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REVIEW ARTICLE

Water security for northern peoples: review of threats to Arctic freshwater systems in Nunavut, Canada

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Abstract Water is a fundamental component of the ecological integrity, economic development, and sustainability of northern regions, as well as the health and well-being of northerners. However, environmental change has altered fragile thermodynamic relationships of northern ecosystems by shifting seasonal transitions, altering precipitation regimes, reducing snow and ice cover, and increasing exposure to solar radiation. This has exacerbated existing pressures on freshwater supply that have arisen from increased resource development, inappropriate or inadequate infrastructure, population stress, erosion of Indigenous knowledge systems and culture, and inadequate policy and management. Since water governance systems in northern Canada are under rapid evolution, we examine key vulnerabilities to both the quantity of accessible freshwater and the quality of available freshwater resources for communities in Nunavut, Arctic Canada, within a water security framework. While the concept of water security is often approached from a human-centred perspective, we note the importance of integrating a biophysical perspective. We also compare information and experiences of the other northern regions to assess how water security is conceptualized and addressed across northern Canada, identifying biophysical and social vulnerabilities as well as implications for governance and adaptation.

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Introduction

Freshwater Arctic ecosystems provide essential ecosystem services, including access to clean freshwater for northern communities. Arctic regions are historically characterized by a multitude of shallow lakes, streams, and wetlands due to impermeable permafrost that limits infiltration. However, recent warming has altered fragile thermodynamic relationships of northern aquatic ecosystems by shifting seasonal transitions, altering precipitation regimes, and reducing snow and ice cover, which increases exposure to solar radiation (Woo 2010). The consequence of polar amplification of warming on northern freshwater ecosystems includes a longer ice-free season potentially leading to increased evaporative stress on lakes. Likewise, reductions in winter precipitation can lead to reduced snow and ice melt contributions, destabilizing water balances across much of the Arctic (Bouchard et al. 2013; Hodson 2013; Lantz and Turner 2015). While the quantity of available water is a growing issue for regions undergoing increased evaporative stress, water quality is also a fundamental concern due to ageing municipal water infrastructure, the rapid growth and expansion of many Arctic communities, and the risk of contamination from burgeoning industrial and resource development (Instanes et al. 2016).

The confluence of environmental change and development pressures in northern Canada has led to the voicing of strong concerns over looming water crises and the sustainability of local fisheries (Ford et al. 2006; Roux et al. 2011; Prno et al. 2011; Instanes et al. 2016). Expanding populations, industrial and resource development, and limited infrastructure has made sustainable water resources a primary issue for northern peoples, which will intensify into the future. Intact healthy freshwater ecosystems are critically important for continued development, socio-economic and cultural sustainability, and health and well-being of northern peoples. Vulnerability to environmental change in northern communities arises from changes in the physical climate and environment, but also from poor planning, inappropriate or inadequate infrastructure exacerbated by population stress, erosion of Indigenous knowledge systems, weak political practices, and fragmentation of previously strong social networks (Ford et al. 2007). Likewise, policy-makers in Arctic regions face additional challenges in obtaining accessible climate change information relevant to their local jurisdiction (Bring et al. 2015). Both mitigation of and adaptation to environmental change rely on knowledge of existing conditions, the direction of change, and the magnitude of change (Ford and Smit 2004); however, decision-making authority, political will, financial support, collaboration among stakeholders, monitoring of change, the quality of information gathered, and both the means and manner by which it is applied are also important. As such, there is a critical need to explicitly consider monitoring that incorporates both qualitative community observations and quantitative measurements of the environment in strategic planning processes in the Arctic (Nilsson et al. 2013b; Azcárate et al. 2013). Finding effective ways to draw on Indigenous knowledge of environmental change is particularly relevant and important in this context.

Given the existing and foreseen continued influence of environmental change and development threats to freshwater resources in the Canadian Arctic, we explore the current status and value of water quantity and quality in this region, as well as the many implications for northern peoples and sustainable water governance. The current state of knowledge of the influence of environmental change on northern ecosystems has been advanced by a major synthesis of freshwater system science in the Arctic (the Arctic Freshwater Synthesis; Prowse et al. 2015), which included reviews of the role of freshwater specific to the atmosphere (Vihma et al. 2016), oceans (Carmack et al. 2016), terrestrial hydrology (Bring et al. 2016), terrestrial ecology (Wrona et al. 2016), and natural resources (Instanes et al. 2016). These works provide global-scale context of how environmental change will influence water security; however, they include limited focus at the community scale. Our review complements broader-scale analysis by focusing at a territorial level, more specifically on Nunavut. This is a jurisdiction that faces important water security issues while having received limited research and policy attention in this area to date. Nunavut was allocated a "D" rating—the lowest of all provinces and territories—in a recent Ecojustice report for its lack of source water protection and low water treatment standards (Ecojustice 2011).

Our objectives are to (1) review how water security is conceptualized and addressed in northern Canada, (2) identify current threats to freshwater quality and quantity in Nunavut, highlighting both biophysical and social vulnerabilities, and (3) discuss implications for governance and adaptation. Our narrative review is based on a broad search of peer-reviewed literature using these keywords: *Nunavut* AND *water security, water quality, water quantity, water management, OR water governance.* We also draw on (a) additional peer-reviewed and grey literature sources that are more widely applicable to either water security in general or water management or environmental change in northern Canada in particular and (b) personal communications with Nunavut water managers and decision-makers.

Water security in northern Canada

Freshwater is a basic necessity for human survival and well-being with strong commodity, amenity, and ethical components. As such, humans are tied to the global hydrological cycle, which is increasingly being stressed by a range of natural and human-induced factors. Water security is complex and affected by a diverse range of biophysical, infrastructural, institutional, political, social, cultural, and financial factors. It is central to other areas of human security, particularly food and energy security (UN-Water 2013). In addition to overuse and mismanagement, climate change is increasing freshwater vulnerability in regions across the globe, with the Arctic deemed particularly sensitive (Bates et al. 2008). Water security as a concept is relatively new, and it continues to evolve largely in the international water and development realm, with recent conceptions tending towards increased breadth and inclusiveness of a range of dynamic dimensions (Lautze and Manthrithilake 2012). Building on previous definitions, the United Nations recently defined water security as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN-Water 2013: 1). Thus, operationally, we can conceptualize water quality, quantity, and sustainability as key areas of focus for water management, to promote and protect human health and well-being, socio-economic development, and environmental sustainability.

Governance issues

The sourcing and allocation of water is a social decision, and enhancing water security has become a governance challenge (Pahl-Wostl et al. 2013: 677–678), particularly in this era of environmental change. The framework for water security recognizes not only that environmental change is largely human-induced, but that human mismanagement of the ecosystem has caused further damage. The approach to water security and interactions between scales is a central concern: “Human water security, when narrowly framed, is often achieved in the short term at the expense of the environment…” (Pahl-Wostl et al. 2013: 676). Moving water governance to a global scale in conception and implementation is an effort to address the “apparent failure of local-scale management strategies to convey benefits that accumulate within the global water commons” (Vörösmarty et al. 2010: 541). A global perspective has also been advocated for equity purposes, for “the world’s available freshwater resources are limited and unevenly distributed” (Yang et al. 2013: 599).

There is significant variation in water governance approaches across Canada’s provinces and territories, particularly with respect to drinking water, watershed management, and water rights (Hill et al. 2008). Since water is different from other resources in that it is generally undervalued and expensive to transport, water security varies by region and is tightly tied to the surrounding geography. Good water governance that integrates both biophysical and social dimensions is deemed essential, and models must be adapted to local, national, and regional conditions and needs (UN-Water 2013). Moreover, in Arctic Canada, local control and decision-making is a critical issue in the context of colonialism and Indigenous self-governance. As Inuit leaders Terry Audla and Duane Smith recently highlighted,

> it is not only audacious but ethically unacceptable in the 21st century to issue a public declaration to guide the research and development of the circumpolar Arctic, indeed to ‘save’ the Arctic for the common good of ‘humanity,’ while neglecting to even consider engaging with the peoples and institutions of the Arctic themselves. (Audla and Smith 2014: 120–121).

The Arctic also has a specific history arising from the failure of neocolonial modernist urban planning, which is notable for its insensitivity to existing social arrangements, lack of inclusion of Indigenous decision-making, and implementation of systems developed for southern environments that were inappropriate for northern environments (Farish and Lackenbauer 2009).

In the territorial north, the federal government maintains the primary stewardship of water and natural resources through Aboriginal Affairs and Northern Development Canada (AANDC). Responsibility for the development, implementation, and interpretation of all legislation and policy relating to responsibilities for water management by AANDC is outlined in Sect. 5 of the DIAND Act (DIAND 2014). However, responsibility for various aspects of water management, including the provision of safe drinking water, has more recently been devolved to each of the three territorial governments. Territorial legislation developed for this purpose includes the Nunavut Waters and Nunavut Surface Rights Tribunal Act (Government of Canada 2014) under the disposition of the Nunavut Land Claims Agreement (Nunavut Tunnagavik Ltd 2010), the amended Mackenzie Valley Resource Management Act (MVRMA 2014) in the NWT, and the Yukon Waters Act (Government of Yukon 2003).

While similarities exist in terms of the types of issues and challenges faced across the Canadian North, unique dynamics must be addressed as each territory works to improve its own water policy and governance. Currently, Nunavut lacks a territory-wide water management policy framework. Municipalities own and operate their respective water infrastructure and treatment systems, with management and maintenance provided by the Department of Community and Government Services (CGS) of the Government of Nunavut (GN). Water use and waste disposal must be licensed by the respective territorial licensing boards or authorized through regulations. For Nunavut, this mandate falls to the Nunavut Water Board (NWB). Indeed, the NWB is regarded as the de facto regulatory board responsible for freshwater resources; yet, several obvious limitations exist regarding its ability to develop broader water policies. As policy articulation is not the focal point of specific licensing decisions, the NWB is limited in its ability to analyse impacts and issues extending beyond any given application.

To date, the Government of Nunavut has no specific agency or person(s) in charge of freshwater resource policy and management, and no policy development or planning has occurred for climate change adaptation with regard to freshwater resources. Indeed, much of the management, operation, and planning behind freshwater resources falls to offices in each of Nunavut’s three regions, the Kivalliq, Kitikmeot, and Qikiqtaaluk (Baffin) with loose oversight and a lack of inter-regional integration. The absence of both policy guidance and territory-wide planning for water use and management makes broader considerations such as addressing cumulative impacts very difficult. However, a territorial freshwater strategy built around the principles of water security is possible. In addition to a water safety framework that includes infrastructure and human dimensions (Kot et al. 2014), we suggest a framework that also includes the natural environment (Fig. 1). As such, policy and planning behind freshwater quantity and quality would complement issues of governance (including public education and effective contributions from Indigenous knowledge systems) and distribution (maintenance, delivery, and reporting).

The Government of the Northwest Territories has taken positive steps towards incorporating diverse stakeholder perspectives to ensure a sustainable water supply to remote communities despite limited infrastructure. The NWT's "made-in-the-North" *Water Stewardship Strategy* (GNWT 2010) and *Action Plan* (GNWT 2011) were developed through a collaborative process led by representatives from Indigenous communities and the territorial government. These documents build on the existing Drinking Water Strategy (GNWT 2005); highlight the links among freshwater, healthy ecosystems and the social, cultural, and economic well-being of NWT residents; and recognize the essential role that rivers, lakes, streams and ponds play in the life of northerners and Indigenous cultures. Both the *Strategy* and *Action Plan* are living documents that encourage adaptive management, including cooperation and communication among water partners and the public; effective research and monitoring to inform policy and practice; effective use of both Western science and local and Indigenous knowledge; responsible water use supported by guidance and regulation; and periodic evaluation to assess progress and make changes where necessary (GNWT 2010, 2011).

The Yukon Territorial Government has followed suit with its own *Water Strategy and Action Plan*, developed with input from a range of stakeholders and released in 2014 (Government of Yukon 2014). The goal of the *Strategy* is to achieve sufficient and sustained water quantity and quality now and for the future for both humans and nature, while allowing for sustainable use. Both the Yukon and NWT are increasing efforts around water monitoring and source water protection in recognition of the general lack of data, knowledge and understanding about territorial waters, as well as the challenges of transboundary issues.

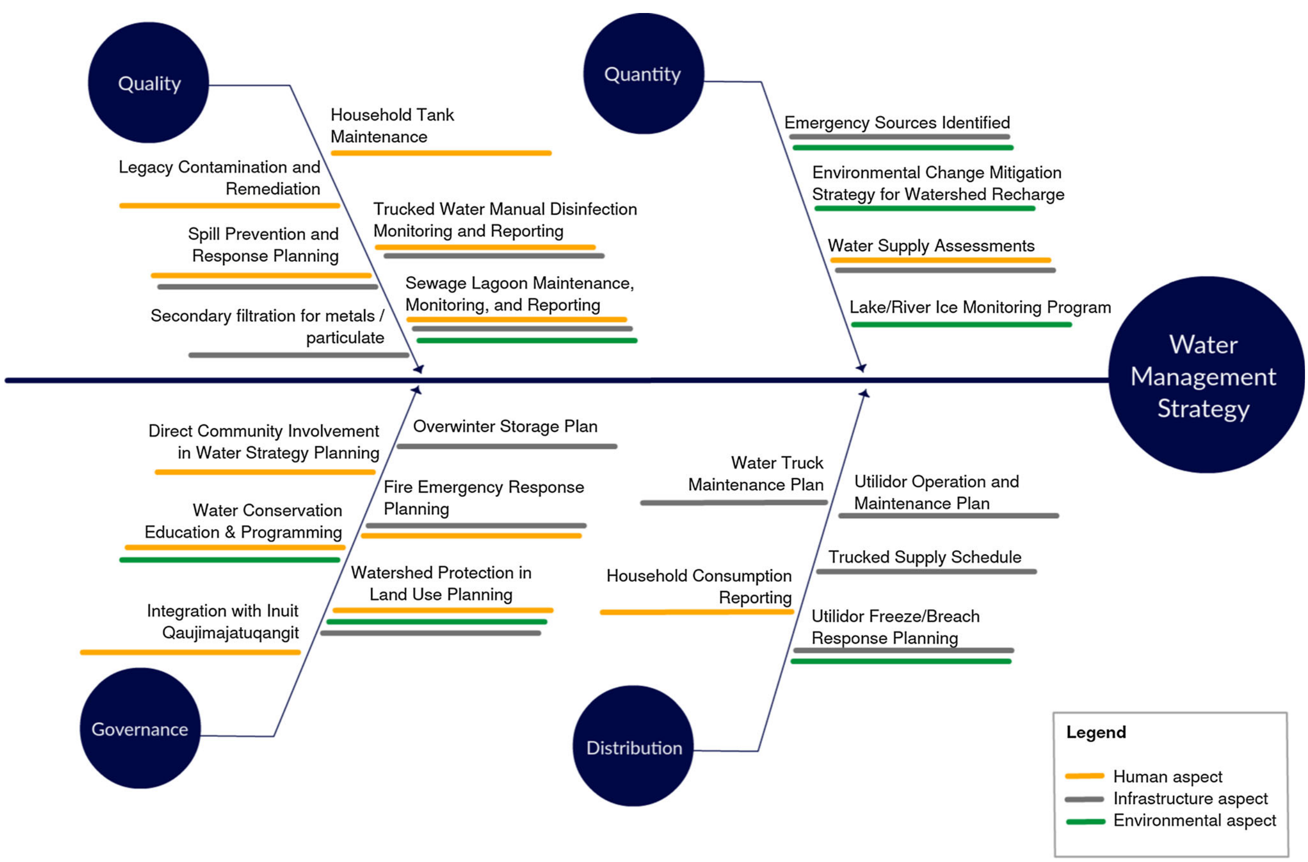

Fig. 1 Schematic of a freshwater management strategy for Nunavut in a water security framework

Freshwater and northern peoples

Indigenous knowledge of the land, water, and climate has historically linked Indigenous communities together and formed the basis of understanding for northern life. Generations of individual and collective experience and knowledge of travel on sea ice, lake and river crossings, and in all types of weather have enabled the development and evolution of intricate hunting, fishing, transportation, recreation, and relational networks (e.g. inter-community connections and food sharing networks) across vast and challenging landscapes. Indigenous community members rely on their knowledge of weather patterns; however, increasingly variable and extreme weather conditions are straining the ability of residents to safely navigate and successfully hunt using both winter and summer routes, adding unpredictability to everyday life (Gearheard et al. 2010).

Changes in river ice conditions, run-off, flow regimes, and water levels can impede access to important fishing areas and increase travel hazards (Fox 2002; Huntington et al. 2005; Prno et al. 2011). These multiple, observed hydrological changes are key touchpoints in the personal experience of environmental change for northern residents (Wesche and Armitage 2010) and reflect an inter-generational timeframe in which Indigenous residents track multiple aspects of change in their environment. Two key elements of survival, water security and food security, are directly linked. For example, reduced water quantity and sediment accumulation in rivers affect both plants and animals, as well as access to important hunting and fishing sites. Huntington et al. (2005) describe how low water levels in the streams, rivers, and lakes surrounding Baker Lake have prevented summer caribou hunting and impacted fish stocks. Similarly, Kugaaruk residents reported extreme limitations on fishing for lake trout and Arctic char due to the drying of a nearby river (Nancarrow and Chan 2010).

Reductions in water levels also affect drinking water availability, as many northern communities draw their municipal water supply from surface water sources (Daley et al. 2014; Bring et al. 2016). Water quality concerns also change residents' perceptions of their environment and the way they use water resources in their daily lives. Residents of many Arctic communities commonly drink untreated water directly from a variety of natural sources, including lakes, streams, and rivers in summer, and from lake ice, icebergs, snow, and multi-year sea ice in winter (Nickels et al. 2006; Martin et al. 2007; Daley et al. 2015). Warming temperatures as well as both long-range and point-source contamination from development pressure may inherently increase the risk of relying on untreated water sources (Bring et al. 2016; Instanes et al. 2016). Northern communities may be vulnerable unless infrastructure is developed to cope with the multiple climatic and anthropogenic factors that impair the quantity and quality of local drinking water supplies. To date, academic scholarship shows limited focus on these issues in Nunavut and across northern Canada.

Threats to water quantity

Arctic and subarctic ecosystems experience strong seasonal controls on water availability and are thus particularly sensitive to alterations in the hydrological cycle (Bring et al. 2016). Northern watersheds are historically characterized by relatively small amounts of run-off during the dry summer due to low summer precipitation (Wrona et al. 2016). Most streams are only active during the short thaw season and depend on spring melt-water (Church 1974; French and Slaymaker 1993); thus, winter precipitation is critical for the sustainability of Arctic lakes and ponds. Likewise, late-lying snow is critical for both the aquatic and terrestrial environments (Woo and Young 2014). If regions experience particularly dry conditions, especially due to lower snowfall, widespread desiccation can occur (Abnizova and Young 2010; Bouchard et al. 2013). For example, Smol and Douglas (2007) chronicle high Arctic lakes that shifted to a negative precipitation–evaporation water balance, leading to their complete desiccation for the first time in millennia.

Environmental change and surface water

The health and sustainability of aquatic systems rely on the flow of energy, which is highly dependent on the underlying hydrology, which is governed by the permafrost horizon. Permafrost, perennially frozen ground that underlies the active layer, controls the amount of space in the soil matrix that is available to groundwater, as well as the movement of water into drainage systems. Thus, the permafrost horizon is arguably the most influential component of the northern water cycle. Increased air temperatures result in higher soil and permafrost temperatures and a northward movement of the permafrost boundary, especially in discontinuous permafrost zones (Serreze et al. 2000; Osterkamp and Romanovsky 1999). Where permafrost thaw occurs, warming temperatures lead to a deeper active layer, a longer thaw period, and increased surface vegetation, which reduces surface water flow as both infiltration and water storage capacity of the active layer increase (Wrona et al. 2016). Therefore, a deepening of the permafrost layer results in a larger portion of water from streams and ponds entering into the soil horizon. This can lead to the collapse of lake shorelines, as well as retrogressive thaw slumps (similar to landslides), where swaths of soils and vegetation enter into aquatic systems (Bring et al. 2016; Wrona et al. 2016).

Similarly, some small lakes and most Arctic ponds exist because the permafrost isolates them from the regional groundwater system or from surface flow (Edwardson et al. 2003). Climate projections indicate that a gradual deepening of the permafrost layer will result in the disappearance of the patchy Arctic wetland that is supported by surface flow from late-lying snow banks (Rouse et al. 1997). Permafrost thaw is also linked to occurrences of catastrophic drainage of Arctic lakes and ponds in some areas (Smith et al. 2005; MacDonald et al. 2012; Lantz and Turner 2015). As such, it is expected that these permafrost isolated systems will undergo a reduction in their water levels and have a greater interaction with the newly exposed active layer as temperatures increase and permafrost thaw occurs. This could have a direct consequence on water availability in northern regions, which is exacerbated by increased water demand. Expanding populations, limited and ageing infrastructure, and high costs have left many communities vulnerable to inadequate water supply in a warming future (Instanes et al. 2016).

Local freshwater management

There are inherent risks of water shortages when a community only has one established water source. While Iqaluit and Rankin Inlet have above- and below-ground water pipe utilidor systems, and Resolute Bay still relies on a highly fragile utilidor system that was slated for decommissioning in 2011 (George 2009), a majority of Nunavut communities deliver drinking water by truck. Each household on trucked water delivery has its own potable water storage tank, which varies in capacity, the typical size being 1200 L (Daley et al. 2015). Small household tanks and inadequate flow from over-burdened pumping stations leaves many homes waiting for water each day (Rohner 2014). Numerous households in Coral Harbour, particularly those with larger families, reported running out of water at least once per week (Daley et al. 2014).

Vulnerabilities also occur at the community scale. For example, Arviat ran completely out of water in 2011 when its reservoir leaked (CBC 2011). Igloolik suffered similarly in 2015 when an unusually harsh winter left its water supply lake without adequate spring recharge (CBC 2015a). Indeed, these water emergencies required municipal operators to extract water from nearby lakes without proper planning, filtration, screening, or treatment. The humic water and concerns over nematode parasites and fish entering household water tanks led to boil-water advisories (CBC 2011, 2015a, c). The effectiveness of responses to these types of water crises is limited by the lack of a cohesive freshwater policy and management in Nunavut. Indeed, the GN Department of Community and Government Services lack centralized estimates of the water volume requirements for most Nunavut communities.

While smaller communities that rely on trucked water delivery are more susceptible to water shortages, both Rankin Inlet and Iqaluit (where the majority of residents are served by utilidor systems) have also had to quickly adapt to looming water shortages. In 2010, the water supply lake for Rankin Inlet, Lake Nipissar, was deemed insufficient to cope with the current population and demand (Bakaic and Medeiros 2016). Residents have long complained about the municipal water supply, which is often turbid due to high particulate loading from the intake of lake sediment and lack of filtration (D. Tootoo, pers. comm. July 2008). In response to Lake Nipissar's current state of drawdown, the GN approved and began extracting water from the nearby Char River outlet adjacent to Lower Landing Lake and proposed the construction of a pipeline to resupply Lake Nipissar during melt-season (June to September). The proposal did not undergo environmental screening as the Nunavut Land Claims agreement exempts municipal projects; thus, only technical reviews of water diversion from Lower Landing Lake were conducted (Stantec 2014). Lower Landing Lake has a long history as a landing site for floatplanes and as a disposal site for oil drums that were used for refuelling (Rob Eno, pers. comm., April 2015), hundreds of which remain buried in the shallow reaches of the lake (pers. observation, 2012). While the drums were presumably mostly empty upon burial, a number of chemical fuel additives can remain (Touhill and James 1983). As such, limited planning, consultation, and regulatory oversight have led to the use of a potentially unsuitable source for the hamlet's water supply.

The capital of Nunavut, Iqaluit, is also currently examining alternative sources for recharge of its main water source, Lake Geraldine (a dammed reservoir). Iqaluit is located on the south end of Baffin Island and is home to over 7000. Iqaluit's expanding population is the main source of its freshwater stress; however, its topography and limited suitability for permanent settlement are also key contributors. When the location was chosen for a United States Air Force Base in 1941, Iqaluit had been an Inuit site for hunting and fishing under continuous seasonal use for at least 4000 years (Samuelson 1998). Centred on the military presence, a shift from nomadic usage towards a permanently settled community occurred during the 1950s and 1960s (Farish and Lackenbauer 2009). The original water supply source for the Air Force Base was insufficient for a large population, and there was little forethought even after Iqaluit's establishment as the capital about the future water supply. With the expanding population and rapid development, the City took drinking water concerns into consideration when developing its 5-year plan in 2010, which proposes to "ensure the protection of Lake Geraldine to ensure adequate fresh drinking water for the future" (City of Iqaluit 2010). However, considering Lake Geraldine's capacity to support 8300 people at current usage rates (City of Iqaluit 2010), and a rapidly growing population of over 7000 people (Government of Canada 2012), the practicality of maintaining this sole freshwater source is questionable (Bakaic and Medeiros 2016). The City has identified the Niaqunguk River (also known as the Apex River) as an alternative. Inuit families have traditionally used this as an untreated source of water; however, the watershed is being encroached upon by urban growth. Numerous housing developments as well as industrial and municipal projects target this area, threatening water quality, with potential health implications for residents.

Threats to water quality

Water quality issues arise from a range of natural and human factors, with human activities being particularly problematic. Legacy contamination from past projects, localized development pressure from resources industries, and community expansion and development can all stress water resources (e.g. Fig. 2). Furthermore, residue from industrial contaminants (e.g. pesticides and metals) entering Arctic hydrological systems via long-range transport from the south via air and water currents has been a pressing problem for northern communities for decades (Oehme 1991; Welch et al. 1991; MacDonald et al. 2000).

Legacy contamination

Many northern communities have a history of military presence, which can include abandoned mining operations and industrial sites. For example, when the United States Air Force Base in Iqaluit was de-commissioned in 1963, much of the remaining diesel fuel, oil, and chemicals for winterized mechanical operations (including persistent, bioaccumulative, and toxic compounds such as polychlorinated biphenyls) were simply buried in proximity to a stream known as Carney Creek (Samuelson 1998). These sites (known as "North 40" and "Lower Base") are a continuous source of fuel and chemical seepage into the water system, severely impairing water quality (Medeiros et al. 2011) and biomagnifying through the food chain (Dick et al. 2010). Indeed, the problem is long-standing, as highlighted by the GN environmental inspector in 2003:

> … the latitude of this problem could be enormous. […] it is potentially beyond the ability – both financial and in terms of in-house technical capacity – of the GN to adequately address this issue on its own. (Eno 2003).

While the contamination in Iqaluit from these legacy sources has been well documented by inspectors and reported by local media (Zarate 2010; CBC 2015b), the GN has failed to address the issue. This is partly due to "questionable ownership" of the land and "inadequacy of Canada's environmental clean-up legislation" (Eno 2003), as well as a cited lack of technical and financial capacity. The limited capacity for waste disposal is a concern across

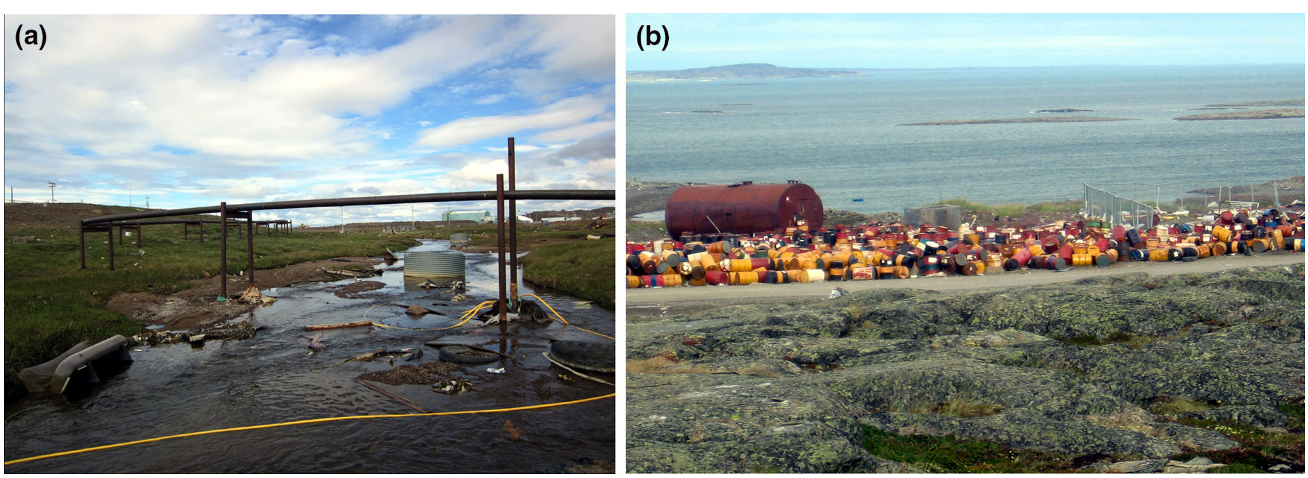

Fig. 2 Images of environmental management challenges from Nunavut; **a** Carney Creek (Airport Creek) in Iqaluit, Nunavut (photograph by: A.S. Medeiros, 2015), **b** Rankin Inlet's "hazardous waste facility" (photograph by: A.S. Medeiros, 2007)

the territory. The cost of transport and disposal is prohibitive for many communities; therefore, hazardous waste is commonly dumped in makeshift, open-air facilities with no safety mechanisms to prevent spills, seepage, or even public access. These areas are often adjacent to water sources (Fig. 2a), raising concerns about possible contamination of food and water supplies.

Resource development pressure

Recent and increasing focus on resource development in the Canadian North has added additional stress to water quality issues facing communities. Resource exploration and extraction are now the main economic driver for territorial governments, and both they and federal government agencies have identified natural resources as a principle advantage for the future growth of northern communities (Vela 2012).

The disposal of mining wastes and tailings presents a threat to surface and groundwater systems across northern regions unless adequately controlled during and following the operational period. Many mineral deposits have the potential to generate acid, which dissolves metals that are toxic to algae, benthic invertebrates, and fish, thus posing a threat to ecosystem services associated with fishing and in some cases also threatening drinking water supplies (Rhéaume and Caron-Vuotari 2013). Currently, "best mining practices" used by the resource extraction industry suggest freezing tailings in permafrost in order to control acidic drainage (Nunavut Regional Adaptation Collaborative 2012). However, the same "best mining practices" acknowledge, but offer no solutions to, increased warming in northern regions that may affect permafrost stability and effluent containment. Furthermore, the economic pressure associated with resource extraction has, for example, motivated Environment Canada to re-designate fish habitat, allowing mining companies to dump tailings waste into once protected freshwater systems (De Souza 2012), which can significantly alter stream biota (Bailey et al. 1998).

Decommissioning of resource development projects has been particularly problematic across the Arctic. Mines abandoned prior to complete remediation frequently have persistent effects, especially on aquatic resources. This legacy has resulted in a large and increasing economic burden. A 2002 audit estimated the costs to government for cleaning up and closing 17 abandoned mines in Canada's North at $555 million, with additional costs for long-term management of impacts at some sites (Office of the Auditor General of Canada 2002).

The Kivalliq region of Nunavut has a long history of water quality concerns from resource development. The North Rankin Inlet Nickel Mine, operational from 1957 to 1962, discharged effluent into ponds below sea level; this leached into Hudson Bay and contaminated its shorelines (Erickson 1995; WESA Inc. 2010). While hazardous tailings were eventually removed by the federal government in 2011, the legacy of 50 years of contamination has engrained itself in the minds of residents (Cater 2013). Furthermore, the site of the mine waste and tailings was identified as unusable for building purposes repurposed into a baseball diamond (Cater 2013). With the Agnico Eagle Meliadine Gold Mine development in progress north of the community, concerns over water quality and fish habitat are renewed (Arnold 2015). The Meliadine mine again threatens an important freshwater ecosystem (the Meliadine River Valley), which contains multiple lakes of cultural (e.g. Iqalugaarjuup Nunanga Territorial Park) and environmental significance.

Community development pressures

There is a long history of growth and expansion of northern communities that has followed industrial and resource development projects. Haley et al. (2011) note that 36.4% of economic output from the three territories is from mining and oil and gas development, which has dramatically increased in the last decade. The growth and expansion of recent development projects, such as the Meliadine Gold Mine near Rankin Inlet and the Meadowbank gold mine near Baker Lake, will increase the burden on municipal water supply and services. Likewise, increased municipal and industrial development will strain the limited infrastructure and services that exist in many northern communities, which can result in a variety of contamination point-sources that impact aquatic systems (e.g. Fig. 2b), including run-off and leaching from municipal landfills and sewage containment areas, hydrocarbon and chemical spills (e.g. waste oil, fuel, lubricants, de-icing liquids), industrial activity, residential waste, stream channel diversion (often accompanying road construction), and increased sedimentation from gravel haul operations (Medeiros et al. 2011).

Increased effluents, tailings, and emissions from resource exploration and industrial development near Arctic communities have renewed concerns over water and food security. The cost of imported food from the south is often prohibitive, and cultural practices continue to be important for community well-being; thus, there is a continued reliance on traditionally harvested fish and marine and land mammals. Likewise, untreated freshwater sources are commonly used during hunting and fishing expeditions for drinking, butchering processes, and meal preparation.

The risk of unexpected contamination can be affected by the source's proximity to features such as airports and the ocean. For example, Marcil Lake in Arctic Bay, Nunavut, faces considerable risk of saltwater intrusion due to its proximity to the ocean. Likewise, the Kugajuk River, water source for the hamlet of Kugaaruk, lacks a freshwater–saltwater barrier, leading to previous contamination of the drinking water supply (Johnson 2013). The fragile nature of Nunavut's municipal water supply systems is illustrated by boil-water advisories and large-scale water outages in Iqaluit, Rankin Inlet, Igloolik, Whale Cove, Sanikiluaq, and Coral Harbour since 2014 (GN 2015). The Guidelines for Canadian Drinking Water Quality issued by Health Canada identify acceptable contaminant levels as well as suggestions regarding treatment for removal; however, these guidelines are often exceeded in northern communities (Table 1). In addition, while Canadian guidelines suggest that total coliforms and *E. coli* can be removed with standard disinfection methods (e.g. applying chlorine, chloramine, chlorine dioxide, or ultraviolet radiation; Health Canada 2012a), other water quality parameters require mechanical filtration that many communities do not currently employ (Table 1). For example, turbidity, aluminium, and iron contaminants all require mechanical filtration (e.g. direct filtration, inline filtration or slow sand filtration; Health Canada 2012b). Furthermore, waste disposal has long been an issue for isolated northern regions. Garbage dumping in proximity to northern communities and around aquatic systems is likely to increase with population growth, thus increasing the likelihood of contamination. These infrastructure and development challenges highlight the critical need for Nunavut to develop a rigorous drinking water quality monitoring and reporting protocol.

Northern water security for the future

Northern communities face key vulnerabilities that challenge water security, including limited technical and financial capacity, limited and ageing infrastructure, growing populations, and a legacy of industrial contamination. Environmental change places water quantity and quality issues, already a challenge from settlement pressures and resource development, at the forefront of concern in a warming Arctic. The combined consequences of increased evaporative stress on freshwater supply, and diminishing water quality due to permafrost degradation,

Table 1 Assessment of Nunavut Community Water Treatment methods and analysis of parameters that exceeded Health Canada Guidelines from 2010 to 2014 (adapted from Williams Engineering Canada Inc 2014: 236)

Community	Parameters exceeding guidelines	Treatment method
Arctic Bay	Total coliforms	Chlorination
Arviat	*E. coli*, total coliforms	Cartridge filter, chlorination
Baker Lake	*E. coli*, total coliforms, turbidity	Sodium hypochlorite
Cambridge Bay	Turbidity, iron	Sodium hypochlorite
Cape Dorset	Total coliforms	Liquid chlorine
Chesterfield Inlet	*E. coli*, total coliforms, iron	Sodium hypochlorite, cartridge filters
Clyde River	Aluminium, iron, total coliforms	Liquid chlorine
Coral Harbour	*E. coli*, total coliforms, iron	Sodium hypochlorite
Gjoa haven	*E. coli*, turbidity	Sodium hypochlorite, rapid sand filter
Grise Fiord	Aluminium, iron, total coliforms	Occasional basic chlorination of glacier and iceberg melt-water
Hall Beach	Total coliforms	Chlorine injection
Igloolik	Total coliforms	Calcium hypochlorite
Iqaluit	–	Ultraviolet disinfection, sand filtration, chlorination
Kimmirut	Total coliforms	Chlorination
Kugaaruk	Turbidity	Sodium hypochlorite
Kugluktuk	Turbidity	Sodium hypochlorite, cartridge filters
Pangnirtung	Total coliforms	Chlorination, fluoridation
Pond Inlet	Total coliforms	Basic chlorination
Qikiqtarjuaq	Total coliforms	Calcium hypochlorite, cartridge filters
Rankin Inlet	Total coliforms	Gaseous chlorine
Repulse Bay	Total coliforms	Sodium hypochlorite
Resolute Bay	Total coliforms	Calcium hypochlorite
Sanikiluaq	Chlorine, TDS, total coliforms	Chlorination
Taloyoak	Turbidity	Sodium hypochlorite, cartridge filters
Whale Cove	Total coliforms	Sodium hypochlorite

increased development, and legacy contamination cascades across both social and scientific disciplines. Indigenous peoples have long demonstrated a capacity to adapt to changing conditions, e.g. altering subsistence harvest, travel, and relational networks (Gearheard et al. 2010). However, cumulative and increasing pressures on freshwater resources challenge efforts towards improving community sustainability.

While adaptation to the impacts of changing environmental conditions on subsistence practices has been a focus of recent research in the north (Ziervogel and Ericksen 2010; Wesche and Chan 2010), this topic requires further investigation on the water security front. Research on freshwater resources in northern regions tends to concentrate on the scientific determination of environmental change impacts in a natural context; however, there is an obvious need to utilize both scientific and Indigenous knowledge of northern systems for adaptation and planning for sustainable communities under a warming climate (e.g. Fig. 1). Likewise, the link between food security and water security is clear, yet access to sustainable and clean freshwater resources has not received the attention it critically requires. Freshwater management policy and planning are currently limited in Nunavut, and future development pressure and climate warming will only increase the vulnerability of northern residents regarding clean and accessible freshwater. While conclusions about the sustainability of future water resources diverge somewhat due to climate model inaccuracies (Nilsson et al. 2013a), the development of adaptation and management plans for freshwater resources based on best available evidence are essential for any stable and healthy population (Ford et al. 2010).

The concept of water security is defined at different scales based on the discipline and is often approached from a human-centred perspective (Cook and Baker 2012). Ensuring water security for northern peoples into the future requires careful assessment and planning to provide continued access for all to clean water at an affordable cost to support healthy people and livelihoods. This must be done in a sustainable manner, where current needs are met without compromising the capacity for future generations to meet their own needs. However, clean and abundant water is also essential for elements of the ecosystem, which provide services that humans rely on. The intertwined nature of social-ecological systems suggests the importance of shifting our approach to water security to better reflect the fundamental nature of ecosystems as a basis for human health and well-being, in other words, an ecohealth approach (Parkes et al. 2010; Bunch et al. 2011).

The water governance system in northern Canada is under rapid evolution, with NWT and Yukon now acting to implement their respective water management strategies. In Nunavut, water management is a critical issue that largely remains to be addressed. Research to evaluate the effectiveness of existing water strategies and their implementation would be very useful for transferring lessons learned to Nunavut. Ultimately, ensuring water security for northern peoples into the future requires careful assessment and planning to provide accessible clean water at an affordable cost in order to meet the basic needs of humans without compromising ecosystem sustainability for future generations. Adaptation to environmental change requires hydrological and hydrochemical monitoring systems that draw on both scientific and Indigenous knowledge (Nilsson et al. 2013b). It also requires inclusive governance processes that value effective community consultation and position northerners as leaders.

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References

Abnizova A, Young KL (2010) Sustainability of high Arctic ponds in a polar desert environment. Arctic 63:67–84. doi:10.14430/arctic648

Arnold S (2015) Peter Lake commercial fisheries feasibility report. Nunavut Department of Environment, Rankin Inlet

Audla T, Smith D (2014) A principled approach to research and development in Inuit Nunangat Starts with the people. Arctic 67:120–121

Azcárate J, Balfors B, Bring A, Destouni G (2013) Strategic environmental assessment and monitoring: Arctic key gaps and bridging pathways. Environ Res Lett 8:044033. doi:10.1088/1748-9326/8/4/044033

Bailey RC, Kennedy MG, Dervish MZ (1998) Biological assessment of freshwater ecosystems using a reference condition approach: comparing predicted and actual benthic invertebrate communities in Yukon streams. Freshw Biol 39:765–774. doi:10.1046/j.1365-2427.1998.00317.x

Bakaic M, Medeiros AS (2016) Vulnerability of northern water supply lakes to changing climate and demand. Arct Sci. doi:10.1139/AS-2016-0029

Bates B, Kundzewicz ZW, Wu S, Palutikof J (2008) Climate change and water, technical paper of the Intergovernmental Panel on Climate Change. Intergovernmental panel on climate change secretariat, Geneva, Switzerland, p 210

Bouchard F, Turner KW, MacDonald LA, Deakin C, White H, Farquharson N, Medeiros AS, Wolfe BB, Hall RI, Pienitz R, Edwards TWD (2013) Vulnerability of shallow subarctic lakes to evaporate and desiccate when snowmelt runoff is low. Geophys Res Lett 40:6112–6117. doi:10.1002/2013GL058635

Bring A, Jarsjö J, Destouni G (2015) Water information and water security in the Arctic. In: Evengård B, Nymand Larsen J, Paasche Ø (eds) The new Arctic. Springer, Cham, pp 225–238

Bring A, Fedorova I, Dibike Y, Hinzman L, Mård J, Mernild SH, Prowse T, Semenova O, Stuefer SL, Woo MK (2016) Arctic terrestrial hydrology: a synthesis of processes, regional effects

and research challenges. J Geophys Res Biogeosci 121:621–649. doi:10.1002/2015JG003131
Bunch MJ, Morrison KE, Parkes MW, Venema HD (2011) Promoting health and well-being by managing for social–ecological resilience: the potential of integrating ecohealth and water resources management approaches. Ecol Soci 16:6. http://www.ecologyandsociety.org/vol16/iss1/art6/. Accessed 26 June 2016
Carmack EC, Yamamoto-Kawai M, Haine TWN, Bacon S, Bluhm BA, Lique C, Melling H, Polyakov IV, Straneo F, Timmermans M-L, Williams WJ (2016) Fresh water and its role in the Arctic Marine System: sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. J Geophys Res Biogeosci 121:675–717. doi:10.1002/2015JG003140
CBC News (2011) Arviat finds solution for its water woes (March 11, 2011). http://www.cbc.ca/news/canada/north/arviat-finds-solution-for-its-water-woes-1.998324. Accessed 26 June 2016
CBC News (2015a) Cold spring weather creates water problems in Igloolik (June 12, 2015). http://www.cbc.ca/news/canada/north/cold-spring-weather-creates-water-problems-in-igloolik-1.3110369. Accessed 26 June 2016
CBC News (2015b) Iqaluit's Airport Creek hazardous to people and sled dogs, say scientists (July 6, 2015). http://www.cbc.ca/news/canada/north/iqaluit-s-airport-creek-hazardous-to-people-and-sled-dogs-say-scientists-1.3139024. Accessed 26 June 2016
CBC News (2015c) Whale Cove, Nunavut, remains under boil water advisory (Aug 13, 2015). http://www.cbc.ca/news/canada/north/whale-cove-nunavut-remains-under-boil-water-advisory-1.3190325. Accessed 26 June 2016
Cater TI (2013) When mining comes (back) to town: exploring historical and contemporary mining encounters in the Kivalliq region, Nunavut. MA Thesis, Memorial University of Newfoundland
Church M (1974) Hydrology and permafrost with reference to northern North America. In: Proceedings, workshop seminar on permafrost hydrology, canada national committee for the international hydrological decade, pp 7–20
City of Iqaluit (2010) City of Iqaluit General Plan, Bi-Law 703. Planning and Lands Department, City of Iqaluit. Prepared by: FoTenn Consultants Inc., Ottawa
Cook C, Bakker K (2012) Water security: debating an emerging paradigm. Glob Environ Change 22:94–102. doi:10.1016/j.gloenvcha.2011.10.011
Daley K, Castleden H, Jamieson R, Furgal C, Ell L (2014) Municipal water quantities and health in Nunavut households: an exploratory case study in Coral Harbour, Nunavut, Canada. Int J Circumpolar Health 73:23843. doi:10.3402/ijch.v73.23843
Daley K, Castleden H, Jamieson R, Furgal C, Ell L (2015) Water systems, sanitation, and public health risks in remote communities: inuit resident perspectives from the Canadian Arctic. Soc Sci Med 135:124–132. doi:10.1016/j.socscimed.2015.04.017
De Souza M (2012) Budget offers new tools to "authorize" water pollution, says Harper Minister, Postmedia News (June 25, 2012). http://www.vancouversun.com/touch/story.html?id=6837627. Accessed 26 June 2016
DIAND (2014) Department of Indian Affairs and Northern Development Act (R.S.C., 1985, c. I-6). http://laws-lois.justice.gc.ca/eng/acts/I-6/index.html. Accessed 26 June 2016
Dick TA, Gallagher CP, Tomy GT (2010) Short-and medium-chain chlorinated paraffins in fish, water and soils from the Iqaluit, Nunavut (Canada), area. World Rev Sci Technol Sustain Dev 7:387–401. doi:10.1504/WRSTSD.2010.032747
Ecojustice (2011) Waterproof 3: Canada's drinking water report card. http://www.ecojustice.ca/wp-content/uploads/2014/11/Waterproof_Essentials_web_corrected_Dec_8.pdf. Accessed 26 June 2016
Edwardson KJ, Bowden WB, Dahm C, Morrice J (2003) The hydraulic characteristics and geochemistry of hyporheic and parafluvial zones in Arctic tundra streams, north slope, Alaska. Adv Water Res 26:907–923. doi:10.1016/S0309-1708(03)00078-2
Eno R (2003) Incident report—Sep. 2, 2003, Government of Nunavut, Department of Environmental Protection, Iqaluit, Nunavut
Erickson P (1995) Reclamation of the North Rankin Nickel Mine tailings: final report. Government of the Northwest Territories, Yellowknife
Farish M, Lackenbauer PW (2009) High modernism in the Arctic: planning Frobisher Bay and Inuvik. J Hist Geogr 35:517–544. doi:10.1016/j.jhg.2009.02.002
Ford JD, Smit B (2004) A framework for assessing the vulnerability of communities in the Canadian Arctic to risks associated with climate change. Arctic 57:389–400. doi:10.14430/arctic516
Ford JD, Smit B, Wandel J, MacDonald J (2006) Vulnerability to climate change in Igloolik, Nunavut: what we can learn from the past and present. Polar Rec 42:127–138. doi:10.1017/S0032247406005122
Ford J, Pearce T, Smit B, Wandel J, Allurut M, Shappa K, Ittusujurat H, Qrunnut K (2007) Reducing vulnerability to climate change in the Arctic: the case of Nunavut, Canada. Arctic 60:150–166. doi:10.14430/arctic240
Ford JD, Pearce T, Duerden F, Furgal C, Smit B (2010) Climate change policy responses for Canada's Inuit population: the importance of and opportunities for adaptation. Glob Environ Change 20:177–191. doi:10.1016/j.gloenvcha.2009.10.008
Fox S (2002) These are things that are really happening: Inuit perspectives on the evidence and impacts of climate change in Nunavut. The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change, Arctic Research Consortium of the United States, Fairbanks, USA, pp 12–53
French HM, Slaymaker O (1993) Canada's Cold Environments. McGill-Queens University Press, Montreal, p 363
Gearheard S, Pocernich M, Stewart R, Sanguya J, Huntington HP (2010) Linking Inuit knowledge and meteorological station observations to understand changing wind patterns at Clyde River, Nunavut. Clim Change 100:267–294. doi:10.1007/s10584-009-9587-1
George J (2009) Scrapping utilidor not popular with Resolute residents. Nunatsiaq News (Aug 5, 2009). http://www.nunatsiaqonline.ca/stories/article/scrapping_utilidor_not_popular_with_resolute_residents. Accessed 26 June 2016
GNWT (2005) Managing drinking water quality in the Northwest Territories: A preventative framework and strategy. NWT, Yellowknife. doi:10.1016/0278-6915(93)90134-K
GNWT (2010) Northern voices, northern waters: NWT water stewardship strategy. NWT, Yellowknife. Retrieved from http://www.nwtwaterstewardship.ca/. Accessed 26 June 2016
GNWT (2011) NWT water stewardship: A plan for action. NWT, Yellowknife. http://www.nwtwaterstewardship.ca/plan_for_action. Accessed 26 June 2016
Government of Canada (2014) Nunavut waters and Nunavut surface Rights Tribunal Act (S.C. 2002, c. 10). http://laws-lois.justice.gc.ca/eng/acts/n-28.8/. Accessed 26 June 2016
Government of Nunavut (2015) Government of Nunavut, Department of Health. http://www.gov.nu.ca/health. Accessed 1 Oct 2015
Government of Yukon (2003) Waters Act. http://www.gov.yk.ca/legislation/acts/waters.pdf
Government of Yukon (2014) Water for nature, water for people: Yukon water strategy and action plan. Government of Yukon, Whitehorse
Haley S, Klick M, Szymoniak N, Crow A (2011) Observing trends and assessing data for Arctic mining. Polar Geogr 34:37–61. doi:10.1080/1088937X.2011.584449

Health Canada (2012a) Guidelines for Canadian drinking water quality: guideline technical document—total coliforms. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Ottawa

Health Canada (2012b) Guidelines for Canadian drinking water quality: guideline technical document—turbidity. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Ottawa

Hill C, Furlong K, Bakker K, Cohen A (2008) Harmonization versus subsidiarity in water governance: a review of water governance and legislation in the Canadian provinces and territories. Can Water Res J 33:315–332. doi:10.4296/cwrj3304315

Hodson D (2013) Identifying uncertainties in Arctic climate change projections. Clim Dyn 40:2849–2865. doi:10.1007/s00382-012-1512-z

Huntington H, Fox S, Berkes F, Krupnik I (2005) The changing arctic: indigenous perspectives. In: Symon C, Arris L, Heal B (eds) Arctic climate impact assessment. Cambridge University Press, Cambridge, pp 61–98

Huntington HH, Fox S, Berkes F, Krupnik I, Whiting A, Zacharof M, McGlashan G, Brubaker M, Gofman V, Dickson C, Paci C, Tsetta S, Gargan S, Fabian R, Paulette J, Cazon M, Giroux D, King P, Boucher M, Able L, Norin J, Laboucan A, Cheezie P, Poitras J, Abraham F, T'selie B, Pierrot J, Cotchilly P, Lafferty G, Rabesca J, Camille E, Edwards J, Carmichael J, Elias W, de Palham A, Pitkanen L, Norwegian L, Fox S, Qujaukitsoq U, Møller N, Mustonen T, Nieminen M, Eklund H, Helander E, Mustonen T, Zavalko S, Terva J, Cherenkov A, Henshaw A, Fenge T, Nickels S, Wilson S (2005) The changing Arctic: indigenous perspectives. ACIA. In: Arctic Climate Impact Assessment, Chap 3, Cambridge University Press, Cambridge, pp 61–98

Instanes A, Kokorev V, Janowicz R, Bruland O, Sand K, Prowse T (2016) Changes to freshwater systems affecting Arctic infrastructure and natural resources. J Geophys Res Biogeosci 121:567–585. doi:10.1002/2015JG003125

Johnson K (2013) Kugaaruk, Nunavut water supply, and alternative water supply study. J North Territ Water Waste Assoc 2013:30–32

Kot M, Castleden H, Gagnon GA (2014) The human dimension of water safety plans: a critical review of literature and information gaps. Environ Rev 23:24–29. doi:10.1139/er-2014-0030

Lantz TC, Turner KW (2015) Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. J Geophys Res Biogeosci 120:513–524. doi:10.1002/2014JG002744

Lautze J, Manthrithilake H (2012) Water security: old concepts, new package, what value? Nat Res Forum 36:76–87. doi:10.1111/j.1477-8947.2012.01448.x

MacDonald RW, Barrie LA, Bidleman TF, Diamond ML, Gregor DJ, Semkin RG, Strachan WMJ, Li YF, Wania F, Alaee M, Alexeeva LB, Backus SM, Bailey R, Bewers JM, Gobeil C, Halsall CJ, Harner T, Hoff JT, Jantunen LMM, Lockhart WL, Mackay D, Muir DCG, Pudykiewicz J, Reimer KJ, Smith JN, Stern GA, Schroeder WH, Wagemann R, Yunker MB (2000) Contaminants in the Canadian Arctic: 5 years of progress in understanding sources, occurrence and pathways. Sci Total Environ 254:93–234. doi:10.1016/S0048-9697(00)00434-4

MacDonald LA, Turner KW, Balasubramaniam AM, Wolfe BB, Hall RI, Sweetman JN (2012) Tracking hydrological responses of a thermokarst lake in the Old Crow Flats (Yukon Territory, Canada) to recent climate variability using aerial photographs and paleolimnological methods. Hydrol Process 26:117–129. doi:10.1002/hyp.8116

Martin D, Bélanger D, Gosselin P, Brazeau J, Furgal C, Déry S (2007) Drinking water and potential threats to human health in Nunavik: adaptation strategies under climate change conditions. Arctic 60:195–202. doi:10.14430/arctic244

Medeiros AS, Luszczek CE, Shirley J, Quinlan R (2011) Benthic biomonitoring in Arctic tundra streams; a community based approach. Arctic 64:59–72. doi:10.14430/arctic4080

MVRMA (2014) Mackenzie Valley Resource Management Act (S.C. 1998, c. 25). http://laws-lois.justice.gc.ca/eng/acts/m-0.2/. Accessed 26 June 2016

Nancarrow TL, Chan HM (2010) Observations of environmental changes and potential dietary impacts in two communities in Nunavut, Canada. Rural Remote Health 10:1370

Nickels S, Furgal C, Buell M, Moquin H (2006) Unikkaaqatigiit—putting the human face on climate change: perspectives from Inuit in Canada. Inuit Tapiriit Kanatami, Ottawa

Nilsson LM, Berner J, Dudarev AA, Mulvad G, Odland JØ, Parkinson A, Rautio A, Tikhonov C, Evengård B (2013a) Indicators of food and water security in an Arctic Health context–results from an international workshop discussion. Int J Circumpolar Health 72:21530. doi:10.3402/ijch.v72i0.21530

Nilsson LM, Destouni G, Berner J, Dudarev AA, Mulvad G, Odland JØ, Parkinson A, Tikhonov C, Rautio A, Evengård B (2013b) A call for urgent monitoring of food and water security based on relevant indicators for the Arctic. Ambio 42:816–822. doi:10.1007/s13280-013-0427-1

Nunavut Regional Adaptation Collaborative (2012) Good Environmental Practices for Northern Mining and Necessary Infrastructure, Task 2 Report, March 2012

Nunavut Tunnagavik Ltd (2010) Nunavut land claims agreement. http://www.tunngavik.com/documents/publications/LAND_CLAIMS_AGREEMENT_NUNAVUT.pdf. Accessed 26 June 2016

Oehme M (1991) Further evidence for long-range air transport of polychlorinated aromates and pesticides: North America and Eurasia to the Arctic. Ambio 20:293–297

Office of the Auditor General of Canada (2002) October Report of the Commissioner of the Environment and Sustainable Development. Chapter 3—Abandoned Mines in the North. Office of the Auditor General, Ottawa

Osterkamp TE, Romanovsky VE (1999) Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafr Periglac 10:17–37. doi:10.1002/(SICI)1099-1530(199901/03)10:1<17:AID-PPP303>3.0.CO;2-4

Pahl-Wostl C, Palmer M, Richards K (2013) Enhancing water security for the benefits of humans and nature—the role of governance. Curr Opin Environ Sustain 5:676–684. doi:10.1016/j.cosust.2013.10.018

Parkes MW, Morrison KE, Bunch MJ, Hallström LK, Neudoerffer RC, Venema HD, Waltner-Toews D (2010) Towards integrated governance for water, health and social–ecological systems: the watershed governance prism. Glob Environ Change 20:693–704. doi:10.1016/j.gloenvcha.2010.06.001

Prno J, Bradshaw B, Wandel J, Pearce T, Smit B, Tozer L (2011) Community vulnerability to climate change in the context of other exposure-sensitivities in Kugluktuk, Nunavut. Polar Res 30:7363. doi:10.3402/polar.v30i0.7363

Prowse T, Bring A, Mård J, Carmack E (2015) Arctic freshwater synthesis: introduction. J Geophys Res Biogeosci 120:2121–2131. doi:10.1002/2015JG003127

Rhéaume G, Caron-Vuotari M (2013) The future of mining in Canada's North. The Conference Board of Canada, Ottawa

Rohner T (2014) Growing Nunavut community struggling with water supply. Nunatsiaq News (Oct 31, 2014). http://www.nunatsiaqonline.ca/stories/article/65674growing_nunavut_community_struggling_with_water_capacity/. Accessed 26 June 2016

Rouse WR, Douglas MSV, Hecky RE, Hershey AE, Kling GW, Lesack L, Marsh P, McDonald M, Nicholson BJ, Roulet NT, Smol JP (1997) Effects of climate change on the freshwaters of Arctic and sub Arctic North America. Hydrol Process 11:873–902. doi:10.1002/(SICI)1099-1085(19970630)11:8<873:AID-HYP510>3.0.CO;2-6

Roux MJ, Tallman RF, Lewis CW (2011) Small-scale Arctic charr Salvelinus alpinus fisheries in Canada's Nunavut: management challenges and options. J Fish Biol 79:1625–1647. doi:10.1111/j.1095-8649.2011.03092.x

Samuelson GM (1998) Water and waste management issues in the Canadian Arctic: Iqaluit, Baffin Island. Can Water Res J 23:327–338. doi:10.4296/cwrj2304327

Serreze MC, Walsh JE, ChapinIII FS, Osterkamp T, Dyurgerov M, Romanovsky V, Oechel WC, Morison J, Zhang T, Barry RG (2000) Observational evidence of recent change in the northern high-latitude environment. Clim Change 46:159–207. doi:10.1023/A:1005504031923

Smith LC, Sheng Y, MacDonald GM, Hinzman LD (2005) Disappearing Arctic Lakes. Science 308:1429. doi:10.1126/science.1108142

Smol JP, Douglas MS (2007) Crossing the final ecological threshold in high Arctic ponds. Proc Nat Acad Sci USA 104:12395–12397. doi:10.1073/pnas.0702777104

Stantec (2014) Seasonal Replenishment of Nipissar Lake, Rankin Inlet, Nunavut. Environmental Screening Report. Prepared by Stantec Environmental Consultants Ltd for Department of Community and Government Services, Government of Nunavut

Touhill CJ, James SC (1983) Environmental assessment of the barrel and drum reconditioning industry. Environ Prog 2:214–221

UN-Water (2013) Water security and the global water agenda. Hamilton. http://i.unu.edu/media/unu.edu/publication/34287/UNWater_watersecurity_analyticalbrief.pdf. Accessed 26 June 2016

Vela T (2012) Meliadine promises as Meadowbank disappoints. Northern News Services Northwest Territories/Nunavut Canada. http://www.nnsl.com/frames/newspapers/2012-02/feb27_12mb.html. Accessed 26 June 2016

Vihma T, Screen J, Tjernström M, Newton B, Zhang X, Popova V, Deser C, Holland M, Prowse T (2016) The atmospheric role in the Arctic water cycle: processes, past and future changes, and their impacts. J Geophys Res Biogeosci 120:586–620. doi:10.1002/2015JG003132

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM (2010) Global threats to human water security and river biodiversity. Nature 467:555–561. doi:10.1038/nature09440

Welch HE, Muir DC, Billeck BN, Lockhart WL, Brunskill GJ, Kling HJ, Olson MP, Lemoine RM (1991) Brown snow: a long-range transport event in the Canadian Arctic. Environ Sci Technol 25:280–286. doi:10.1021/es00014a010

Wesa INC (2010) The North Rankin Nickel mine site records review report. WESA Inc, Kingston

Wesche S, Armitage DR (2010) As long as the sun shines, the rivers flow and the grass grows: vulnerability, adaptation and environmental change in Deninu Kue Traditional Territory, Northwest Territories. In: Hovelsrud GK, Smit B (eds) CAVIAR—community adaptation and vulnerability in the Arctic regions. Springer, Dordrecht, pp 163–189

Wesche SD, Chan HM (2010) Adapting to the impacts of climate change on food security among Inuit in the Western Canadian Arctic. EcoHealth 7:361–373

Williams Engineering Canada Inc (2014) Locate alternate sources of drinking water for each Nunavut Hamlet final report. Williams Engineering Canada Inc, Yellowknife

Woo MK (2010) Cold ocean seas and northern hydrology: an exploratory overview. Hydrol Res 41:439

Woo MK, Young KL (2014) Disappearing semi-permanent snow in the High Arctic and its consequences. J Glaciol 60:192–200. doi:10.3189/2014JoG13J150

Wrona FJ, Johansson M, Culp JM, Jenkins A, Mård J, Myers-Smith IH, Prowse TD, Vincent WF, Wookey PA (2016) Transitions in Arctic Ecosystems: ecological Implications of a changing hydrological regime. J Geophys Res Biogeosci 120:650–674. doi:10.1002/2015JG003133

Yang H, Pfister S, Bhaduri A (2013) Accounting for a scarce resource: virtual water and water footprint in the global water system. Curr Opin Environ Sustain 5:599–606. doi:10.1016/j.cosust.2013.10.003

Zarate G (2010) Biologist sounds alarm over polluted creek. Nunatsiaq News (Sept 9, 2010). http://www.nunatsiaqonline.ca/stories/article/biologist_sounds_alarm_over_polluted_creek/. Accessed 26 June 2016

Ziervogel G, Ericksen PJ (2010) Adapting to climate change to sustain food security. Wiley Interdiscip Rev Clim Change 1:525–540