Chapter 6  Drivers, Trends and Uncertainties of Changing Freshwater Systems

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Key messages
• The limited number of survey gauges, and significant data gaps where gauges exist largely preclude any assessment of trends in river runoff in the region.
• Shifts in precipitation to evaporation ratios are leading to pronounced shrinkage of shallow ponds, and warming is leading to decreases in ice cover on lakes and changes in phytoplankton and bacterial communities, along with enhanced nutrients and/or water temperature changes.
• Hydrological modelling efforts predict higher peak flows, longer flow duration and increased suspended sediment loads over the twenty first century (due to increases in precipitation and warming fall temperatures).
• Permafrost degradation and thermo-erosion processes are likely to continue to disturb the landscape, drain ponds and ultimately transform the hydrology, biogeochemistry, and ecosystems of surface waters in the Eastern Canadian Arctic.
• Nunavut lakes are likely to experience warming rates well above the global average, but with large variations among individual lakes. This will affect ice cover duration, water mixing and aquatic ecosystem properties such as biological production, greenhouse gas fluxes, species composition and fish stocks. Paleoenvironmental proxy records indicate a range in surface water runoff changes across the region, including areas where snowmelt runoff has decreased, and other sites where snowmelt, rainfall and/or glacially derived runoff have increased over the long-term.
Abstract

Freshwater ecosystems, water quality and quantity are directly affected by climate, and indirectly via climate driven changes in permafrost and landscapes. Recent observations and trends of freshwater systems (including rivers, ponds, wetlands, and lakes) in the region are presented. The sparse number of observational records, combined with the challenges associated with field measurements of water balance parameters (e.g., end of year snow accumulation and run-off) preclude robust interpretations of trends in river flows and water budgets across the region. Satellite data has been used successfully to identify trends in lake ice conditions (later freeze-up and earlier break-up) and snow cover duration (decrease of approximately 3 weeks) across the region over approximately the last 30 years. Paleoenvironmental proxy records and paleoecological studies have been used to determine the longer-term trends in freshwater hydrology and ecology. Paleoenvironmental proxies largely indicate an intensification of runoff due to increases in snowfall, rainfall and glacial mass wasting, while paleoecological studies indicate changes in aquatic ecosystems related to increased ice off, nutrients and/or water temperatures. Active layer thickening and permafrost disturbances have significantly transformed the hydrology and ecosystems of ponds, wetlands and lakes, as well as the sediment, nutrient, metal and ion loads in rivers and downstream water bodies. Extreme ecological changes such as the loss of epishelf lakes and drying of ponds have been observed across the region. Continued and expanded monitoring of the responses of water quantity, water quality, and aquatic ecology to climate change is required to improve our understanding of how freshwater ecosystems are changing across the region.
6.1 Introduction

Freshwater systems, including lakes, ponds, wetlands, and rivers, are the foundation of major ecosystems, and represent a key resource for communities in the Arctic. Climate change will have multiple direct, and interacting, impacts on both the volume and integrity of freshwater systems. Examples include, impacts on the physical processes that control the inputs and losses of water (such as rain, snowfall, ground ice melt, ice cover, and evaporation), and the terrestrial conditions (such as active layer depth, thermokarst topography, slope stability) that control the movement, storage, and export of freshwater on the landscape (Figure 1).

This chapter includes a brief review of the recent observations and trends in precipitation, and active layer and permafrost conditions that are presented in Chapters 2 and 4 of this report, and discusses these changes in the context of their control on surface hydrology in the region. Understanding the characteristics of changes in precipitation, such as precipitation type and seasonality, as well as changes in ground thermal regime, are important for projecting changes in watershed hydrology and water quality. Recent observations of conditions and changes in freshwater systems in the Eastern Canadian Arctic, including changes to water volumes, water quality in rivers, wetlands, and lakes are also discussed. Changes in glaciers are not included as these are the presented in Chapter 3 of this report.

Over the last 10-15 years significant integrated long term research and monitoring efforts at a number of sites across the Eastern Canadian Arctic, including the Cape Bounty Arctic Watershed Observatory (Melville Island), Ward Hunt Island, Bylot Island, Lake Hazen (Ellesmere Island), and the Apex River watershed in Iqaluit, have significantly advanced our knowledge of the direct connection between climate change and freshwater resources, biogeochemical processes, and ecosystem health. These studies have observed and documented the impact of rapidly warming temperatures on Arctic freshwater systems, during some of the warmest years on record in the region. Much of the knowledge gained from these studies is reviewed in this chapter and/or elsewhere in this IRIS 2 report.

6.2 Climate change as driver of freshwater systems

The surface air temperatures in the Arctic between 2005-2010 were higher than for any other five-year period since measurements began in the late 1800’s (AMAP 2011). As reported in Chapter 2, the warming in the Eastern Canadian Arctic was more rapid than most other Arctic regions, and is most pronounced in fall and winter, in response to later sea-ice formation. This warming began relatively recently (~1993), and is driven by both anthropogenic forcing as well as changes in the North Atlantic sea surface temperatures and the Arctic Oscillation (Chapter 2). Over the last 30 years the coldest months have warmed more than twice the rate as the warmest months (Chapter 2). The discussion below highlights the important implications of these warming temperatures on the various aspects of Arctic freshwater hydrology.

6.2.1 Timing, volume and type of precipitation

Changing climate will directly impact the type (liquid/solid), volume and timing of precipitation. As air temperatures increase, so do the rates of evaporation and the capacity for the atmosphere to hold water vapour. As a result, the likelihood of increased frequency and/or intensity of precipitation will also increase; especially if/where there is an unlimited source of moisture at the surface.

Air temperatures in the Arctic have exhibited warming in all months (Derksen et al. 2012) and increases in evaporation rates and water vapour have also been observed (Boisvert and Stroeve 2015, Serreze et al. 2012). The ocean and freshwater lakes represent important sources of water vapour to the atmosphere, hence climate driven decreases in the extent of lake and sea-ice cover feedback on (or influence) the hydrologic cycle and climate by increasing the availability of liquid water and thus evaporation rates. Increases in atmospheric vapour are expected to lead to higher rates of precipitation and possibly increased storm
Climate station data for the 1981-2010 indicates that roughly 65% of all precipitation in the region occurs in the summer and fall (Chapter 2, Figure 9). Although observations generally suggest there have been increases in precipitation, there is considerable uncertainty concerning these trends for the region (Chapter 2). For example, although the average of the nine climate stations in IRIS 2 exhibited significant increases in both rainfall and snowfall during the 1950-2013 period, part of this increase is attributed to abnormally low snowfall amounts prior to 1965 (Chapter 2, Figure 10). If the period prior to 1965 is omitted, significant increasing trends are observed for both rainfall (5.3% per decade) and snowfall (3.0% per decade). However, the trends over the most recent 30-year period were not significant (Chapter 2).

The importance of these changes originate from the control that the timing and amount of precipitation have on the volume and timing of both the peak snowmelt runoff and summer rainfall volumes, which in turn have important implications for fisheries, recreational activities, water supply, and water quality (sediment, pathogens, nutrients, contaminants) (Figure 1).

6.2.2 Snow cover and snow cover duration

Seasonal snow cover exists for 7-9 months out of the year across the Arctic, and is a critical factor determining river, lake and wetland water volumes in unglaciated watersheds. Snow cover in the IRIS 2 region varies widely, from very deep (up to 500mm) in the mountainous regions of Ellesmere and Baffin Islands, to relatively thin and patchy across the large lowlands of Bathurst and Melville Islands (Chapter 2).

Snow cover duration is largely a function of latitude and altitude, but spring radiation budgets (air temperatures) that typically lead to rapid melt in May-June are also important (Chapter 2, Figure 11). Snow cover duration increases moving north-east across the IRIS 2 region, with the earliest onset and longest duration of snow cover occurring at high altitudes in the mountainous regions of Ellesmere Island, Axel Heiberg Island, and on the north-east coast of Baffin Island.

Surface observations and satellite data indicate a decrease of approximately 3 weeks in the snow cover duration since 1950, which is largely attributed to a delay in snow cover onset as a result of enhanced air temperatures in the fall (Chapter 2). Climate stations indicate an average -20% decrease in snow depth across the region since the 1950’s however, estimates of the trends in maximum annual accumulation as snow water equivalence (SWE) from satellite data show increases in SWE over the region (Chapter 2).
Snowfall accumulation has a direct impact on spring runoff volumes across the Arctic, and the timing and amount of snow depth has a significant impact on ground temperatures. Experimental snow augmentation experiments at the Cape Bounty Watershed Observatory (CBAWO) on Melville Island, demonstrate that increases in snow depth on the order of 40 cm (approximately triple the ambient snow cover), can lead to a 7-10 °C increase in mean monthly winter soil temperatures (Lafrenière et al. 2013). Similarly, very deep snow accumulation that occurs on land or in stream channels has a strong heat retention effect, with soil and channel surface temperatures up to 30 °C warmer than air temperatures mid-winter (Bonnaventure et al. 2016). However, a delay in onset of snow accumulation can substantially lower winter soil temperatures, despite considerably higher end of season snow accumulation (Lafrenière et al. 2013).

6.2.3 Ice cover duration, evaporation in rivers and lakes

Ice cover plays an important role in the thermal regime of lakes, including mixing, and rates of evaporation. As is highlighted in Chapter 2, the lack of in situ observations of lake and river ice in the region limits our ability to assess trends for these conditions in the region. However, a Pan Arctic assessment of in situ and river ice trends shows a trend towards earlier break-up dates across the Arctic (Duguay et al. 2006, Lacroix et al. 2005). Data from satellite imagery from 1985-2004 indicates that lakes within the IRIS 2 region were consistent with the Arctic-wide trend of later freeze-up (~0.8 days/year later) and earlier break-up. (1.2 days/yr earlier) (Latifovic and Pouliot 2007). Changes at Ward Hunt Lake on northern Ellesmere Island suggest that the summer perennial ice regime was relatively stable from 1953 to 2007, but experienced rapid thinning beginning in 2008, and was ice free in the warm summer of 2011 (Figure 2, Paquette et al. 2015). The increase in the time and extent of open water conditions has important implications for water balance due to changes in evaporation rates, and also lake ecology due to changes in water temperature and wind-induced mixing of the water column.

6.2.4 Ground thermal conditions, active layer thickness

The rate and depth of seasonal thaw, hence active layer thickness, exerts an important control on surface water hydrology in permafrost watersheds. As the extent of the active layer increases (i.e., as the frost table descends), the storage capacity available for water in the subsurface increases, which delays the time required for surface water runoff to respond to precipitation inputs. Hence any processes affecting the development of the active layer, also have direct impacts on soil moisture, potential evaporation, groundwater flow and storage, and surface runoff.

Ground thermal conditions which are largely a function of air temperatures, hence active layers within the region are generally thin due to the extended cold winters, and relatively short and typically cool summers (Chapter 4). At the local scale active layer thickness varies as a function of ground cover (e.g., organic vs. mineral soil), and soil moisture, with greater active layer thickness developing in mineral soils, and/or where moisture is lowest.

There are sparse records of active layer depths in the IRIS 2 region from 4 Circumpolar Active Layer Monitoring (CALM) sites including: Eureka, Tanqueray Fiord, Lake Hazen and Alexandria Fiord. These records show the active layer extending to between 41-62 cm depth between 1996 and 2001 (https://www2.gwu.edu/~calm/). These data are too sparse to interpret temporal and spatial trends, but the thickest active layers were found in 2000 and 2001. Given that significant increases in mean annual air temperatures have been observed across all stations in the region over the last 30 years (Chapter 2), increases in active layer thickness can be expected across this region.

Thickening of the active layer can have significant implications for surface water runoff and quality in areas of ice rich permafrost, which is particularly susceptible to subsidence and disturbances, such as active layer detachments (ALDs), retrogressive thaw slumps (RTS), and thermokarst gullies (gullies) (see also Chapter 4). Disturbances such as ALDs, RTS and thermokarst gullies are associated with warming and are abundant across the region (Godin and Fortier
2012, Lamoureux et al. 2009, Rudy et al. 2013, Rudy et al. 2016). These studies indicate that recent warming has initiated widespread thermokarst and disturbance across the region, but it remains unclear the extent to which this represents a trend. Studies have shown these features have occurred sporadically over the region during the past 50 years, but it appears likely that the recent observations are unusual in density and frequency (Rudy et al. 2013).

6.3 Observations of change in freshwater systems

6.3.1 Changes in river flow volumes

Very little is known about recent changes in surface run-off volumes, or river flow in the Eastern Canadian Arctic (Spence and Burke 2008). Despite the presence of a number of water survey gauges in the region, the limited length of the records precludes the inference of trends from observational data. Even less is known about how Arctic river
quality (e.g., sediment loads, nutrient, dissolved ions, metals) is being affected by climate and related watershed changes.

In unglacierized watersheds, surface runoff in the region is largely a function of the difference between precipitation and evapotranspiration, plus contributions from subsurface water flows (e.g., thawing of ground ice, or permafrost ice), and any groundwater flow in areas where permafrost is absent. Because recent observations and projections for the next 100 years indicate both increases in precipitation and evaporation due to warming (Chapter 2), even estimating the direction of change of river runoff for small rivers is not straightforward. Trends for runoff from the Yukon and the Mackenzie rivers between 1957-1996 suggest that for these subarctic rivers, runoff is more dependant on precipitation inputs than losses from evapotranspiration (ACIA 2005, Table 6.12).

Glacier watersheds and non-glacier watersheds may respond differently to climate warming, as glacier ice melt in warm and relatively dry years drives increases in discharge, while non-glacial watersheds experience decreases in runoff associated with the higher rates of evaporation and diminished precipitation inputs (Lafrenière and Sharp 2003). Given the accelerating rates of glacier mass losses in the Eastern Canadian Arctic, it can be expected that glacial rivers will continue to see increases in runoff volumes in the near future. However, as glacier areas diminish these rivers will reach a tipping point where runoff volumes will eventually decrease (Pelto 1996), or trigger a reorganization of watershed boundaries and stream courses where the melting glacier is situated on a drainage divide (e.g., recent river piracy Slims River, Yukon, Shugar et al. 2017).

The Apex River in Iqaluit is one of only a few unglacierized rivers in the region with a Water Survey of Canada gauge (Spence and Burke 2008). A study investigating the relationship between climate and discharge in the Apex River, between 1973-1995, and 2006-2013 indicates that both the seasonal discharges (including only years with complete records, n=19) and the flow duration (the time from onset of runoff to freeze up) between 2007-2013 were higher than the long term mean (Kjikjerkovska 2016). These observations for the Apex River are consistent with other Canadian subarctic rivers that have shown a trend toward later freeze up as a result of warmer autumn temperatures (Magnuson et al. 2000). The 11-year gap in the discharge record, as well as the absence of data pertaining to precipitation type (snow vs. rain) after 1997, significantly limited the analysis of the relationships between the climate variables (temperature, precipitation) and the seasonal components of runoff (snowmelt runoff, rainfall runoff and baseflow) in the Apex River. This study highlights how the absence of consistent long-term observations in the Eastern Canadian Arctic limits our capacity to describe, let alone predict, the response of the river flows to changing climate.

In a study that combined hydrological modelling with downscaled climate projections in effort to predict twenty first century runoff trends for a small High Arctic river (West River at the Cape Bounty Arctic Watershed Observatory, Melville Island) Lewis and Lamoureux (2010) determined that total runoff for this river would increase, because projected increases in precipitation exceeded projected increases in evaporation. This modelling effort also predicts higher peak flows and delays in flow cessation (hence longer flow duration) in this High Arctic system over the twenty first century due to increases in precipitation (snow storage during the winter and total precipitation) and warming fall temperatures (Lewis and Lamoureux 2010; Figure 3).

A number of paleoenvironmental proxy and anecdotal observations indicate substantial changes in surface water conditions, ice cover and river discharge in recent decades. For instance, Smol and Douglas (2007) showed that a series of ponds that have been studied for 30 years have sharply reduced volumes and in some cases have dried out entirely (e.g., Figure 4). They noted that the volume reduction had clear impact on the concentration of dissolved solids and constituted a major change for aquatic communities in the ponds. This work parallels reconstructed river discharge in the northern Arctic coast that suggests snowmelt runoff in major rivers has declined substantially during the past 400 years (Lamoureux et al. 2006). By contrast, other lake sediment proxy records suggest increased runoff due to...
FIGURE 3. Modified from Figure 8 in Lewis and Lamoureux (2010). Modelled 21st century Julian day (JD) of first flow, JD of last flow, and number of days with flow. JD of first (and last) flow is defined as three or more consecutive days with discharge greater than (and less than) 0.05 m$^3$/s. Monitored data are shown where applicable. The hydrologic model was also run with historical modelled (CGCM 20CM3 scenario) and measured meteorological data (Mould Bay precipitation, and synthetic Cape Bounty air temperature). Symbols are monitored hydrologic data from Cape Bounty. Best-fit linear regression lines are also shown.
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snow melt intensity (Lamoureux and Bradley 1996) or rainfall intensity (Lapointe et al. 2012). Glacial systems also show increasing runoff in the 20th century in many areas of the region (Lamoureux and Gilbert 2004, Lewis et al. 2002, Moore et al. 2001). These proxies suggest important changes to surface water environments in the region but long-term patterns indicate a substantial range of surface water change.

An extensive network of paleoecological studies based on fossil indicators such as diatoms have been carried out in the region and show a clear change in aquatic ecosystems interpreted to be related to increased ice-off duration, along with enhanced nutrient and/or water temperatures (Smol et al. 2005). The timing of the initiation of these changes ranges from the mid-1800 period in small pond systems to the late 20th century in larger lakes, suggesting an increasing climate effect across a wide range of pond and lake environments.

6.3.2 Changes in water quality

6.3.2.1 Observations of climate change and disturbance impacts on sediment loads

Sediment and particulate organic matter constitute an important component of surface water quality. Much of the region is covered with fine grained sediments of glacial and marine origin and as a result, sediment erosion and transport is widespread, particularly in the central and western regions of IRIS 2. The primary controls over sediment erosion are the availability, or sources of sediment, and hydrological pathways (or connectivity) to transport the sediment downstream (Orwin et al. 2012). Most research in the region has focused on the transport of suspended sediment (e.g., Lamoureux and Lafrenière 2014) and little is known about coarser bedload since the pioneering work of Church (1972). Suspended sediment comprises clay, silt and sand-sized fractions that are highly mobile in stream and river flow, and can

FIGURE 4. Drying Ponds at Allison Inlet, Bathurst Island, after a warm dry summer late August 2011.
also travel considerable distances in lakes and ponds under ice cover (Cockburn and Lamoureux 2008). Few long term sediment transport data sets exist in the region to assess responses to climate and hydrological change. A number of studies have investigated sediment transport on a short term (1-3 year) basis and indicate a strong association between higher discharge and sediment transport and yield. In snowmelt dominated settings, this transport varies according to the quantity of snow (or SWE) in the catchment at the end of winter (Lewis et al. 2012). In years with greater snow, high discharge conditions are sustained for a longer period and result in disproportionately higher sediment transport across different landscape types (Forbes and Lamoureux 2005, McDonald and Lamoureux 2009). Summer rainfall has the potential to increase sediment transport significantly, and an intense rainfall event (c. 30 mm total) can outstrip snowmelt sediment transport substantially (Cogley and McCann 1976, Lewis et al. 2012). In glacial systems, sediment transport is sustained throughout the summer melt period and depends on specific flow pathways on, within, below and adjacent to the ice (Moore et al. 2009).

Few hydrological modelling efforts have been undertaken in the region to consider the impact of climate change on runoff and sediment transport. Lewis and Lamoureux (2010) modelled suspended sediment transport for a small High Arctic river and found the climate projections increase discharge, and have a disproportionate increase in suspended sediment transport. Their model results indicated that sediment yields would increase by 100-600% by 2100. They suggested that these estimates are likely to be minimums, as the models did not account for changes in sediment supply due to permafrost change (Lewis and Lamoureux 2010).

Landscape disturbance due to permafrost degradation is one key mechanism to increase sediment availability for erosion and transport (Figure 5). In locations where fine grained, ice-rich surface materials occur (principally the western islands and lowland coastal regions), slope failures such as thermo erosional niching and active layer detachments (ALD) (Figure 5) can substantially increase local sediment availability (Chapter 4). Lamoureux and Lafrenière (2009) noted that new disturbances had an immediate and large downstream impact on sediment yields, but over a longer timescale, these effects were less evident in larger river systems (Lewis et al., 2012). Sediment yields from disturbed slopes exhibited in excess of 1000 times higher sediment yields compared to undisturbed slopes. In addition to erosion of mineral sediment, research suggests that disturbance mobilizes a proportionate amount of particulate organic carbon (POC), about 1% of the mineral yield (Lamoureux and Lafrenière, 2014). Most notably, the eroded POC appears to be substantially older and has implications for downstream biogeochemical cycling and aquatic ecosystem. In a long term study of the impact of these disturbances, Lamoureux...
et al. (2014) showed that the impact varies by disturbance according to hydrological conditions and flow pathways, and further demonstrated that recovery was comparatively rapid and five years after disturbance, disturbances produced much lower sediment yields. This contrasts to larger and sustained forms of permafrost disturbance such as retrogressive thaw slumps that appear to generate long term, extensive downstream sediment transport effects (Rudy et al. 2015). Given the clear association between permafrost degradation and increased sediment availability, the likelihood of increased suspended sediment yields in surface waters is substantial and could have important impacts on water quality in the region.

6.3.2.2 Climate change and permafrost disturbance impacts on dissolved loads

Solutes are the dissolved constituents in water, and in the broadest terms a solute can be any material that passes through a 0.45 μm filter. Solutes are typically examined from the perspective of several major groups of constituents:

- major ions (such as sodium (Na⁺), calcium (Ca²⁺), magnesium (Mg²⁺), chloride (Cl⁻), bicarbonate (HCO₃⁻), and sulfate (SO₄²⁻) among others);
- nutrients (including nitrate (NO₃⁻), ammonium (NH₄⁺), and phosphate PO₄³⁻ (or other dissolved forms of phosphate);
- dissolved organic matter (DOM), which includes dissolved organic carbon (DOC), and dissolved organic nitrogen (DON);
- and metals, which may include common metals like aluminium (Al) and iron (Fe), as well as other trace metals (e.g., zinc (Zn), copper (Cu), mercury (Hg)) that are present in concentrations that are orders of magnitude lower than for Al and Fe, and many have important toxicological effects (see Box A).

Solutes in water are important determinants of water quality, as they can determine the suitability for the potential end use (e.g., human consumption or ecosystem support (e.g., fisheries)). The concentrations of solutes in water (usually expressed in mg/L or ppm), as well as the total mass export, or loads (i.e., kg per season) are largely controlled by the source and amount of water, and as well as the pathway the water follows in the watershed prior to reaching the stream or river. Solute loads are therefore intimately tied to climate change, specifically through it’s impacts on: the amount, timing and type of precipitation (rain vs. snow); the thickness of the active layer available for storage and movement of water in the subsurface; and permafrost disturbance, which influences the nature of surface flow pathways (Figure 1).

Lewis et al. (2012) found that the source of water (snowmelt vs. rainfall) could be more important than the total volume of runoff in determining the dissolved inorganic ions and DOC yields. They found that although snowmelt typically dominates the water yields, the major ion, DOC and total dissolved nitrogen (TDN) loads can be dominated by contributions from rainfall runoff following significant late summer rainfall events. This study concludes the disproportionate solute response to rainfall runoff is a result of the input of water to the soil when the active layer is thick, which enhances the weathering and release of soluble ions from previously frozen soil.

Thermal perturbations (deep thaw) and physical disturbance of permafrost have the potential to significantly alter the quantity and composition of solutes in runoff. Thermal perturbation releases previously frozen inorganic solutes (metals and major ions), while physical disturbances remove much of the organic rich surface soil and expose the previously buried and frozen solute rich mineral soils at the surface. Lewis et al. (2012) found that localized physical disturbance had no discernable impact on the dissolved solutes (major ions, DOC, and TDN). The authors attributed the limited impact of the disturbances to the low proportion of the catchment area that was disturbed (~3%), and the limited water flow through the disturbances (i.e., disturbances were hydrologically disconnected). Subsequent research at CBAWO comparing smaller catchments with varying degrees of permafrost disturbance supports that the major ion concentrations and loads are only significantly affected by disturbance if the spatial extent of the
BOX A. Trends of mercury in landlocked char in the High Arctic and possible climate influences

Non-anadromous or landlocked Arctic char (*Salvelinus alpinus*), are the only fish species in lakes of the Canadian high Arctic islands which are isolated from the ocean (Power et al. 2008). Char are the top predator and preferentially feed on benthic chironomids (Order Diptera), the dominant invertebrate (Chételat et al. 2010, Gantner et al. 2010, Lescord et al. 2015). Their importance in lake food webs and wide distribution makes them a key sentinel species in studies of impacts of climate change on lake ecosystems. A major question being addressed is how climate warming may influence methyl mercury, the toxic and bioaccumulative form of mercury, in Arctic freshwater environments. This has been investigated using long term time series of methylmercury concentrations in arctic char (measured as total mercury (Hg)) from 6 lakes on Cornwallis Island (Amituk, Char, North, Small, Nine-Mile, and Resolute) as well as in Lake Hazen in Quttinirpaaq National Park on Ellesmere Island (82 °N). In addition, studies conducted at the Cape Bounty Arctic Watershed Observatory (CBAWO) have developed a time series (2008-2016) for mercury in char from two adjacent lakes, East Lake and West Lake. The West catchment has experienced numerous large active layer detachments during 2007-2008 as well as subaqueous slumps, turning the lake very turbid, while the East catchment has experienced relatively minor disturbances. The time series are based on annual collections of 7 to 25 adult char by gill netting in late July and early August. Further details on sampling and analysis of the char can be found in Gantner et al. (2010) and Lescord et al. (2015). Temporal trend analyses and multiple linear regression modelling was conducted with length-adjusted Hg concentrations and climate variables. Statistically significant declines in length adjusted mercury concentrations in char muscle were found for 7 of 9 lakes (Amituk, Char, East, Hazen, North, and Resolute). Annual percent declines ranged from 2.0% (Nine-Mile; 2005-16) to -8.5% (Char Lake; 2005-12). Small Lake and West Lake showed significant increases of 8.0% and 4.8% over the period 2007-2016 and 2009-2016. While Small Lake is not turbid it has higher DOC (2.2 mg/L) than all other lakes except West Lake (1.9 mg/L), which may be due to its greater area of bogs and wetland. The percent declines of mercury in char were significantly inversely related to dissolved organic carbon ($R^2 = 0.60, p=0.014$) (Figure 1) but not to particulate carbon ($p=0.29$) or dissolved methyl mercury in the water column, watershed-lake area ratio, or distance from the ocean. These declines are much more rapid than atmospheric Hg concentrations over the same period at Alert (north Ellesmere Island) which are about 1%/year (Cole et al. 2013). Prior to the mid-2000s Hg concentrations in char from lakes Amituk, Resolute and Hazen, where long term data (1990s to 2016)
are available, appeared to be steady or increasing. Over this longer period, Hg concentrations in char from Resolute and Hazen Lake were significantly correlated with values of the spring Pacific North-America pattern (PNA) an influential climate index in the Northern Hemisphere mid-latitudes (Hazen: $R^2 = 0.41$, $p=0.014$, $n=14$; Resolute: $R^2 =0.29$, $p=0.026$, $n=17$) (Figure 2). Results of the multiple linear analysis for each lake showed that equations which included Previous Fall Temperature (PFT) and PNA had strong predictive power. However, the PFT term was negative in each model, suggesting that higher temperatures result in lower Hg concentration in char. Evans et al. (2013) also found temperature term was consistently negative in their models for Hg in lake trout from Great Slave Lake. Thus the declining mercury in 7 of 9 lakes appears to coincide with higher summer and fall temperatures in the period 2005-2012. Higher temperatures are also associated with earlier ice out and may result in dietary shifts for char.

In summary, long term studies are providing information on possible impacts of climate warming on methyl mercury accumulation landlocked Arctic char and on the biogeochemistry of mercury in the High Arctic freshwater environments. Mercury may be declining in char due to warming but this make be countered by enhanced methyl mercury availability in lakes influenced by changes in their catchments such as permafrost degradation and greater wetland productivity. Higher snow accumulation and/or summer rainfall might also influence mercury in char by increasing DOC inputs to lakes. Ongoing research will attempt to address these questions.
FIGURE 6. Conceptual diagram showing the relationships between late summer air surface temperatures and precipitation, relative thaw depth, proximity of thaw to the solute rich transition layer, and impacts on solute transport. Adapted from Lamhonwah et al. (2017).
dissolved nitrogen are essential building blocks for metabolism and energy transfers in the aquatic food chain. Both the amount and the type of organic matter and nitrogen are important in determining ecosystem function. Higher amounts of biologically available nitrogen (NO$_3^-$ and NH$_4^+$) as well as more readily biodegradable (i.e., labile) organic matter can enhance the biological productivity of aquatic ecosystems. Studies conducted at the CBAWO following the formation of a number of slope disturbances indicate that runoff from disturbances exported suspended sediment contained older (Lamoureux and Lafrenière 2014) and more labile and less degraded organic compounds (Grewer et al. 2015), relative to undisturbed areas. Molecular analysis of the newly disturbed soils also showed that microbial activity was substantially increased when compared with undisturbed soils (Pautler et al. 2010). Similarly, a study investigating the composition of DOM in runoff from a series of catchments subject to varying degrees of disturbance, indicates that although streams from disturbed watersheds delivered slightly less DOM relative to less disturbed (or undisturbed) catchments, the composition of the DOM was more easily degradable (low molecular weight, less aromatic) and fresher (less degraded) with increasing extent of disturbance (Fouché et al. 2017). Runoff following late season rainfall events also delivered elevated concentrations of more easily degradable, and fresher DOM across all catchments (Fouché et al. 2017). A parallel study that investigated the potential impact of disturbances on the dissolved nitrogen loads, showed that the disturbed catchment exported substantially more NO$_3^-$ than the undisturbed catchment, especially following late season rainfall (Lafrenière et al. 2017). Other work demonstrates that the additional NO$_3^-$ was microbially derived, likely from enhanced mineralization of dissolved organic matter (Louiseize et al. 2014).

Together these investigations indicate that organic matter derived from the deeper portion of the active layer or from recently thawed upper permafrost soil is older, but more biodegradable than near surface organic matter. This is important as this indicates that organic matter mobilized from permafrost degradation could serve to stimulate biological productivity in streams and soils, and the release of old C to the atmosphere, and that the impacts of disturbance on the composition of nutrients and DOM can persist for several years following a disturbance event.

### 6.4 Hydrology of wetlands and the response to climate change

#### 6.4.1 Introduction

Wetlands are grounds that are saturated for at least a portion of the year with some types allowing hydrophilic plants to persist. In the High Arctic polar desert landscape, where vegetation is usually sparse, these often-lush vegetated sites offer a critical ecosystem for migratory birds and other fauna. Wetlands can include ponds < 2 m in depth, small strips of wet, vegetated ground alongside lakes, streams, arctic coastlines, or downslope of semi-permanent hillslope snowbeds. At the mesic to regional scale, wetlands usually comprise a mosaic of ponds of varying sizes, wet meadows, and both wet and dry ground. Often a network of low-centered and high-centered polygons exists and is indicative of massive ground ice (Woo and Young 2006). Maintenance of wetlands in the Eastern Canadian High Arctic depends on (1) the presence of permafrost and a shallow active layer (< 0.7 m), which limits the subsurface storage capacity, serving to keep water levels above or near the ground surface; (2) a regular supply of water (meltwater, ground ice melt) which exceeds seasonal losses (evaporation, seepage); and (3) the existence of peaty soils and wetland plants, including moss, which help modify water storage and thermal properties of the ground promoting ground ice formation, and in some cases permafrost growth.

The water budget is a useful framework to examine the hydrology of High Arctic wetlands. Here it is defined as:

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P(Sn+R)+Gin-Gout-E = ±\Delta S
\]

where $P$ is precipitation either snow(snowmelt) ($Sn$) and rainfall ($R$), $Gin$ and $Gout$ are lateral inflow or outflow respectively, $E$ is evaporation which here includes transpiration, and $\Delta S$ is the change in storage. This term can comprise fluctuating pond water levels, water tables, and soil moisture changes in wet meadows. It also includes the residual or error term for the complete water budget,
especially if wetland storage cannot be directly assessed (Young et al. 2015).

6.4.2 Emerging patterns

6.4.2.1 Snowcover

Snow continues to be an important source of water for wetland systems in the High Arctic but variability in end-of-winter snow conditions continues to be the norm, and accurate measurement of end-of-year snow accumulation (in terms of water equivalence) continues to be a significant challenge to closing the water balance in Arctic watersheds (Young et al. 2015). At Polar Bear Pass, an extensive low gradient wetland located in the middle of Bathurst Island (75°43’N, 98°40’W), snow receipt on low-lying ponds, wet meadows, lakes and incised polygonal ground is highly variable across space (e.g., ponds) and from one year to the next (Table 1). Nearby hillslope snowbeds and incised stream valleys continue to capture the most snow. Like other sites in the Eastern Canadian Arctic (see Godin et al. 2016) the deeply incised polygonal wetland area in the headwaters of a hillslope stream typically capture more snow than the low-gradient wetlands. Strong winds are also effective in redistributing snow from elevated regions (plateau) into the lee of hillslopes and onto the adjacent wetland (Young et al. 2013).

6.4.2.2 Rainfall

Impact of rainfall in High Arctic wetland ecosystems is strongly tied to its timing. Rain during seasonal snowmelt can accelerate melt by increasing the flux of heat into the snowpack and/or cause its dissipation through mechanical erosion. Arrival of rainfall at the tail-end of seasonal snowmelt may prolong surface runoff into ponds, lakes and wet meadows, gullies, or catchment outlets as the ground is still largely frozen (Abnizova et al. 2014, Godin et al. 2014). Episodic and minimal rainfall during the thawed season may do little to encourage runoff, especially if the storage capacity of the active layer or pond is large and evaporation demand matches or exceeds rainfall inputs (Godin et al. 2014, Young and Labine 2010, Young et al. 2015) However, frequent rainfall events, even small ones spaced throughout a season can be sufficient in maintaining or raising saturated conditions until a larger rainfall event triggers surface flow. Peak runoff from wetlands caused by summer rains can occasionally match nival levels (Miller and Young 2016, Young and Woo 2003).

6.4.2.3 Evaporation

Evaporation (including transpiration) continues to be an important loss of water from wetland surfaces including large low-gradient wetlands (see Bowling et al. 2003, Lilijedahl et al. 2001, Muster et al. 2012, Young, 2017). Highest rates of evaporation from wetlands typically occur right after snowmelt when incoming radiation levels are high and water is freely available owing to a shallow thawed ground. Later in the season, evaporation rates can be modified by changes in water availability and/or energy flux. Open-water bodies, like ponds show greater losses than wet meadow sites (Young and Labine 2010). In warm, dry seasons in the High Arctic (e.g., 2011, 2012), drying of ponds is common especially in areas that do not have access to alternative water supplies (Figure 4, (Abnizova and Young 2010). In some cases, emergent plants can inundate shallow ponds transitioning them into wet meadows (Figure 7).

6.4.2.4 Lateral inflow/outflow

Ponds and wet meadows that receive additional inputs of water either as surface inflow or groundwater at the tail-end of the snowmelt season are generally resilient against losses of water either due to evaporation losses or water seepage as the active layer deepens. These terrestrial inflows are also critical in depositing DOC and nutrients into nearby ponds (Abnizova et al. 2014). In a recent study, Young et al. (2016) showed that following the snowmelt season melt-water from a late-lying snowbed supplied groundwater to a downslope wet meadow raising water levels during both dry and wet years but these ground water inputs were not significant in comparison to seasonal snowmelt or summer rainfall in terms of the seasonal water budget. Likewise, groundwater outflow from this same wet meadow into a
nearby pond was also negligible when assessed in terms of the pond’s seasonal water budget. This study along with the one by Woo and Young (2014) signaled that for some High Arctic sites, meltwater from late-lying snowbeds is no longer an important source of water for wetlands, especially in the post-snowmelt season. This finding differed from earlier wetland studies on Cornwallis Island, which showed semi-permanent snowbeds were critical in sustaining high water tables and outflow in a groundwater-fed wetland over several arctic summers (Young and Woo 2000). The Young et al. (2016) study also suggested that it is the future changes in seasonal snowcover and rainfall in High Arctic landscapes that will directly affect the resiliency of wetlands at scales from small to extensive.

Our understanding of runoff from extensive low-gradient wetlands in the High Arctic, especially in non-glacierized catchments is still inadequate. Runoff from patchy wetlands (Young and Woo 2000, Young and Woo 2003) and small polygonal wetland catchments in response to thermoerosion gullying have been quantified (Godin et al. 2016). In Northern Canada studies suggest that streamflow is intensifying in response to recent climate warming (Dery et al. 2009). In some mainland watersheds, peak streamflow is occurring earlier because of earlier snowmelt, while baseflow is higher due in part to greater permafrost thaw which has enhanced the storage capacity of watersheds (Dery et al. 2009).
Stream runoff from the eastern sector of PBP (area=102.6 km²) is shown for two contrasting years (Figure 8). In 2012, owing to an extremely warm spring, peak runoff occurred by mid-June, and after a few days fell to baseflow levels where it remained for the rest of the season. Here, the early peaks are driven by snowmelt coming from the northern part of the Pass (southerly aspect) and with the secondary peaks attributed to meltwater from the southern half of the Pass (northern aspect). In 2013, runoff is delayed well into early July and while the snowmelt from the northern half of the Pass initiates runoff, it is the meltwater inputs from the southern part of the Pass that define peak runoff (Figure 9). While two years of data is inadequate to come to any defining conclusions, it is conceivable that these two contrasting years could bracket the range in responses that extensive wetlands like PBP can expect for the future as

FIGURE 8. Estimates of streamflow from the Polar Bear Pass watershed (Eastern Sector-102.6 km²) in 2012 [warm/early melt] and 2013 [cool/late melt].

FIGURE 9. Photograph of the typical snow cover pattern during snowmelt across Polar Bear Pass. North part of the Pass melts out earlier than the southern part of the Pass which is still snow covered. Photo taken mid-June, 2010.
the Canadian Eastern High Arctic continues to warm and extreme climatic conditions become more common.

6.4.2.5 Wetland storage

Estimates of wetland storage are often determined as the residual in a water budget, and subsequently they will include errors in the water budget components (see Young and Woo 2004). Most wetland ponds experience negative seasonal storage as evaporation losses draw down water levels and these losses are not replenished. Wet meadows can show either negative or positive water storages, with ground ice melt often raising soil moisture levels. At the regional scale storage at PBP is much larger ranging from -52 mm (cool year) to -125 mm (warm year) (Young 2017).

This estimate differs from an extensive low-gradient low arctic coastal wetland (see Bowling et al. 2003) where storage ranged from only -2 to -25 mm over two seasons. Finally, episodic thermo-erosion processes such as gully- ing (Godin et al. 2014, Godin et al. 2016), frost cracks (Abnizova and Young 2010), and erosion of polygonal rims (Boike et al. 2008) can drain ponds and polygonal landscapes quickly, thus enhancing overland flow connectivity, and ultimately altering soil moisture conditions and vegetation cover even over small areas (Godin et al. 2014, Godin et al. 2016).

6.5 Aquatic ecosystem responses to climate change in the region: Trends and uncertainties for lakes and ponds

Lakes and ponds are a major component of the northern landscape (Rautio et al. 2011, Verpoorter et al. 2014, Muster et al. 2017), and in the Eastern Canadian Arctic they occur in diverse landscape types spanning the 2500 km latitudinal gradient from 60 to 83°N, and across the vast 2500 km east-west expanse of Nunavut. They encompass a great variety of ecosystem types, from shallow waters that melt out and mix completely each year to deep, stratified lakes that retain their ice cover through most of summer. As to be expected from these diverse settings, aquatic ecosystems in the region vary greatly in their current responses to climate change, and in their likely sensitivity to ongoing climate impacts. This section examines current changes that have been observed in lakes and ponds within the region, and the implications and uncertainties regarding future shifts.

The most severe ecological impact of climate change is the complete loss of ecosystems and even certain ecosystem types. One mechanism of this ecosystem extinction is through changes in the hydrological balance, with shifts in the ratio of precipitation to evaporation. Many lakes and ponds in the North are shallow, yet often support large populations of aquatic organisms including zooplankton. They are maintained because of replenishment by snowfall (in some cases by glacial meltwaters) combined with prolonged ice cover and low temperatures that ensure low evaporative losses. An additional factor is the underlying permafrost in these catchments that keeps the water table high and favours rapid transfer of meltwaters to the lake. There are likely to be large interannual variations in these shallow waters, and the biota of these habitats are adapted to sustain these changes. For example, experiments on High Arctic microbial mats, which form a layer over the base of many Arctic lakes, ponds and streams and often dominate their total ecosystem biomass, have a high tolerance to the salinity stress that would accompany evaporation (Lionard et al. 2012). However, the long term drying up of ponds will push even these hardy organisms to extinction. A pronounced shrinkage of shallow ponds has been observed in parts of Nunavut, with evidence at Cape Herschel on eastern Ellesmere Island of complete evaporative loss of some ponds (Smol and Douglas 2007).

In several parts of the circumpolar Arctic, the degradation of permafrost around thermokarst lakes and ponds (thaw lakes) is resulting in the complete drainage and disappearance of these waters, or loss by infilling. Conversely, in other parts of the Arctic, including in Nunavik, immediately to the south of Nunavut, thaw lakes are expanding in abundance and size (Vincent et al. 2011, Vonk et al. 2015). These trends have not been well assessed throughout the Nunavut, although there is evidence of recent thaw lake drainage in Nettilling Lake region on the Great Plain of the Koukdjuak (Baffin Island).
Another mechanism of climate-induced loss of freshwater environments is through changes in ice barriers that are structurally or hydrologically essential to the integrity of the ecosystem. Epishelf lakes, which are freshwater environments dammed by ice shelves, are especially vulnerable to such impacts. These ecosystems have unique physical, chemical and biological characteristics, with freshwater biota in the upper layer and marine biota at depth, in exchange with the Arctic Ocean (Van Hove et al. 2001). More than a dozen of these lakes occurred along the northern coastline of Ellesmere Island at the beginning of the last century, but with the attrition of the ice shelves, these have been mostly lost (Veillette et al. 2008). The largest was Disraeli Fiord epishelf lake, which was lost in by the fracturing of the Ward Hunt Ice Shelf over the period 1999-2002 (Mueller et al. 2003). The sole remaining epishelf lake is in Milne Fiord, which has a pronounced layering of its biological communities (Veillette et al. 2011b). This system has recently shown large year-to-year variations in its microbial community composition (Thaler et al. 2017), and the ongoing thinning of the Milne Ice Shelf implies that this ecosystem is on the brink of extinction (Hamilton et al. 2017). The surface of the Arctic ice shelves contain melt ponds with rich communities of microscopic life (Vincent et al. 2004). As in Antarctica, these have been considered as models for life on early Earth during periods of global glaciation (Vincent and Howard-Williams 2000, Hoffman 2016), but are they are now close to complete extinction as a result of climate warming.

Shifts in ice cover of Nunavut lakes are already apparent, and are likely to be much greater in the future. In a remote sensing study of 11 lakes in Nunavut over a 15 year period, from 1997 to 2011, all of the lakes showed an earlier onset of melting and ice-out; for Lake Hazen, the deepest lake in the High Arctic, the melt onset began two weeks earlier, and for Eleanor Lake on Cornwallis Island, it was more than 3 weeks earlier (Surdu et al. 2016). This extension of open water conditions has wide-ranging effects on lake ecology, including via increased exposure to direct wind induced mixing. This may entrain nutrients from deeper waters and stimulate production. For example, loss of ice in Lake A on the northern coast of Ellesmere Island resulted in a shifting in phytoplankton species composition and an increase in picocyanobacteria (Veillette et al. 2011a). This loss of ice and mixing may also increase the residence time of contaminants in the lake by decreasing the under-ice through-flow of river inputs (Veillette et al. 2012).

An extreme example of ice loss is Ward Hunt Lake at latitude 83.1 °N. This is the most northern lake in Nunavut, and in the past was overlaid by perennial ice, up to 4.3 m in thickness. From 2008 onwards, however, this has undergone rapid thinning, with complete loss of ice cover in 2011 and 2012 (Paquette et al. 2015). This is reducing the amount of bedfast ice in winter, a trend that has been recently documented in the shallow lakes of northern Alaska (Surdu et al. 2014). This in turn increases the availability of liquid water habitats that persist under the ice during winter darkness, resulting in conditions that allow microbial production of greenhouse gases, especially methane (Figure 10, Mohit et al. 2017). An experimental study has shown that changes in light exposure in Ward Hunt Lake as a result of ice loss can result in major shifts in species composition of protists at the base of the food web (Charvet et al. 2014). A paleolimnological study of this lake showed that limnological change began more than 100 years ago (Antoniades et al. 2007), prior to this acceleration of changing ice conditions.

Loss of ice is also likely to increase the extent of lake warming, however there are no long term records for Nunavut to assess the magnitude of this effect. Global syntheses of lake temperature data show that on average lakes are warming at about the same rate as air temperature increases, but with large variations among lakes even from the same region due to differences in depth, wind exposure and transparency (O’Reilly et al. 2015). Duration of ice cover is another factor, and Nunavut lakes are likely to experience warming rates well above the global average, but with large variations among individual lakes. This change in water temperature is likely to have wide-ranging impacts on the physical, chemical and biological characteristics of northern lakes. Certain lakes such as Lake Hazen on Ellesmere Island may shift from one period of mixing per year (monomictic) to two periods each year (dimictic), which would likely stimulate primary production and
perhaps all food web processes. Nunavut lakes contain diverse assemblages of microscopic life (e.g., Comeau et al. 2016, Chenard et al. 2015, Thaler et al. 2017, Mohit et al. 2017), and these communities are likely to change substantially in the future in response to shifts in the physical and chemical environment. Warming beyond the temperature thresholds of cold region biota may push certain species to extinction.

In several parts of the world, lake waters are becoming browner as a result of increases in runoff of coloured dissolved material, and in northern catchments this may be compounded by increased terrestrial plant growth (Wrona et al. 2016). Such changes can accelerate warming, as well as alter the lake biota at several trophic levels (Williamson et al. 2015). Conversely, increased soil weathering and nutrient run-off in a warmer climate may lead to the greening of Arctic lakes (Wrona et al. 2016), with potential ramifications for oxygen regimes, phytoplankton species shifts (including to toxic species) and food supplies for higher trophic levels. Increases in lake productivity are thought to have an influence on Arctic char behaviour, with migration possibly ceasing once productivity in these lentic environments exceeds a certain as yet undefined threshold (Reist et al. 2006).

6.6 Summary and outlook

Warming air temperatures and increases in precipitation observed across the IRIS 2 region over the past 30 years or more, have had both direct and indirect impacts on water budgets, water quality and freshwater ecosystems. Although sparse and short term observations across the region substantially limit the degree of certainty, these changes are largely consistent, even if the magnitude is often still poorly constrained.

The combination of warmer air and water temperatures, enhanced precipitation, progressive active layer expansion
and disturbance of the permafrost will continue to alter the hydrological and ecological properties of surface waters in the Eastern Canadian Arctic. Observations support that evaporation and precipitation (both snow and rain) are likely to continue to increase, as well as flow duration. Runoff volumes are anticipated to increase, as it does not appear that the increases in evaporation due to warming will outweigh increases in precipitation inputs. Warming temperatures and increasing rainfall will also result in more frequent and extensive permafrost degradation including thermokarst features that have been shown to substantially alter sediment, nutrient and contaminant loads in streams and lakes. The impact of rainfall on hydrology and water quality is very difficult to predict, as this is strongly tied to the timing, frequency and intensity of rainfall, and also importantly to the extent and nature of permafrost degradation.

Observations from a number of studies across the region indicate that the cumulative effect of these changes (warming water temperatures, higher nutrients, longer runoff seasons) could result in priming freshwater ecosystems to a new equilibrium by pushing certain species to extinction, stimulating primary production and perhaps all food web processes. Wetland ecosystems, ponds and epishelf lakes appear to be particularly vulnerable to changing climate, and here the impacts can range from increases in the number of ponds due to thermokarst, to complete losses of water bodies and ecosystems, to notable changes in nutrient levels, contaminants, and ecosystem structure.

Although remote sensing methods have greatly improved our capacity to continue to monitor and observe some elements of the freshwater systems (e.g., water vapour, soil moisture, SWE), these data sets are nevertheless relatively recent and certain aspects of freshwater hydrology and quality require manual sample collection and measurements. Although much knowledge of freshwater systems has been gained from a number of multiyear research projects in the region, the temporal extent of these observations is short relative to the timeframe over which environmental change has been occurring, and the spatial extent is minimal given the size and diversity of terrain, geology and climate in the region. There is therefore a critical need for the continuation, indeed expansion of monitoring efforts, in order to collect the observations necessary to facilitate the management of freshwater ecosystems and resources in the future.

It is however not possible to sustain a widespread monitoring effort with a handful of disparate research programs. Sustaining and expanding observation networks will necessitate the engagement and collaboration of northern communities and governments, so that research programs can help build the capacity for communities to sustain these efforts and facilitate community based assessment and management of freshwater resources and ecosystems.

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