Canada is collected and compiled in the HYDAT database by the Water Survey of Canada and Environment Canada (Environment Canada 2013). An example of flow and water-level data extracted from the HYDAT database is shown in Supplementary Figs S1 and S2 for the lower Peace River, a major headwater tributary in the Mackenzie River Basin. A key feature in the HYDAT database is the inclusion of a “flag” associated with flow data having noteworthy conditions: “A” for partial day, “E” for estimated and “B” (backwater) for ice conditions. Note that a B flag-designated date should be assessed to ensure that backwater conditions resulted from known ice timing effects and not from log-jam or beaver-dam effects (Monk et al. 2012). Given the known effects of ice on the stage–discharge relationship discussed above, the presence of ice would have had to be determined and likely recorded in other cold-region jurisdictions. For instance, Hodgkins et al. (2005) assessed the number and timing of days of ice-affected flow in New England states over the years 1930–2000 using US Geological Survey data.

As presented in the Environment Canada Data Explorer Software (HYDAT Version 1.0) and HYDAT database, the B flag designation can be used to identify the first (typically in the autumn) and last day (typically in the spring) when channel hydraulics are affected by ice (Zhang et al. 2001). The extraction of this ecologically-relevant information enables the identification of the water year (i.e. 1 October to 30 September) when open-water channel hydraulics prevailed and when the flows were affected by ice conditions. Advantages to separating the water year into two periods are the ability to: (a) investigate whether or not a trend and/or step change detected on an annual basis in one of the hydrological indicators was an open-water and/or an
ice-influenced seasonal phenomenon, and (b) include in the analyses hydrometric stations that were operated on a seasonal basis (March–October) for operational reasons and/or because of the cessation of streamflow during the cold winter months (Peters et al. 2012b); ~25% of the currently active sites in the HYDAT data set are seasonally operated at this time.

Similar to the work of Hodgkins et al. (2005) in the USA, a few studies have capitalized on the use of the B flag contained in the HYDAT data set to identify potential effects of climate variability/change on river systems in Canada. For instance, Zhang et al. (2001) investigated trends in streamflow over the years 1947–1996 and found evidence to suggest a change to earlier river ice break-up (defined as the last B day), particularly in eastern Canada, and later freeze-up (defined as the first B day), particularly in western Canada. More recently, Monk et al. (2012) applied this methodology in the Athabasca River basin, and found no significant trends present over the years spanning 1958–2009. The authors went a step further, extracting the magnitude of flow corresponding to the freeze-up and break-up dates, and found a significant decline in the magnitude of flow associated with the first B date taken as the autumn freeze-up date. Zhang et al. (2001) utilized a count of B flagged flow days to estimate the duration of river ice cover, which, if continuous, is the river ice span between the freeze-up and break-up dates as applied by Monk et al. (2012). We recommend the Zhang et al. (2001) approach for extraction of river ice freeze-up and break-up dates and calculation of the ice-cover duration as it is applicable to regions that experience mid-winter break-up events and continuous ice cover.

In addition to assessing monotonic trends in hydrological indicators extracted from streams considered natural, the cold-region indices can be used to assess step or regime changes arising from development in the channel and/or within the watershed. For instance, regulation of the Peace River headwaters (see Fig. 3 for location) in 1968 for the generation of hydro-electric power resulted in substantial changes to the flow regime as a result of the storage of the spring freshet and summer rainfall-driven mountain runoff, and subsequent release of water during the following cold winter months, leading to a hydrograph inversion immediately below the dam (Peters and Prowse 2001). In this case, a better understanding of changes to the flow regime resulting from climate change and flow regulation would be derived by assessing the 1-day minimum and maximum flow for both the open-water and ice-influenced periods. Also discernible was the elimination of the ice-cover regime directly downstream of the dam due to the release of relatively warm hypolimnetic reservoir water over the winter months (Prowse et al. 2002). This can be clearly seen in Fig. 6, showing the mean daily flows and mean ice cover duration prior to construction of the dam (1960–1967) and since operation of the dam (1972–2010). The effect of regulation on the flow and ice regime can be detected >300 km downstream at the town of Peace River. Some >1000 km downstream near the Peace Delta, the timing of the ice cover has not been significantly affected by regulation according to Prowse et al. (2002). However, subsequent studies noted important increases in the magnitude of flow at the time of autumn freeze-up near the delta (Peters and Buttle 2010), with potential implications for the generation of spring ice-jam flood events due to the higher than natural autumn freeze-up stage that requires sufficient spring freshet flow to lift and break-up a competent ice cover (Beltaos et al. 2006).

Also crucial for the understanding of cold-region aquatic environments is the timing and magnitude of the annual spring freshet resulting from snowmelt and heavy rainfall, which generally follows an extended low-flow period over the winter months. The spring freshet will be one of the major noticeable impacts of climate warming on the flow regimes of rivers in Canada and other cold regions (Dery et al. 2009). Historically, the winter snow accumulation has served as a natural water reservoir in Canada, sustaining river flows throughout the dry summer months. Identification of the spring freshet initiation date involves identifying an inflection point on the hydrograph (see Figs 2 and 6). Previous studies conducted in snowmelt-dominated streams have shown that the spring freshet or flood event can be a predictor of macroinvertebrate community sensitivity to flow (Poff 1996, Clausen and Biggs 1997, Olden and Poff 2003). Zhang et al. (2001) defined this variable as the date when the increase in the daily streamflow across four days was greater than the average flow from January to July. This approach cannot be applied to seasonally operated hydrometric stations having no data typically from November to March, and thus an approach that requires only a short period (a few weeks) of data prior to the onset of the freshet is needed to permit analysis of a greater number of hydrometric stations across Canada. We recommend the approach of Burn et al. (2004) who identified the
spring freshet initiation date as the day on which the daily runoff value exceeded 1.5 times the average of the preceding 16 days. The authors applied this indicator in the Mackenzie River Basin and demonstrated that the spring freshet was increasingly occurring earlier in the year over the period 1970–2005, particularly in the headwater sub-basins. As for all the indicators, the chosen period of analysis may influence the results. For instance, Monk et al. (2012) found no trend in the timing of the spring freshet onset in one of the headwater tributaries (Athabasca River) for the years spanning 1958–2009. Yet, in the other headwater sub-basin of the Mackenzie River, reservoir operation has led to the elimination of the spring freshet directly below the dam, with the effects diminishing along the Peace River mainstream with additions of snowmelt water from downstream tributaries (Fig. 6).

As highlighted by the work of de Rham et al. (2008) and discussed above, annual extreme flood...
conditions in cold regions may not necessarily occur during open-water conditions (typically represented as peak flow magnitude). Associated with the spring freshet onset and river-ice break-up condition in many cold regions is the generation of the annual high water level with considerably less flow than generated under open-water conditions (Fig. 5). For instance in 2010, a peak instantaneous stage of 214.210 m a.s.l. driven by 2100 m$^3$ s$^{-1}$ on the lower Peace River was observed on 19 April vs a flow of 3070 m$^3$ s$^{-1}$ and stage of almost 1 m lower (213.262 m a.s.l.) on 1 June (Environment Canada 2013; Figs S1 and S2). The difference in these peak water levels could translate into dramatically different extents of riparian zone inundation. Such a difference is illustrated via comparison of remotely sensed images in Fig. 7(a) and (b) corresponding to extreme hydrological events in the Peace-Athabasca Delta (PAD; see Fig. 3 for location), a Ramsar Convention designated deltaic wetland ecosystem of international importance. Large ice-jam events in late April/early May 1974 inundated most of the PAD riparian wetlands areas, whereas the historical high flow on the lower Peace River during the summer of 1990 did not overbank into these areas (Peters et al. 2006).

Not surprisingly, spring-freshet-driven ice-jamming events have been identified as the primary mechanism for recharging highly elevated wetlands in the Peace-Athabasca Delta, as well as the more northern Mackenzie Delta, without which many wetlands will eventually dry up to form terrestrial environments (Peters et al. 2006, Lesack and Marsh 2010). Clearly, as highlighted here and elsewhere (e.g. Prowse and Culp 2003), an important addition to a cold region suite of hydro-ecologically relevant variables is the peak water level generated during ice-influenced conditions. As with other extreme event variables, it is also important to include its timing and flow magnitude to understand change over time and linkages to ecological responses. Another deviation from the IHA approach is the extraction of the 1-day minimum and maximum flow magnitude and timing for both the open-water and ice-influenced periods. Previous studies (see Poff et al. 1997) have identified the ecological importance of extreme flow conditions in driving community distributions, and thus are not fully discussed here.

Table 1 presents the list of CHIC variables that our study has, through a literature review, deemed hydro-ecologically relevant for assessing temporal trends and/or regime shifts in river across Canada and other regions of the world where flows and water levels are affected by an ice cover and dominated by the spring snowmelt-driven freshet. The reader will notice that several of the variables presented in Table 1 under the “Annual Period” heading have not been discussed herein. For instance, the median monthly flow magnitude, baseflow value, rise and fall rates, number of hydrograph reversals and the number and duration of low- and high-flow pulses during each water year. Given that these hydrological indicators have already been presented in the IHA approach (TNC 2007) and have been widely applied, we refer the reader to the papers of Poff et al. (1997), Richter et al. (1996, 1997) and
| Period            | Hydro-ecological variables                                    | Example of ecological influence                                                                 |
|-------------------|----------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| **Annual**        | Monthly median flow magnitude                                  | Availability and temporal variability of suitable aquatic and riparian habitat                 |
|                   | Baseflow value                                                | Shorter-term availability of aquatic and riparian habitat during low-flow period              |
|                   | Mean 90-day minimum flow magnitude                            | Seasonal low flows affect availability of aquatic and riparian habitat                        |
|                   | Mean 90-day maximum flow magnitude                            | Seasonal high flows influence availability of aquatic and riparian habitat                   |
|                   | Rise rate                                                     | Stress and habitat recovery relating to rising water levels                                  |
|                   | Fall rate                                                     | Stress and habitat recovery relating to falling water levels                                 |
|                   | Number of hydrograph reversals                                | Habitat availability and connectivity relating to overall water level variability             |
|                   | Number of low pulses/year                                     | Occurrence of potentially stressful low-flow conditions                                       |
|                   | Median duration of low pulses within each year                 | Duration of potentially stressful low-flow conditions                                         |
|                   | Number of high pulses/year                                    | Occurrence of potentially stressful high-flow conditions                                     |
|                   | Median duration of high pulses within each year                | Duration of potentially stressful high-flow conditions                                       |
|                   | Number of zero-flow days within each year                     | Extreme loss of aquatic habitat availability and connectivity                                  |
|                   | Spring freshet initiation date                                 | Freshet represents the primary driving annual hydrological event for most systems           |
|                   | Flow magnitude on day of freshet initiation                   | Represents flows that structuring aquatic habitat availability and channel morphology through substrate scour and ice jam-associated flooding |
| **Open water**    | 1-day minimum open-water flow magnitude                       | Short-term extreme low-flow conditions affect habitat availability                           |
|                   | Date of 1-day minimum open-water flow                         | Timing of short-term extreme low-flow conditions can influence aquatic spawning              |
|                   | 1-day maximum open-water flow magnitude                       | Short-term extreme high-flow conditions affects availability and connectivity of habitat     |
|                   | Date of 1-day maximum open-water flow                         | Timing of short-term extreme high-flow conditions can influence ecological processes cued to water availability |
|                   | Duration of open-water period                                 | Critical for photosynthetic production and oxygenation in aquatic systems                   |
| **Ice influenced**| Date of freeze-up                                             | Timing of winter ice formation can reduce habitat availability and alter distribution         |
|                   | Magnitude of flow at freeze-up                                 | Magnitude of flow at time of freeze-up can be directly related to loss of shallow water habitat and reduction in the dilution of contaminants |
|                   | Date of break-up                                              | Timing related to habitat availability and cues for spawning                                 |
|                   | Magnitude of flow at break-up                                 | Magnitude related to ecological processes                                                   |
|                   | Duration of ice-influenced period                             | Duration of under ice conditions including effects of solar radiation, thermal regime change and oxygen levels |
|                   | 1-day minimum ice-influenced flow magnitude                   | Availability of habitat and stressful conditions for aquatic taxa relating to ice conditions |
|                   | Date of 1-day ice-influenced minimum flow                     | Timing of winter low flows related to habitat availability                                  |
|                   | 1-day maximum ice-influenced flow magnitude                   | Availability of habitat and stressful conditions for aquatic taxa relating to ice conditions |
|                   | Date of 1-day ice-influenced maximum flow                     | Timing of winter low flows related to habitat availability                                  |
|                   | Peak water level during ice-influenced period                 | Related to habitat availability, especially channel connectivity                             |
|                   | Date of peak water level during ice-influenced period         | Timing important for connectivity                                                            |
|                   | Flow magnitude on day of ice-influenced peak water level      | Related to habitat availability, especially channel connectivity                             |
Monk et al. (2011, 2012) for details and rationale of their application beyond that provided in the right column of Table 1. The reader may also notice that the 3-, 7-, 15- and 30-day mean flow variables found in the IHA approach (see Monk et al. 2011) are not included in the CHIC suite of variables; this was done to minimize redundancy in indicator use as highlighted by Olden and Poff (2003) and Monk et al. (2012). Based on the work of Peters and Buttle (2010) and Monk et al. (2012), the 90-day maximum and minimum flow was included in the list because sustained flows were linked to lake levels and occasional overbanking into shoreline wetlands. Lastly, given the identification of temporary streams as “sentinel systems of hydro-ecological change” for cold regions (see Buttle et al. 2012), the number of zero-flow days during the water year has become a topic of research interest in Canada (Peters et al. 2012b) and thus is retained in Table 1.

Enhancement of the standard IHA variable set (TNC 2007) with cold-region specific indicators in EFN assessments fills a key knowledge gap identified in Peters et al. (2012a). In combination with the Range of Variability Approach (RVA; see Richter et al. 1997, for details), we consider that CHIC and RVA used together can support first-tier EFN assessments in Canada, as recently proposed by Peters et al. (2012a), as they provide a “hydrological standard” and offer an approach focused on protection of the whole ecosystem when combined with an “ecological performance indicator”. Given that cold-regions hydro-ecology is still a developing science, an important next step will be to explore the response of the macroinvertebrate community composition (Canadian Aquatic Biomonitoring Network; CABIN database) as quantified through the Canadian Ecological Flow Index (CEFI; Armanini et al. 2011, 2012) to the CHIC variables, thus providing a basis for hypothesis development and testing. The CEFI summarizes the flow sensitivity preferences across the sampled macroinvertebrate community and is incorporated in the EFN framework as the ecological performance indicator (Armanini et al. 2011, Peters et al. 2012a).

The use of the proposed cold-region hydrological indicators of change variables may help inform sustainable management strategies within these regions. For instance, work is ongoing to select key hydrological variables for use by the Canadian Environmental Sustainability Indicators (CESI; http://www.ec.gc.ca/indicateurs-indicators/default.asp) programme to measure the progress of sustainable development strategies, report on the state of the environment and describe Canada’s progress on key environmental sustainability issues, such as the effects of climate variability/change on water quantity.

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**SUPPLEMENTARY MATERIAL**

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