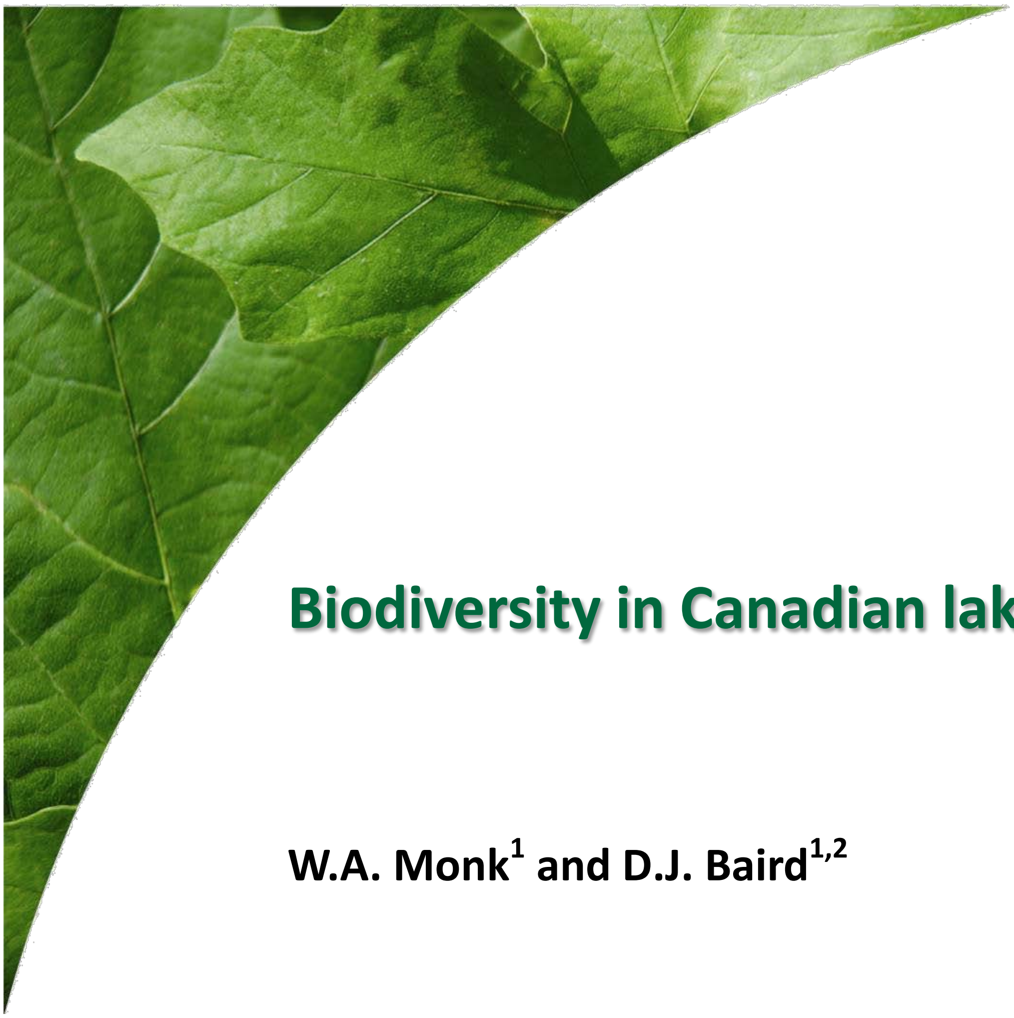

Biodiversity in Canadian lakes and rivers

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PREFACE

The Canadian Councils of Resource Ministers developed a Biodiversity Outcomes Framework[1] in 2006 to focus conservation and restoration actions under the *Canadian Biodiversity Strategy*.[2] *Canadian Biodiversity: Ecosystem Status and Trends 2010*[3] was a first report under this framework. It assesses progress towards the framework's goal of "Healthy and Diverse Ecosystems" and the two desired conservation outcomes: i) productive, resilient, diverse ecosystems with the capacity to recover and adapt; and ii) damaged ecosystems restored.

The 22 recurring key findings that are presented in *Canadian Biodiversity: Ecosystem Status and Trends 2010* emerged from synthesis and analysis of technical reports prepared as part of this project. Over 500 experts participated in the writing and review of these foundation documents. This report, *Ecosystem status and trends report: biodiversity in Canadian lakes and rivers*, is one of several reports prepared on the status and trends of national cross-cutting themes. It has been prepared and reviewed by experts in the field of study and reflects the views of its authors.

Contributing authors

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Acknowledgements

Data for the hydrological analyses were provided through Water Survey of Canada's HYDAT database. Additional geospatial data were accessed through Geogratis and Geobase. We also thank the reviewers of this report.

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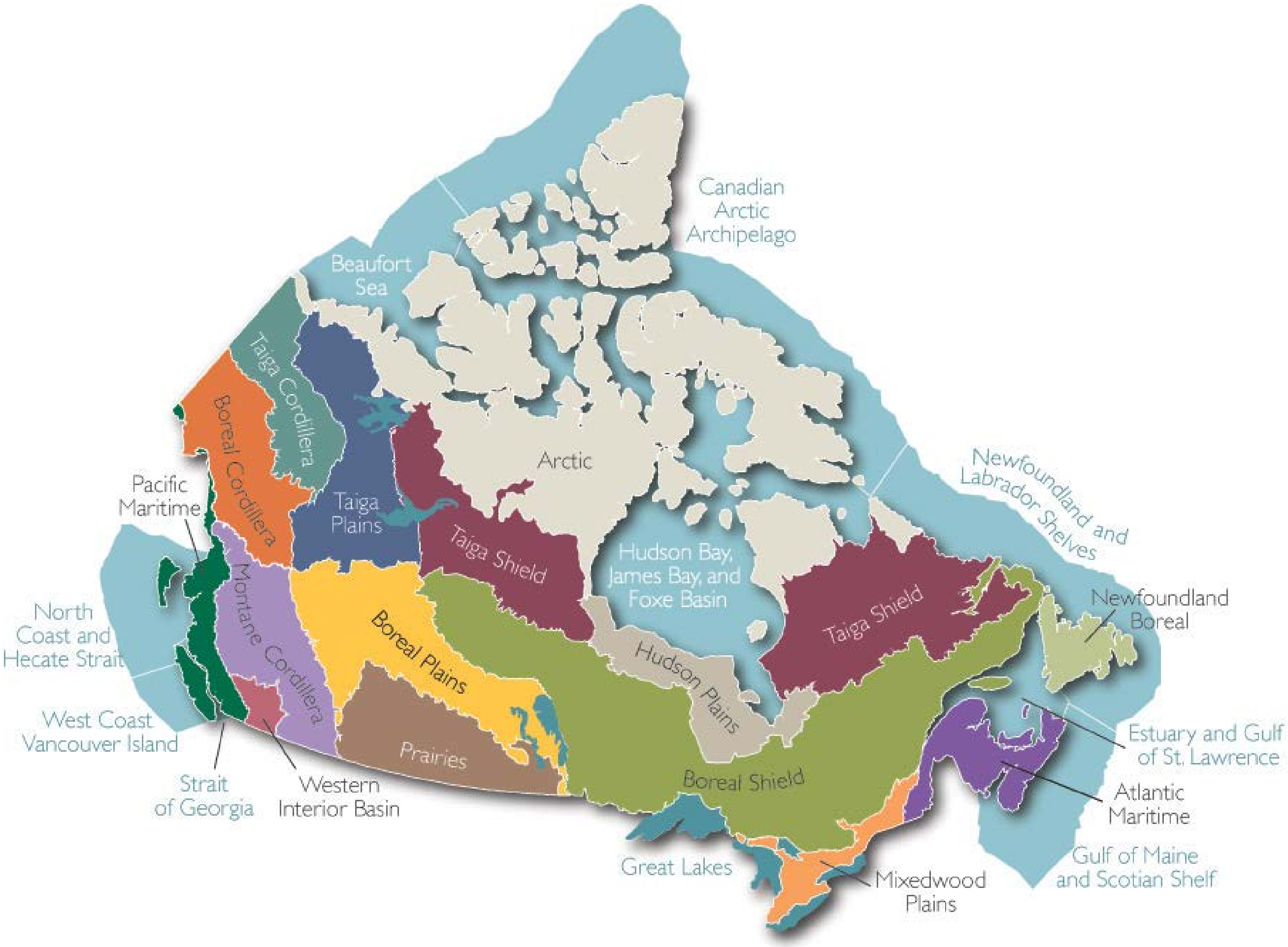
[1] Environment Canada. 2006. Biodiversity outcomes framework for Canada. Canadian Councils of Resource Ministers. Ottawa, ON. 8 p. http://www.biodivcanada.ca/default.asp?lang=En&n=F14D37B9-1

[2] Federal-Provincial-Territorial Biodiversity Working Group. 1995. Canadian biodiversity strategy: Canada's response to the Convention on Biological Diversity. Environment Canada, Biodiversity Convention Office. Ottawa, ON. 86 p. http://www.biodivcanada.ca/default.asp?lang=En&n=560ED58E-1

[3] Federal, Provincial and Territorial Governments of Canada. 2010. Canadian biodiversity: ecosystem status and trends 2010. Canadian Councils of Resource Ministers. Ottawa, ON. vi + 142 p. http://www.biodivcanada.ca/default.asp?lang=En&n=83A35E06-1

Ecological Classification System – Ecozones$^+$

A slightly modified version of the Terrestrial Ecozones of Canada, described in the *National Ecological Framework for Canada*,[4] provided the ecosystem-based units for all reports related to this project. Modifications from the original framework include: adjustments to terrestrial boundaries to reflect improvements from ground-truthing exercises; the combination of three Arctic ecozones into one; the use of two ecoprovinces – Western Interior Basin and Newfoundland Boreal; the addition of nine marine ecosystem-based units; and, the addition of the Great Lakes as a unit. This modified classification system is referred to as "ecozones$^+$" throughout these reports to avoid confusion with the more familiar "ecozones" of the original framework.[5]



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[4] Ecological Stratification Working Group. 1995. A national ecological framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch. Ottawa/Hull, ON. 125 p. Report and national map at 1:7 500 000 scale.

[5] Rankin, R., Austin, M. and Rice, J. 2011. Ecological classification system for the ecosystem status and trends report. Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 1. Canadian Councils of Resource Ministers. Ottawa, ON. http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-1

Table of Contents

List of Figures

List of Tables

EXECUTIVE SUMMARY

- Over 8,500 rivers and 2 million lakes cover almost 9% of Canada's total land area. Canada's watersheds flow into five major ocean drainage basins: the Arctic, Pacific, and Atlantic oceans; Hudson Bay; and the Gulf of Mexico, with almost three-quarters of their volume flowing north into the Arctic Ocean and Hudson/James Bay.
- Within Canada, it remains challenging to assess status or trends in freshwater ecosystems and their biodiversity due to a lack of long-term, nationally consistent observational data. There have been positive moves to address this, for example through the development of a national aquatic biomonitoring network (CABIN).
- As a direct consequence of habitat loss, competition from alien invasive species, and overexploitation, the number of imperilled fish species in Canada has risen steadily from 12 in 1979 to 62 in 2008.
- It was not possible to determine national trends in lake levels for this report due to a lack of data. However, research in prairie lakes indicates an overall decline in lake levels in that region over the past 90 years as a result of reduced levels of precipitation consistent with predictions from climate warming models.
- Trends in ecologically important properties of river flows were analysed for the period 1970 to 2005 and results indicate a significant increase in their variability, together with regional trends in the magnitude of both short-term and longer-term minimum and maximum runoff.
- While few statistically significant trends in ice freeze-up or break-up were found, the majority of sites monitored demonstrated a tendency towards earlier break-up, and also an earlier date of the annual one-day maximum flow (often related to the spring freshet), which seems to correspond with an earlier arrival of the spring 0°C-isotherm date.
- Dam construction (>10 m in height) peaked between 1950 and 1980, and has since declined across Canada.
- From 1980 to 2006, sulphur dioxide emissions in Canada and the U.S. declined by about 45% and emissions of nitrogen oxides declined by about 19%. Although significant declines in lake sulphates followed closely behind the emission reductions, the response of lake acidity, measured by pH, has been slow and less widespread, due in part to declines in calcium which are also related to acid deposition.
- Beyond the Great Lakes region of Canada, there is a lack of data by which to assess long-term trends in contaminant levels in biota. One area of recent concern, the Canadian Arctic, exemplifies the problem of data scarcity, with localised patterns being reported in some studies, over time periods too short to properly observe trends.

INTRODUCTION

This report provides an analysis of status and trends in freshwater biodiversity within Canada's lakes and rivers using a combination of: i) quantitative data; ii) qualitative data from a literature review; and iii) evidence from the peer-reviewed scientific literature. This report considers biodiversity in the broadest sense, focusing specifically on lake and river ecosystems. Its scope is limited, with no specific consideration of wetlands. The Great Lakes are reported on in the State of the Great Lakes Reports (for example, Environment Canada and U.S. Environmental Protection Agency, 2009) and Lake Winnipeg is covered in the Boreal Plains evidence for key findings summary and supplemental background information (ESTR Secretariat, 2014), so they are not included here. During the writing of the report, it became apparent that any conclusions drawn from the data would be necessarily limited due to a general lack of quantitative, nationally consistent, observational data for aquatic species in Canada. For this reason, proxies, for example habitat trends, have been employed to examine likely trends in biodiversity. These trends are also explored further within the context of the ecozone$^+$-specific reports that are part of the Ecosystem Status and Trends Report (ESTR). With this proviso, we attempt to explore key trends in lake and river ecosystems, with coverage of the following areas: i) fish species at risk; ii) hydrological regimes; iii) ice freeze-up and ice break-up; iv) habitat loss and fragmentation; v) contaminants, nutrients, and acidification; and vi) future climates. Finally, it should be noted that this report uses the ecozone$^+$ framework consistent with other reports produced in this series. This has implications for the assessment of trends in freshwater ecosystems, which do not follow ecozone$^+$ geographical boundaries.

Lakes and rivers in Canada

Canada has an area of 9,984,670 km^2 of which 9,093,507 km^2 are land and 891,163 km^2 is water (The Atlas of Canada, 2004a). Canada's borders span a continental land mass and therefore contain a wide range of climates. This climatic diversity, coupled with large topographic variation and significant human modification of the environment, has strongly influenced Canada's hydrology (Meteorological Survey of Canada, 2003). Both local and regional climates are heavily influenced by the interaction of a westerly circulation, with natural topographic features which include vast mountain ranges, wide plains, and extensive river basins (Meteorological Survey of Canada, 2003; Bonsal and Shabbar, 2011). Annual precipitation varies from less than 100 mm in the dry regions of the Arctic Archipelago to more than 4,000 mm along the wetter parts of the Pacific coast (The Atlas of Canada, 2007a). Moving north from its southern border, the climate shifts from continental to subarctic to arctic. In addition, a secondary maritime influence in coastal regions affects both the west and east coast climates, while permafrost underlies about half of Canada's land area in the mid- to northern latitudes (The Atlas of Canada, 2004b).

Lakes and reservoirs provide a potentially important source of trend information as they reflect the influence of climate through changes in water levels and water quantity (Williamson et al., 2009). Canada is covered by over two million lakes, which together with rivers, cover almost 9%

of the country (The Atlas of Canada, 2004a). There are more than 900,000 lakes larger than 0.1 km^2, which together represent 37% of the total lake area of the world (Minns et al., 2008). This includes over 560 lakes which exceed 100 km^2 in area (Table 1). The largest group, the Great Lakes, span the Canada–United States border, and contain 18% of the world's freshwater lake volume (The Atlas of Canada, 2007b). Strongly influenced by geological history, the majority of larger lakes are found within the Canadian Shield, the Interior Plains, and the St. Lawrence Lowlands, while glacial activity had a strong role in the formation of other lakes, for example Great Bear Lake, Great Slave Lake, Lake Athabasca, Lake Winnipeg, and the Great Lakes. Table 1 provides a summary of the distribution of lakes by size class across Canada.

Table 1. The number of lakes in each region of Canada by size category.

Region	**Lake size (km^2)**							**Total**
	3–99	**100–199**	**200–399**	**400–999**	**1,000–2,499**	**2,500–9,999**	**10,000–36,000**	
Atlantic provinces	1,761	19	5	4	1	2	0	**1,792**
Quebec	8,182	49	27	12	5	0	0	**8,275**
Ontario	3,837	34	12	9	1	2	4	**3,899**
Prairie provinces	5,245	65	39	18	8	5	1	**5,381**
British Columbia	838	6	12	4	1	0	0	**861**
Territories	11,328	108	60	35	8	3	2	**11,544**
Canada	**31,191**	**281**	**155**	**82**	**24**	**12**	**7**	**31,752**

Atlantic provinces = New Brunswick, Prince Edward Island, Nova Scotia, and Newfoundland and Labrador; Prairie provinces = Manitoba, Saskatchewan, and Alberta; Territories = Nunavut, Northwest Territories, and Yukon Territory.
Source: data from Environment Canada (1973) as reported in The Atlas of Canada (2008a)

Of the 25 largest rivers in North America ranked by annual discharge, 14 flow completely or partly within Canada (Benke and Cushing, 2005). Canadian rivers flow into five major ocean drainage basins: the Arctic, Pacific, and Atlantic oceans; Hudson Bay; and the Gulf of Mexico. However, almost three-quarters of the rivers in Canada, making up almost half (47.9%) of the total annual discharge, flow north into the Arctic Ocean or into Hudson/James Bay (Déry and Wood, 2005). Most rivers in Canada show pronounced seasonal variation in runoff, and the majority of high flows are driven by spring snowmelt. Secondary flow variation arises from seasonal rainfall patterns, while glacial meltwater sustains flow in mountainous regions. For most unmodified rivers, low flows generally occur in late summer, arising from reduced precipitation and high evaporation, or in late winter, as precipitation accumulates in the form of ice and snow.

Monitoring national hydrological trends is accomplished by summarizing data collected from hydrometric gauging stations, through the Water Survey of Canada's extensive hydrometric network (but see also Shrubsole, 2000). Extended site-specific hydrological time series have also been developed using palaeo-environmental data to allow longer-term analysis of the impacts of a changing climate. For example, a recent study by Wolfe *et al.* (2008) extracted a long time series of water levels over the past thousand years for the upper Mackenzie River system using this approach. Using palaeo-environmental data from the Peace-Athabasca Delta, water levels for Lake Athabasca appeared to directly reflect overall water availability. Their results demonstrated that lake water levels showed systematic fluctuations over time, reflecting a maximum glacier extent during the Little Ice Age (1700s to 1900s) and a glacial minimum during the comparatively warm 11th century (Wolfe et al., 2008). In this context, recent hydrological trends suggest a trend towards lower water levels as high elevation snow and glacier contributions continue to decline. Shifts in the shape and timing of the annual hydrographs were also suggested to reflect a greater variability in the spring freshet during the Medieval period, a delayed spring freshet during the Little Ice Age, and a delayed spring freshet throughout the 20th century (Wolfe et al., 2008).

An increasing number of human activities currently pose threats to Canada's rivers (see examples in Environment Canada, 2001; Environment Canada, 2004). These include dams for flood control or hydropower (for example, Poff et al., 2007), irrigation and municipal water use (for example, Fitzhugh and Richter, 2004), chemical contamination (for example, Wan et al., 2006; Smith et al., 2007; Bordeleau et al., 2008), and the spread of invasive alien species (for example, Boyer et al., 2008). All of these threats are likely to be further exacerbated by the pervasive effects of climate warming, through the need to alter national infrastructure to adapt to a changing climate. Hydrological systems are naturally dynamic (Milly et al., 2008), as can be seen, for example, in the variation in permafrost levels driving changes in the hydrological landscape of the north (Vallee and Payette, 2007). Given this changing baseline, detecting additional effects as a result of global climate change is challenging (for example, Rand et al., 2006). However, it is obvious that both natural and anthropogenic activities can significantly alter water quality and quantity and thus influence habitat diversity (for example, Charron et al., 2008). As a component of biodiversity, habitat diversity strongly influences other biodiversity attributes, such as species or genetic diversity. Therefore, in the absence of any historical data arising from strategic monitoring of species and/or genetic diversity, an examination of how habitat itself is changing through time can be used as a surrogate. Nevertheless, we acknowledge that the systematic, strategic collection of monitoring data on the remaining components of biological diversity, currently lacking for freshwater ecosystems in Canada, is required to address these questions directly.

Linking lake and river systems with ecozones$^+$

This report focuses on river and lake ecosystems across Canada. Watershed boundaries are commonly used as the basis for analyses of freshwater ecosystems as they represent drainage networks of connected systems. A watershed can be defined as the land area that topographically drains surface water to a particular point of interest (for example, a river, stream, or lake). The main criteria for defining a watershed are topography and the presence of a water body. An ecozone is defined based on a different set of criteria which includes climate, plants, soils, landforms, animals, and water features, and therefore implies taking into account biodiversity. From Figure 1, it is clear that the watershed boundaries (as defined by the Environment Canada, 2006c) and the terrestrial ecozone$^+$ delineations used in ESTR are not spatially contiguous. Within a drainage basin, there will be variations in habitats and communities along natural longitudinal gradients. This report is structured by ecozone⁺ but it is important to realize that an activity within a specific ecozone⁺ within a drainage basin will be influenced by upstream ecological processes in contiguous ecozones⁺.

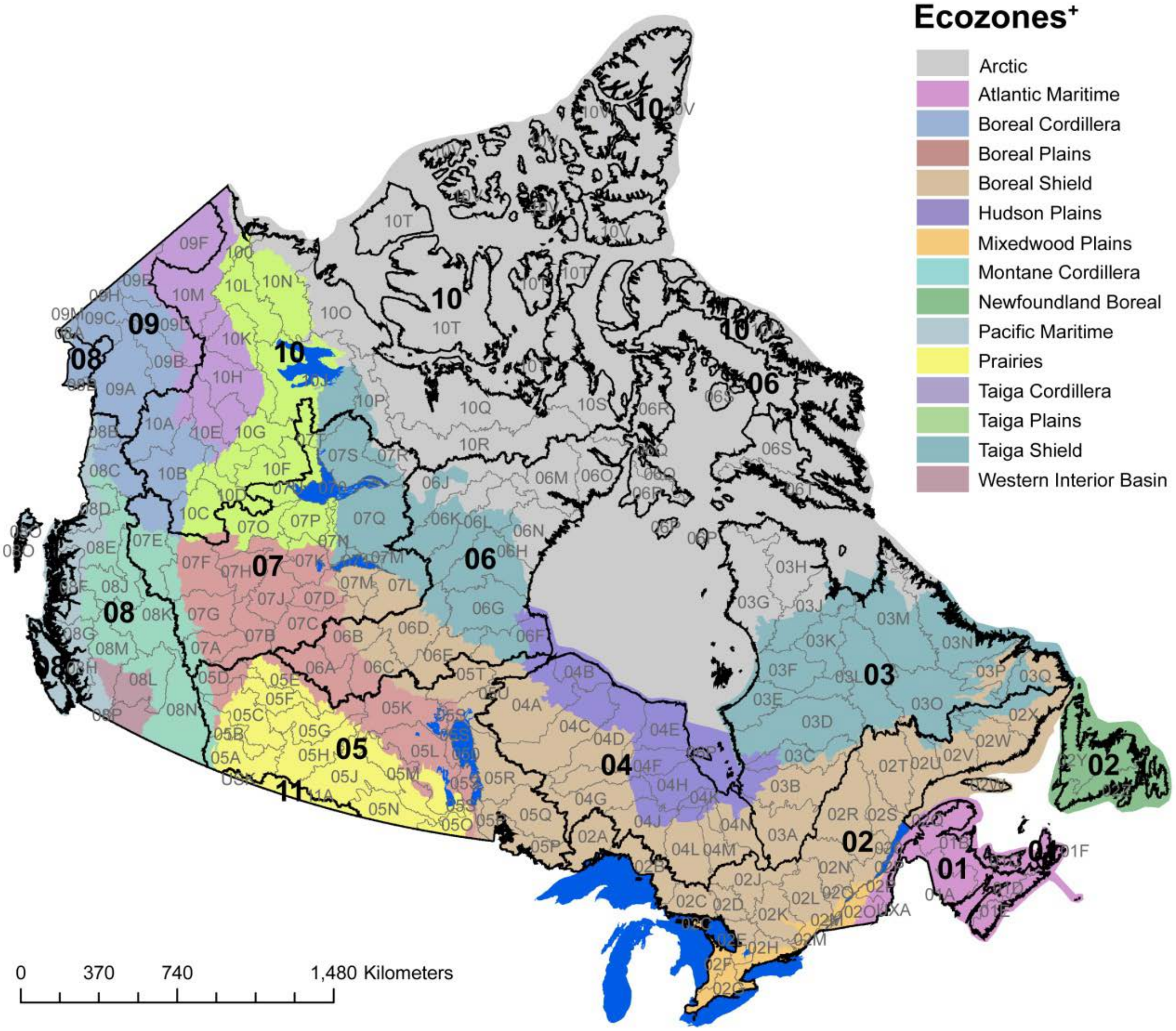

Figure 1. Ecozones⁺ and major drainage basins designated by the Water Survey of Canada.
Major drainage areas: 01 – Maritime provinces; 02 – St. Lawrence; 03 – Northern Quebec and Labrador; 04 – Southwestern Hudson Bay; 05 – Nelson River; 06 – West and North Hudson Bay; 07 – Great Slave Lake; 08 – Pacific; 09 – Yukon River; 10 – Arctic; 11 – Mississippi River
Sub-drainage areas are outlined in grey.
Source: Environment Canada (2006c)

Canada's major river systems encompass a wide variety of habitats and ecosystems. They include endemic species, as well as a diverse range of hydrological and climatic characteristics. Characterized by high runoff, draining westward into the Pacific Ocean through the Pacific drainage basin, the majority of coastal Pacific rivers have their headwaters at high elevation across a series of mountain ranges with considerable topographic relief throughout their catchments (Richardson and Milner, 2005). For example, the Fraser River is the fifth longest river system in Canada, flowing 1,400 km from its headwaters in Mount Robson Provincial Park, through both the Montane Cordillera and Pacific Maritime ecozones$^+$, to its mouth at Vancouver on the Pacific coast (Abell et al., 2000; Burridge and Mandrak, 2009a). Rivers within the Montane Cordillera, Boreal Cordillera, and Pacific Maritime ecozones$^+$ exhibit high annual runoff, both westward to coastal areas and eastward to the Prairies Ecozone$^+$ in the south and the Boreal Plains and Taiga Plains ecozones$^+$ to the north (Environment Canada, 2010a). Runoff within montane coastal rivers often exceeds 3,000 mm per year while within the drier prairies it can average under 200 mm annually (Environment Canada, 2010a). Classified as temperate upland freshwater habitat, the Nelson River drainage basin has several large rivers including the Churchill, Nelson, and Saskatchewan rivers, and many interconnected lakes (Abell et al., 2000). For example, over a total distance exceeding 3,000 km before discharging into Hudson Bay, the Nelson River covers more than 1 million km^2 of the interior of North America—892,300 km^2 in Canada and 180,000 km^2 in the United States (Rosenberg et al., 2005). The habitat within this region includes slow, meandering rivers flowing through wide, interconnected valleys. Here freshwater fish species diversity is low, with a number of introduced species thought to be responsible for the decline of several native species.

Moving east to the Great Lakes, annual runoff ranges from 100 mm in the northwest, to 800 mm in the southeast, to over 1,000 mm along the Atlantic Maritime coast (Environment Canada, 2010a). The greatest diversity of freshwater fish species in Canada is found in the Great Lakes and southern Hudson Bay areas with 87 freshwater species recorded, including 18 diadromous fish species within the main stem of the St. Lawrence River alone (Thorp et al., 2005). As an example, the Mixedwood Plains Ecozone$^+$ is an area of extensive wetlands within the populated area of southern Ontario and southern Quebec. The climate in this area is strongly influenced by the Great Lakes causing a continental to modified continental climate. Numerous streams, rivers and lakes, springs, spring ponds, and wetland areas are found within and near this ecozone$^+$ with annual runoff ranging from 200 mm in the southwest to over 600 mm at the northeastern end of the ecozone$^+$ (Thorp et al., 2005; Environment Canada, 2010a). However, this area has historically been strongly influenced by urbanization, including several large cities (Abell et al., 2000; World Wildlife Fund and The Nature Conservancy, 2008a). Surrounded by the Canadian Shield, the extensive wetlands of the Hudson Plains Ecozone$^+$ drain northward to Hudson and James bays.

Moving further east towards the Atlantic coast, runoff continues to increase significantly, varying from 600 mm annually in the western part of the Atlantic Maritime Ecozone$^+$ to over 2,000 mm along the Atlantic coast (Burridge and Mandrak, 2009b; Burridge and Mandrak, 2009c; Burridge and Mandrak, 2009d; Environment Canada, 2010a). Flowing through extensive forest cover with numerous inland waters towards the Atlantic Ocean (Cunjak and Newbury, 2005), the Saint John is the largest river system within the Atlantic Maritime Ecozone$^+$ (Burridge and Mandrak, 2009c). Within this ecozone$^+$, several rivers, including the St. Croix and the Upper Restigouche rivers in New Brunswick and the Hillsborough and Three Rivers systems in Prince Edward Island, are designated as Canadian Heritage Rivers (Burridge and Mandrak, 2009b; Burridge and Mandrak, 2009c). In addition, this ecozone$^+$ has several small lakes with the largest being GrandLake in New Brunswick. The freshwater fish diversity within the Atlantic Maritime Ecozone$^+$ is relatively low and is dominated by freshwater fishes with some salt-water tolerance, for example sturgeons (*Acipenser* spp.), American eels (*Anguilla rostrata*), killifishes (*Fundulus* spp.), and smelts (*Osmeridae*). In addition, there are important nesting sites for osprey (*Pandion haliaetus*) and ring-necked duck (*Aythya collaris*) (Burridge and Mandrak, 2009b; Burridge and Mandrak, 2009c; Burridge and Mandrak, 2009d).

The Newfoundland Boreal Ecozone$^+$ exists in a maritime climate with low freshwater fish diversity. The Main and Bay du Nord rivers are Canadian Heritage Rivers (Burridge and Mandrak, 2009b). Many of the freshwater fish species are saltwater-tolerant and exhibit diadromy, for example the shad (*Alosa* spp.) and the Atlantic salmon (*Salmo salar*). The main rivers draining the ecozone$^+$ include the Exploits, Gander, Humber, and Main, with many glacial finger lakes also being characteristic of this region (Burridge and Mandrak, 2009b).

Few data on runoff are available for the Northern Arctic portion of the Arctic Ecozone$^+$, which is characterized by very low precipitation (100 to 200 mm annually) (Environment Canada, 2010a). Even less is known concerning runoff from the glaciated, mountainous Arctic Cordillera portion of the Arctic Ecozone$^+$. This latter region encompasses the Arctic drainage basin in addition to part of the Northern Quebec and Labrador drainage area. The diversity of freshwater fish species is among the lowest in North America, with no known endemic species (Abell et al., 2000; World Wildlife Fund and The Nature Conservancy, 2008a).

With the seventh largest basin in North America, encompassing an area of 839,200 km^2 (Bailey, 2005), the Yukon River area is characterized by a mixture of sub-arctic and tundra conditions, draining part of Alaska, the Boreal Cordillera, and Taiga Cordillera ecozones$^+$, and also a small part of the Pacific Maritime Ecozone$^+$. In addition to being one of the most important salmon-bearing rivers in the world, the “Thirty Mile Section” of the Yukon River has been designated a Canadian Heritage River (Abell et al., 2000; World Wildlife Fund and The Nature Conservancy, 2008a). With no known endemic freshwater fish species and only 30 recorded fish species, fish diversity is relatively low (Bailey, 2005).

The Mackenzie River flows through Canada’s largest river basin, draining nearly 1.8 million km^2 (20%) of Canada's land area (Culp et al., 2005). The system includes a number of other important systems, including the Athabasca, Peace, Liard, Slave, Arctic Red, and Peel rivers before flowing into the Mackenzie Delta (The Atlas of Canada, 2008a; The Atlas of Canada, 2008b). In addition, the system has two major inland deltas (the Peace-Athabasca and the Slave) as well as three very large lakes (Athabasca, Great Slave, and Great Bear) (Culp et al., 2005). The Mackenzie system supports 34 fish species on the main stem, with 52 species occurring throughout the basin (Culp et al., 2005).

Broader implications for aquatic biodiversity

River flow and lake level regimes are driven by climate and basin controls, and vary considerably over space and time. Such hydrological regimes are determined in part by lake or river dimensions, but are also influenced by factors including geology and topography (Poff et al., 1997). Local environmental conditions determine rates of change and other aspects of flow variability, including seasonal flow patterns and the timing, frequency, predictability, and duration of extreme events such as floods and droughts (Richter et al., 1996; Poff et al., 1997). The resulting hydrological regimes directly affect river and lake ecosystem characteristics, including the physical nature of lake habitats and river channels, sediment regimes, and prevailing water quality conditions which, in turn, drive the key aquatic ecosystem processes. Hydrological variability influences the structure of aquatic habitats and the composition of ecological communities, including plankton, plants, benthic macroinvertebrates (for example, Monk et al., 2008), and vertebrates, including fish, amphibians, reptiles, birds, and mammals.

Climate variability has direct and indirect effects on aquatic communities by influencing the timing, duration, magnitude, and flashiness of runoff, by altering the water temperature regime and water chemistry, and by driving geomorphological change. In addition, the availability of local resources, including the provision of dispersal opportunities, the maintenance of habitat heterogeneity and connectivity, the degree of biotic interactions, and the overall genetic capacity and adaptive potential together determine the degree of species richness, biodiversity, range, and distribution of species, within the limitations of current knowledge (see Wrona et al., 2005 for examples in Arctic systems).

One of the major obstacles to understanding and managing the relationships between hydrological variability and the structure and biodiversity of aquatic communities is the lack of appropriate coupled standardized, large-scale data collected over the long term. Often long-term biodiversity data is only available at local scales. Drawing on data from Abell *et al.* (2000) and Scott and Crossman (1998), Abell *et al.* (2008) identified 21 freshwater ecoregions in Canada based on the faunal similarity of 166 secondary watersheds obtained through a cluster analysis of freshwater fish occurrences within these watersheds. The study classified Canada's freshwater ecoregions into six different habitat types: i) large lakes, for example the Great Lakes; ii) large river deltas, for example the Upper Mackenzie; iii) polar freshwaters, for example the Arctic coastal region; iv) temperate floodplain rivers and wetlands, for example the St. Lawrence; v) temperate coastal rivers, for example the Pacific drainage region; and vi) temperate upland rivers, for example the Upper Saskatchewan. Their analyses demonstrated that the diversity of freshwater fish species is relatively low in Canada, with the exception of the Great Lakes region. The associated website provides additional information from their study (see http://www.feow.org hosted by World Wildlife Fund and The Nature Conservancy, 2008a). One of the analyses attempted to quantify water stress on lake and river systems, with the authors concluding that Canada's lakes and rivers were generally under minimal stress (Figure 2). However, it should be noted that, in this case, the water stress index was related to water use by human activity, and ecosystem requirements were not factored into the analysis. Attempts to overlay the ecozones$^+$ show that there are potential hydrological impacts in some of the freshwater systems in the Boreal Shield, Boreal Plains, Prairies, and Mixedwood Plains ecozones⁺, which had 30 to 50% of their land cover converted for human use[6] (World Wildlife Fund and The Nature Conservancy, 2008b).

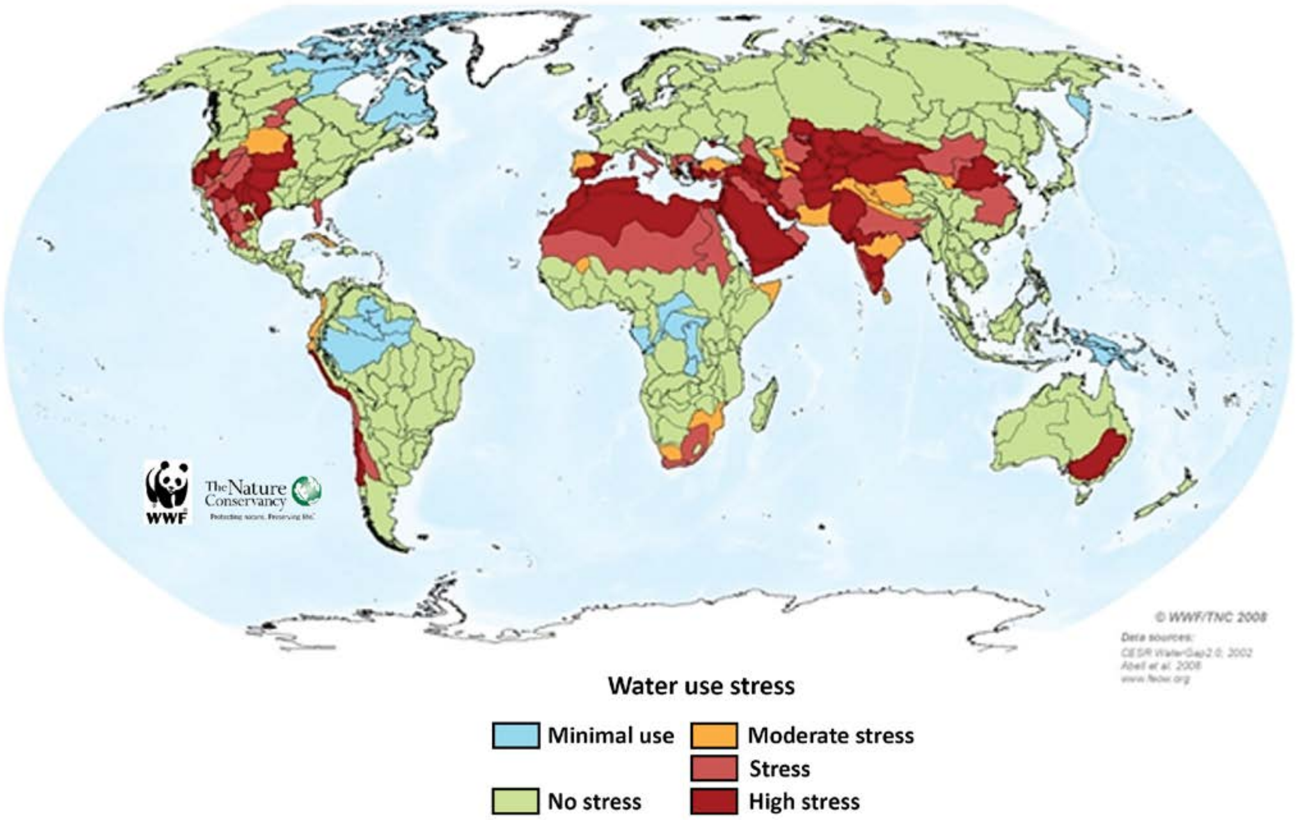

Figure 2. Water use stress worldwide.
Source: World Wildlife Fund and The Nature Conservancy (2008b), calculated from data provided by WaterGAP. Accessed February 21, 2009. Copyright © 2008 by The Nature Conservancy and World Wildlife Fund, Inc. All Rights Reserved.

TRENDS IN FRESHWATER FISH OF SPECIAL INTEREST

Environmental and anthropogenic pressures have resulted in more than 20% of the world's freshwater fish becoming extinct, endangered, or threatened in recent decades—with some analyses stating that this is an underestimate (for example, Bräutigam, 1999). This section focuses on freshwater fish species and is necessarily limited in scope because of a general absence of data consistently collected or observed across the country for all taxa, including fish, and a general lack of national data for non-fish taxa. As of September 2010, the Committee on

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[6] Converted lands are cultivated and managed areas, cropland mosaics, and artificial surfaces and associated areas. The analysis of converted lands is provided by freshwater ecoregions. The ecozones⁺ which encompass those freshwater ecoregions are identified in the text.

the Status of Endangered Wildlife in Canada (COSEWIC) had assessed 18% (35 species) of freshwater and diadromous fishes as Endangered or Threatened throughout all or parts of their ranges. Fifty-eight species (29%) were assessed as at risk, which includes species assessed as Extirpated and of Special Concern, as well as those that are Endangered or Threatened (Hutchings and Festa-Bianchet, 2009; Hutchings, 2010; COSEWIC, 2010c). A 2008 compilation of imperilled freshwater and diadromous fish species in North America found that 89% had the same or worse conservation status in 2008 compared with a 1989 study that explored the same dataset (Jelks et al., 2008). Within freshwater ecoregions of Canada, the numbers of imperilled fish taxa increased from 12 in 1979, to 22 in 1989, to 62 in 2008 (Figure 3). Habitat degradation and introduced species were identified as the main threats to many species, many of which have restricted ranges (Jelks et al., 2008).

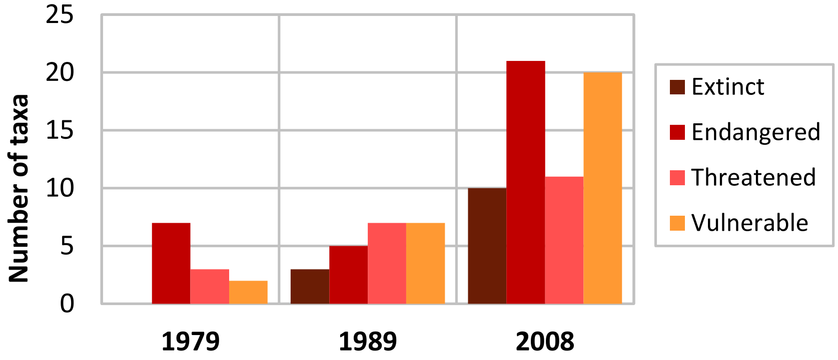

Figure 3. Total number of at-risk freshwater and diadromous fish taxa for North American freshwater ecoregions found in Canada, 1979, 1989, and 2008.
The word 'taxon' (pl. taxa) is used instead of 'species' because the list was updated to include regional divisions as well as relevant taxonomic level, such as genus-level taxa. Previous lists may have ignored at-risk taxa because they did not include all relevant units, but rather focused on taxonomically-recognized species. Definitions of status categories differ slightly from COSEWIC and are described in Jelks et al. (2008)
Source: adapted from Jelks et al. (2008)

Chu *et al.* (2003) explored freshwater fish biodiversity in Canada in relation to environmental and stress metrics. Despite a lack of recent data, their results suggest that anthropogenic stresses and associated species introductions (either accidental or deliberate) were the major cause of extinction and extirpation in Canada. In addition, the authors note that the largely unmeasured effects of overexploitation of fisheries stocks, combined with the likely significant impacts of future climate change, would exacerbate these anthropogenic pressures.

For this report, a literature search of reports by COSEWIC (2010b) was completed to examine the threats causing individual freshwater fish species decline in Canada. Results suggest habitat degradation and loss, species introductions, siltation, dams and impoundments, and urban, agricultural, and industrial development are the main threats to freshwater fish species in Canada. Additional threats identified from the literature search include: water extraction, overexploitation, acid rain effects, channel modification, and contaminants. Six examples of freshwater fish species assessed by COSEWIC and listed under the federal *Species at Risk Act* have been selected to provide information about the impacts of anthropogenic threats on freshwater fish species. These species were chosen to provide examples of the different impacts affecting aquatic communities across Canada. We selected two populations of Atlantic salmon (both Inner Bay of Fundy and Lake Ontario), banded killifish, coho salmon (Fraser River), river redhorse, and white sturgeon as examples of at-risk fish communities affected by anthropogenic and natural habitat alterations (including climate variability and fragmentation), overexploitation, and the spread of invasive species.

Inner Bay of Fundy population of Atlantic salmon

Within the Atlantic Maritime Ecozone+, the Inner Bay of Fundy population of Atlantic salmon (*Salmo salar*) has been assessed as Endangered (COSEWIC, 2006b; COSEWIC, 2010a). Within this area, populations of Atlantic salmon have been under continuous threat since the 17th century from a range of human activities including dam construction, overfishing, overexploitation, and pollution. Occurring in New Brunswick, Nova Scotia, and the Atlantic Ocean, the historical population likely exceeded 40,000 adults. By contrast, the fall spawning estimate in 2003 was less than 100 adults in the 32 historically populated rivers (COSEWIC, 2006b) and estimates from 2008 put the total number of wild salmon at less than 200 (COSEWIC, 2010a). Examination of individual rivers within the inner Bay of Fundy demonstrates similar patterns. For example, the number of returns within the Big Salmon River dramatically declined by more than 96.7% over 30 years from a recorded peak of 5,043 (80% BCI[7]=3,996 to 6,686) in 1966 to an estimated 55 (80% BCI=18 to 133) individuals in 2002 (COSEWIC, 2006b). Data from historical commercial fisheries from 1975 to 1984 highlight the dramatic decline of the catch of Inner Bay of Fundy Atlantic salmon. Despite the high inter-annual variability, the overall declining trend is clear, with the highest landings from 1875 to 1924, smaller landings from 1925 to 1973, and the lowest landings from 1974 to the closure of the fishery in 1985 (Figure 4). Although the reasons for population collapse are not completely understood, it is suggested that there has been reduced survival from smolt to adulthood in marine waters, potentially caused by community shifts through increased interactions with farmed and hatchery salmon, environmental shifts (increasing water temperatures), and fisheries (COSEWIC, 2006b). In addition, there has been a historical loss and degradation of habitat (for example, through logging and barriers to migration) (COSEWIC, 2006b). See the Atlantic Maritime Ecozone+ status and trends assessment (Eaton, 2013) for more information.

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[7] BCI = Bayesian Confidence Interval

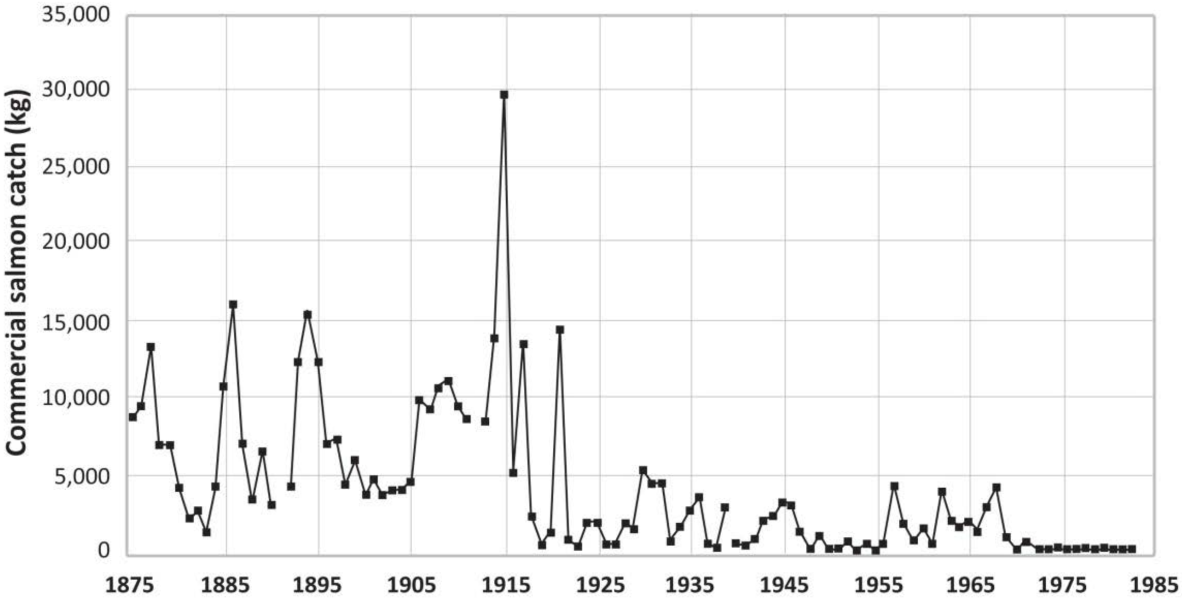


Figure 4. Commercial Atlantic salmon catches in the inner Bay of Fundy, from fishery districts in Albert and Westmorland counties, New Brunswick, 1875–1984.
The fishery was closed to commercial exploitation in 1985.
Source: R.W. Dunfield (personal communication to P. Amiro, DFO, Bedford Institute of Oceanography, as cited in COSEWIC (2006b)

Lake Ontario population of Atlantic salmon

The Lake Ontario population of Atlantic salmon was assessed as Extirpated by COSEWIC in 2006 (COSEWIC, 2006a). Based on historical evidence, the population began a marked decline in the mid-1800s, with no observation of a wild Atlantic salmon within the watershed after 1898. The population collapse was likely caused by habitat destruction and overexploitation following the colonization of Upper Canada in the late 1700s (COSEWIC, 2006a). Despite recent efforts to restore habitat, restocking attempts have failed. Part of this may be attributed to the direct and indirect impacts of urbanization (including pollution, channelization, and loss of habitat) in the Greater Toronto Area (COSEWIC, 2006a).

Banded killifish

Within the Newfoundland Boreal Ecozone^{+}, the banded killifish (*Fundulus diaphanus*) has been assessed as Special Concern (COSEWIC, 2003a). Although widely distributed across North America, the Newfoundland population is threatened due to the limitations of population movement and range expansion because of steep gradients and impassable habitat, coupled with the risks associated with future logging operations (COSEWIC, 2003a).

Interior Fraser coho salmon

Interior Fraser coho salmon (*Oncorhynchus kisutch*) are a genetically distinct population of coho salmon that spawn and rear in the interior portion of the Fraser River watershed, north of Hope, BC. From 1975 to 2011, escapement of Interior Fraser coho declined 72% (Decker and Irvine, 2013), with the largest declines (in excess of 60%) occurring between 1990 and 2000 (Figure 5)

(COSEWIC, 2002). Between 1975 and 1988, the number of spawners averaged 60,000, while only 9,000 spawners returned in 1996, the lowest year on record (Decker and Irvine, 2013).

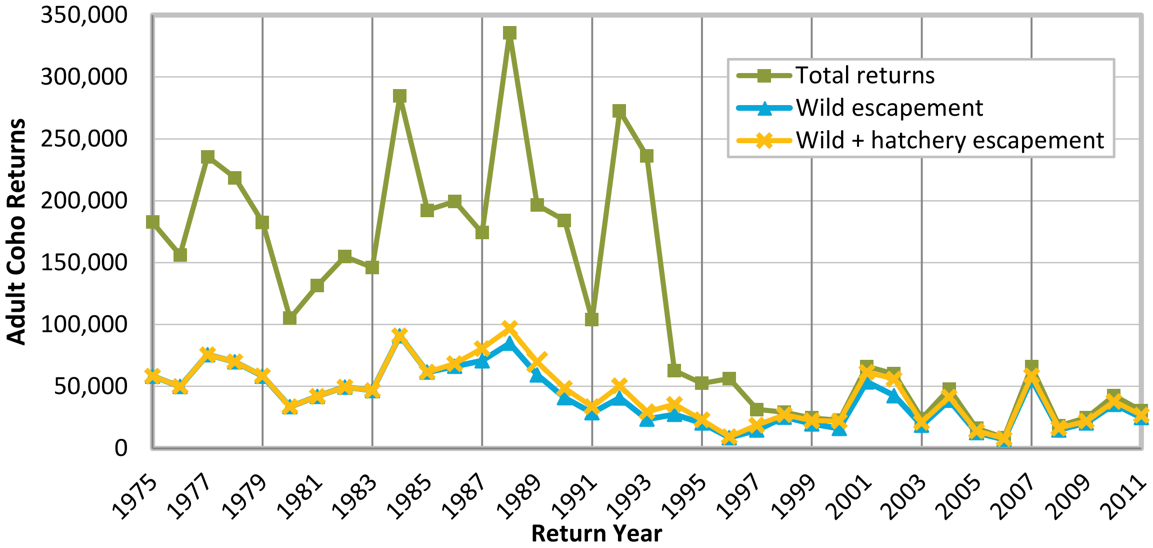


Figure 5. Reconstructed time series of wild coho salmon escapements, total escapements (wild + hatchery fish), and total returns (escapement + catch) for the interior Fraser River watershed, 1975–2011.
Source: data from Decker and Irvine (2013)

Assessed as Endangered by COSEWIC in 2002, this population's migratory behaviour and habits make it susceptible to both natural and anthropogenic impacts (COSEWIC, 2002). Declines during the 1990s were attributed to declining marine survival exacerbated by overfishing, but escapement has also remained low in the 2000s compared to pre-1991 levels (Decker and Irvine, 2013). From 2001 to 2011, there have been four years where production of returning spawners was below replacement levels, even in the absence of fishing (Decker and Irvine, 2013). However, average escapement from 2009–2011 was estimated at 27,000, indicating some recovery has occurred (Decker and Irvine, 2013). In general, escapement has increased gradually across the five conservation units (CUs) that make up the range of interior Fraser coho with the exception of the Lower Thompson CU, which has seen a larger 72% increase in escapement, and the Fraser Canyon CU, which has seen a 58% decrease in escapement (Figure 6) (Decker and Irvine, 2013). Key threats to the long-term survival of interior Fraser coho continue to be fishing and habitat perturbations, as well as climate change (Decker and Irvine, 2013).

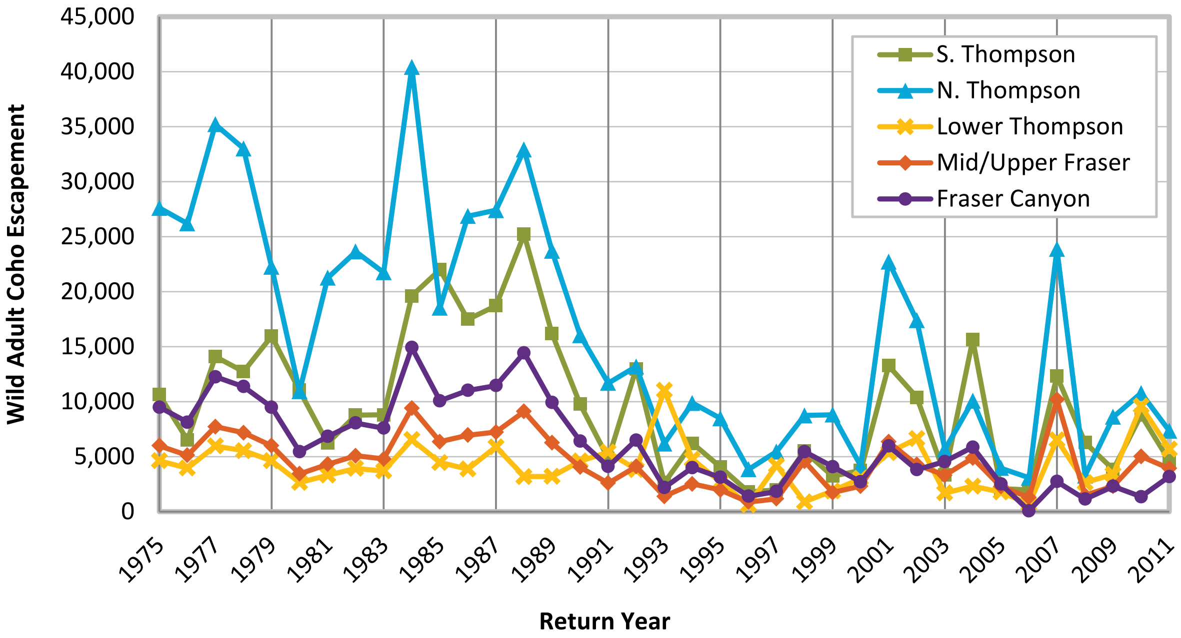


Figure 6. Reconstructed time series of wild coho salmon escapements for the five Conservation Units (CUs) within the interior Fraser River watershed, 1975–2011.
Data for the Lower Thompson CU prior to 1984 and for the Mid/Upper Fraser and Fraser Canyon CUs prior to 1998 are extrapolated based on observed escapements for the other units. Exploitation rates for 1975–1985 are the average of estimates for 1986–1996. See Decker and Irvine (2013) for further details.
Source: data from Decker and Irvine (2013)

River redhorse

The Canadian range of the river redhorse (*Moxostoma carinatum*) includes areas of southern Ontario and Quebec and has been threatened because of habitat degradation (such as pollution and siltation), stream regulation from dams, and habitat fragmentation (COSEWIC, 2006c). Assessed as Special Concern by COSEWIC, populations have been lost from the Ausable, Châteauguay, Noire, and Yamaska rivers but were still present in the Mississippi, Ottawa, and Richelieu rivers in 2004 (COSEWIC, 2006c). The river redhorse was common in the 1940s in the St. Lawrence River but has markedly decreased since then in that system through fragmentation from canal diversions and dam developments (COSEWIC, 2006c).

White sturgeon

White sturgeon (*Acipenser transmontanus*), the largest freshwater fish in Canada, is restricted to the west coast of North America (Welch et al., 2006). Its size (up to 6 metres), longevity (over 100 years), and late maturity (14 to 30 years), make it especially vulnerable to overexploitation and habitat degradation (COSEWIC, 2003b). Populations of white sturgeon have substantially declined in Canada over the last century (COSEWIC, 2003b). Of the six white sturgeon populations in BC, three are declining (Columbia, Kootenay, Nechako), one is now more stable, with some fluctuations (lower Fraser), and two are stable (mid- and upper Fraser) (COSEWIC, 2003b; McAdam, 2009, pers. comm.).

Poor juvenile survival, linked to river diversions, changes in sediment quantity and quality, and water flow regulation associated with dams, are the primary reasons for endangerment of the three declining populations (COSEWIC, 2003b; McAdam et al., 2005).These declining populations are projected to decline by more than 83% in the next generation, although conservation efforts including hatchery spawning and release of juveniles are being carried out to attempt to mitigate this decline (COSEWIC, 2003b).Juvenile production (or recruitment) of the Nechako River population illustrates this trend (Figure 7). Recruitment failure of the Nechako population is hypothesized to result from altered substrates in the river, particularly following two slide events that collectively added 1 million m^3 of silt, sand, and fine gravel into the main channel, with roughly half of this material subsequently moving downstream (McAdam et al., 2005).

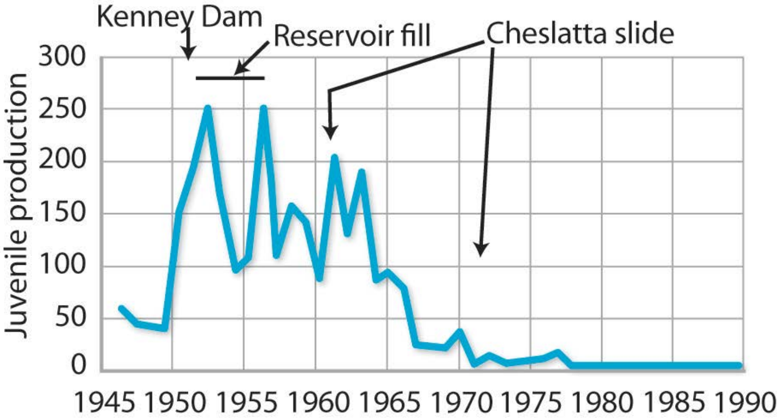


Figure 7. Juvenile production of white sturgeon, Nechako river populations, 1945–1990. Estimated based on age composition data collected from 1995–1999. Source: McAdam et al. (2005)

TRENDS IN HYDROLOGICAL REGIMES

The Water Survey of Canada coordinates the national database, HYDAT (Environment Canada, 2006b), which, as of 2006, contained national hydrometric information for >2500 active water level and discharge monitoring stations and an additional >5500 discontinued stations located on lakes, rivers, and streams across Canada. The majority of stations are located in the southern half of the country near centres of population and development, with fewer stations with fewer consecutive years of data in the north (Figure 8).

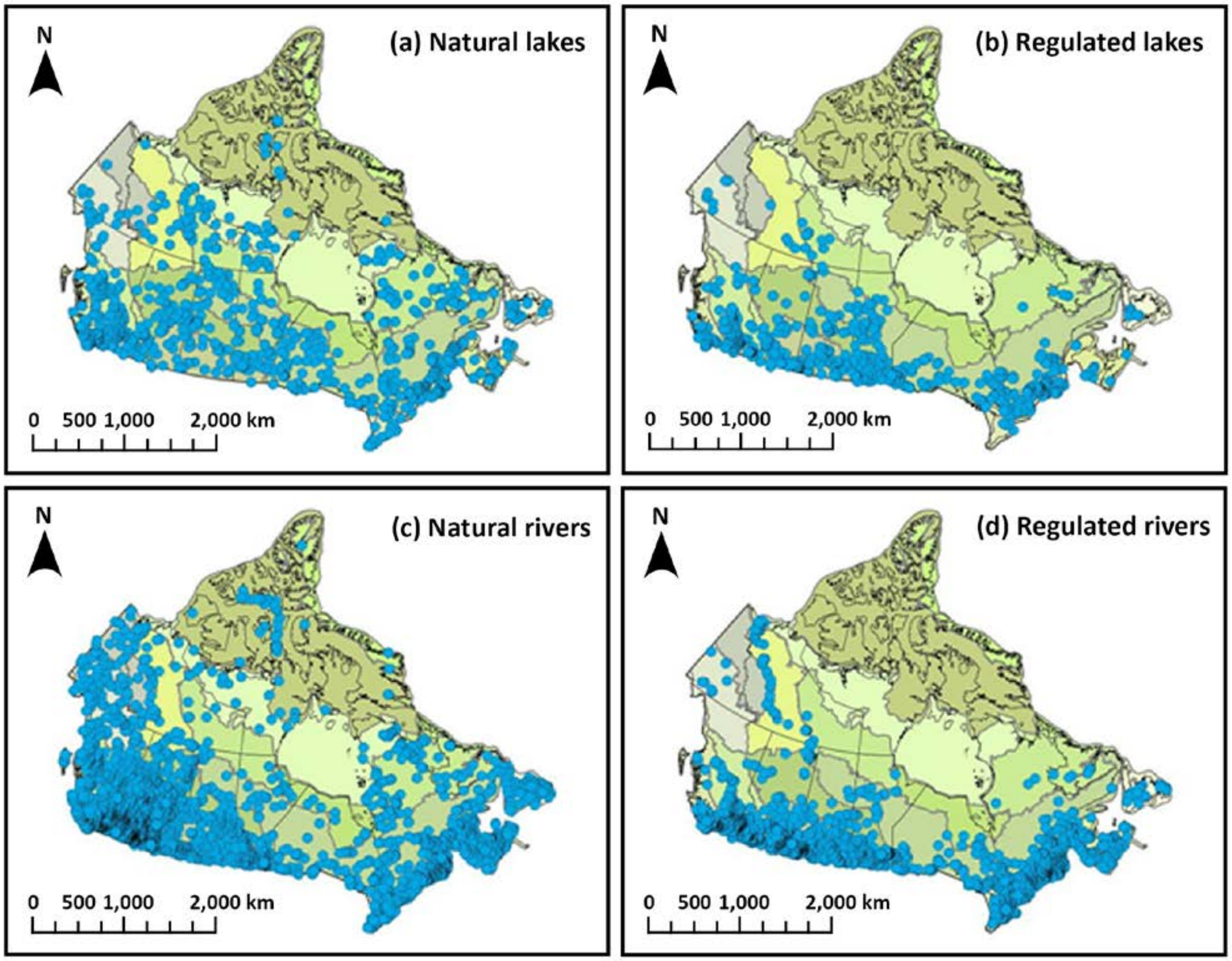


Figure 8. Distribution of existing and historically gauged water monitoring stations across Canada: (a) natural lakes; (b) regulated lakes; (c) natural rivers; and (d) regulated rivers.
Source: data from Environment Canada (2006b)

Hydrometric stations are designated as either "natural" or "regulated" by the Water Survey of Canada. Natural sites reflect gauging stations with minimal regulation or impact upstream of the site (Environment Canada, 2010b). Regulated sites vary regionally in their hydrological alteration in terms of water abstraction, impoundment, or diversion of flow. While daily observations have been recorded for some sites since the early 1800s, the majority of data in HYDAT were collected from the 1970s to the early 1990s (Figure 9). Network rationalisation during the 1990s resulted in significant station loss, reducing the spatial coverage of the network. Early monitoring appears to have focused on regulated river and lake systems. Although all site types show a recent increase in monitoring, the strongest increase appears to be for natural river systems. The majority of sites within the HYDAT database have less than 18 consecutive years of data (Figure 10). With the need for long-term continuous records for monitoring current trends and projecting future trends in hydrological regimes, it is imperative that sites with longer records are maintained and that additional sites are brought online where trends monitoring is required, for example for the ongoing assessment of climate change.

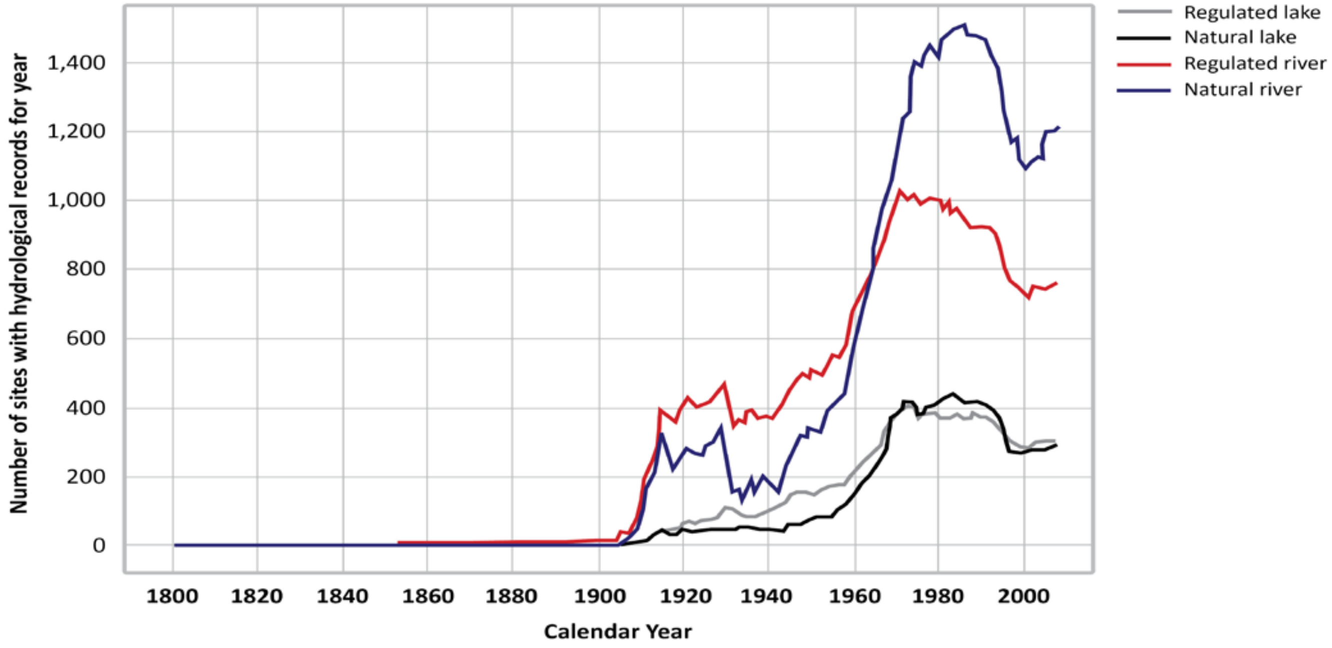


Figure 9. Number of sites with hydrological records for regulated and natural lakes and rivers, 1800–2006.
Source: data from Environment Canada (2006b)

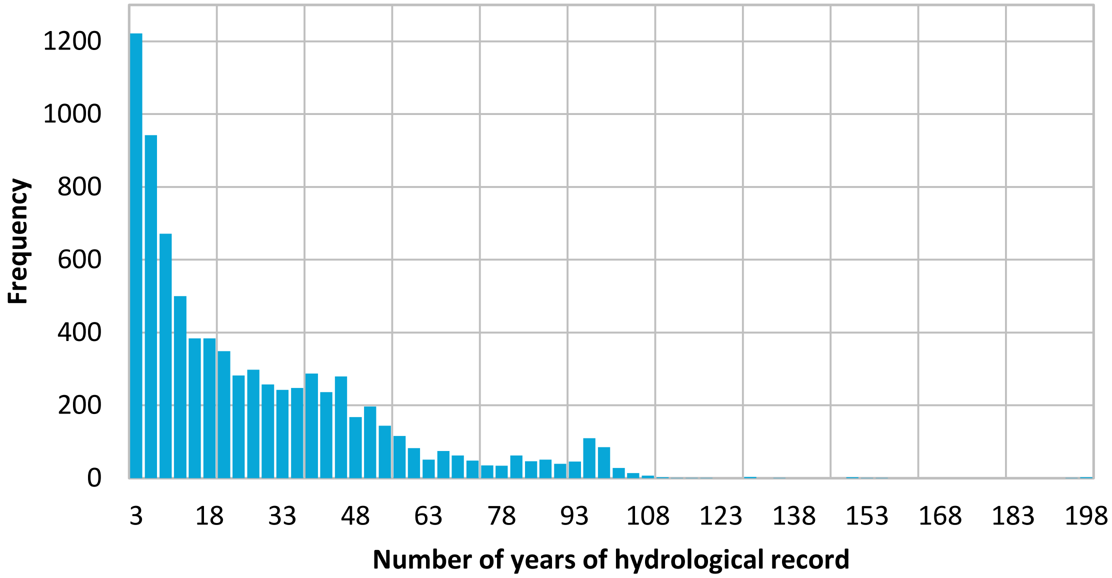


Figure 10. Frequency histogram for the total number of years of data at each hydrometric site.
Source: data from Environment Canada (2006b)

Exploring hydro-ecological trends

Aquatic communities are generally adapted to natural inter-annual variability in the flow regime and the magnitude, timing, and predictability of high and low flow periods (Jowett and Duncan, 1990). Previous studies have quantitatively explored the ecological significance of components of the flow regime for hydro-ecological research and for environmental flow recommendations and related methods development (for example, Monk et al., 2008). Additionally, research has explored trends in hydrological regimes across North America (see examples in Table 2). Schindler and Donahue (2006) reported, for example, that mean summer (May to August) flows of the Athabasca River decreased by 20% since 1958. In addition, changes in the drivers of the hydrological regime have been reported—for example, the total precipitation falling as snow declined in western Canada and the Prairies from 1900 to 2003 as a result of climate warming trends (Vincent and Mekis, 2006).

Table 2. Summary of published scientific papers exploring statistical trends in streamflow and runoff in Canadian rivers.

Study catchment(s)	**Area of study**	**Ecozone$^+$**	**Number of sites Analysis method Analysis period (with # sites for period)**	**Results / direction of trends**	**Reference**
Liard, Peace, Athabasca	YK, AB, BC, SK, NT	Boreal Cordillera, Taiga Plains, Boreal Plains, Montane Cordillera	26 hydrometric Mann-Kendall 1970–2005 (26) 1965–2005 (21) 1960–2005 (18)	• Spring freshet occurring earlier with the timing shift stronger in headwater catchments • Part attributed to effects by Pacific Decadal Oscillation, North Atlantic Oscillation, North Pacific Index and Atlantic Multi-decadal Oscillation	Burn (2008)
Liard	YT, NT, BC and AB	Taiga Plains, Taiga Cordillera, Boreal Plains, Boreal Cordillera	12 hydrometric Mann-Kendall 1975–1999 (13) 1970–1999 (12) 1965–1999 (8) 1960–1999 (7)	• Increasing winter flow and increasing minimum flow • Slight decreasing trend in the summer months' flow • Spring freshet occurring earlier and earlier spring peak flow related to increases in air temperatures • Increased winter flows related to Pacific Decadal Oscillation • Clear spatial differences along catchment, e.g., upper catchment experiencing decreasing trends overall but lower catchment presents increasing trends	Burn (2004)
Athabasca, Peace, Great Slave, Liard, Mackenzie, Northern Peel, Coppermine	AB, SK, BC, NT, YT	Taiga Shield, Boreal Shield, Boreal Plains, Montane Cordillera, Taiga Plains, Taiga Cordillera, Boreal Cordillera	54 hydrometric 10 meteorological Mann-Kendall 1975–2000 (54) 1970–2000 (46) 1965–2000 (34) 1960–2000 (21)	• Strong increasing trends over the winter months (December to April) • Increasing annual minimum flow • Weak decreasing trends in annual mean flow and the early summer and late fall flows • Earlier onset of spring freshet	Aziz and Burn (2006)

Study catchment(s)	Area of study	Ecozone[+]	Number of sites Analysis method Analysis period (with # sites for period)	Results / direction of trends	Reference
248 sites across Canada	All areas	All ecozones[+] except Arctic Cordillera portion of Arctic Ecozone[+]	248 RHBN hydrometric 1940–1997 1950–1997 1960–1997 1970–1997 All available records at stations	• Spatial patterns in significant trends suggest impacts are not spatially uniform • Decreasing trend in annual maximum flow in the south and an increasing trend in the north • Date of ice breakup is earlier, probably as a result of earlier onset of spring melt conditions • Strong increasing trend in March and April flow indicative of an earlier onset of spring snowmelt • June flow displays a strong decreasing trend • October flows display increasing trends in the east and north and decreasing trends in the west	Burn and Hag Elnur (2002)
25 streams across the Prairies	AB, SK, MB	Prairies, Boreal Plains, Boreal Shield, Taiga Shield, Taiga Plains	25 hydrometric 16 meteorological 1976–2005 (26) 1971–2005 (24) 1966–2005 (17)	• Decreasing trends in the spring snowmelt runoff volume and peak flow • Earlier spring snowmelt peak • Decreasing trends in seasonal (March–October) runoff volume • Attributed to reductions in snowfall and increases in winter air temperatures	Burn *et al.* (2008)
26 subcatchments within the Churchill–Nelson	BC	Montane Cordillera, Pacific Maritime, Western Interior Basin	26 hydrometric 19 air temperature 18 precipitation Mann-Kendall 1960–1999	• Decrease in magnitude of hydrological events • Earlier snowmelt runoff events • Spring mean monthly flow increased due to greater snow melt potential • Timing of hydrological event strongly influenced by changes in air temperature • Decreasing trends in the southern region, while increasing trends in the northern regions	Cunderlik and Burn (2004)

Study catchment(s)	Area of study	Ecozone$^+$	Number of sites Analysis method Analysis period (with # sites for period)	Results / direction of trends	Reference
156 hydrometric stations across Canada	All areas	All ecozones$^+$ except Arctic Cordillera portion of Arctic Ecozone$^+$	156 RHBN hydrometric 1974–2003 (156)1964–2003 (102) 1954–2003 (49)	• Fluctuating trends in minimum flows (1-, 7-, 15-, and 30-day annual and seasonal low flow regimes) • Sensitivity of results to analysis time frame	Khaliq *et al.* (2008)
Winnipeg River	ON, MB	Boreal Shield	9 hydrometric Adjusted Historical Canadian Climate Data and gridded climate dataset Mann-Kendall 1924–2003	• Increasing trend in streamflow with winter streamflow increasing by 60–110% over the entire basin • Changes related to climate as accounted for regulated vs. natural gauges • Basin hydrology has amplified coincident but smaller increases in summer / autumn precipitation	St. George (2007)
Miramichi River	NB	Atlantic Maritime	2 hydrometric 3 meteorological Linear regression 1970–1999	• Spring and summer air temperature increases • Discharge relatively unchanged in winter / autumn • Increasing duration of low flow conditions reflecting greater evaporation rates from increased air temperatures • Earlier spring peak flows	Swansburg *et al.* (2004)
151 hydrometric stations across Canada	All areas	All ecozones$^+$ except Arctic Cordillera portion of Arctic Ecozone$^+$	151 RHBN hydrometric Mann-Kendall 1967–1996 (151) 1957–1996 (71) 1947–1996 (47)	• General decrease in mean annual streamflow with significant decreases in the southern part of Canada • Large decreases in August and September flow • Increase in spring (March / April) flow • Significantly earlier spring freshet in British Columbia. • Earlier freeze up, particularly in Eastern Canada	Zhang *et al.* (2001)

Study catchment(s)	Area of study	Ecozone^{+}	Number of sites Analysis method Analysis period (with # sites for period)	Results / direction of trends	Reference
248 hydrometric stations	All areas	All ecozones^{+} except Arctic Cordillera portion of Arctic Ecozone^{+}	248 RHBN hydrometric Statistical trend estimate. Divided into ten geospatial regions. Each region with differing data length. Max. time series = 1908–1997 (Mountain region) Min. time series = 1961–1997 (NWT/NU)	• Significant increase in July (Prairie and Pacific region) and December (NWT/NU) flow • Decreasing trend for annual mean flow (Central, Mountain-North and Pacific region) • Significant decrease in annual maximum daily flow (Central/East, Mountain-North, Pacific, NWT/NU) • Significant increasing trend in annual maximum daily flow (Central and Prairie) • Significant increasing annual minimum flow (Western Quebec/Southern Ontario, Mountain-North and Pacific) • Decreasing trend in annual minimum flow (Central/East region)	Adamowski and Bocci (2001)
Mackenzie basin	AB, SK, BC, NT, YT	Taiga Shield, Boreal Shield, Boreal Plains, Montane Cordillera, Taiga Plains, Taiga Cordillera, Boreal Cordillera	16 hydrometric 9 meteorological Spearman's rank correlation 1972–1999	• At the scale of the Mackenzie basin, no obvious streamflow trends were present at either monthly or annual time scale • At the scale of individual rivers, evidence of earlier ice break up possibly linked to increasing air temperatures for the snowmelt months (April to June) • Overall, date and magnitude of peak flow show no trend but greater variability for lower Mackenzie and Peace rivers • Tendency of increasing streamflow variability	Woo and Thorne (2003)

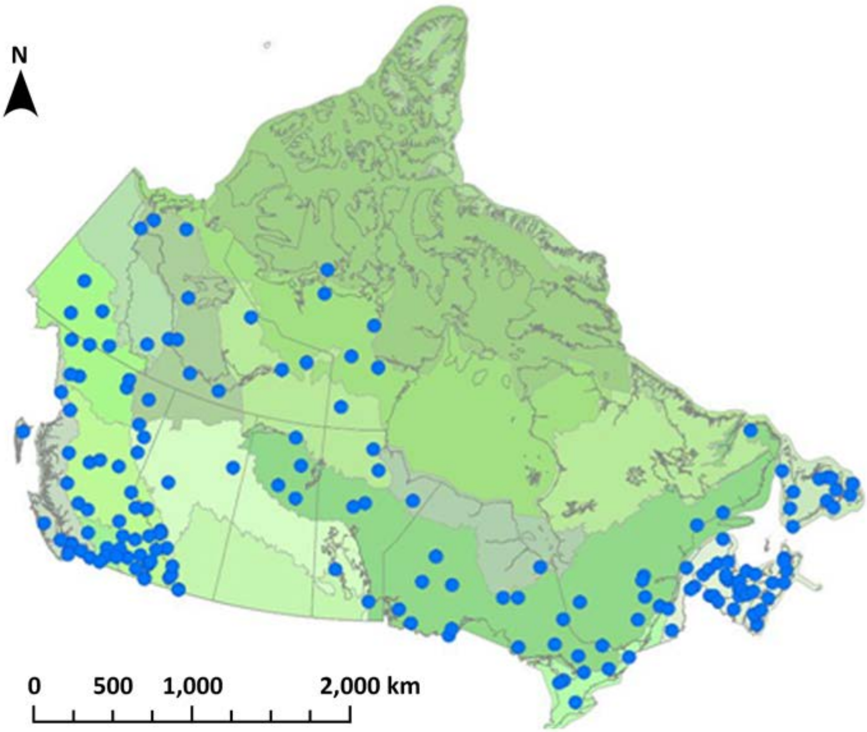
Study catchment(s)	Area of study	Ecozone^{+}	Number of sites Analysis method Analysis period (with # sites for period)	Results / direction of trends	Reference
64 hydrometric sites draining to high-latitude oceans	YT, NT, NU, QC, ON, MB, NL	Northern Arctic, Southern Arctic, Arctic Cordillera Taiga Cordillera, Taiga Plains, Hudson Plains, Taiga Shield	64 hydrometric Mann-Kendall 1964–2003	• Significant decreased trend in total annual freshwater discharge leading to a 10% decrease in the total annual discharge to the Arctic and North Atlantic Oceans • Attributed to decreased trend in precipitation over same period and suggests that changes in river discharge over northern Canada are driven primarily by precipitation rather than evapotranspiration	Déry and Wood (2005)
42 rivers draining into Hudson, James and Ungava bays	NU, ON, SK, AB, MB, QC	Northern Arctic, Southern Arctic, Taiga Shield, Taiga Plains, Hudson Plain, Boreal Shield, Boreal Plains	42 hydrometric Mann-Kendall 1964–2000	• Decreasing trends in discharge for 36 out of 42 rivers • Total annual freshwater discharge in 2000 into Hudson, James and Ungava bays decreased by 13% from its value in 1964 • Peak discharge rate associated with snowmelt has advanced by eight days and diminished in intensity • Spring freshet varies by five days for each degree of latitude	Déry *et al.* (2005)
56 rivers across North America (14 flow into Arctic Ocean and 42 flow into Hudson, Ungava and James bays)	YT, NT, NU, QC, ON, MB, NL	Taiga Cordillera, Taiga Plains, Southern Arctic, Northern Arctic, Arctic Cordillera Taiga Shield, Hudson Plains,	56 hydrometric Mann-Kendall 1964–2000	• Discharge to Arctic Ocean decreased from sites in North America • Discharge from sites draining Hudson, Ungava and James bays decreased by about 2.5 km^{3}/y/y during 1964–2000 • Reconstructed discharge from the Yukon River showed no significant change in discharge • Suggest concomitant decreases in precipitation and river discharge	McClelland *et al.* (2006)

A subset of hydrometric gauging stations form the Reference Hydrological Basin Network (RHBN) (Environment Canada, 2010b). This hydrological network of unimpacted catchments across Canada provides the national contribution to the World Meteorological Organization Monitoring Program for Climate Change. Brimley *et al.* (1999) and Harvey *et al.* (1999) defined the six original RHBN station selection criteria: i) stations should be minimally impacted with less than 10% modification from natural conditions; ii) absence of significant regulations or diversions upstream of the gauging station; iii) a minimum of 20 years of hydrological data; iv) future longevity of the station in its current pristine or stable state; v) accuracy of data records assessed by local experts for both open-water and ice-cover conditions; and vi) breadth of coverage of the different types of hydrometric stations (seasonal, continuous, streamflow, and lake level). From the original list of 255 RHBN gauging stations, 7 are lake level stations, 37 are seasonal stations, and 211 are continuous discharge monitoring stations (Environment Canada, 2006b).

Trends in lake levels were not considered in the analysis for this report because of the limited number within the RHBN database precludes any meaningful derivation of national trends at this time. There are, however, notable regional analyses on trends in lake levels. Van der Kamp *et al.* (2008), for example, explored patterns in long-term water level changes in 16 closed-basin lakes in the semi-arid prairie region of Canada. Their results indicated an overall declining trend in lake levels of 4 to 10 metres from circa 1920 to 2005. However, some east-central lakes demonstrated rising water levels from the 1960s onwards, which was linked to either higher precipitation or lower evaporation, in addition to sensitivity to changing land use relating to their low-lying relief (Van der Kamp et al., 2008). This further underscores the influence of regional climate variation in masking habitat change.

Daily mean flow data from 1969 to 2005 (which corresponds to the 1970 to 2005 hydrological years) were extracted from the Water Survey of Canada HYDAT database (Environment Canada, 2006b) for the 211 RHBN continuous flow river monitoring stations across Canada. Data were assessed for missing data and data quality. With catchment areas ranging from 3.9 to 145,000 km^2, the majority of stations had more than 30 years of data over the 1970 to 2005 time period, with the remaining stations having more than 20 years of data. Following the approach of Burn and Hag Elnur (2002), no more than five years of data during the common period (1970 to 2005) could be missing for a station to be included in the analysis. A minimum of 31 years of data, with less than five years of missing records, were selected for this analysis as this record length ensured maximum time series length (Figure 11). Selecting a common period of record for the analysis allows investigation of variable climatic conditions.

The spatial coverage of hydrological gauging stations encompassed all ecozones$^+$ (Figure 11); however, the distribution of stations across ecozones$^+$ was non-uniform with the highest density by area of suitable gauging stations in the Western Interior Basin and the Atlantic Maritime ecozones$^+$. More northerly ecozones$^+$ presented lower densities. In addition, the spatial bias reflected a lack of stations with suitable data in northeastern Canada and the Prairies, where seasonal operation of gauging stations was common. Due to the low number of stations in some regions, caution should be observed when interpreting the results of the trend analyses.



Ecozone^{+}	Number of stations used
Arctic - Northern	2
Arctic - Southern	3
Taiga Cordillera	1
Taiga Plains	11
Boreal Cordillera	9
Taiga Shield	6
Pacific Maritime	11
Montane Cordillera	27
Boreal Plains	6
Boreal Shield	31
Newfoundland Boreal	12
Hudson Plains	2
Prairies	4
Western Interior Basin	8
Atlantic Maritime	34
Mixedwood Plains	5

Figure 11. Map of stations with suitable hydrological data used in trend analyses and table summarizing the number of suitable stations by ecozone^{+}*.*

Richter *et al.* (1996) identified 32 annual hydro-ecological variables, known as the Indicators of Hydrologic Alteration (IHA), which represent ecologically important flow regime components (Table 3 and Table 4). These 32 IHA variables were calculated for hydrometric stations for each hydrological year from 1970 to 2005 (defined as October 1st to September 30th). The IHA variables quantify the magnitude (size), frequency, timing, duration, and flashiness (rate of change) of the flow regime. The IHA variables were calculated using the Nature Conservancy's IHA software (The Nature Conservancy, 2007). In the absence of long-term ecological data, these IHA variables describing the hydrological regime offer a surrogate assessment of the habitat suitability for aquatic communities.

Table 3. Description of flow regime components, their instream ecological impacts, and exemplar variables.

Flow regime component	Description	Ecological impacts	Exemplar variables
Magnitude	A measure of the amount of water passing a fixed point per unit time. Flow can vary with climatic conditions and catchment size both within and among river systems. Magnitude can be used as an indicator of the suitability of a habitat.	• Habitat availability for species • Soil moisture availability for plants • Influences water temperature, oxygen levels, and photosynthesis in the water column	Mean monthly flow Maximum or minimum flow
Frequency	A measure of the rate of recurrence of hydrological events above a given magnitude over a specified time interval.	• Availability of floodplain habitats • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Influences bedload transport, channel sediment textures	Number of low or high flow events per year above a certain magnitude
Duration	A measure of the period of time over which a hydrological condition, such as an extreme event or a normal condition, persists. Duration can be associated with a particular flow event or defined as a composite expressed over a given time period.	• Duration of stressful conditions, for example, low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, and floodplains • Duration of high flows for aeration of spawning beds in channel sediments	Number of days per year of a specified flow magnitude
Timing	A measure of the regularity of hydrological conditions of a defined magnitude.	• Predictability/avoidability of stress for organisms • Spawning cues for migratory fish • Evolution of life history strategies and behavioural mechanisms	The Julian date of the annual 1 day maximum flow
Rate of change (flow variability)	Refers to the speed at which conditions change from one magnitude to another, for example, 'stable' streams have slow rates of change compared to 'flashy' systems that have rapid rates of change in flow conditions.	• Stranding of species in isolated habitat patches (falling levels) • Entrapment on islands and floodplains (rising levels)	Number of daily positive/negative changes in flow

Source: Richter et al. (1997) and Poff et al. (1996)

Table 4. Ecologically relevant hydrological parameters used in the Indicators of Hydrologic Alteration (IHA) and their characteristics.

IHA group	Hydrological regime component	Hydrological Parameters
Group 1 Magnitude of monthly runoff	• Magnitude • Timing	• Median value for each calendar month (October–September)
Group 2 Minimum and maximum of annual runoff	• Magnitude • Duration	• Annual mean 1-day, 3-day, 7-day- 30-day and 90-day minimum • Annual mean 1-day, 3-day, 7-day- 30-day and 90-day maximum • Baseflow (7-day minimum / mean annual flow)
Group 3 Timing of annual one day minimum and one day maximum runoff	• Timing	• Julian date of each annual 1-day minimum • Julian date of each annual 1-day maximum
Group 4 Frequency and duration of high and low runoff	• Magnitude • Frequency • Duration	• No. of low pulses each year (where a pulse threshold is the median -25%) • No. of high pulses each year (where a pulse threshold is the median +25%) • Median duration of low pulses within each year • Median duration of high pulses within each year
Group 5 Variability in runoff	• Frequency • Rate of change	• Median of all negative difference between consecutive daily means • Median of all positive difference between consecutive daily means • No. of hydrograph rises (daily positive changes in flow) • No. of hydrograph falls (daily negative changes in flow) • No. of reversals (number of switches between positive and negative flow)

Source: adapted from Richter et al. (1996)

River flow data (m^3/s) were converted to runoff (mm/day) to standardize the effects of differing drainage areas. Most variables were calculated using non-parametric (percentile) statistics because of the naturally skewed nature of many hydrological data records. The exception was the moving average variables (1-day to 90-day minimums and maximums) as these are always calculated as means. The variables were calculated for individual hydrological years and were used in the trend analysis. The presence of trends at each station for each variable was analysed using the Mann-Kendall methods to determine the significance of the detected trends using a permutation procedure (see Box). The analysis was completed using the MAKESENS program, a Microsoft Excel worksheet-based application (Salmi et al., 2002). Results were deemed statistically significant at the 10% level where $p<0.1$, consistent with other studies of this type (for example, Aziz and Burn, 2006).

Box: Details of Mann-Kendall trends analysis

A non-parametric statistic method was used to detect trends in the IHA variables because of the naturally skewed nature of many hydrological data records. The Mann-Kendall trend analysis was applied to minimize the problems associated with differentiating between natural variability and data trends (Burn and Hag Elnur, 2002; Burn and Cunderlik, 2004; Kundzewicz and Robson, 2004). Originally derived by Mann (1945) and subsequently developed by Kendall (1975), the Mann-Kendall non-parametric test for trend analysis has been applied by other researchers in similar studies (e.g., Burn and Hag Elnur, 2002; Chu et al., 2003; Burn and Cunderlik, 2004; Bonsal et al., 2006). The Mann-Kendall test is non-parametric and compares the relative magnitudes of input data as opposed to actual data values (Mann, 1945; Khaliq et al., 2008). The test statistic can be given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k-1}^{n} sign(x_j - x_k)$$

where

$$\begin{aligned} sign(x_j - x_k) &= 1 \text{ if } x_j - x_k > 0 \\ &= 0 \text{ if } x_j - x_k = 0 \\ &= -1 \text{ if } x_j - x_k < 0 \end{aligned}$$

where x_1, x_2, …x_n represent n data points, and x_j represents the data point at time j

Results: national summary and spatial distribution of hydrological trends, 1970 to 2005

Published research has explored the correlations in hydrological trends with changes in the climate (see examples in Table 2). However, as the results have been variable, it is important to interpret longer-term trends in streamflow with inter-decadal shifts in climate in addition to accounting for basin characteristics (Woo and Thorne, 2008). A national summary of the results of the application of the non-parametric Mann-Kendall trend analysis is presented in Table 5 and on Figure 12, and results are summarized by ecozone$^+$ in Figure 13 and Figure 14. The results are then examined at the national and ecozone$^+$ level in three sections: magnitude of runoff; timing frequency and duration; and flashiness. It is difficult to draw conclusions regarding trends for several ecozones$^+$ because of the limited number of suitable hydrometric RHBN stations within them (that is, they have less than 10 stations). These ecozones$^+$, Mixedwood Plains, Hudson Plains, Taiga Shield, Boreal Plains, Prairies, Taiga Cordillera, Arctic, and Boreal Cordillera, are not considered further in this section. In order to restrict potential bias and reduce error in conclusions the data for all ecozones$^+$ are provided in Appendix 1.

Table 5. Trend results for the Indicators of Hydrologic Alteration (IHA) variables for 172 RHBN stations used in this analysis, using data for hydrological years 1970–2005.

IHA Statistics Group	IHA variables	% of stations with significant increasing trend (p<0.1)	% of stations with significant decreasing trend (p<0.1)
Group 1 Magnitude of monthly runoff	**October**	4.7	8.1
	November	8.7	3.5
	December	16.9	7.6
	January	18.6	8.1
	February	14.0	8.7
	March	12.2	2.9
	April	29.1	3.5
	May	2.3	22.1
	June	5.8	19.8
	July	6.4	13.4
	August	4.7	28.5
	September	5.8	18.0
Group 2 Minimum and maximum of annual runoff	**1-day minimum**	12.8	26.2
	3-day minimum	13.4	25.6
	7-day minimum	14.0	25.0
	30-day minimum	15.7	23.3
	90-day minimum	16.3	21.5
	Baseflow	12.2	15.7
	1-day maximum	6.4	18.0
	3-day maximum	5.8	18.0
	7-day maximum	6.4	18.0
	30-day maximum	5.2	16.9
	90-day maximum	6.4	14.5
Group 3 Timing of annual one day minimum and one day maximum runoff	**Date of 1-day minimum**	16.3	8.1
	Date of 1-day maximum	6.4	10.5
Group 4 Frequency and duration of high and low runoff	**Low pulse number**	11.6	2.3
	Low pulse duration	7.0	14.5
	High pulse number	4.1	7.0
	High pulse duration	5.2	6.4
Group 5 Variability in runoff	**Rise rate**	8.1	20.9
	Fall rate	15.1	5.8
	Hydrograph reversal	30.2	10.5

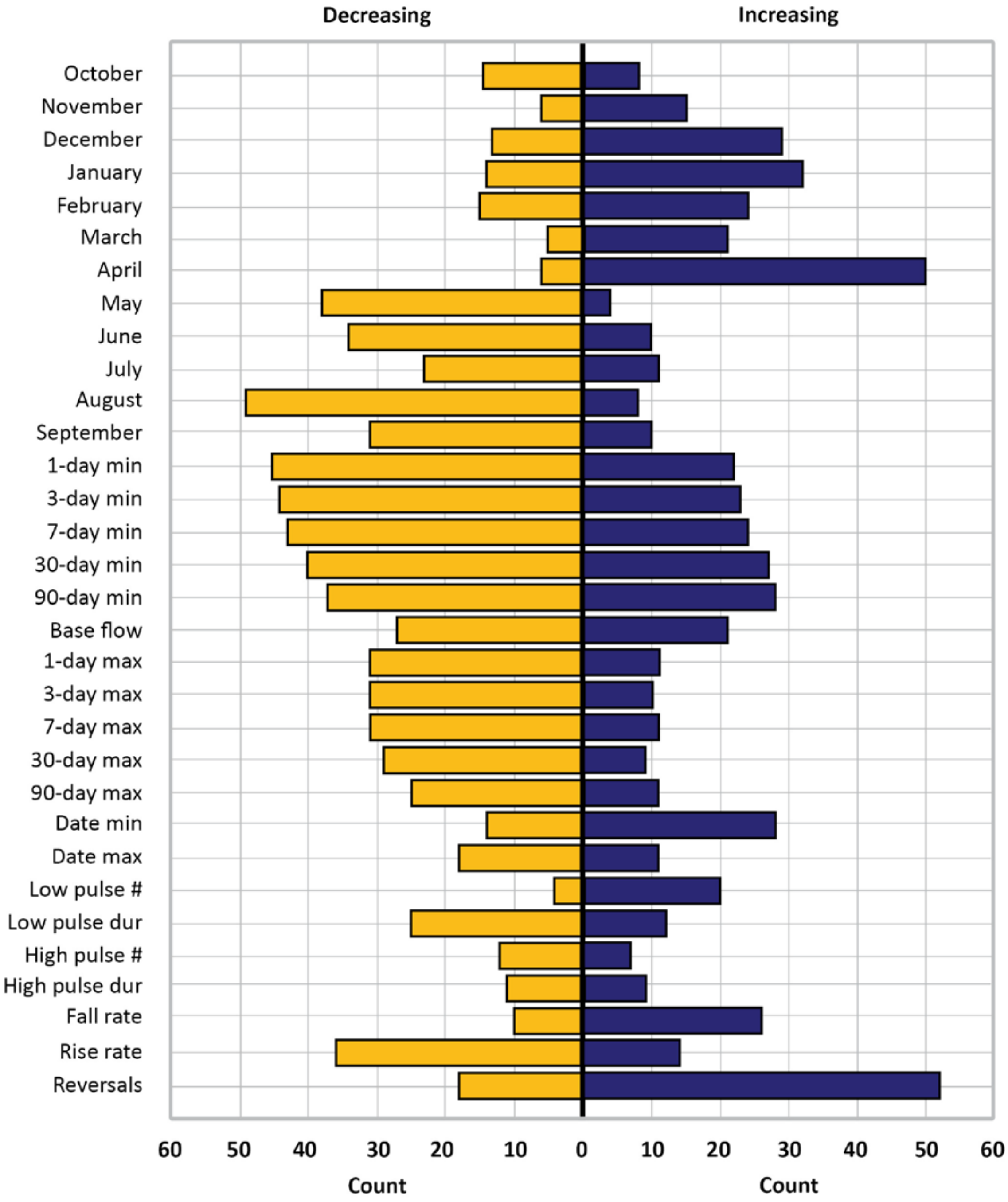


Figure 12. Summary of the total number of stations displaying significant (p<0.1) increasing and decreasing trends for each IHA variable, using data for hydrological years 1970–2005.

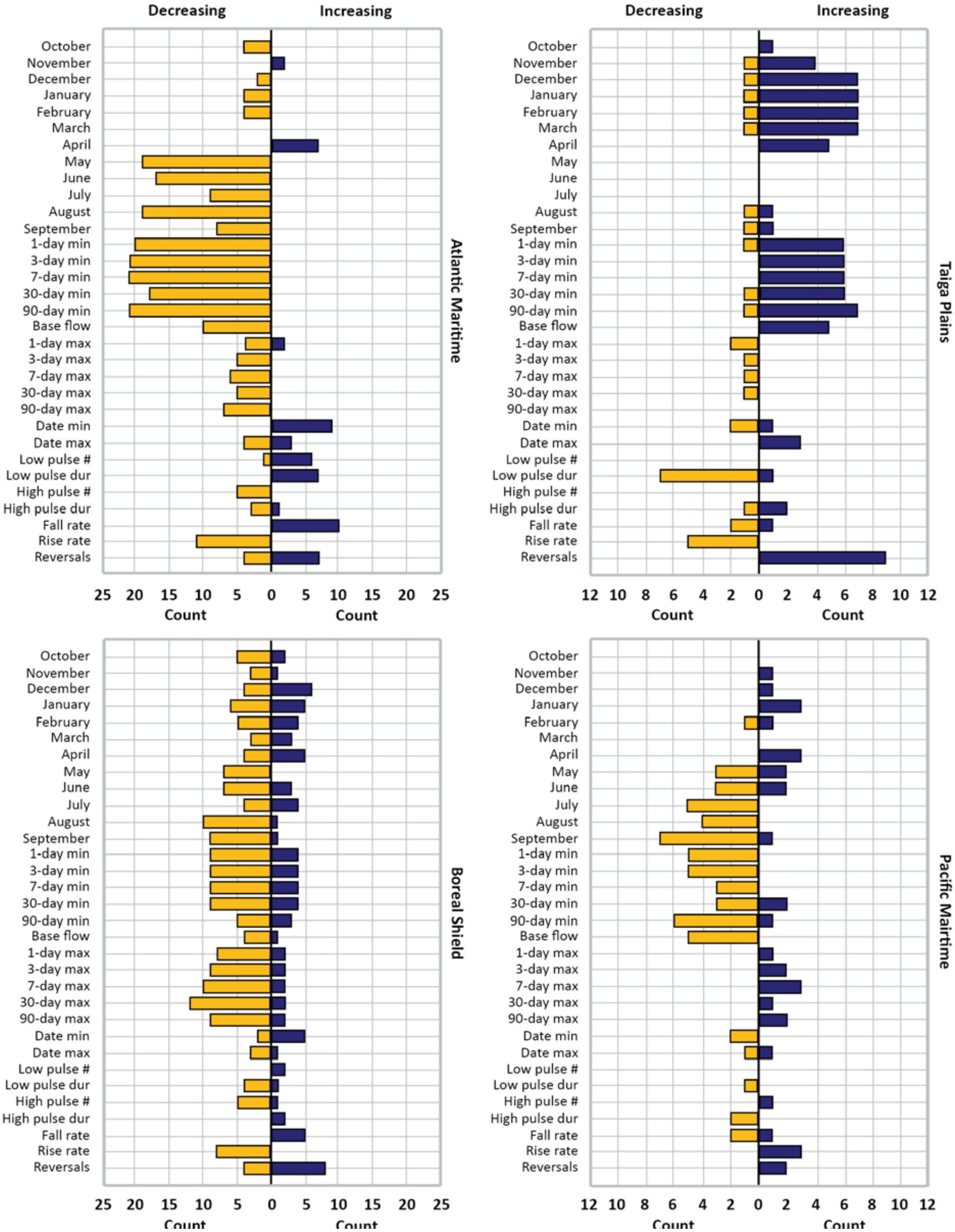


Figure 13. Summary of the total number of stations displaying significant (p<0.1) increasing and decreasing trends for each IHA variable for the Atlantic Maritime, Taiga Plains, Boreal Shield, and Pacific Maritime ecozones^{+}, using data for hydrological years 1970–2005.
Note the different x-axis scales. Only stations presenting significant trends are included.

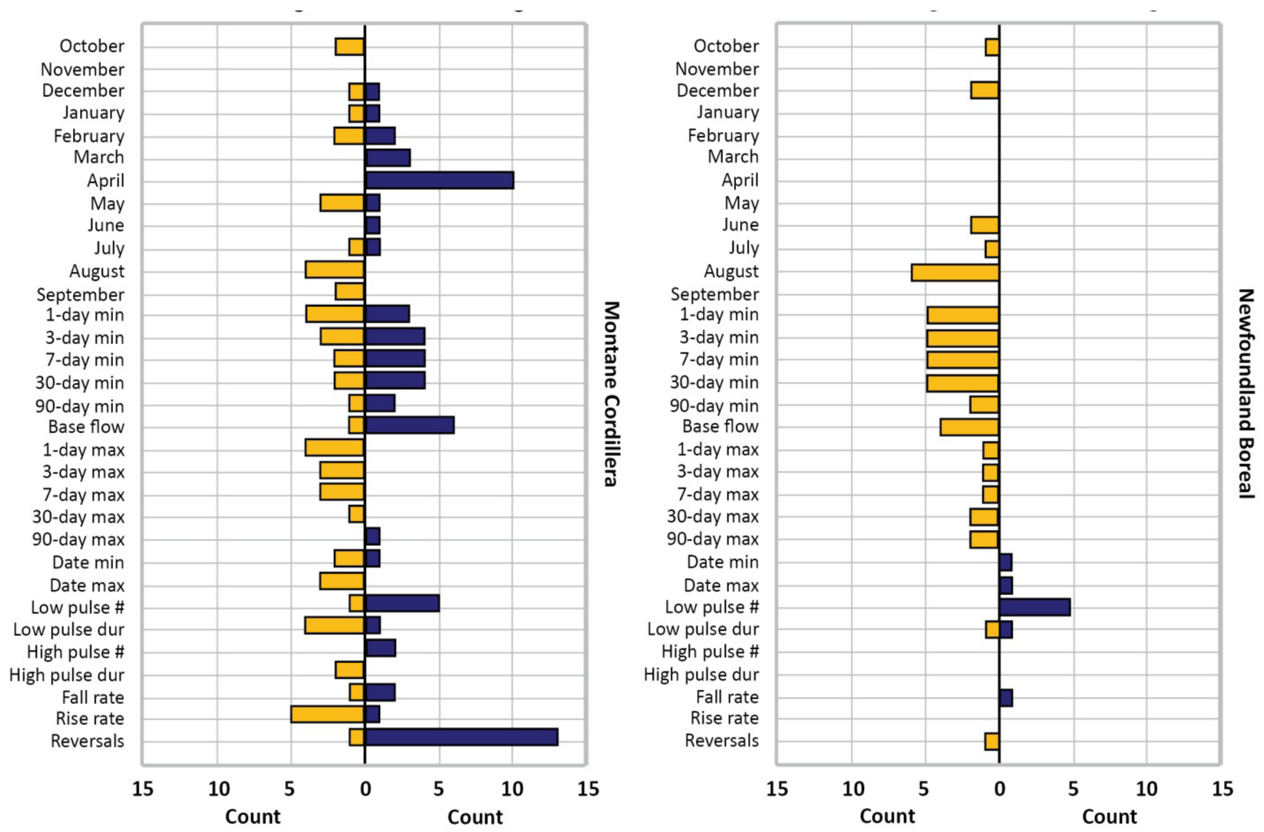


Figure 14. Summary of the total number of stations displaying significant (p<0.1) increasing and decreasing trends for each IHA variable for the Montane Cordillera and Newfoundland Boreal ecozones⁺, using data for hydrological years 1970–2005.
Only stations presenting significant trends are included.

We focus primarily on the statistically significant (p<0.1) directional trends, although we have also reported non-significant (p>0.1) directional tendencies. Although we acknowledge that these are much more likely to be as a result of chance because of the inherently noise associated with hydrological data, they do provide a method for visualising regional consistency where a majority of stations have demonstrated a directional pattern. In addition, these non-significant results do not mean that trends are absent, but rather indicate that significant trends cannot be detected with the short data series available. Thus, these are used in the context for broad spatial characterisation within each ecozone⁺ rather than to draw specific conclusions about individual station response. This approach has been used by other researchers, for example Hannaford and Marsh (2006) who explored regional hydrological trends within the United Kingdom.

Trends in the magnitude of runoff

The magnitude, or size, of runoff can reflect differences in the availability of suitable habitat for aquatic communities in addition to influencing water temperature and oxygen levels, especially in areas with seasonal ice cover. Due to the large variability in driving factors (such as climatic and natural watershed differences), there is a lack of a consistent pattern across the country causing differences in the monthly timing of hydrological events, such as initiation of the spring freshet. There was large variability in the percentage of trends in runoff among different months (Table 5 and Figure 15). For example, a greater proportion of stations demonstrated statistically significant increasing trends (p<0.1) for the winter months (December to February) than demonstrated a decrease for the same months. The pattern for spring and summer runoff was mixed, with significant increases for median April runoff while the majority of trends showed significant decreases for runoff between May and September. In particular, August runoff significantly decreased for over 28% of the stations. There were a few spatial patterns for monthly runoff trends, for example the majority of stations in western Canada demonstrated significantly increasing trends in April runoff with a cluster of stations showing decreasing trends in the Great Lakes region.

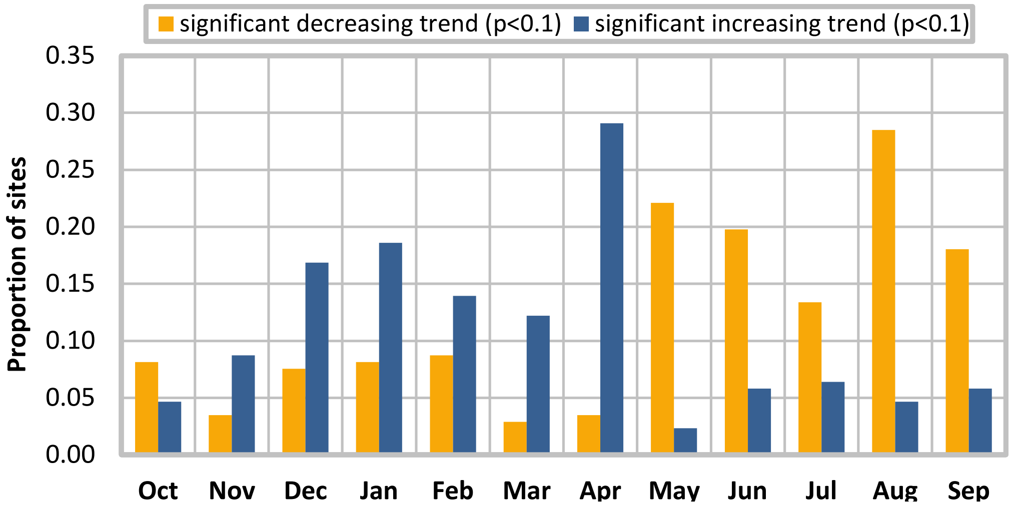


Figure 15. Trends in long-term monthly runoff for RHBN stations using data for hydrological years 1970–2005.

Minimum flows are ecologically important as they can limit the availability of specific aquatic habitats and also influence water temperatures and dissolved oxygen levels. Within the dataset, a greater proportion of stations demonstrated significant (p<0.1) decreasing trends than significant increasing trends in minimum runoff for all variables analyzed (Table 5 and Figure 16). These significant trends were more prominent, however, for variables describing minimum flows over shorter durations. For example, 26.2% of stations demonstrated significantly decreasing 1-day minimum flow compared with 21.5% of stations for minimum flow over 90 days. The tendency towards shorter duration trends could reflect the larger-scale overriding influences of seasonality over the longer term. Geographically, stations with significant trends towards reductions in 1-day minimum runoff were concentrated in southeastern and Atlantic Canada, and in southwestern Canada (Figure 17). Stations which demonstrated significant increases in 1-day minimum runoff were predominantly located in northwestern Canada and the few stations across northern Canada.

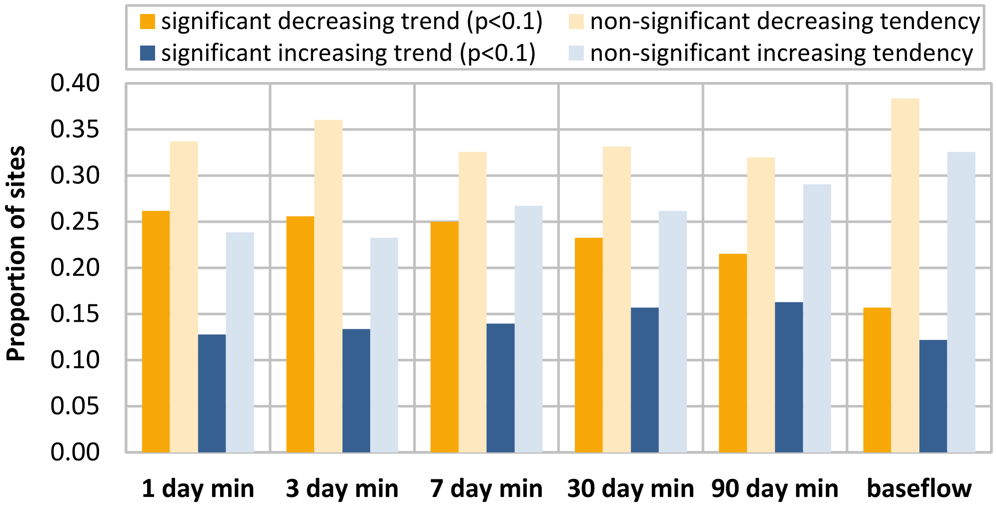


Figure 16. Trends in the magnitude of the 1-day, 3-day, 7-day, 30-day, and 90-day minimum runoff and in baseflow for RHBN stations using data for hydrological years 1970–2005.

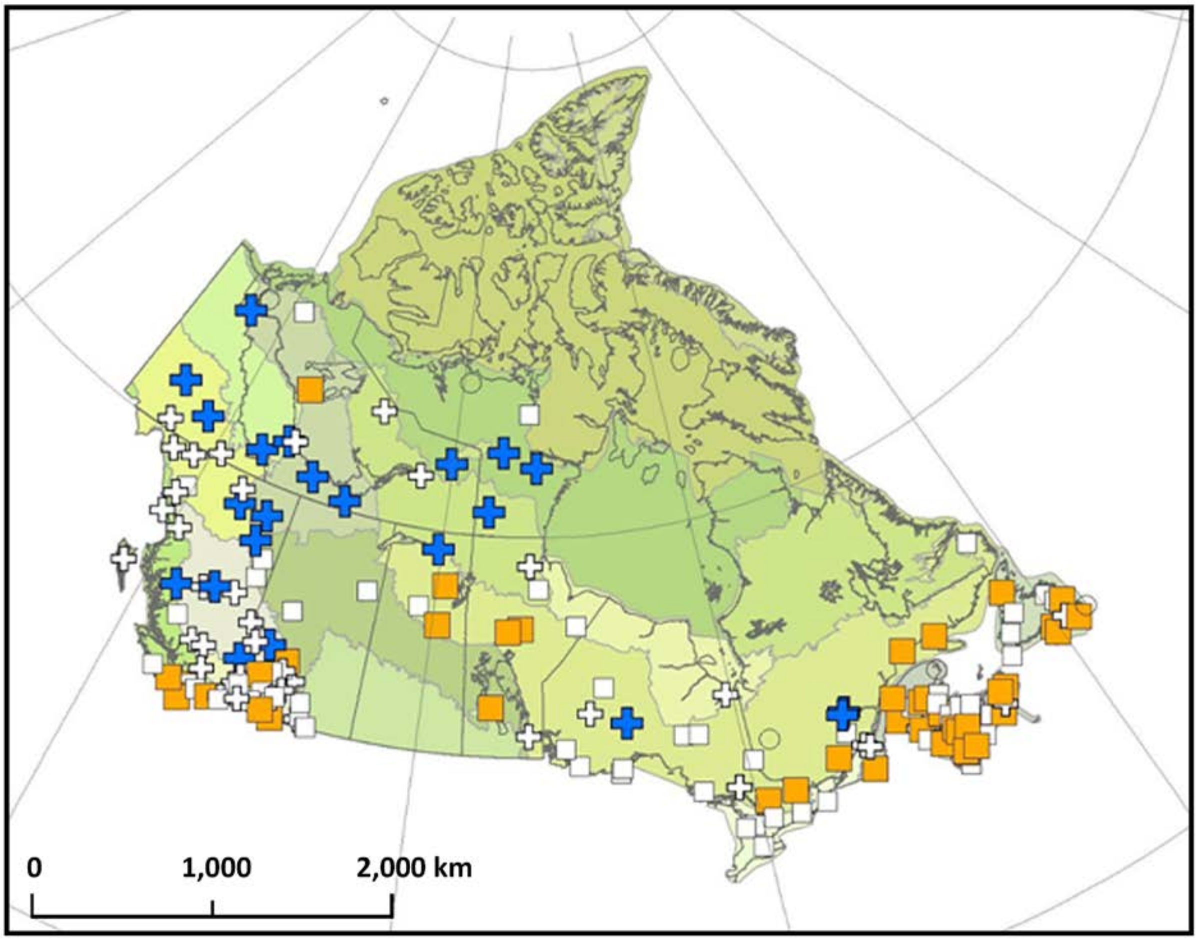


Figure 17. Map showing trends in 1- day minimum river flow in natural rivers across Canada, using data for hydrological years 1970–2005.

+significant increasing trend (p<0.1), + increasing tendency (p>0.1),■significant decreasing trend (p<0.1), ☐decreasing tendency (p>0.1), ○ no trend

For all of these variables, observed trends could reflect real change in aquatic processes, for example there could be a decreased amount of nutrient exchange between rivers and floodplains, in addition to more protracted and stressful low flow periods. Overall fewer stations showed statistically significant trends in maximum runoff, regardless of duration (Figure 12 and Figure 18). However, there appeared to be a tendency towards lower maximum runoff between 1970 and 2005 (Figure 18 and Figure 19). Spatially, there appeared to be significant decreasing trends in 1-day maximum runoff around the Great Lakes and St. Lawrence area but the remaining trends did not show a clear spatial pattern (Figure 19). Shorter and mid-duration (3-day to 30-day) maximum runoff variables demonstrated decreasing trends for groups of stations in eastern and lower western Canada. Spatial patterns in the 90-day maximum runoff reflect decreasing trends in lower latitude stations but greater number of significant increasing trends in western coastal areas and upper latitude stations. Strong spatial patterns in decreasing trends were noted in eastern and lower western Canada while increasing trends were noted in northwestern parts of Canada.

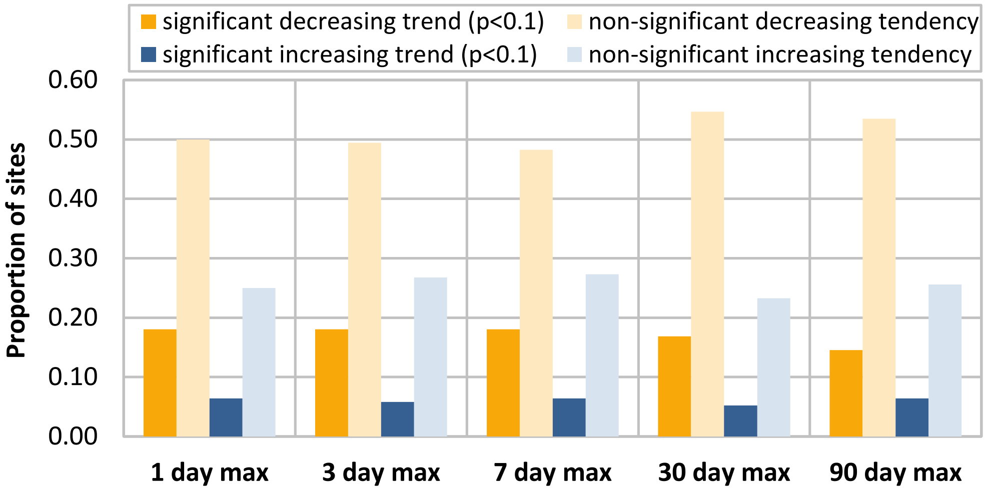


Figure 18. Trends in the magnitude of the 1-day, 3-day, 7-day, 30-day, and 90-day maximum runoff for RHBN stations using data for hydrological years 1970–2005.

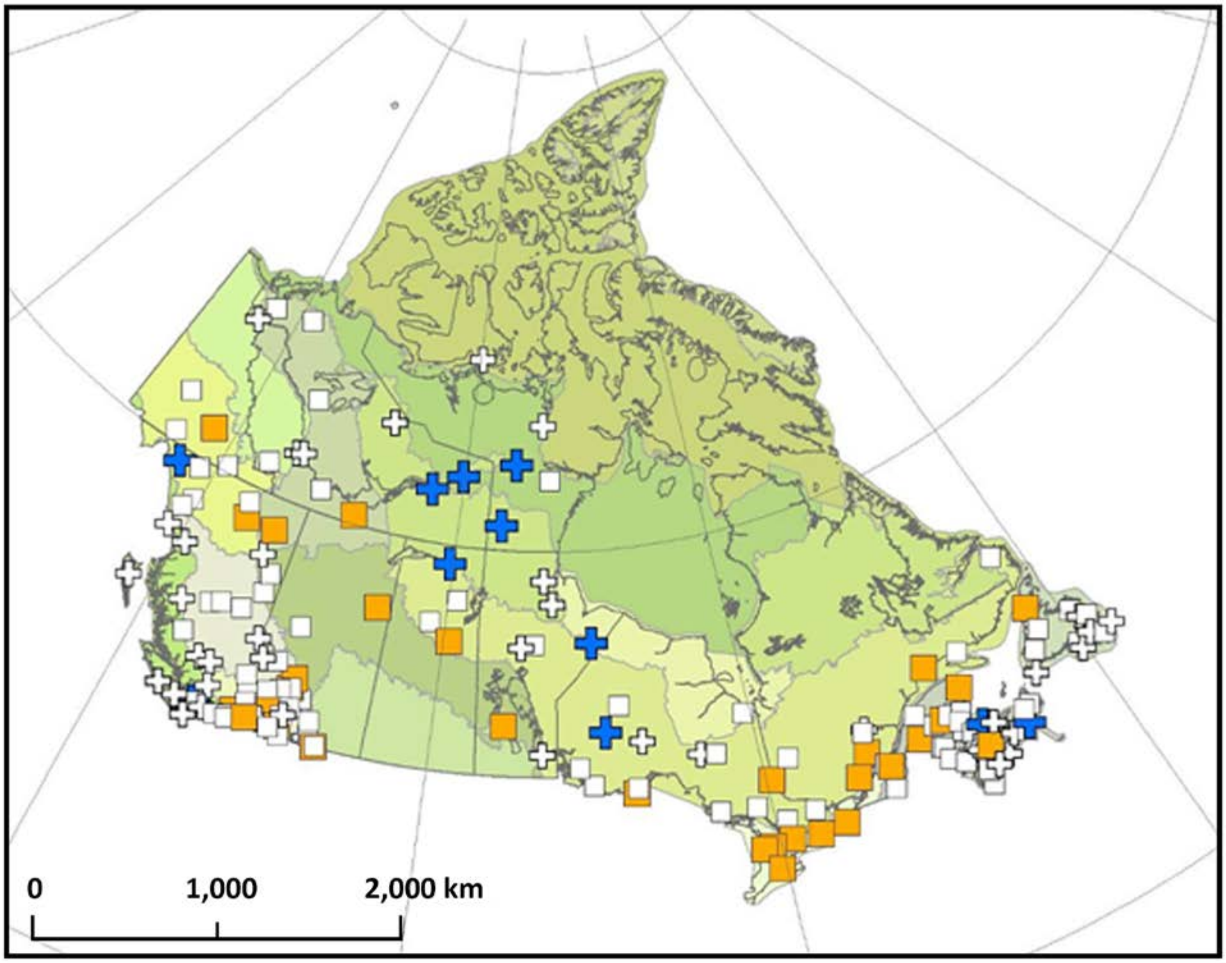


Figure 19. Map showing trends in the 1-day maximum river flow in natural rivers across Canada, using data for hydrological years 1970–2005.
✚significant increasing trend (p<0.1), +increasing tendency (p>0.1), 🟧 significant decreasing trend (p<0.1), ☐decreasing tendency (p>0.1), ○no trend

Summary of trends by ecozone$^+$

Atlantic Maritime Ecozone$^+$ (n = 34) (Figure 17, Figure 19, Figure 13): Few stations presented significant (p<0.1) trends in median monthly runoff with the exception of May and June, with 19 and 17 of 34 stations, respectively, significantly decreasing, and August, where 19 of 34 stations significantly decreased. All stations with a statistically significant change (an average of 20 of 34 stations) demonstrated a decrease in minimum flow, regardless of duration. In addition, the majority of the remaining non-significant stations (an average of 13 of 14) had a tendency towards a reduction in the minimum flow. Although the variable describing baseflow conditions did not present strong significant trends (10 of 34), most stations (23 of 34) showed a tendency towards a reduction in value. The majority of stations also demonstrated reductions in maximum flow, regardless of duration with an average of five stations presenting significant decreasing trends with no stations showing a significant increasing trend. An additional average of 19 stations demonstrated a non-significant decreasing tendency.

Newfoundland Boreal Ecozone^{+} (n = 12) (Figure 17, Figure 19,Figure 14): Few stations demonstrate significant trends in monthly runoff with the exception of August runoff where half of the stations showed a statistically significant decrease. The majority of stations showed a decrease in minimum runoff, regardless of duration. There were no clear patterns in maximum runoff where stations were split between tendencies towards increasing or decreasing directions.

Boreal Shield Ecozone^{+} (n = 31) (Figure 17, Figure 19,Figure 13): Few stations showed a statistically significant trend in monthly runoff at the 10% level, with the exception of late summer runoff when 10 and 9 of 31 stations demonstrating decreasing trends for August and September runoff, respectively. The lack of clear directional trends could reflect the large longitudinal gradient in the spatial extent of this ecozone^{+}. A greater proportion of stations presented significantly decreasing trends in both minimum and maximum runoff variables with the majority of the remaining stations showing a tendency towards a reduction.

Taiga Plains Ecozone^{+} (n = 11) (Figure 17, Figure 19, Figure 13): 7 out of 11 stations demonstrated a statistically significant increase in winter and early spring runoff (January to March). Strong significant increasing trends in minimum runoff were observed for an average of six stations within this ecozone^{+} with the majority of the remaining stations also showing a tendency towards an increase. In addition, five stations demonstrated a significant increase in baseflow. There were few significant trends in maximum runoff.

Montane Cordillera Ecozone^{+} (n = 27) (Figure 17, Figure 19, Figure 14): The majority of stations did not demonstrate significant trends in monthly median runoff with the exception of April which showed a strong increasing trend. Although not statistically significant, stations trended towards an increase in minimum runoff, particularly with longer duration variables. The majority of stations demonstrated decreasing maximum runoff but these were often non-significant.

Pacific Maritime Ecozone^{+} (n = 11) (Figure 17, Figure 19, Figure 13): Few trends in monthly median runoff variables were apparent although there did appear to be an overall decreasing trend in late summer runoff (July, August, and September). There was a clear decreasing trend in minimum runoff, regardless of duration, while the majority of stations showed a significant decrease in baseflow. Conversely, the majority of stations showed a tendency towards increased maximum runoff but these were generally not significant.

Trends in the timing, frequency, and duration of extreme hydrological events

Many species respond to the timing of low and high flows to determine life cycle processes, for example as spawning cues for migratory fish or to provide access to marginal habitats during reproduction. Few stations demonstrated significant trends in the timing of the 1-day minimum and 1-day maximum runoff (Table 5 and Figure 20). However, the majority of stations (78 of 172) showed a tendency towards a later date in the annual minimum flow, while 85 out of 172 stations demonstrated a tendency towards an earlier date in the annual maximum flow. The latter is particularly important as it relates to the annual spring freshet for most river systems. The suggestion of trends for an earlier annual peak flow reflects previously reported earlier ice breakup trends (see Trends in river and lake ice break-up/freeze-up). Geographically, stations presenting a later 1-day minimum runoff were predominantly located in eastern Canada and the Great Lakes region while stations with earlier 1-day minimum were located in lower and coastal western Canada in addition to the Great Lakes and northeastern Canada. Later trends are noted in stations in the northern latitudes and lower eastern Canada.

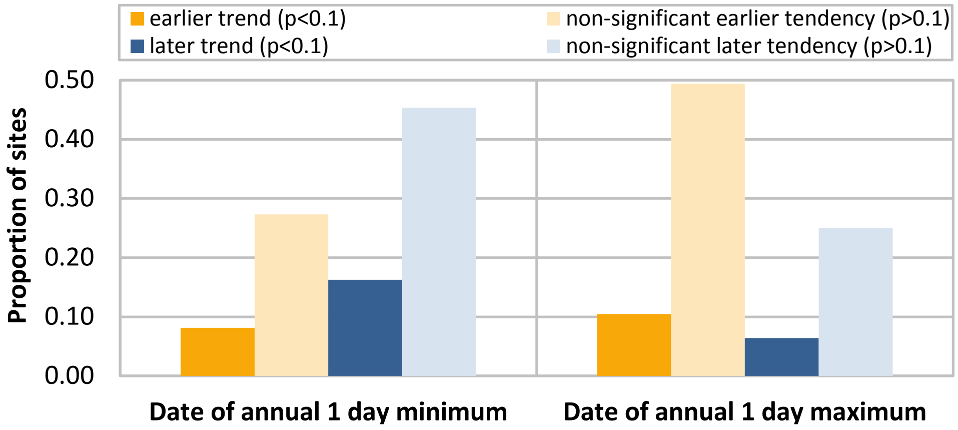


Figure 20. Trends in date of annual 1-day minimum and 1-day maximum runoff for RHBN stations using data for hydrological years 1970–2005.

Exposure to extreme high and low flow periods can cause stress to aquatic communities in addition to affecting the abiotic environment. For example, these extreme flows can influence bedload transport of aquatic sediment, thereby affecting sediment composition and disturbance. Longer low flow periods may affect access for water birds for feeding, resting, and reproduction. Few stations demonstrated statistically significant increasing or decreasing trends with a split between trend direction in variables quantifying these extreme conditions (Figure 21). Despite a low number of significant trends in the number of low pulses, stations in eastern Canada demonstrated an increasing trend (both significant and non-significant) in the duration of low pulses (Figure 22). Stations in western and northwestern Canada presented shorter duration (both significant and non-significant) in the low flow periods with the exception of the southern portion of the Montane Cordillera which presented trends in longer durations of low flow periods.

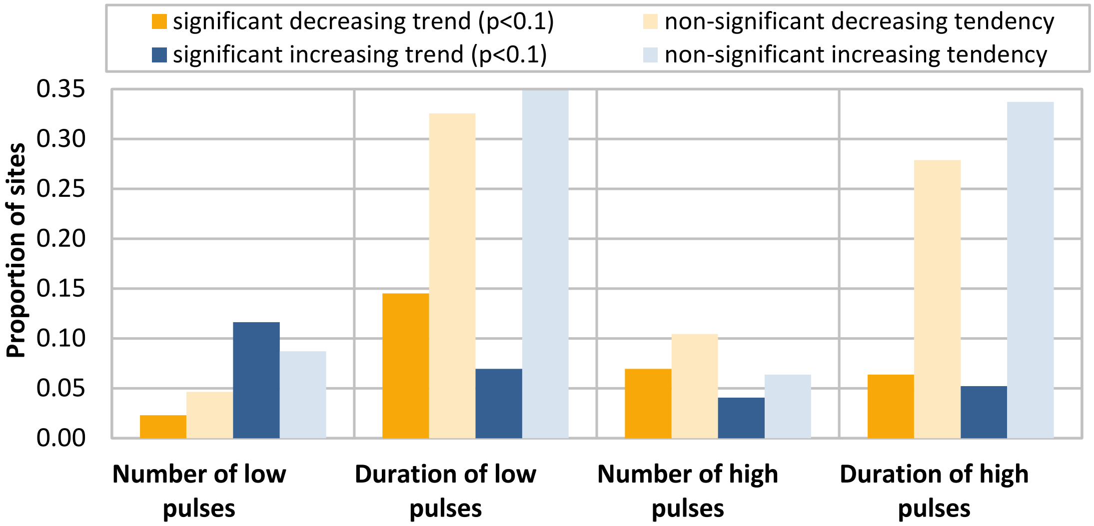


Figure 21. Trends in the frequency and duration of low and high pulses for RHBN stations using data for hydrological years 1970–2005.

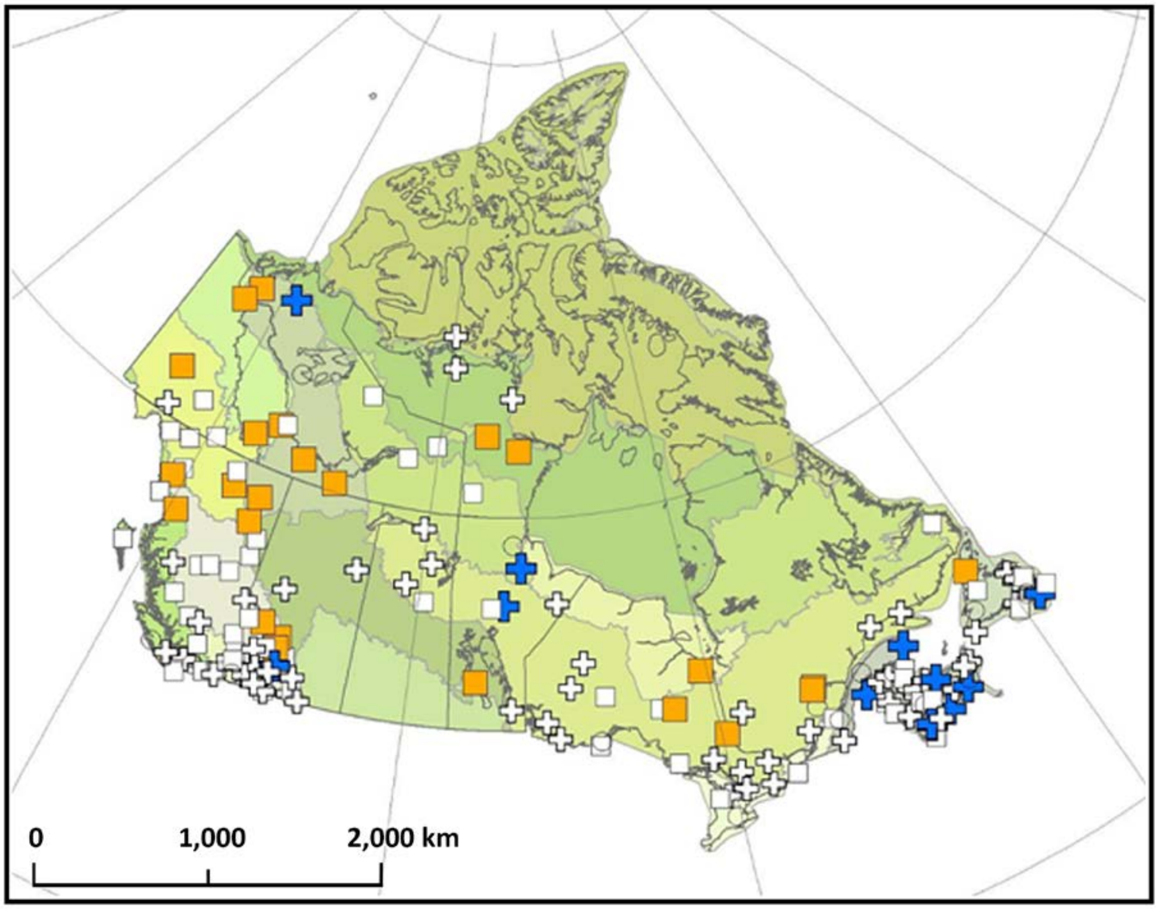


Figure 22. Map showing trends in the duration of low pulses for natural rivers across Canada, using data for hydrological years 1970–2005.
✚significant increasing trend (p<0.1), + increasing tendency (p>0.1), ■significant decreasing trend (p<0.1), ☐decreasing tendency (p>0.1), ○ no trend

Summary of trends by ecozone+

Atlantic Maritime Ecozone+ (n = 34) (Figure 13, Figure 22): Stations showed a tendency towards a reduction in the number of high pulses (20 of 34 stations). In addition, the majority of stations demonstrated a tendency towards an increase in the duration of low pulse events but the pattern for the number of low pulse events was not clear.

Newfoundland Boreal Ecozone+ (n = 12) (Figure 14, Figure 22): The majority of stations showed a tendency towards a later date of both the annual maximum and the annual minimum. The tendency towards a later annual maximum is not reflected across the country where the majority of stations are demonstrating an earlier spring freshet.

Boreal Shield Ecozone+ (n = 31) (Figure 13, Figure 22): Over half of the stations had a tendency towards an earlier date of annual maximum runoff (18 of 31 stations) suggesting an earlier spring freshet. A large proportion of stations (19 of 31) showed a tendency towards increased duration of high pulse events.

Taiga Plains Ecozone+ (n = 11) (Figure 13, Figure 22): Stations within the region did not demonstrate any clear patterns in the number of low and high pulses nor in the duration of high and low flow pulse events. However, 7 out of 11 stations showed a statistically significant ($p<0.1$) decreasing trend in the duration of low pulse events.

Montane Cordillera Ecozone+ (n = 27) (Figure 14, Figure 22): Although not statistically significant, the majority of stations demonstrated a tendency towards an earlier date of maximum runoff. There did not appear to be any clear trends in high and low pulse events with the exception of a tendency towards a decreased duration of high pulse events.

Pacific Maritime Ecozone+ (n = 11) (Figure 13, Figure 22): Stations demonstrated a tendency towards an earlier date of maximum runoff, potentially reflecting an earlier spring freshet. Stations demonstrated a tendency towards a decreased duration of low pulse events.

Trends in flashiness

Variability in flows can alter the availability of habitat and nutrients. Although naturally flashy systems are often considered ecologically disturbed or 'harsh' systems, decreases in flashiness can still stress aquatic communities, as organisms attempt to adapt to new conditions. Several stations demonstrated significant trends (both increases and decreases) in the variables quantifying the variability of the annual flow regime (50 for rise rate, 36 for fall rate, and 70 for number of hydrograph reversals[*], out of 172 stations) (Table 5 and Figure 23). Interestingly, a greater number of stations presented statistically significant increases in the variability of annual runoff, as quantified by the number of reversals (52 of 172 stations with significant trends and an additional 43 stations demonstrated a tendency towards an increase)

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[*] The number of hydrograph reversals quantifies the variability of the flow regime by calculating the number of times that flow switches either from a rising to a falling condition or from a falling to a rising condition. This reversal may directly affect aquatic communities, for example macroinvertebrates often lack the mobility to respond to rapidly changing conditions (The Nature Conservancy, 2007).

(Figure 23). Spatially, these stations were largely found in western and northwestern Canada, in addition to some stations in southeastern Canada (Figure 24).

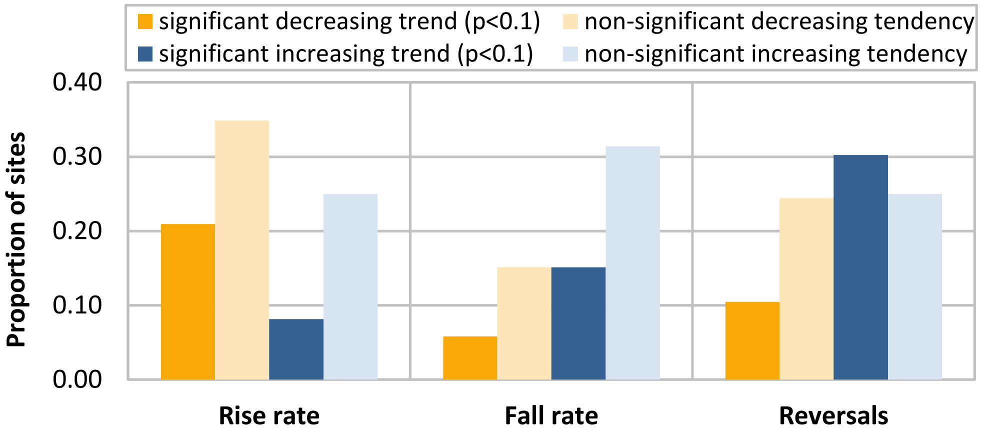

Figure 23. Trends in the variability of runoff for RHBN stations using data for hydrological years, 1970–2005.

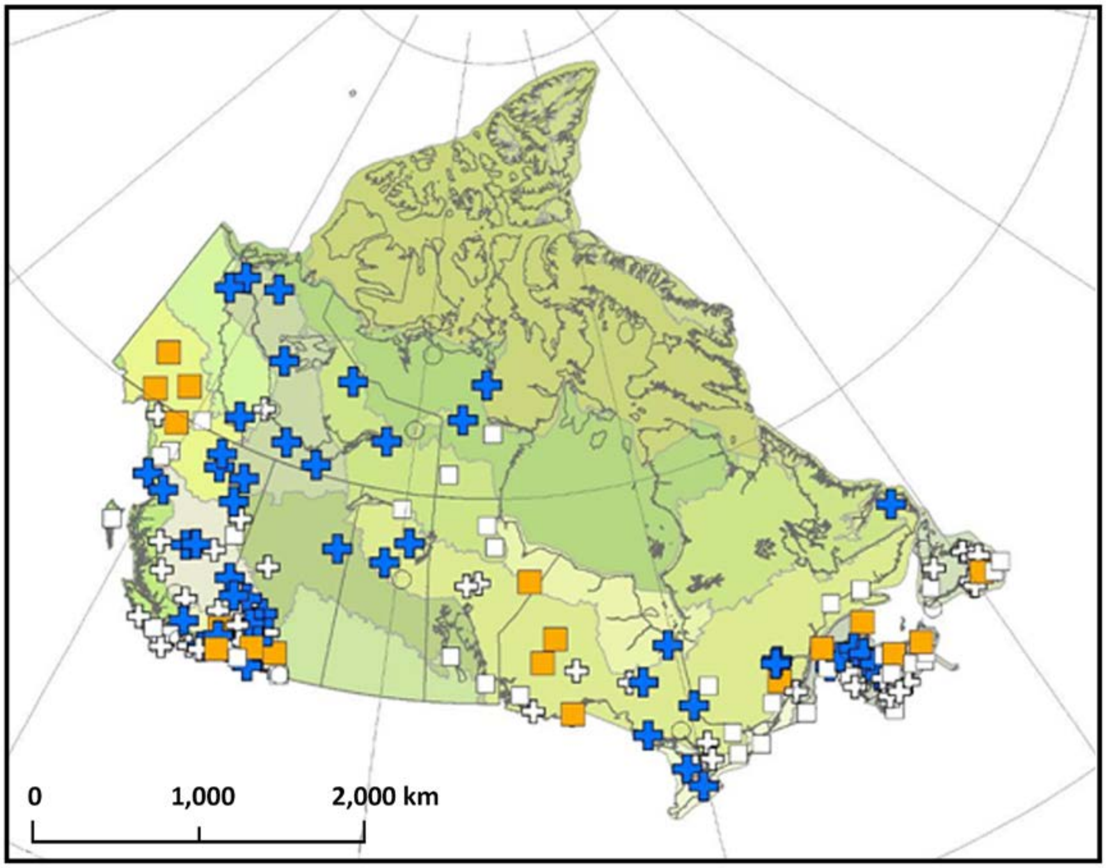

Figure 24. Map showing trends in the number of hydrograph reversals in natural rivers across Canada, using data for hydrological years 1970–2005.
+significant increasing trend (p<0.1), + increasing tendency (p>0.1), 🟧significant decreasing trend (p<0.1), ☐decreasing tendency (p>0.1), ○ no trend

Summary of trends by ecozone+

Atlantic Maritime Ecozone+ (n = 34 stations) (Figure 13, Figure 24): Decreasing trends in rise rates were demonstrated for 11 stations and an additional 16 stations showed a decreasing tendency. Conversely, 10 stations showed an increasing trend in fall rates with an additional 20 stations showing a tendency towards an increase. The number of reversals did not show a directional trend.

Newfoundland Boreal Ecozone+ (n = 12) (Figure 14, Figure 24): There were few significant trends in variability (pulse rates, rise and fall rates, or number of reversals). However, the majority of stations demonstrated a tendency towards an increase in the fall rate.

Boreal Shield Ecozone+ (n = 31) (Figure 13, Figure 24): A quarter of stations demonstrated a significant increase in the number of flow reversals reflected in an increase in the fall rate and a decrease in the rise rate. These results suggest increased variability in flows, and therefore on habitat, in rivers within this ecozone+.

Taiga Plains Ecozone+ (n = 11) (Figure 13, Figure 24): The majority of stations (9) presented a significant increasing trend in the number of reversals with the remaining two stations showing a tendency towards an increase. This demonstrates variability in runoff has increased and suggests increased levels of potential hydrological stress within the system.

Montane Cordillera Ecozone+ (n = 27) (Figure 14, Figure 24): The majority of stations showed a tendency towards a decrease in rise rates with five being significant ($p<0.1$). In addition, there was a tendency towards an increase in fall rate. This is reflected in the majority of stations demonstrating a tendency towards an increase in flow variability as quantified by the number of flow reversals, with 13 being statistically significant ($p<0.1$).

Pacific Maritime Ecozone+ (n = 11) (Figure 13, Figure 24): Stations demonstrated a tendency towards an increase in the rise and fall rates in addition to the number of reversals. Reflecting the other variables, this suggests an increased variability within these rivers.

Summary of hydroecological trends

The application of the non-parametric Mann-Kendall analysis to identify trends in hydro-ecological variables from the Canadian RHBN network has resulted in the identification of spatial and temporal patterns for the period 1970 to 2005. Using IHA variables (Richter et al., 1996), we have attempted to quantify trends in ecologically important hydrological habitat.

Few monitored rivers demonstrated significant trends in monthly median runoff with the exception of April and August. Examination of trends in maximum and minimum flows revealed limited numbers of statistically significant trends at the national scale. However, for both minimum and maximum runoff, the majority of significant trends were decreasing. In addition to the significant stations, a third of stations demonstrated a tendency towards decreased minimum flows while just over half of the stations showed a tendency towards decreased maximum flows. The implications for decreased magnitude in runoff are significant, for example effects on habitat availability for aquatic communities. However, there is some spatial variability in these minimum and maximum runoff trends, for example, stations within the Taiga Plains and Pacific Maritime ecozones^{+} presented an increase in these variables while the remaining studied ecozones^{+} demonstrated an overall decrease.

A greater proportion of significant stations showed a significant trend towards earlier date of the annual 1-day maximum with an additional 56% of stations demonstrating a tendency towards this. The annual 1-day maximum runoff often occurs during the spring freshet thus this suggests that ice break-up is occurring earlier. Combined with a tendency towards later ice freeze-up (see Trends in river and lake ice break-up/freeze-up section below), this suggests an extension to the open water season which will affect the aquatic ecosystem. The majority of stations do not show significant trends in the frequency and duration of extreme high and low flow events. However, the majority of stations showed a tendency towards a decrease in the rise rate, an increase in the fall rate, and an increase in the number of reversals, suggesting a trend towards an increase in flow variability.

TRENDS IN RIVER AND LAKE ICE BREAK-UP/FREEZE-UP

Ice cover plays a fundamental role in the biological, chemical, and physical processes that structure freshwater ecosystems (for example, Prowse, 2001a; Prowse, 2001b; Prowse and Culp, 2003; Huusko et al., 2007; Prowse et al., 2007b), in addition to their effects on artificial structures (for example, Jasek, 1998; Beltaos et al., 2006). The hydrological regimes of 58% of rivers in the Northern Hemisphere are affected by seasonal ice cover with major ice cover developing on 29% of these rivers (Prowse, 2005; Bennett and Prowse, 2010). Prowse (2005) reported that seasonal ice can develop as far south as 33°N in North America and 26°N in Eurasia, affecting 7 of the world's 15 largest rivers and 11 of the 15 largest lakes (Prowse et al., 2007a). Canada is located north of 48°N and lake and river systems (in all ecozones^{+}) are affected by ice ranging from periodic skim ice in the more southerly temperate regions to ice thickness in excess of 2 m in the high latitudes.

River ice is an integral component of the flow regime in cold region environments due to its hydraulic effect on water levels, its ability to restrict or alter flows in rivers, and to restrict gas exchange in lakes. Ice freeze-up, cover, and break-up can cause both direct (such as timing and magnitude of extreme hydrologic events such as low-flow and ice jam-flood events, for example, Beltaos et al., 2006) and indirect changes to the hydrological regime. These changes can significantly modify channel geomorphology (such as through bed scour), alter aquatic chemical processes, and affect aquatic ecological communities. In addition, ice cover disconnects both flowing and standing water in lakes and rivers from the atmosphere and limits the sun's energy input, influencing key physio-chemical and biological processes (such as dissolved gas concentration and photosynthetic capacity). Despite the clear importance of ice processes to freshwater ecosystems, long-term biological monitoring data during the ice season are limited and few trend datasets are available.

Prowse and Culp (2003) provided a thorough review of the effects of ice on aquatic ecological communities. Aquatic communities are susceptible to any changes in the hydrological, cryospheric, and atmospheric regimes. In general, the life cycles of many aquatic organisms are directly and indirectly influenced by ice cover duration, water temperatures, and hydrological variability (see Table 6 for examples). Using data from 1991 to 1998 for an alpine region in western Norway, Borgstrøm (2001) found the annual growth rates of brown trout (*Salmo trutta*) were negatively correlated with spring snow depth. Results showed that during the deep snow years, 1992 to 1995, the observed average annual growth of the age-classes 6 to 8 reduced by about 50% compared to years with less snow in spring (1991 and 1996). Another study by Cunjak *et al.* (1998) demonstrated that inter-annual variability in the survival of juvenile Atlantic salmon in Catamaran Brook, New Brunswick, improved with increasing average winter flow but highest mortalities were associated with winter breakups and ice-jams triggered by rain-on-snow snowmelt events.

Table 6. Literature review summary of physical habitat changes and the direct and indirect effects on instream biodiversity and habitat availability in ice impacted rivers.

	Physical habitat change	**Impacts and effects on instream biodiversity**	**Example study**
Ice freeze-up	Decline in water temperature	• Lower metabolism (-) • Decline in food requirements (-) • Reduced activity (-)	
	Reduction in amount and quality of habitat	• Redistribution of juvenile fish to more desirable wintering habitat (-)	Rimmer *et al.* (1984)
	Creation of new refugia (e.g., border ice)	• Protection from predation (+) • Low velocity refugia (+)	
	Development of frazil ice	• Offers incubating medium for Atlantic tomcod (*Microgadus tomcod*) (+) • Abrasion of gills (-) • Plugging gill rakers (-) • Movement of fish away from preferred specific velocity habitat (-)	Power *et al.* (1993)
	Supercooled water/ development of anchor ice	• Significant mortality of benthic invertebrates and fishes (eggs / juveniles) (-) • Ice in spawning habitats restricts oxygen to redds (-) • Alteration to flow regime leading to stranding / suffocation (-) • Increased downstream drift on release of anchor ice (-) • Alteration in habitat use	Power *et al.* (1993) Stickler *et al.* (2008)
	Decline in river flow/ water levels	• Exposure of redds (-)	Cunjak *et al.* (1998)

Main winter	Increased ice in littoral zone	• Organisms migrate deeper (-) • Adopt diapauses (-) • Ability to overwinter in anchor ice (-) • Mortality from prolonged exposure to minimum temperatures (-) • Lower metabolic rate in juvenile Atlantic salmon	Li *et al.* (2007) Finstad *et al.* (2004)
	Development of isolated pools causing habitat disruption	• Provide overwintering habitat for some fish species (+) • Use of spring-fed habitat for overwintering of eggs and provision of food (+) • Effect on predator/prey relationships (-)	
	Establishment of ice cavity habitat	• Shoreline access for aquatic mammals (+) • Well insulated air cavities provide habitat (+) • Stress for aquatic plants (-) • Prolonged ice cover can reduce food sources, e.g., periphyton (-)	
	Reduced dissolved oxygen	• Increasing susceptibility to stress, predation and contaminants (-) • Sublethal effects, e.g., changes to cardiac and metabolic functions, reduced growth and swimming capacity (-) • Localized winterkills of fish from overcrowding in habitats (-)	
Ice break-up	Scouring of river bed	• Low survival rates of eggs and juveniles (-) • Loss / shifts in of aquatic and riparian vegetation (-) • Macroinvertebrate larvae can demonstrate avoidance behaviour by using the substrate as refugia (-)	Cunjak *et al.* (1998) Cameron and Lambert (1971) Scrimgeour *et al.* (1994)
	Transport of large bedload material	• Loss of habitat (-) • Affect survival rates of eggs and juveniles (-) • Effect highly dependent on timing of breakup (-)	Cunjak *et al.* (1998)
	Ice jam flooding	• Sustaining water levels in riparian ponds and wetlands (+)	Prowse and Culp (2003)
	Changing water levels	• Stranding and suffocation of fish (-)	Needham and Jones (1959) Cott *et al.* (2008) Clague and Evans (1997)
	High sediment levels	• Improved productivity because of increased organic material (+) • Reductions in species diversity and abundance through loss of quantity and quality of habitat (-) • Often immediate effect on benthic invertebrates but lagged effect in fish (-)	Elwood and Waters (1969)

Previous analyses of variability in ice cover on Canadian freshwater lakes and rivers have been limited in geographic scope, focusing on phenomenological metrics, such as timing of autumn freeze-up or spring break-up (for example, Williams, 1970; Brimley and Freeman, 1997; Jasek, 1998; Lacroix et al., 2005). The date of freeze-up is defined as the first day on which a water body is observed to be totally ice covered, while the break-up date is the day of the last ice observed, before the open-water phase. To date, trends research in river and lake ice break-up and freeze-up has been limited by a lack of long-term observations of consistent, objectively defined parameters. Within Canada, monitoring of ice cover began in 1822 in Toronto Harbour, Lake Ontario, with additional sites added to the network over time (Power et al., 1993; Wania and Mackay, 1993). Although the Canadian Ice Database contains 63,656 records covering the period from ice season 1822/1823 to 2000/2001, the network has dramatically declined in recent years, due to a lack of funding (Lenormand et al., 2002). For instance, the freeze-up/break-up network as of the 2000/2001 ice season represented only 4% of the 1985/1986 network (Lenormand et al., 2002). Recent developments in satellite imagery analysis (Brown and O'Neill, 2002) and the development of the national volunteer ice monitoring program, IceWatch (Environment Canada and Ice Watch, 2008), could allow the current network to be expanded and increase the spatial information for the largely inhabited areas of Canada.

A recent study explored long-term trends in lake ice data using records from as early as 1822 across Canada (Environment Canada and Ice Watch, 2008). The study combined data from IceWatch, a volunteer-run monitoring scheme, with data collected by the Meteorological Service of Canada and the Canadian Ice Service. Of the 950 sites within the database, nearly a third were represented by only one or two years of data (Environment Canada and Ice Watch, 2008). Limiting our analysis to sites with at least eight years of data, where the last observations were in or after 1990, a non-parametric Mann-Kendall time-series analysis demonstrated that 15 of the 195 sites showed significant trends towards earlier freeze-up ($p<0.05$) and an additional 15 sites demonstrated significant trends towards later freeze-up ($p<0.05$) (Environment Canada and Ice Watch, 2008). Trends were also reported in the timing of spring thaw, with 40 of the 258 sites demonstrating significant trends towards earlier melt ($p<0.05$) compared with only 5 showing significantly later melt ($p<0.05$) (Environment Canada and Ice Watch, 2008). Examination of the sites with non-significant trends shows that 168 of the 258 sites are demonstrating a tendency towards earlier spring melt compared with 75 sites showing a tendency towards later spring melt, although these trends were not statistically significant (Environment Canada and Ice Watch, 2008). Further examination of the results clearly shows that the rate of change of lake ice thaw was much more rapid from 1950 to the present as compared with the first half of the 20th century (Environment Canada and Ice Watch, 2008).

The record length for each site was variable within this analysis, however, and thus we revisited the data for this report to provide an additional analysis using consistent record lengths and time periods. We selected data for two separate analyses: i) 1970 to 2002, with a minimum of 25 years of data; and ii) 1900 to 2000, with a minimum of 80 years of data. These periods were chosen to maximize the number of sites for analysis while maintaining strict data quality controls. However, it should be noted that not all variables were available for all years, with a bias towards those related to ice break-up. In addition, although more recent data were available (up to 2007 within this dataset), there were no sites with longer-term data for more recent years. Our analysis followed the approach outlined in the IceWatch report (2008), in terms of variable selection and treatment. For the 1970 to 2002 period, only one out of 24 sites with suitable data demonstrated a significantly later date for freeze-up ($p<0.05$). The remaining sites did not demonstrate a tendency towards either earlier or later freeze-up. Examination of the break-up dates suggests eight out of 69 sites showed a statistically significant trend ($p<0.05$) for earlier break-up. Reflecting the results of the original IceWatch report, a large proportion of the remaining sites (46 out of 69 sites) showed a tendency towards earlier break-up with only 14 out of 69 sites demonstrating a tendency towards later break-up. Of the 14 available sites for analysis of the long-term data (1900 to 2000), only one site presented a statistically significant trend towards earlier break-up but this was at the 10% level. However, 10 of the 14 sites showed a (non-significant) tendency towards earlier break-up. The three sites with freeze-up data demonstrated statistically significant trends towards later freeze-up ($p<0.01$).

Despite lacking long-term data from a spatially extensive network, a study by Magnuson *et al.* (2000) reported consistent evidence of later freezing and earlier break-up (see example Canadian lakes and rivers in Table 7 and Table 8). The analysis on data from 39 lakes and rivers across the Northern Hemisphere from 1846 to 1995 demonstrated that freeze-up occurred on average 5.8 days later per century, and break-up occurred 6.5 days earlier per century. These results were likely largely the result of an increase in average air temperature of about 1.2°C per century. Three of the sites from Russia, Finland, and Japan had records extending back to the 18th century. These records suggest that trends were already apparent at that time, but that the trend rates continued to increase after 1850. For example, Lake Suwa, Japan, indicated freeze dates later by 2.0 days per century ($p<0.0001$) for the 550-year record. However, breaking the trend into time blocks demonstrated that freeze dates ranged from 3.2 days per 100 years (1443 to 1592) to 20.5 days per 100 years (1897 to 1993) (Magnuson et al., 2000). However, the study was geographically limited and thus it is inadvisable to draw wider conclusions at this time.

Although the continental-scale relationships indicate a significant decrease in ice cover in the Northern Hemisphere over the past 300 years, regional responses have demonstrated greater variability (see examples summarized in Table 7 for freeze-up and Table 8 for break-up). For example, a study by Williams (1970) found that the break-up on the Saint John River, New Brunswick, occurred 15 days earlier in the 1950s than in the 1870s. Also, the median break-up and freeze-up dates for the Red River at Winnipeg, Manitoba, were 12 and 10 days earlier and later, respectively, in the 19th century than in the 20th century (Rannie, 1983). Other regional and continental scale studies using observations that are more detailed have demonstrated strong patterns in freeze-up and break-up timing between decades and regions reflecting larger-scale atmospheric patterns (see examples summarized in Table 7 and Table 8). For example, Duguay *et al.* (2006) explored lake ice break-up and freeze-up trends for sites across Canada (example of lake break-up in Figure 25). Using the non-parametric Mann-Kendall trend analysis, they compared trends for three separate 30-year time periods: 1951 to 1980, 1961 to 1990, and 1971 to 2000 in addition to exploring 1966 to 1995. Their results demonstrated few clear spatial trends in lake freeze-up for the three periods (exceptions are presented in Table 7) with the few significant spatial clusters suggesting more local or regional influences. These results are not consistent with those found by Zhang *et al.* (2001) who showed widespread trends towards earlier freeze-up across Canada but this may reflect the different spatial and temporal distribution of sites between these two studies.

Table 7. Summary of scientific studies quantifying trends in freeze-up for Canadian lakes and rivers using data up to and including the year 2000.

Site	Location	Habitat	Record years	# yrs with data (# sites, if applicable)	Trend direction	Trend significance	Reference
Mackenzie River	Taiga Shield, Boreal Shield, Boreal Plains, Montane Cordillera, Taiga Plains, Taiga Cordillera, Boreal Cordillera	River	1868–1978	10	6.1 days later/100 years	<0.01	Magnuson *et al.* (2000)
Red River	Southern Manitoba (unsure of ecozone[+])	River	1799–1981	16	13.2 days later/100 years	<0.001	Magnuson *et al.* (2000)
Toronto Harbour	Mixedwood Plains	River	1822–1920	11	36.9 days later/100 years	<0.001	Magnuson *et al.* (2000)
Red River	Boreal Plains, Prairies	River	1815–1981	153	12 days later during 20th century		Rannie (1983)
Frame Lake	Boreal Plains	Lake	1956–1980	25	0.4 days later/year	<0.1	Duguay *et al.* (2006)
RHBN stations across Canada	Canada	River	(a) 1967–1996 (b) 1957–1996 (c) 1947–1996	(a) 30[*] (151) (b) 40[+](71) (c) 50[+] (47)	(a) earlier at 21.4% of sites(b) earlier at 38.2% of sites(c) earlier at 50.0% of sites	<0.1	Zhang *et al.* (2001)
Grand Lake	Atlantic Maritime	Lake	1952–1980	29	0.58 days earlier/year	<0.1	Duguay *et al.* (2006)
Lake Athabasca	Taiga Shield, Boreal Shield, Boreal Plains	Lake	1965–1990	23	1.25 days later/year	<0.01	Duguay *et al.* (2006)
Deadman's Pond	Newfoundland Boreal	Lake	1961–1990	28	0.5 days earlier/year	<0.05	Duguay *et al.* (2006)
Lake Utopia	Atlantic Maritime	Lake	1971–2000	30	1.23 days later/year	<0.001	Duguay *et al.* (2006)
Island Lake	Boreal Shield	Lake	1971–1998	21	0.42 days earlier/year	<0.05	Duguay *et al.* (2006)
Rivers across Canada	Canada	River	(a) 1951–1980 (b) 1961–1990 (c) 1966–1995 (d) 1950–1998	(a) 30[†] (50) (b) 30[‡] (68) (c) 30[‡] (60) (d) 49[‡] (41)	(a) 1.0 days later/decade (b) 0.1 days earlier/decade (c) 0.1 days later/decade (d) 0.3 days later/decade	<0.1	Lacroix *et al.* (2005)

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[*] Each site does not necessarily have data for each year in the analysis

[†] All sites have data for >2/3 of the years in the analysis

Table 8. Summary of scientific studies quantifying trends in break-up for Canadian lakes and rivers using data up to and including the year 2002.

Site	**Ecozone[+]**	**Habitat**	**Record years**	**# yrs with data (# sites)**	**Trend direction**	**Trend significance**	**Reference**
Red River	Southern Manitoba (unsure of ecozone[+])	River	1799–1993	180	10.6 days earlier/100 years	<0.001	Magnuson *et al.* (2000)
Toronto Harbour	Mixedwood Plains	River	1822–1985	111	7.4 days earlier/100 years	NS	Magnuson *et al.* (2000)
Miramichi River	Mixedwood Plains	River	1822–1955	127	7.3 days earlier/100 years	<0.01	Magnuson *et al.* (2000)
Canoe Lake	Mixedwood Plains	Lake	1982–2001	17	Mann-Kendall Z = -1.65	<0.05	Futter (2003)
St. Nora Lake	Mixedwood Plains	Lake	1968–1990	21	Mann-Kendall Z = -3.14	<0.001	Futter (2003)
Scugog	Mixedwood Plains	Lake	1872–1995	102	Mann-Kendall Z = -1.73	<0.05	Futter (2003)
Simcoe	Mixedwood Plains	Lake	1853–1995	130	Mann-Kendall Z = -1.82	<0.05	Futter (2003)
Stoney	Mixedwood Plains	Lake	1956–1988	30	Mann-Kendall Z = -2.30	<0.01	Futter (2003)
Thirteen Islands	Mixedwood Plains	Lake	1992–2001	10	Mann-Kendall Z = -1.70	<0.05	Futter (2003)
Red River	Prairie, Boreal Plains	River	1815–1981	157	10 days earlier during 20th century		Rannie (1983)
Mackenzie River basin	Taiga Shield, Boreal Shield, Boreal Plains and Cordillera, Montane Cordillera, Taiga Plains and Cordillera	River	1970–2002	33[‡] (17)	~1 day/decade in upstream basin	<0.1	de Rham *et al.* (2008)
Yukon River	Boreal Cordillera, Taiga Cordillera	River	1896–1998		~5 days earlier/100 years		Jasek (1998)
RHBN stations across Canada	Canada	River	(a) 1967–1996 (b) 1957–1996 (c) 1947–1996	a) 30[*] (151) (b) 40[*] (71) (c) 50[*] (47)	(a) earlier in 15.1% of sites (b) earlier in 21.8% of sites (c) earlier in 30.0% of sites	<0.1	Zhang *et al.* (2001)

[‡] Each site does not necessarily have data for each year in the analysis

Site	Ecozone[+]	Habitat	Record years	# yrs with data (# sites)	Trend direction	Trend significance	Reference
Colpoys Bay (Lake Huron)	Mixedwood Plains	Lake	1951–1980	29	0.5 days later/year	<0.1	Duguay *et al.* (2006)
Brochet Bay (Reindeer Lake)	Boreal Plains	Lake	1951–1980	30	0.5 days earlier/year	<0.05	Duguay *et al.* (2006)
Gull Lake	Mixedwood Plains	Lake	1961–1990	30	0.44 days later/year	>0.1	Duguay *et al.* (2006)
Lake Utopia	Atlantic Maritime	Lake	1961–1990	30	0.52 days earlier/year	<0.01	Duguay *et al.* (2006)
Back Bay (Great Slave Lake)	Taiga Plains	Lake	1971–1996	26	0.4 days later/year	<0.05	Duguay *et al.* (2006)
Diefenbaker Lake	Prairie	Lake	1971–2000	30	0.33 days earlier/year	<0.05	Duguay *et al.* (2006)
Rivers across Canada	Canada	River	(a) 1951–1980 (b) 1961–1990 (c) 1966–1995 (d) 1950–1998	(a) 30[§] (61) (b) 30[+] (79) (c) 30[+] (71) (d) 49[+] (45)	(a) 1.0 days later/decade (b) 2.2 days earlier/decade (c) 2.0 days later/decade (d) 1.6 days later/decade	<0.1	Lacroix et al. (2005)

[§] All sites have data for >2/3 of the years in the analysis

Conversely, trends in lake ice break-up reported by Duguay *et al.* (2006) suggest greater spatial coherence. Depending on the time period chosen for analysis, results suggest an earlier spring thaw in western Canada and a later spring thaw in eastern Canada (1951 to 1980). The 1961 to 1990 time period showed a nationwide trend towards earlier break-up and the 1971 to 1990 reflects that trend. Analysis of the 1966 to 1995 period reflects that of the 1961 to 1990 period with a general trend towards earlier break-up and few regional freeze-up trends. Previous studies (for example, Bonsal and Prowse, 2003; Bonsal et al., 2006) have demonstrated the link between ice break-up/freeze-up and the air temperature between one to three months before the event. As shown in Figure 25, the earlier trends in lake ice break-up follow the earlier arrival of the spring 0°C-isotherm date (Duguay et al., 2006). These results suggest a high degree of synchrony, with 78% of sites demonstrating a correlation (r>0.5) between the isotherm date and the date of ice break-up.

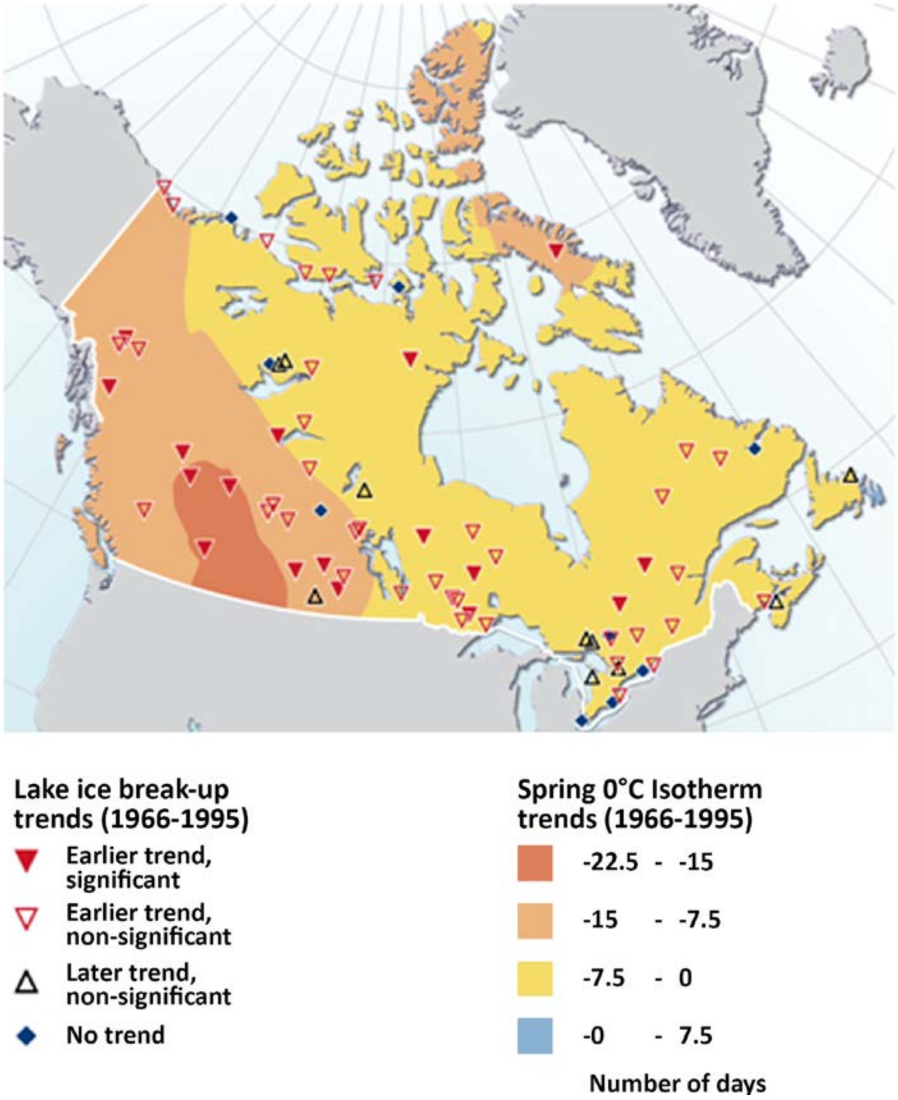

Figure 25. Trends in lake ice break-up dates and spring temperature in Canada, 1966–1995. Source: UNEP (2007) with data from Duguay et al. (2006)

Summary and future direction

Trends towards both later and earlier break-up and freeze-up across Canada have been reported in the scientific literature, but particularly towards earlier break up across Canada. Results from the IceWatch report (2008) suggested little evidence for trends in lake ice freeze-up but there were trends towards earlier lake ice break-up. These results were reflected in our analyses, particularly for the long-term data series. Within individual ecozones+, there was large variability. For example, data from stations in the Atlantic Maritime, Newfoundland Boreal, and Boreal Cordillera ecozones+ indicated earlier freeze-up trends in these ecozones+ while data from the majority of remaining regions indicated mixed trends. The majority of regions demonstrated earlier trends in ice break-up. There is a need to maintain and build on successful monitoring databases, such as IceWatch, in addition to developing GIS-based analyses of satellite imagery.

TRENDS IN HABITAT LOSS AND FRAGMENTATION

Habitat alteration is the most important threat facing freshwater fishes at risk in Canada (Dextrase and Mandrak, 2006). Habitat fragmentation in aquatic ecosystems occurs when river or lake habitat connectivity is disrupted through the addition or alteration of natural or human barriers to dispersal. Actively dispersing riverine species are particularly vulnerable because of their linear habitat use. The longitudinal and lateral fragmentation of lake and river systems is one of the most significant global threats to freshwater systems, often leading to habitat degradation and loss of biodiversity (Revenga et al., 2000; Jones and Bergey, 2007). Disruption of the natural habitat regime by longitudinal barriers (such as dams, weirs, and roads) and by degradation of the riparian zone (for example, gaps in riparian buffers) adversely affects aquatic communities, most notably by disrupting fish and wildlife passage (for example, Levesque, 2005; Reid et al., 2008a). For example, pipeline crossings within river and stream channels disrupt habitat continuity and negatively affect the physical and chemical nature of fish habitat (Levesque, 2005). Moreover, impoundments have been found to promote the spread of invasive alien species. Using data from the Laurentian Great Lakes region, a study by Johnson *et al.* (2008) demonstrated that invasive alien species were 2.4 to 300 times more likely to occur in impoundments than in natural lakes, with impoundments frequently supporting multiple invasive taxa. The authors suggest that anthropogenically-altered systems act as 'stepping stone' habitats for the continuing spread of invasive species because of the increased proximity of invaded water bodies with natural systems as numbers of impoundments expand (Johnson et al., 2008).

Globally, the rate of freshwater system degradation through the modification of waterways, draining of wetlands, construction of dams and irrigation networks, and by interbasin transfers[13] has been accelerating since the early 1900s (Figure 26) (Nilsson et al., 2005).

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[13] An interbasin diversion is the withdrawal of water, more or less continuously, over all or part of a year, by ditch, canal, or pipeline, from its basin of origin for use in another drainage basin.

In North America, interbasin transfers and diversions have irreversibly altered the hydrological regime (both water quantity and quality) for a number of large rivers (Figure 26). Created mainly for hydropower generation in Canada, these are predominantly concentrated in northern Saskatchewan and Quebec with additional diversions across Ontario, Newfoundland and Labrador, and British Columbia (Figure 26). These changes have disconnected river and lake systems from the normal hydrological cycle, with negative effects on habitat availability and biodiversity.

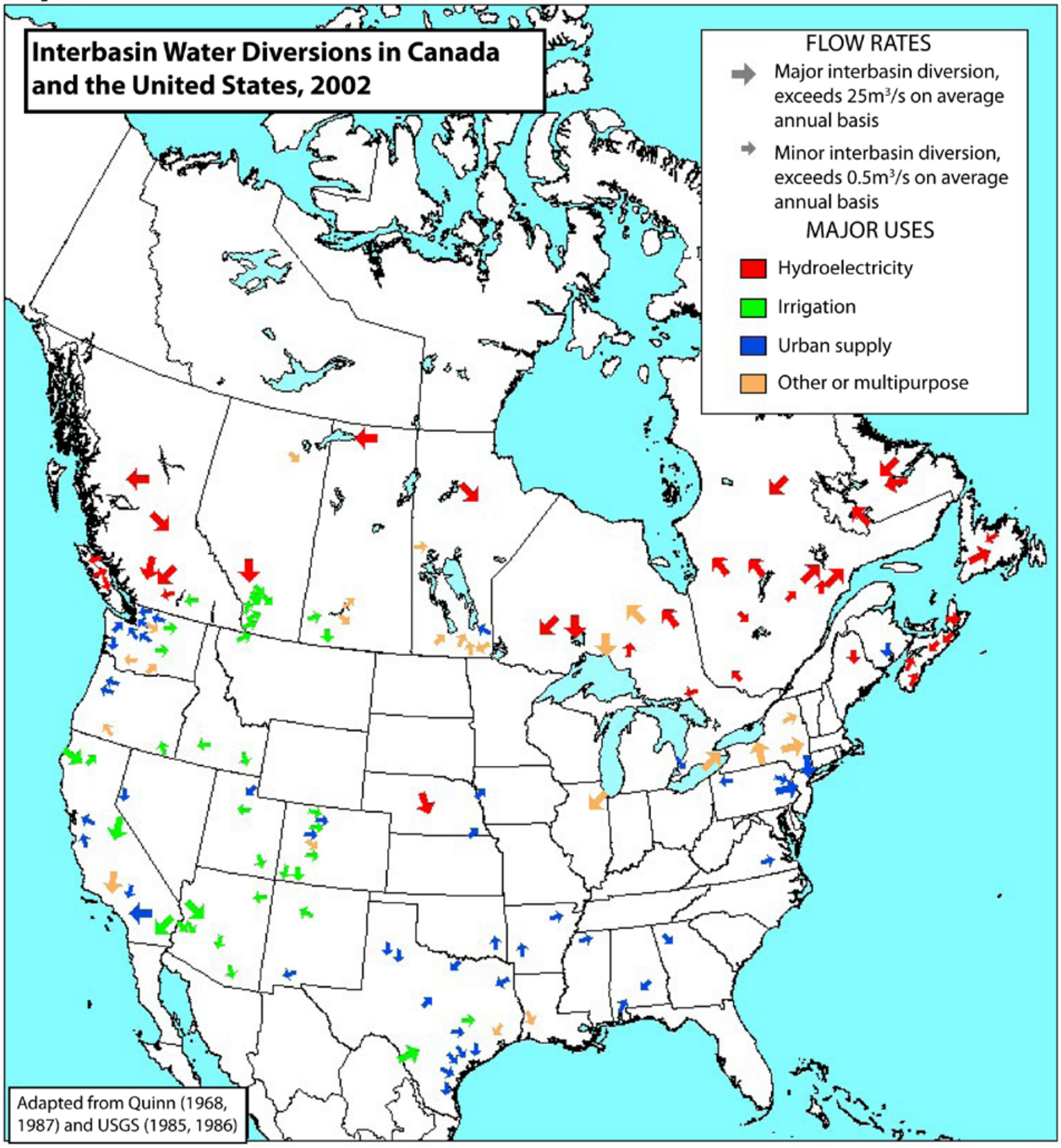


Figure 26. Map showing major water diversions and transfers in Canada and the United States. Source: Quinn (2004)

Modifications of freshwater systems worldwide have been extensive (Table 9). Globally, Revenga *et al.* (2000) reported that large dams have increased sevenfold since 1950 and now impound 14% of the world's runoff. Of the world's largest 227 rivers, 60% are strongly or moderately fragmented by dams, diversions, and canals (Revenga et al., 2000). At the same time, water withdrawals have increased six-fold between 1900 and 1995 despite 40% of the world's population living in areas of high water stress. In addition, flow alteration from dams can lead to flow homogenization, particularly affecting the magnitude and timing of high and low flows (Poff et al., 2007). This can have a negative effect on aquatic communities, particularly locally adapted native species (Poff et al., 2007).

Table 9. Trends in the alteration of freshwater systems worldwide, pre-1900 to 1996/98.

Alteration	Pre-1900	1900	1950–60	1985	1996–98
Waterways altered for navigation (km)	3,125	8,750	-	>500,000	-
Canals (km)	8,750	21,250	-	63,125	-
# of large reservoirs (>0.1 km^3)	41	581	1,105	2,768	2,836
Volume of large reservoirs (>0.1 km^3) (km^3)	14	533	1,686	5,879	6,385
# of large dams (>15 m high)	-	-	5,749	-	41,413
Installed hydro capacity (MW)	-	-	<290,000	542,000	~660,000
Hydro capacity under construction (MW)	-	-	-	-	~126,000
Water withdrawls (km^3/year)	-	578	1,984	~3,200	~3,800
Wetlands drainage (km^2)	-	-	-	160,600	

Source: Revenga et al. (2000) as adapted from Naiman et al. (1995)

Trends in dam completion in Canada

Habitat fragmentation from construction of dams has been monitored within Canada since the 1830s. Using data from the Canadian Dam Association (2003), Figure 27 summarises the number of dams greater than 10 m in height completed in Canada from 1895 to 2005. The number of dams rapidly increased from 1910, peaked between 1950 and the early 1980s, and has declined since then. Early dam construction was focused around the St. Lawrence/Great Lakes region and the Pacific coast (Figure 28). The majority of dams are within the southern regions of the country with the highest population densities (Figure 28). Recent dam developments have been concentrated in northern Quebec. Further examination of trends in dam construction grouped by ecozone⁺ demonstrates the majority of dams were completed in the Boreal Shield (n = 265) and the Taiga Shield (n = 177) (Figure 29). The timing of dam construction was variable across ecozones⁺ with dams completed predominantly in Mixedwood Plains and Pacific Maritime ecozones⁺ prior to 1920, while more recent construction was focused within Taiga Shield, Boreal Shield, and Prairies (Figure 29). Between 1930 and 1980, dams were constructed across most regions with a dominance of sites within the Taiga Shield towards the latter period (Figure 29). For some regions, the construction was fairly constant from the early 1900s onwards, for example in the Boreal Shield, Atlantic Maritime, Western Interior Basin, and Montane Cordillera ecozones⁺ (Figure 29).

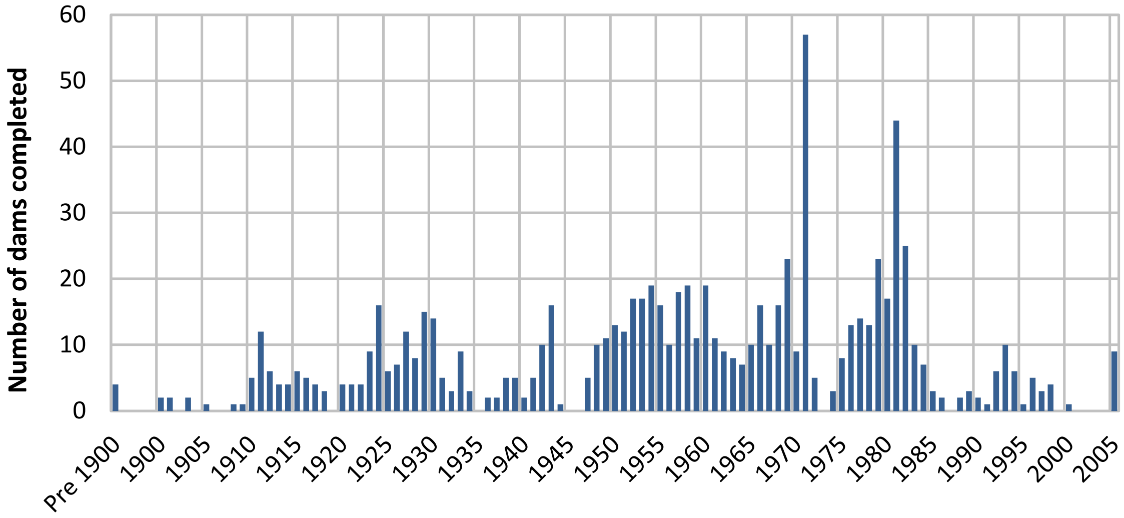


Figure 27. Number of dams (>10 m in height) completed each year in Canada, pre-1900–2005. Records for pre-1900 go back to 1830.
Source: data from Canadian Dam Association (2003) updated to include data up to 2005

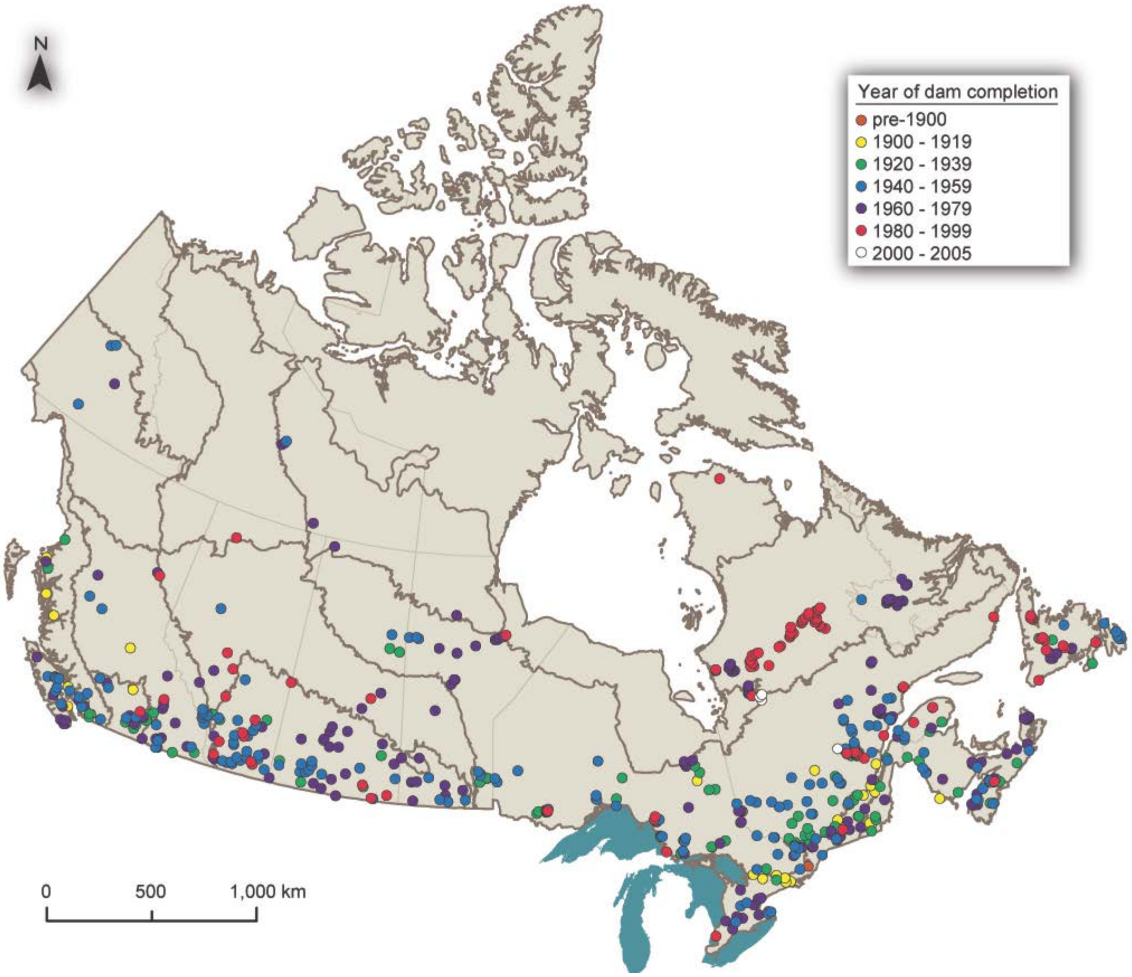


Figure 28. Spatial distribution of dams (>10 m in height) grouped by year of completion, 1830–2005.
Source: data from Canadian Dam Association (2003) updated to include data to 2005

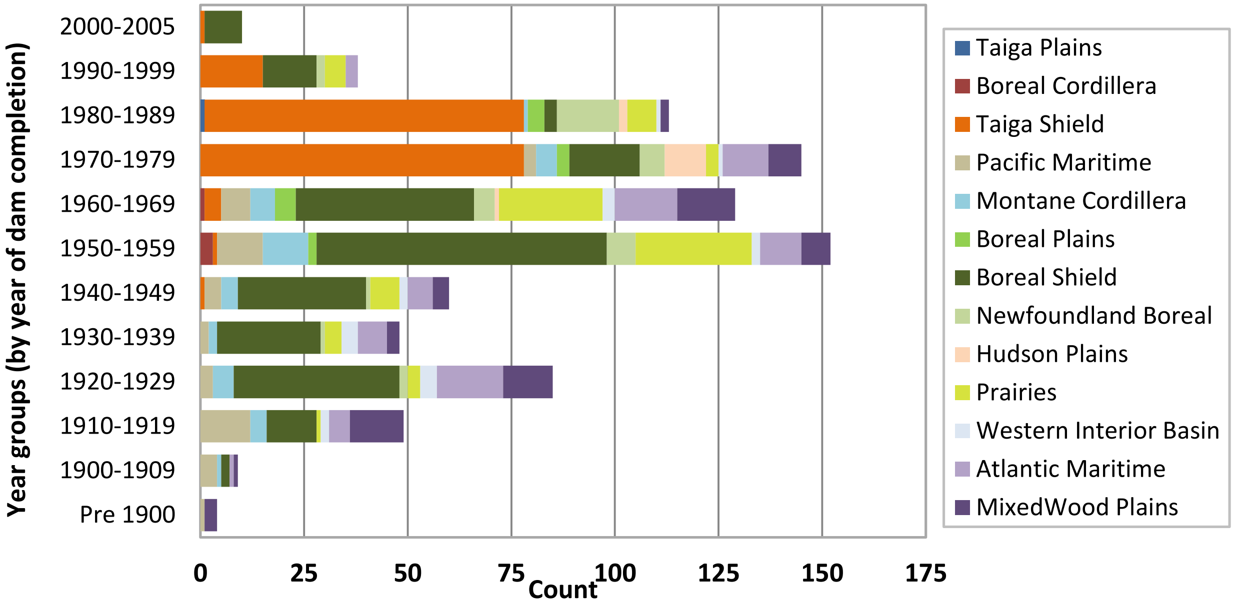


Figure 29. Temporal distribution of dams (>10 m in height) by decade and ecozone^{+}, pre-1900–2005. Source: data from Canadian Dam Association (2003) updated to include data to 2005

Dams interrupt fish migration routes, destroy riparian habitat, increase sedimentation, affect habitat availability, and cause changes in water chemistry and water availability (McAllister et al., 2000). Fragmentation of river systems can also lead to a loss of genetic diversity and increase differentiation between isolated populations (e.g., Neraas and Spruell, 2001; Meldgaard et al., 2003). However, such effects depend on the nature of the dams and the ecological characteristics of individual species. For example, Reid *et al.* (2008b) found no evidence of population structure effects as a result of damming in black redhorse (*Moxostoma duquesnei*), a fish species found only in the Grand and Thames rivers in Ontario and assessed as Threatened by COSEWIC in 1998 (COSEWIC, 2005) This suggests dams on these rivers do not present substantial dispersal barriers to this species and that other factors, such as high nutrient levels, altered flow regimes, and physical habitat degradation, are more important factors contributing to its endangerment.

Examples of changing land use

Altering land use within watersheds directly affects lake and river ecosystems. For example, changing the proportion of urban or agricultural land will affect water quantity and quality through altered infiltration, transpiration, and runoff rates. Boyle *et al.* (1997) examined published data, aerial photos, and additional historical information to look at land use changes in the Lower Fraser Basin of southwestern British Columbia. The analysis quantified estimates of land cover for the years prior to 1827 (the start of European settlement) and for 1930 and 1990 (Boyle et al., 1997). The total area of wetlands (fen, swamp, bog, and marsh) declined from 831 km^2 prior to 1827 to 163 km^2 in 1930 to 121 km^2 in 1990. These declines coincided with a dramatic increase in urban and agricultural area from none pre-1827 to 2,184 km^2 in 1990 (Boyle et al., 1997). These changes resulted in a dramatic decline in waterfowl from numbers estimated to be in the billions in 1920 to 506,600 in 1995 (Boyle et al., 1997).

Timoney and Argus (2006) explored trends in riparian vegetation cover in response to variability in water levels in the Peace–Athabasca delta using five common willow species. Between 1993 and 2001, overall willow cover declined but there was large variability between species, for example *Salix bebbiana* and *Salix discolor* appeared to be the most susceptible to flooding. There was a strong correlation between willow dieback and water depth, duration of flooding, and time since flooding. In addition, more rapid willow establishment coincided with a drying period in the delta, increased regional wildfire activity, a decline in river discharge, and a decline in the level of Lake Athabasca, during the early 1980s. An increase in willow cover followed and reached a peak around 1993 while flooding in the mid- to late 1990s resulted in a decline in willow cover (Timoney and Argus, 2006).

TRENDS IN POLLUTANTS IN LAKE AND RIVER SYSTEMS

Contaminants

Contaminants entering the environment will partition into different environmental compartments (such as water and biota) in a fashion determined by their chemical and physical properties. Since the environment itself is in a state of constant physio-chemical flux, it is not always straightforward to predict by which pathway or in which compartment specific substances will accumulate. For this reason, spatial and temporal interpretation of contaminant monitoring data is often hampered by a lack of sufficient observations, and by other confounding factors such as analytical method inconsistencies (Braune et al., 1999). Moreover, observations within a single system may not easily be generalized to other systems: for example, where food web structure varies between lakes food-chain bioaccumulation of contaminants by top predators will vary according to food chain length and trophic position, even where contaminant levels at the base of the food web are similar (Baird et al., 2001). For this reason, and given the general lack of available time series data within Canada on contaminants, either in terms of water or tissue/biota concentrations (see below), it was not possible to carry out a scientifically credible analysis of contaminants trends across ecozones+.

Given public concerns regarding environmental pollution arising from the emission of contaminants from human activities, it is surprising that relevant data for assessing trends in substances of concern in river and lake ecosystems are almost completely lacking beyond the Great Lakes region (which is itself covered in a separate Technical Ecozone+ Report). This situation is clearly illustrated for a region where contaminants are considered to be an important ongoing threat to freshwater ecosystems: the Canadian Arctic. In an authoritative review of existing data on contaminants in this area, Braune *et al.* (1999) state unequivocally that:

> *"Reviews of contaminant data in freshwater fish from Arctic and sub-Arctic Canada available to 1991 (Muir et al., 1990; Lockhart et al., 1992) indicated that information on the levels and geographic variation of OCs, PAHs and heavy metals was limited while data on temporal trends were non-existent."*

The limited number of studies carried out on contaminants in the Canadian Arctic have tended to focus on marine ecosystems (for example, Muir and Norstrom, 2000). Where trend data in freshwater ecosystems are reported, they tend to be locally focused, consist of relatively few sequential observations, and relate to the very recent past (for example, Michelutti et al., 2009). For example, in a research synopsis produced by the Northern Contaminants Program (2008), trends were observed in certain groups of persistent organic pollutants (POPs): HCH, PCBs, toxaphene, and DDT levels in fish tissue were generally seen to be declining across sites studied, whereas mercury trends in fish tissue showed a more complex pattern, with significant increases being observed for some species and locations (for example, lake trout (*Salvelinus namaycush*) in Great Slave Lake), and no change being reported for species in other areas (for example, charr in lakes in Qausuittuq and Quttinirpaaq). This pattern of spot measurements, patchily distributed and relying on opportunistic sampling as part of short-term local or regional initiatives, has resulted in the current situation, where for much of Canada, time series data on contaminants in freshwater ecosystems are absent. Despite a lack of temporal trend information, the appearance and persistence of bioaccumulative, persistent organic pollutants in remote areas such as the Arctic, which were originally emitted in the more developed southern parts of the North American continent, is a newly emerging trend. This phenomenon is a direct result of global fractionation, a process which was not fully recognised until recently (Wania and Mackay, 1993), and whose implications for transport of a host of substances from industrialised regions to more remote regions is still not completely understood.

Nutrients

Results from the 2008 Canadian Environmental Sustainability Indicators report demonstrated that phosphorus water quality guideline limits were frequently exceeded at 125 of the 369 (34%) monitoring sites (Environment Canada, 2009b). Similarly, the percentages of sites exceeding guidelines in 2002–2004 and 2003–2005 were 38 and 37% respectively (Environment Canada, 2006a; Environment Canada, 2007). In part to evaluate these frequent exceedences, Environment Canada (2011) recently completed a national report exploring trends from 1990 to 2006 in phosphorus and nitrogen in lake and river systems across Canada. Trend analyses of data between 1990 and 2006 demonstrated that 39 of the 77 monitoring sites showed no change in phosphorus levels, 22 showed significant decreasing trends, while 16 showed increasing trends (Figure 29) (Environment Canada, 2011).

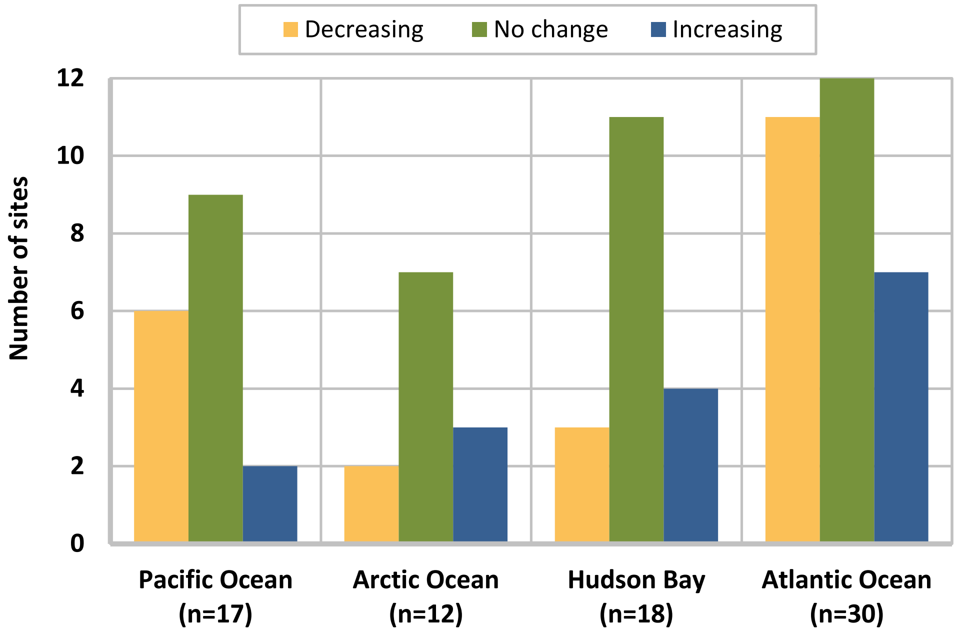
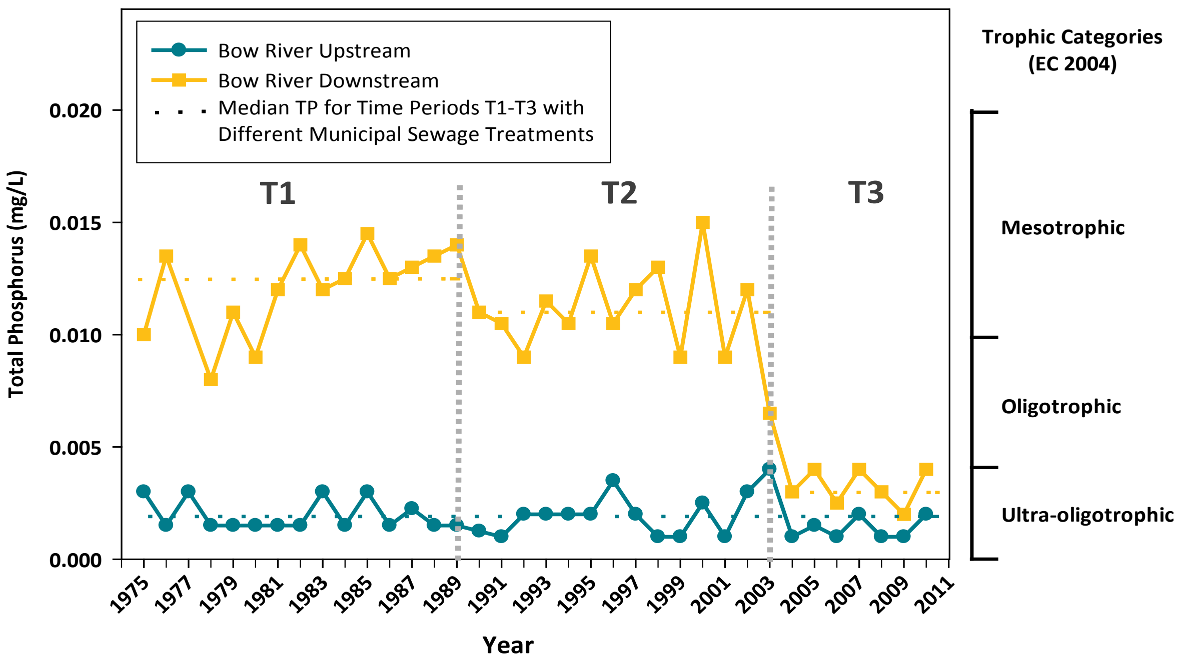


Figure 30. Number of water quality monitoring sites in each major ocean drainage basin with increasing, decreasing, and unchanged phosphorus levels between 1990 and 2006.
Only sites with statistically significant results are shown (p<0.05).
Source: Environment Canada (2011)

Glozier *et al*. (2004) quantified long-term trends in water quality in Banff and Jasper National Parks to assess the effectiveness of sewage treatment plants. Their report applied non-parametric seasonal Mann-Kendall analysis to assess trends in phosphorus concentrations at five monitoring locations on the Bow, North Saskatchewan, and Athabasca rivers. Results from the first report (Glozier et al., 2004) showed improvements in concentrations of nutrient and bacteriological parameters were observed at downstream sites, particularly in the lower Bow River for the period since 1989. These improvements are largely related to the upgrade of the sewage treatment facility in Banff. Glozier (Glozier, 2009, pers. comm.) reported the results of a follow-up analysis to assess the effectiveness of an upgrade in all three municipalities to tertiary treatment with phosphorus removal. Trend analyses showed that the new facility dramatically reduced phosphorus concentrations in the Bow and Athabasca rivers with median concentrations restored to levels similar to upstream, naturally occurring concentrations (Figure 31). Thus, management practices have dramatically improved water chemistry in these rivers. With continued monitoring, the effects of improved water quality on aquatic communities can be observed.

A) Median Total Phosphorus



B) Median Total Dissolved Phosphorus

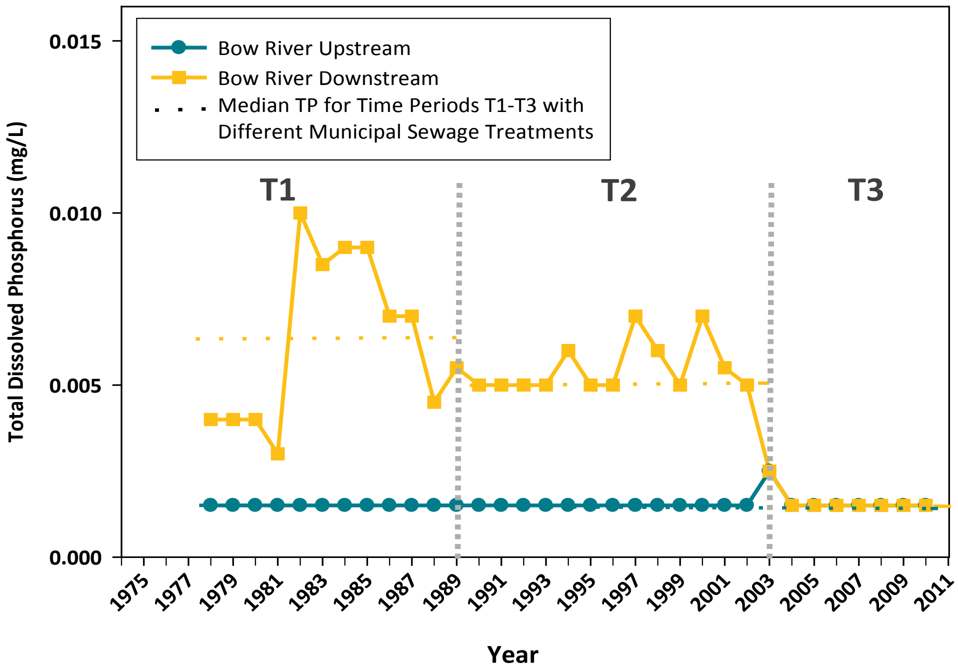


Figure 31. A) Median total phosphorus and B) dissolved phosphorus concentrations in the Bow River, 1975–2010.
Three distinct municipal treatment regimes through the period of record are indicated as: T1–secondary treatment and settling aeration, T2–high rate activated sludge plant with UV disinfection, and T3–tertiary treatment including phosphorus removal.
Source: Glozier et al. (2004) and updated by Glozier with unpublished data

Acidification

Concerns about acidification of surface waters arising from atmospheric release of sulphur dioxide (SO_2) and nitrogen oxides (NO_x) have been prevalent since the 1970s, when scientists first observed declining pH levels, particularly in southeastern Canada (Jeffries et al., 2003a). From 1980 to 2006, SO_2 emissions in Canada and the U.S. declined by about 45% and NO_x emissions declined by about 19% (Canada-United States, 2008)(Figure 32), due in part to declines in calcium which are also related to acid deposition (Canada-United States, 2008). Declines in calcium also threaten keystone zooplankton species (Jeziorski et al., 2008).Encouraging biological improvements have been seen in some locations (Snucins, 2003; Snucins and Gunn, 2003; Weeber et al., 2005; Environment Canada, 2005; Aurora Trout Recovery Team, 2006; Yan et al., 2008b). Even with chemical recovery, however, biological communities remain altered from their pre-acidification state because many factors beyond acidity influence biological recovery (Yan et al., 2008a; Yan et al., 2008b). The widespread devastation arising from deposition of pollutants carried by atmospheric transport (see also the example of contaminants) presents significant challenges beyond simple emission reduction targets, which challenge our knowledge of ecosystem recolonization and the re-establishment of ecosystem services.

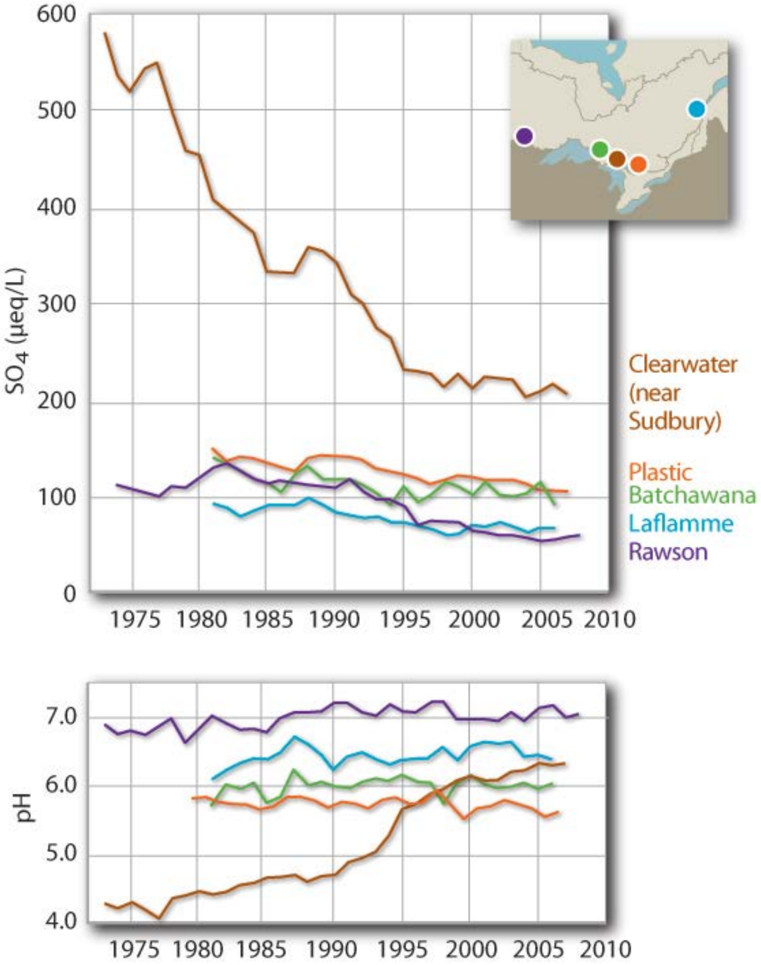


Figure 32. Trends in sulphate levels and acidity (pH) in lakes at five intensive monitoring sites in southeastern Canada, 1972 to 2008.
Note that the strong response for Clearwater Lake (relative to the others) is related to its location very near the strong SO$_2$ emission source (nickel smelter) at Sudbury.
Source: updated from Jeffries et al. (2003b) by author

Ecosystems have different sensitivities to acid depending upon their geology and soils. Thus the maximum level of acid deposition that terrain can withstand without harming ecological integrity, called the "critical load", differs across ecosystems (Figure 33) (Jeffries and Ouimet, 2005). Acid-sensitive terrain is generally underlain by slightly soluble bedrock and overlain by thin, glacially derived soils (National Atlas of Canada, 1991) and has less buffering capacity.

Critical loads can be exceeded either when extremely sensitive terrain receives low levels of acid deposition or when less-sensitive terrain receives high levels of acid deposition. Figure 34 shows where critical loads have been exceeded in the Boreal Shield Ecozone$^+$.

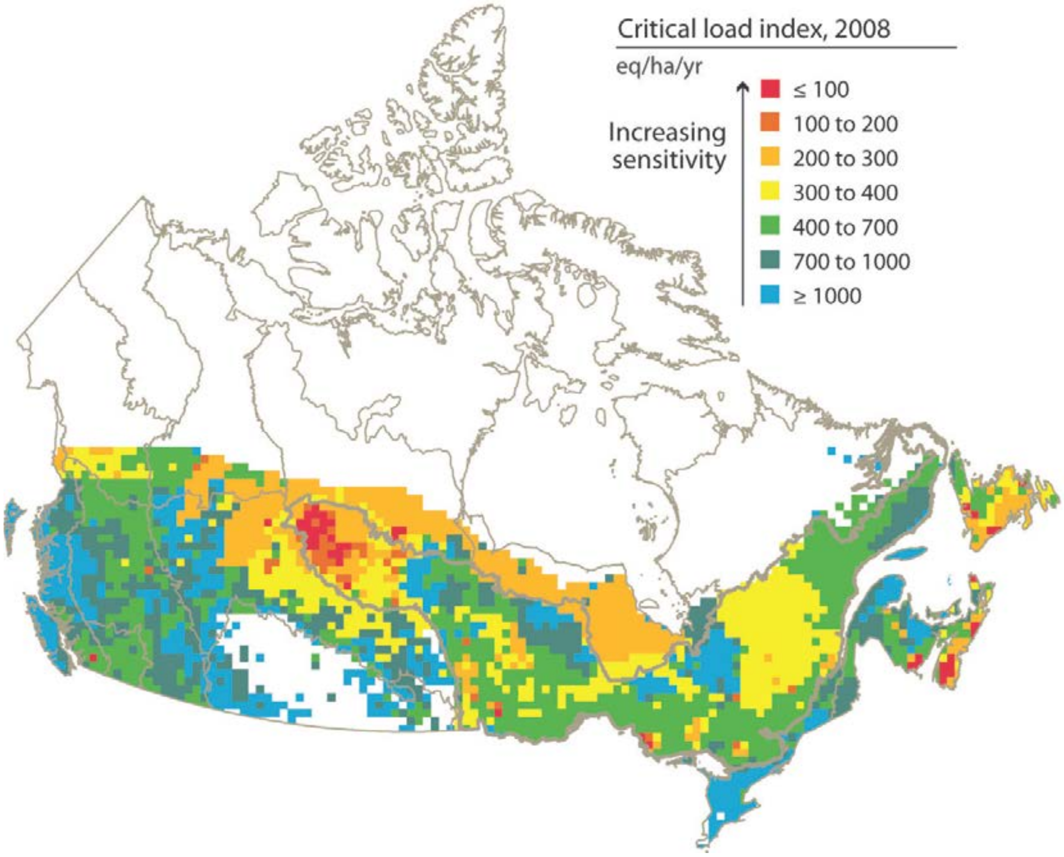


Figure 33. Combined aquatic and terrestrial atmospheric deposition critical load index for Canada, 2008. Source: Jeffries et al. (2010a)

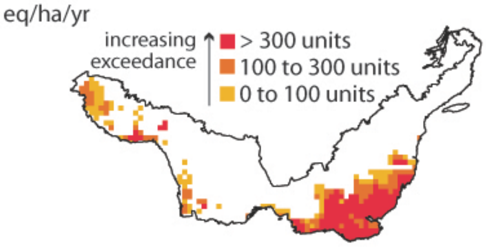


Figure 34. Areas where the critical load has been exceeded in the Boreal Shield Ecozone$^+$, 2009. Source: Jeffries et al. (2010b)

Despite having the lowest rates of acid deposition in eastern North America, the Atlantic Maritime Ecozone$^+$ has some of the most acidic waters due to the poor buffering ability of the terrain (Clair et al., 2004; Clair et al., 2007). Since the 1980s, there has been no measurable recovery in pH despite declines in sulphur dioxide emissions. This has resulted in the most heavily impacted fish habitat in North America (Figure 35) (Clair et al., 2007). Atlantic salmon are highly sensitive to acidity, and by 1996, 14 runs in coastal Nova Scotia were extinct because of water acidity, 20 were severely impacted, and a further 15 were lightly impacted (Watt et al., 2000). Recovery of water chemistry and ecology is expected to take several more decades in Nova Scotia than in other parts of Canada (Watt et al., 2000; Clair et al., 2004; Clair et al., 2007).

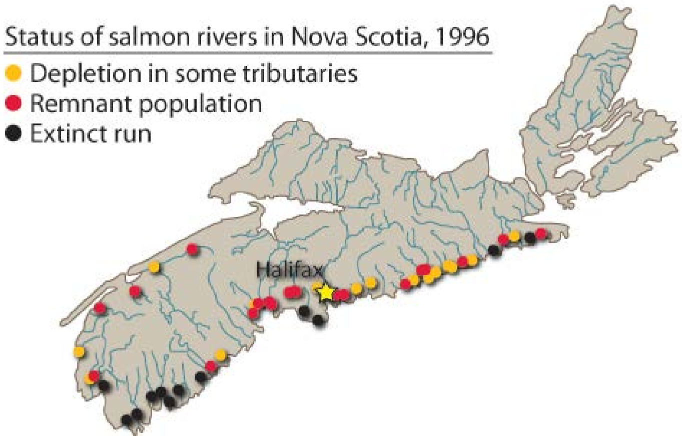


Figure 35. Impact of acidification on Atlantic salmon, 1996
Source: adapted from Watt et al. (2000)

While the acidification of lakes has largely been seen as an issue for the Boreal Shield and Atlantic Maritime ecozones+, concerns are being voiced about the potential vulnerability of areas in western Canada. In particular, the potential for critical loads to be exceeded in northwest Saskatchewan is a concern due to the high degree of acid sensitivity of many of the lakes in this area (68% of 259 lakes assessed in 2007/2008) and its location downwind of acidifying emissions from oil and gas developments (Scott et al., 2010) . Similarly, transportation-related sulphur emissions in southwest British Columbia are an emerging issue, with terrestrial critical loads exceeded in 32% of the Georgia Basin in 2005/2006 (Nasr et al., 2010).

FUTURE CLIMATE IMPACTS ON LAKES AND RIVERS

Water resources in North America are already over-allocated in many regions and, therefore, are highly susceptible to future change., Bates *et al.* (2008) discussed the impacts of changes to the timing, volume, quality, and spatial distribution of freshwater resources in North America expected with increased rates of warming. Precipitation in Canada is forecast to increase in the range of +20% for the annual mean and +30% for winter under the highest emissions scenario in addition to widespread increases in extreme precipitation events (Bates et al., 2008). For example, the projected increases in precipitation, earlier and more severe spring flooding, and increased duration of summer drought periods in British Columbia will affect streamflow and, in turn, fish survival. The Intergovernmental Panel on Climate Change (2007) synthesized scientific studies using data between 1970 and 2004 to explore changes in physical (such as snow, ice, frozen ground, hydrology, and coastal processes) and biological (terrestrial, marine, and freshwater) systems in relation to changing surface temperatures on all continents, including North America (Intergovernmental Panel on Climate Change, 2007). Of the North American studies reviewed, 334 of 355 (94%) data series exploring physical systems and 419 of 455 (92%) data series exploring biological systems could be attributed to warming (Intergovernmental Panel on Climate Change, 2007). Future climate change is very likely to have both direct and indirect effects on aquatic community structure and function within lake and river ecosystems in Canada.

Future climate change will affect the volume and timing of precipitation and evaporation in addition to causing increased variability in precipitation type. These changes will affect the hydrological regimes of rivers in addition to lake levels (Bates et al., 2008). Regional variations in response are forecast with large-scale relative changes in annual runoff for the period 2090 to 2099 relative to 1980 to 1999. For the majority of northern latitude areas in Canada, there is a projected 20 to 40% increase in runoff. The remainder of Canada, with the exception of the Prairies, is projected to experience a 5 to 20% increase (Milly et al., 2005). Biological effects of climate-related warming have already been observed, for example shifts in species composition, abundance, productivity, and phenological shifts (for example, fish migration). Increases in water temperatures and precipitation, in addition to longer periods of low flows, will cause significant effects in lake and river systems through increases in sediment levels, runoff levels, and thermal pollution. Aquatic communities will be affected by changes in water levels and temperatures; for example, cold-water salmonid species are predicted to be negatively affected while warm-water species will likely benefit (for example, Eaton and Scheller, 1996; Wrona et al., 2006).

Under climate warming scenarios, snow and ice cover will continue to decline, particularly in spring and summer (Bates et al., 2008). Using satellite images over the 1966 to 2005 period, Bates *et al.* (2008) reported that snow cover in the Northern Hemisphere has decreased in every month, with the exception of November and December. Under future climate warming, widespread reductions in snow cover are forecast, in addition to increases in thaw depth over much of the permafrost regions as a result of increased air temperatures (Bates et al., 2008). However, despite the reductions in lake and river ice cover, the effect may be less severe in large northward-flowing rivers because of reduced regional contrasts in south-to-north temperature and hydrological gradients (Bates et al., 2008). Lake and river ice regimes will continue to change under future climates, for example the length of ice cover will continue to decrease. Any future changes in climate could affect aquatic morphology and therefore the ice regime, in both a direct and indirect manner. For example, longer term changes in lake water levels could affect the ice regime of tributary rivers (Beltaos and Burrell, 2003).

SYNTHESIS OF DATA

Biodiversity is a notoriously complex and often poorly defined concept. Reporting on biodiversity patterns by simply amassing existing data on the occurrence of species and habitats across Canada will quickly run into problems of data comparability. For example, combining single species surveys (such as from fisheries stock assessment or endangered species plans) into distribution maps may seem to yield consistent information, until one realises that how, when, and where observations were made is likely to vary considerably depending on the study. When collating data in this way, apparent species 'absences' are open to a variety of interpretations. Such problems are compounded when site-collected species data are combined to examine patterns of faunal richness at larger geographical scales. For scientifically sound interpretation of biodiversity patterns, therefore, data should ideally be collected using a consistent methodology. Of course, this is often impossible to achieve when combining historical data, and extremely difficult in new multi-partner initiatives, as methods standardization is a highly contentious issue with significant transaction costs. A possible solution to this problem is the development of metadata approaches, which permit data to be shared within a network, even when collected using a diversity of methods. Here the metadata can form the basis of a screening tool to extract data with common properties for specific reporting purposes, while still permitting data to be shared among a diversity of partners.

Table 10, Table 11, and Table 12 summarize the important trends in lakes and rivers in Canada derived from data analyses, literature analyses, and published scientific studies nationally and for each ecozone$^+$. One of the major conclusions that can be drawn from this analysis is a general lack of consistently collected, longer-term data sets. Despite recently developed national biomonitoring strategies (for example, see Canadian Aquatic Biomonitoring Network in Environment Canada, 2009a), records for biological community monitoring are limited. Our knowledge of the biodiversity within Canada's freshwater ecosystems is highly fragmented, with much valuable information currently inaccessible for monitoring and reporting purposes. While some aspects of biodiversity, notably habitat diversity, are being captured by ongoing initiatives, such as the Nature Conservancy of Canada's freshwater habitat mapping studies (Ciruna et al., 2007), others remain lost in an institutional hinterland of fragmented and neglected data archipelagos. To improve our ability to work with this untapped resource of currently unavailable data, there is an urgent need for improved, strategic efforts in the area of ecoinformatics. Linking up existing on-line data sources through improved data discovery tools, and making currently off-line data available is an important first step in understanding national-level patterns in aquatic biodiversity, and how these have been changing in recent years.

Table 10. Summary of national trends from this analysis, literature analysis, and previous published scientific research.

	Variable	**Trend description**
Trends derived for data from 1970 to 2005	Magnitude of monthly conditions	Few trends apparent. Strong ↑ in April runoff and ↓ trend for May to August runoff
	Magnitude of runoff-minimum	Majority ↔ esp. longer duration. ~ quarter of sites ↓
	Magnitude of runoff-maximum	Majority ↔ but large number of sites showing tendency towards ↘ esp. long duration
	Timing of annual minimum	Few sites with significant trends Nearly half of sites showing tendency towards ↗ (later) annual minimum
	Timing of annual maximum	Few sites with significant trends. Majority of sites showing tendency towards ↘ (earlier) annual maximum
	Frequency of extreme low flow events	Majority of sites ↔
	Frequency of extreme high flow events	Majority of sites ↔
	Duration of extreme events	Majority of sites ↔. Slight trend towards ↓ trend in duration of low pulse events.
	Flashiness of events	Few sites with significant trends for rise rate and fall rate. Tendency towards ↗ in fall rate and ↘ in rise rate for nearly half of sites. ↑number of reversals for third of sites.
	Ice freeze-up	IceWatch (2008) report suggests little evidence for changes in ice freeze-up. Analysis for this report shows sites reflects this result.
	Ice break-up	IceWatch (2008) report showed 40 of the 285 sites showed significantly (p<0.05) earlier spring melt (with an additional 168 sites showing a non-significant (p>0.05) earlier tendency) Analysis for this report demonstrated 8 out of 69 sites showed a significantly (p<0.05) earlier spring melt (with an additional 46 sites demonstrating a non-significant (p>0.05) earlier tendency)
	Habitat connectivity	Peak number of dams > 10m in height (57) completed in 1971. Earliest large dam completed in 1830. Majority of dams completed between 1950 and 1990 with recent decline. Interbasin transfers and diversions (mainly for hydropower) have altered hydrological regimes, particularly in SK, QC, ON, and NL. Trends in land use changes have caused shifts in hydrological regimes, e.g., Lower Fraser Basin
	Contaminants	Few long-term trends information outside the Great Lakes region. Studies in the Arctic indicate continued concerns with rising POP levels from pollutants transported from the industrialised south
	Nutrients	Glozier et al. (2009 - draft report) provide a national summary of long-term (1990–2006) trends in nitrogen and phosphorous in aquatic systems
	Acidification	Acidic deposition in eastern Canada has reduced since the 1970s and pH levels in lakes affected in these regions are recovering. However, there is little evidence of any biological recovery in many affected lakes.

↑ = significant increase (p<0.1); ↗ tendency towards increase (p>0.1); ↓ = significant decrease (p<0.1); ☐ = tendenc towards decrease (p>0.1); N.D. = not enough available data

Table 11. Summary of hydrological trends by ecozone$^+$, 1970–2005.

Ecozone$^+$	**Magnitude of monthly conditions**	**Magnitude of runoff-minimum**	**Magnitude of runoff-maximum**	**Timing of annual minimum**	**Timing of annual maximum**	**Frequency of extreme low flow events**	**Frequency of extreme high flow events**	**Duration of extreme events**	**Flashiness of events**
Arctic	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Atlantic Maritime	Strong ↓ for late spring and summer runoff	↓	Tendency towards ↘	Tendency towards ↗ (later) minimum	Tendency towards ↘ (earlier) maximum	↔	Tendency towards ↘	↔	Tendency towards ↘ rise rate and ↗ fall rate; ↔ in reversals
Boreal Cordillera	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Boreal Plains	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Boreal Shield	Few sites with trends	↓ and ↘ (except longer duration ↔)	↓ and ↘	↗ in southern area; ↘ across area + western area	↘ across area; ↗in central + western area	↔	Tendency towards ↘	Tendency towards ↗ in extreme low + high flow events	Tendency towards ↘ rise rate, ↗ in fall rate; ↔ reversals
Hudson Plains	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Mixedwood Plains	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Montane Cordillera	Few clear trends but strong ↑for April runoff	↔	Tendency towards ↘	↔	Tendency towards ↘ (earlier) maximum	↔	Tendency towards ↗	↔	Tendency towards ↗ rise rate; ↔ fall rate; ↑in reversals
Newfoundland Boreal	No clear trend. Slight ↓ for August	↓ and ↘	↔	Trend towards ↗ (later) minimum	Trend towards ↗ (later) maximum	↔	↔	↔	↔
Pacific Maritime	↓ trend in late spring and summer runoff	↓ and ↘	↑ and ↗	Tendency towards ↗ (later) minimum	Trend towards ↘ (earlier) maximum	Tendency towards ↗	Tendency towards ↗	↔	↔
Prairie	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Taiga Cordillera	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Taiga Plain	↑ trend in winter and early spring runoff	↑	↔	↔	↔	↔	↔	↔	↔ for rise rate and fall rate; ↑ reversals

Ecozone+	Magnitude of monthly conditions	Magnitude of runoff-minimum	Magnitude of runoff-maximum	Timing of annual minimum	Timing of annual maximum	Frequency of extreme low flow events	Frequency of extreme high flow events	Duration of extreme events	Flashiness of events
Taiga Shield	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Western Interior Basin	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

↑ = significant increase (p<0.1); ↗ tendency towards increase (p>0.1); it between increasing ↓ = significant decrease (p<0.1); ☐= tendenc
and decreasing trends; N.D. = not enough available data

Table 12. Summary of trends from this analysis, literature analysis, and previous published scientific research by ecozone$^+$.

Ecozone$^+$	**Ice freeze-up (using evidence from Table 7)**	**Ice break-up (using evidence from Table 8)**	**Habitat connectivity (using data from Canadian Dam Association)**	**Contaminants**	**Nutrients**	**Acidification**
Arctic	N.D.	Trend towards earlier break-up (c)	No dams recorded	Few long-term trends information outside the Great Lakes region. Studies in the Arctic indicate continued concerns with rising POP levels from pollutants transported from the industrialised south.	Glozier *et al.* (2009 - draft report) provide a national summary of long-term (1990–2006) trends in nitrogen and phosphorous in aquatic systems.	Acidic deposition in eastern Canada has decreased since the 1970s and pH levels in lakes affected in these regions are recovering. However, there is little evidence of any biological recovery in many affected lakes.
Atlantic Maritime	Earlier (a)	Later (b); No clear trend (a)	74 dams, development throughout 20th century			
Boreal Cordillera	Earlier (a)	Earlier (a, b and c)	4 dams, built between 1950 and 1970			
Boreal Plains	Mixed trend (c)	Trend towards earlier break-up (c)	14 dams, built between 1950–1990			
Boreal Shield	N.D.	N.D.	265 dams, development throughout 20th century 42% built between 1950–1980			
Hudson Plains	N.D.	N.D.	13 dams, built between 1960 and 1990 10 of 13 built between 1970–1980			
Mixedwood Plains	Mixed trend (c)	Later (b); Mixed trend (c)	67 dams, development throughout 20th century			
Montane Cordillera	Mixed trend (c)	Trend towards earlier break-up (c)	39 dams, development throughout 20th century			
Newfoundland Boreal	Earlier trend (c)	Trend towards earlier break-up (c)	39 dams, development throughout 20th century with 38% built between 1980–1990			
Pacific Maritime	N.D.	N.D.	47 dams, development throughout 20th century			
Prairie	Mixed trend (c)	Earlier (a and b); Mixed trend (c)	83 dams, majority (64%) built between 1950 and 1970			
Taiga Cordillera	N.D.	N.D.	No dams reported			
Taiga Plain	N.D.	N.D.	1 dam, built in 1989			
Taiga Shield	Trend towards later freeze-up (c)	Trend towards earlier break-up (c)	177 dams Majority (88%) built between 1970 and 1990			
Western Interior Basin	N.D.	N.D.	19 dams, development throughout 20th century			

Sources: (a) 1957–1996: Zhang et al. (2001); (b) 1960–1997: Burn and Hag Elnur (2002); (c) 1961–1990: Duguay et al. (2006)

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Appendix 1. Summary of ecozone^{+} trends in Indicators of Hydrologic Alteration (IHA) variables.

IHA variable	Trend direction	Atlantic Maritime	Boreal Shield	Boreal Plains	Boreal Cordillera	Hudson Plains	Mixedwood Plains	Montane Cordillera	Newfoundland Boreal	Northern Arctic	Pacific Maritime	Prairie	Southern Arctic	Taiga Cordillera	Taiga Plains	Taiga Shield	Western Interior Basin
Number of sites:		34	31	6	9	2	5	27	12	2	11	4	3	1	11	6	8
October	↓ p<0.1	0	2	0	0	0	0	0	0	0	0	0	3	0	1	2	0
	↑ p<0.1	4	5	2	0	0	0	2	0	0	0	0	0	0	0	0	0
	No trend	30	24	4	9	2	5	25	12	2	11	4	0	1	10	4	8
November	↓ p<0.1	2	1	0	1	1	0	0	0	0	1	0	2	1	4	2	0
	↑ p<0.1	0	3	2	0	0	0	0	0	0	0	0	0	0	1	0	0
	No trend	32	27	4	8	1	5	27	12	2	10	4	1	0	6	4	8
December	↓ p<0.1	0	6	1	5	1	0	1	0	0	1	0	2	1	7	1	3
	↑ p<0.1	2	4	2	0	0	0	1	0	0	0	0	0	0	1	1	0
	No trend	32	21	3	4	1	5	25	12	2	10	4	1	0	3	4	5
January	↓ p<0.1	0	5	1	4	1	2	1	0	0	3	0	1	1	7	2	4
	↑ p<0.1	4	6	2	0	0	0	1	0	0	0	0	0	0	1	0	0
	No trend	30	20	3	5	1	3	25	12	2	8	4	2	0	3	4	4
February	↓ p<0.1	0	4	1	4	0	0	2	0	0	1	0	2	1	7	2	0
	↑ p<0.1	4	5	2	0	0	0	2	0	0	1	0	0	0	1	0	0
	No trend	30	22	3	5	2	5	23	12	2	9	4	1	0	3	4	8
March	↓ p<0.1	0	3	0	3	0	0	3	0	0	0	0	2	1	7	1	1
	↑ p<0.1	0	3	1	0	0	0	0	0	0	0	0	0	0	1	0	0
	No trend	34	25	5	6	2	5	24	12	2	11	4	1	0	3	5	7

IHA variable	Trend direction	Atlantic Maritime	Boreal Shield	Boreal Plains	Boreal Cordillera	Hudson Plains	Mixedwood Plains	Montane Cordillera	Newfoundland Boreal	Northern Arctic	Pacific Maritime	Prairie	Southern Arctic	Taiga Cordillera	Taiga Plains	Taiga Shield	Western Interior Basin
April	↓ p<0.1	7	5	0	5	1	0	10	0	0	3	3	2	1	5	1	7
	↑ p<0.1	0	4	0	0	0	2	0	0	0	0	0	0	0	0	0	0
	No trend	27	22	6	4	1	3	17	12	2	8	1	1	0	6	5	1
May	↓ p<0.1	0	0	0	0	0	0	1	0	0	2	0	1	0	0	0	0
	↑ p<0.1	19	7	2	0	0	1	3	0	0	3	2	0	0	0	1	0
	No trend	15	24	4	9	2	4	23	12	2	6	2	2	1	11	5	8
June	↓ p<0.1	0	3	0	2	0	0	1	0	0	2	0	1	0	0	1	0
	↑ p<0.1	17	7	1	2	0	0	0	0	0	3	0	0	0	0	0	2
	No trend	17	21	5	5	2	5	26	12	2	6	4	2	1	11	5	6
July	↓ p<0.1	0	4	1	1	0	0	1	0	0	0	0	2	0	0	2	0
	↑ p<0.1	9	4	1	1	0	0	1	0	0	5	0	0	0	0	0	1
	No trend	25	23	4	7	2	5	25	12	2	6	4	1	1	11	4	7
August	↓ p<0.1	0	1	1	1	0	0	0	0	0	0	0	2	0	1	2	0
	↑ p<0.1	19	10	1	2	0	0	4	0	0	4	1	0	0	1	0	1
	No trend	15	20	4	6	2	5	23	12	2	7	3	1	1	9	4	7
September	↓ p<0.1	0	1	0	1	0	0	0	0	0	1	0	2	1	1	3	0
	↑ p<0.1	8	9	1	0	0	1	2	0	0	7	0	0	0	1	0	2
	No trend	26	21	5	8	2	4	25	12	2	3	4	1	0	9	3	6
1-day minimum	↓ p<0.1	0	4	0	3	0	0	3	0	0	0	0	2	1	6	2	1
	↑ p<0.1	20	9	1	0	0	0	4	0	0	5	0	0	0	1	0	0
	No trend	14	18	5	6	2	5	20	12	2	6	4	1	0	4	4	7
3-day minimum	↓ p<0.1	0	4	0	3	0	0	4	0	0	0	0	2	1	6	2	1
	↑ p<0.1	21	9	1	0	0	0	3	0	0	5	0	0	0	0	0	0
	No trend	13	18	5	6	2	5	20	12	2	6	4	1	0	5	4	7

IHA variable	**Trend direction**	**Atlantic Maritime**	**Boreal Shield**	**Boreal Plains**	**Boreal Cordillera**	**Hudson Plains**	**Mixedwood Plains**	**Montane Cordillera**	**Newfoundland Boreal**	**Northern Arctic**	**Pacific Maritime**	**Prairie**	**Southern Arctic**	**Taiga Cordillera**	**Taiga Plains**	**Taiga Shield**	**Western Interior Basin**
7-day minimum	↓ $p<0.1$	0	4	1	3	0	0	4	0	0	0	0	2	1	6	2	1
	↑ $p<0.1$	21	9	2	0	0	0	2	0	0	3	0	0	0	0	0	1
	No trend	13	18	3	6	2	5	21	12	2	8	4	1	0	5	4	6
30-day minimum	↓ $p<0.1$	0	4	1	4	0	0	4	0	0	2	0	2	1	6	2	1
	↑ $p<0.1$	18	9	1	0	0	1	2	0	0	3	0	0	0	1	0	0
	No trend	16	18	4	5	2	4	21	12	2	6	4	1	0	4	4	7
90-day minimum	↓ $p<0.1$	0	3	1	4	1	0	2	0	0	1	0	2	1	7	2	4
	↑ $p<0.1$	21	5	1	0	0	0	1	0	0	6	0	0	0	1	0	0
	No trend	13	23	4	5	1	5	24	12	2	4	4	1	0	3	4	4
Baseflow	↓ $p<0.1$	0	1	0	4	0	1	6	0	0	0	0	2	1	5	0	1
	↑ $p<0.1$	10	4	1	1	0	0	1	0	0	5	0	0	0	0	1	0
	No trend	24	26	5	4	2	4	20	12	2	6	4	1	0	6	5	7
1-day maximum	↓ $p<0.1$	2	2	0	1	1	0	0	0	0	1	0	1	0	0	3	0
	↑ $p<0.1$	4	8	2	2	0	5	4	0	0	0	1	0	0	2	0	2
	No trend	28	21	4	6	1	0	23	12	2	10	3	2	1	9	3	6
3-day maximum	↓ $p<0.1$	0	2	0	1	1	0	0	0	0	2	0	1	0	0	3	0
	↑ $p<0.1$	5	9	2	1	0	5	3	0	0	0	1	0	0	1	0	3
	No trend	29	20	4	7	1	0	24	12	2	9	3	2	1	10	3	5
7-day maximum	↓ $p<0.1$	0	2	0	1	1	0	0	0	0	3	0	1	0	0	3	0
	↑ $p<0.1$	6	10	2	0	0	5	3	0	0	0	0	0	0	1	0	3
	No trend	28	19	4	8	1	0	24	12	2	8	4	2	1	10	3	5
30-day maximum	↓ $p<0.1$	0	2	0	1	1	0	0	0	0	1	0	1	0	0	3	0
	↑ $p<0.1$	5	12	2	1	0	5	1	0	0	0	0	0	0	1	0	0
	No trend	29	17	4	7	1	0	26	12	2	10	4	2	1	10	3	8

IHA variable	Trend direction	Atlantic Maritime	Boreal Shield	Boreal Plains	Boreal Cordillera	Hudson Plains	Mixedwood Plains	Montane Cordillera	Newfoundland Boreal	Northern Arctic	Pacific Maritime	Prairie	Southern Arctic	Taiga Cordillera	Taiga Plains	Taiga Shield	Western Interior Basin
90-day maximum	↓ p<0.1	0	2	0	1	0	0	1	0	0	2	0	2	0	0	3	0
	↑ p<0.1	7	9	2	1	0	2	0	0	0	0	1	0	0	0	0	1
	No trend	27	20	4	7	2	3	26	12	2	9	3	1	1	11	3	7
Date of 1-day minimum	↓ p<0.1	9	5	0	1	1	0	1	0	0	0	0	1	1	1	5	2
	↑ p<0.1	0	2	1	2	0	0	2	0	1	2	0	2	0	2	0	0
	No trend	25	24	5	6	1	5	24	12	1	9	4	0	0	8	1	6
Date of 1-day maximum	↓ p<0.1	3	1	1	0	0	0	0	0	0	1	0	1	0	3	0	0
	↑ p<0.1	4	3	0	2	0	2	3	0	0	1	0	0	0	0	0	3
	No trend	27	27	5	7	2	3	24	12	2	9	4	2	1	8	6	5
Number of low pulses	↓ p<0.1	6	2	0	1	0	1	5	0	0	0	0	0	0	0	0	0
	↑ p<0.1	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0
	No trend	27	29	5	8	2	3	21	12	2	11	4	3	1	11	6	8
Low pulse duration	↓ p<0.1	7	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0
	↑ p<0.1	0	4	1	3	1	0	4	0	0	1	0	2	1	7	0	0
	No trend	27	26	5	6	1	5	22	12	2	10	4	1	0	3	5	8
Number of high pulses	↓ p<0.1	0	1	1	0	0	0	2	0	0	1	0	0	0	0	0	2
	↑ p<0.1	5	5	1	0	1	0	0	0	0	0	0	0	0	0	0	0
	No trend	29	25	4	9	1	5	25	12	2	10	4	3	1	11	6	6
High pulse duration	↓ p<0.1	1	2	0	0	0	2	0	0	0	0	0	2	0	2	0	0
	↑ p<0.1	3	0	1	0	0	0	2	0	1	2	0	0	0	1	0	1
	No trend	30	29	5	9	2	3	25	12	1	9	4	1	1	8	6	7
Rise rate	↓ p<0.1	0	0	1	4	1	0	1	0	0	3	0	2	0	0	0	2
	↑ p<0.1	11	8	3	1	1	0	5	0	1	0	0	0	0	5	1	0
	No trend	23	23	2	4	0	5	21	12	1	8	4	1	1	6	5	6

IHA variable	Trend direction	Atlantic Maritime	Boreal Shield	Boreal Plains	Boreal Cordillera	Hudson Plains	Mixedwood Plains	Montane Cordillera	Newfoundland Boreal	Northern Arctic	Pacific Maritime	Prairie	Southern Arctic	Taiga Cordillera	Taiga Plains	Taiga Shield	Western Interior Basin
Fall rate	↓ p<0.1	10	5	1	4	1	0	2	0	0	1	0	0	0	1	0	0
	↑ p<0.1	0	0	0	0	1	2	1	0	1	2	0	0	0	2	0	1
	No trend	24	26	5	5	0	3	24	12	1	8	4	3	1	8	6	7
Number of reversals	↓ p<0.1	7	8	1	1	1	2	13	0	1	2	0	1	1	9	2	3
	↑ p<0.1	4	4	0	4	1	0	1	0	0	0	1	0	0	0	0	2
	No trend	23	19	5	4	0	3	13	12	1	9	3	2	0	2	4	3