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Hydrological Analysis of Municipal Source Water Availability in the Canadian Arctic Territory of Nunavut

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ABSTRACT. In the Canadian Arctic, the availability of sustainable drinking water supplies is threatened by pressures such as increasing populations, climate change, and the remote geographic nature of the communities. The objective of this study was to conduct a screening level vulnerability assessment of municipal drinking water supplies in the Canadian territory of Nunavut with consideration for climate change, population growth, and infrastructure changes. A hydrological analysis of primary drinking water supply watersheds was performed to evaluate the relative vulnerability level in 24 Nunavut communities. We used a water balance model to predict annual water yield from each watershed using historical and projected future climate data. Approximately 25% of the study communities were projected to experience high vulnerability to water shortages by 2070, defined as using greater than 40% of available water from their source watershed on an annual basis. A medium level of vulnerability (using 20%–40% of annual available water) was determined for 8% of the study communities and a moderate level for 12% (using 10%–20% of annual available water). A low vulnerability level to 2070 (using less than 10% of annual available water) was determined for 55% of the communities. The vulnerability level was primarily influenced by source watershed size. The results of this study could be used as a component of a proactive strategy to help address water security issues in Nunavut.

Key words: water resource assessment; climate change; Arctic; water management; water security; Arctic hydrology; drinking water vulnerability

RÉSUMÉ. Dans l'Arctique canadien, la disponibilité d'approvisionnements durables en eau potable est menacée par diverses contraintes, comme la croissance des populations, le changement climatique et l'éloignement géographique des collectivités. Cette étude avait pour but d'effectuer l'évaluation préalable de la vulnérabilité des approvisionnements municipaux en eau potable dans le territoire canadien du Nunavut, en tenant compte du changement climatique, de la croissance de la population et des changements en matière d'infrastructures. Une analyse hydrologique des principaux bassins versants d'alimentation en eau potable a été réalisée afin d'évaluer le degré de vulnérabilité relative de 24 collectivités du Nunavut. Nous avons utilisé un modèle du bilan hydraulique pour prévoir l'apport annuel en eau de chaque bassin versant en recourant à des données climatiques historiques et projetées. Selon nos projections, environ 25 % des collectivités étudiées devraient connaître une grande vulnérabilité en matière de pénurie d'eau d'ici 2070, ce qui est défini comme utilisant plus de 40 % de l'eau provenant de leur propre bassin versant annuellement. Un degré de vulnérabilité moyen (utilisant de 20 % à 40 % de l'eau utile annuellement) a été déterminé pour 8 % des collectivités étudiées, tandis qu'un degré de vulnérabilité modéré a été déterminé pour 12 % des collectivités (utilisant 10 % à 20 % de l'eau utile annuellement). Un faible degré de vulnérabilité jusqu'en 2070 (utilisant moins de 10 % de l'eau utile annuellement) a été déterminé pour 55 % des collectivités. Le degré de vulnérabilité était principalement influencé par la taille du bassin versant à la source. Les résultats de cette étude pourraient faire partie d'une stratégie proactive pour aider à rectifier les enjeux en matière de sécurité de l'eau au Nunavut.

Mots clés : évaluation des ressources en eau; changement climatique; Arctique; gestion de l'eau; sécurité de l'eau; hydrologie de l'Arctique; vulnérabilité de l'eau potable

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INTRODUCTION

The provision of municipal drinking water faces unique challenges in many Arctic communities, which are typically remote, experience an extreme cold climate, have high infrastructure costs, and often have limited skilled technical staff (Daley et al., 2017). It is anticipated that a changing climate will impact source water availability and introduce additional challenges to some regions (Hinzman et al., 2005; Instanes et al., 2016).

The Territory of Nunavut covers a large expanse of the Canadian Arctic (1.9 million km^2; Statistics Canada, 2017).

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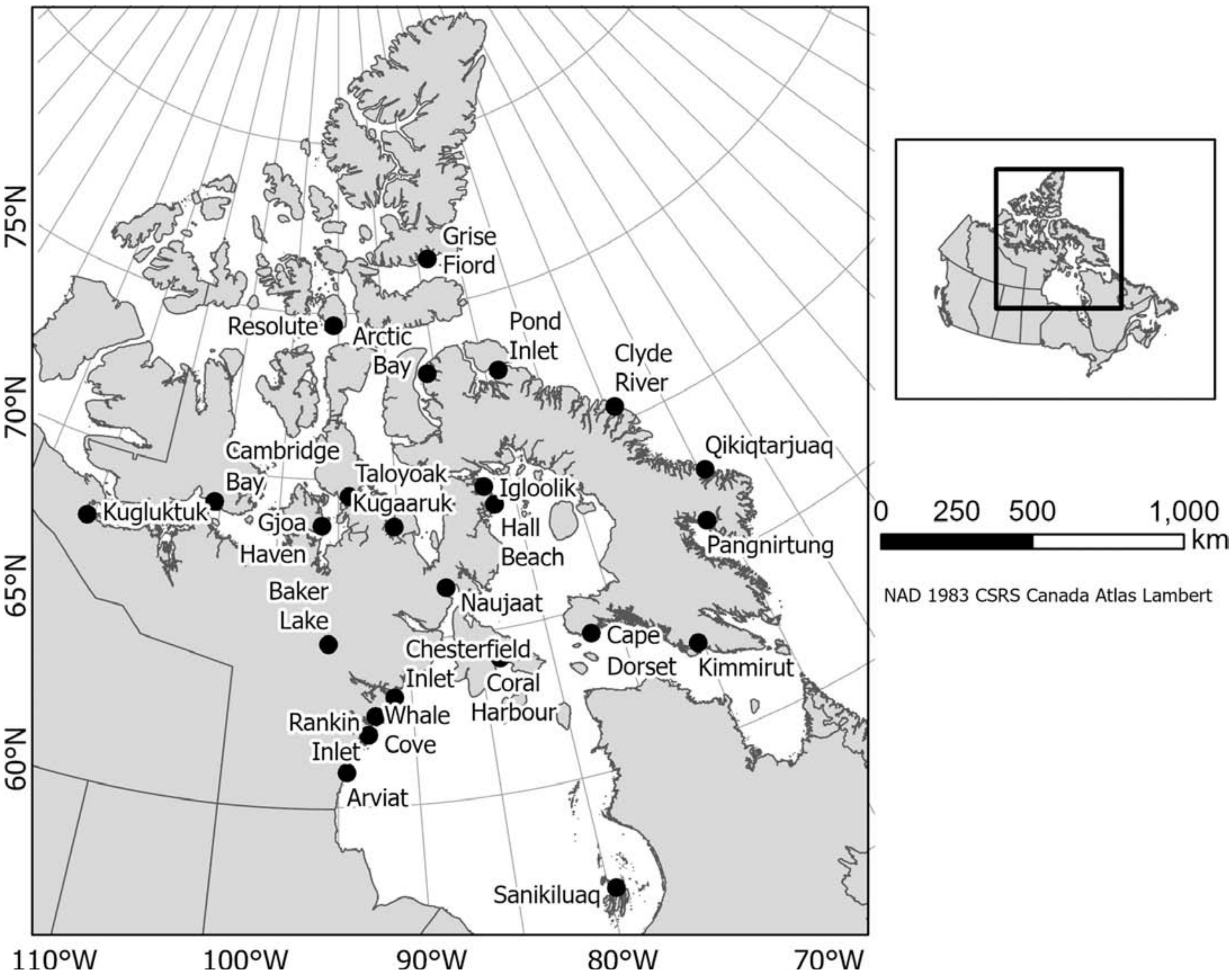

FIG. 1. Location of study communities in Nunavut, Canada.

There are 25 communities in Nunavut, which are sparsely distributed across the territory (Fig. 1). Each community is relatively small with populations of less than 2500 people, with the exception of Iqaluit (6700; GN, 2012; Table 1). There are no roads connecting communities to each other or to the south; therefore, all transport of goods and materials is via aircraft and, during the ice-free season (≈ June to October), via cargo ships. As a result, the construction and maintenance of municipal water infrastructure are relatively expensive and challenging compared to southern Canada (Johnson, 2007). Generally, the Canadian Arctic is characterized by an arid and very cold climate environment. Nunavut receives less than 250 mm of precipitation annually, mostly as snow, and average daily temperatures do not often rise above 7˚C in the warmest month of July (Johnson, 2017).

Source water is extracted from surface water bodies (rivers and lakes) in Nunavut, as the entire territory is in the zone of continuous permafrost (Daley et al., 2017). Drinking water is collected from source locations and in some cases stored in reservoirs before treatment and distribution (Johnson, 2008). The temporal extraction window can be limited in some communities because of ice cover and the large seasonal variability in stream flows (Medeiros et al., 2017), while other communities are able to extract water from deeper lakes throughout the year on an as-need basis. Another challenge associated with the provision of drinking water in Nunavut is the presence of continuous permafrost, which hinders the use of buried infrastructure. Most communities in Nunavut (22 of 25) rely on water delivery trucks to convey treated drinking water to each individual household and establishment (Smith and Emde, 1999). Communities on trucked water distribution typically use much less water than residents in Southern Canada—approximately 100 L per capita per day in comparison to 330 L per capita per day (Daley et al., 2014). Only three communities in Nunavut (Iqaluit, Resolute Bay, and Rankin Inlet) currently use piped water distribution systems. Notably, several Nunavut communities have already begun to experience severe

TABLE 1. Community information including current and future populations and source water characteristics.

Community	Coordinates	Population 2011 Census[1]	2040 Projected	2070 Projected	Water source	Distribution	Watershed area (ha)
Arctic Bay	73°02′11″N, 85°09′09″W	823	1111	1170	Marcil Lake	Trucked	1.33E+04
Arviat	61°06′29″N, 94°03′25″W	2318	4477	9067	Wolf Creek	Trucked	5.82E+04
Baker Lake	64°19′05″N, 96°01′03″W	1872	3076	4751	Baker Lake	Trucked	2.40E+07
Cambridge Bay	69°07′02″N, 105°03′11″W	1608	2048	2578	Water Supply Lake	Trucked	2.78E+02
Cape Dorset	64°13′54″N, 76°32′25″W	1363	2027	2908	T Lake	Trucked	7.29E+01
Chesterfield Inlet	63°20′27″N, 90°42′22″W	313	535	798	First Lake	Trucked	1.97E+03
Clyde River	70°28′26″N, 68°35′10″W	934	1504	2385	Water Source Lake	Trucked	5.70E+01
Coral Harbour	64°08′13″N, 83°09′51″W	834	1594	3062	Post River	Trucked	2.56E+04
Gjoa Haven	68°37′33″N, 95°52′30″W	1279	1842	2643	Swan Lake	Trucked	9.39E+02
Grise Fiord	76°25′03″N, 82°53′38″W	130	171	201	Snowmelt runoff	Trucked	2.73E+01
Hall Beach	68°46′38″N, 81°13′27″W	546	1455	2722	Water Supply Lake	Trucked	1.01E+03
Igloolik	69°22′34″N, 81°47′58″W	1454	2949	4775	South Lake	Trucked	1.29E+02
Kimmirut	62°50′48″N, 69°52′07″W	455	568	690	Fundo Lake	Trucked	8.10E+02
Kugaaruk	68°31′59″N, 89°49′36″W	771	1320	1984	Kugajuk River	Trucked	1.82E+05
Kugluktuk	67°49′32″N, 115°05′42″W	1450	1904	2355	Coppermine River	Trucked	5.13E+06
Naujaat	66°31′19″N, 86°14′06″W	945	1997	4627	Nuviq Luktujuq Lake	Trucked	2.59E+03
Pangnirtung	66°08′52″N, 65°41′58″W	1425	2144	2483	Duval River	Trucked	9.27E+03
Pond Inlet	72°41′57″N, 77°57′33″W	1549	2515	4220	Salmon River	Trucked	3.74E+03
Qikiqtarjuaq	67°33′29″N, 64°01′29″W	520	597	692	Tulugak River	Trucked	2.40E+03
Rankin Inlet	62°48′35″N, 92°05′58″W	2266	4102	6545	Char River and Nipissar Lake	Piped	6.76E+03/2.69E+02
Resolute	74°41′51″N, 94°49′56″W	214	287	341	Char Lake	Piped	4.12E+02
Sanikiluaq	56°32′34″N, 79°13′30″W	812	1408	2397	Sanikiluaq Lake	Trucked	1.78E+03
Taloyoak	69°32′13″N, 93°31′36″W	899	1424	2212	Canso Lake	Trucked	3.30E+02
Whale Cove	62°10′22″N, 92°34′46″W	407	653	1021	Fish Lake	Trucked	2.37E+02

[1] Government of Nunavut, 2012.

water supply problems, such as seasonal water shortages in Grise Fiord and saline intrusion in Kugluktuk, Kugaaruk, and Sanikiluaq (Johnson, 2017).

Climate change poses new uncertainties in the future availability of source water for Arctic communities (Evengard et al., 2011). According to the Intergovernmental Panel on Climate Change (IPCC), precipitation is projected to increase in high latitude environments; however, water shortages may still be anticipated due to increased variability in river hydrology, such as earlier ice breakup and lower summer precipitation (Cisneros et al., 2014). In addition, higher average ambient air temperatures are projected to increase the rate of evaporation from Arctic regions (Cisneros et al., 2014). On the arctic tundra, evapotranspiration can often be the dominant water loss mechanism and can exceed summer precipitation (Mendez et al., 1998).

In recent years, there has been research focused on drinking water quality risks in Arctic communities (Dudarev et al., 2013; Goldfarb et al., 2013). Daley et al. (2014) identified that recent research frameworks on water security have highlighted the importance of the provision of adequate drinking water quantities in addition to water quality (Bakker, 2012; Cook and Bakker, 2012; Loring et al., 2013). Recent studies have involved both qualitative and quantitative assessments of drinking water availability in a few northern communities. Residents of Rigolet, Nunatsiavut, reported changes in the temporal and spatial availability of freshwater (Goldhar et al., 2014). Bakaic and Medeiros (2016) and Bakaic et al. (2018) modeled the accessible volume of water supply sources in Iqaluit (Geraldine Lake and the Apex River) and Rankin Inlet (Nipissar Lake) over the next 20 years. They found that both communities could be at risk of end-of-winter water shortages in the near future.

A number of indices developed for assessing freshwater availability (see Dunn and Baker, 2011; Plummer et al., 2012) have included both physical and socioeconomic factors that could create vulnerability. The Arctic Water Resource Vulnerability Index (AWRVI) is a community-centered vulnerability index that incorporates both physical and social indicators to quantify a community's adaptive capacity (Alessa et al., 2008). The physical subindex describes the natural supply, municipal supply, water quality, permafrost, and subsistence habitat, while the social subindex considers the community's knowledge capacity, economic capacity, institutional capacity, and cultural capacity. The AWRVI is meant to enable Arctic communities to self-diagnose potential risks to their water resource availability and determine where they are resilient or vulnerable. While the AWRVI is a comprehensive approach for assessing vulnerability, there are challenges in applying this methodology for regional comparative assessments. Williams et al. (2019) outlined some of these challenges, such as the reliance on subjective qualitative assessments of vulnerability and the inability to independently verify the accuracy of the results. A less comprehensive type of water vulnerability index is the use-to-resource ratio. For example, the water stress index (Vörösmarty et al., 2005) is simply the ratio of water withdrawal to average annual availability. Threshold ratios of 0.2 and 0.4 (20%–40%) use-to-resource are often used to indicate medium and high stress, respectively (Raskin et al., 1997).

Previous studies have illustrated potential vulnerabilities associated with municipal water supply quantities in Arctic communities, but a regional assessment of relative water supply vulnerabilities in Nunavut has not been undertaken. Such assessments are necessary to proactively identify vulnerable communities and to develop risk mitigation strategies. As highlighted earlier, there are several components of Arctic community water supply systems that have vulnerabilities, including the capacity and integrity of water storage and distribution infrastructure and seasonal variability in streamflow. However, one of the first risk factors that should be assessed is whether current municipal source watersheds have the ability to provide enough water to meet current and future needs of Arctic communities. This study focused on this risk factor and involved a regional assessment of annual municipal water supply quantities for the Territory of Nunavut, accounting for population growth, the potential impacts of climate change, and changes to water distribution infrastructure (i.e., trucked vs piped distribution). For each community, contributing watershed areas were delineated, and a water balance model was used to predict annual water yield using historical climate data as well as projected future climate data generated from downscaled global circulation model (GCM) output. The percentage of annual water yield from the source watershed used by the community was computed and used as a metric to characterize and rank vulnerability levels for the various scenarios.

METHODS

Study Site Descriptions

This study assessed source water availability in 24 communities located in Nunavut, Canada (Fig. 1). The capital city of Iqaluit was not included in the assessment as it has already been the focus of detailed water availability studies (Bakaic et al., 2018) and is dissimilar to the other communities in terms of population, infrastructure, financing, and technical capacity. Table 1 provides the location, population, water source type, water distribution type, and watershed area for each community. Source water systems and extraction locations were identified by municipal engineers with the Community and Government Services Department (CGS) of the Government of Nunavut. Nunavut has a cold, arid climate, with considerable inter-community variability due to the vastness of the territory. For example, between 1981 and 2010, Resolute, one of the most northern hamlets, saw average daily temperatures of −15.7˚C and received an average of 161.2 mm of annual precipitation. For the same period, the more southern hamlet of Arviat had average daily temperatures of −9.3˚C and average annual precipitation totals of 286.5 mm.

Water Balance Calculations

Water budgets (as volumes) were computed on an annual basis assuming steady conditions with respect to storage within the watershed:

$$W_a = P - ET - W_{use} \qquad \text{[Eq. 1]}$$

where W_a is the water volume available after abstractions, P is the precipitation volume, ET is the estimated evapotranspiration volume, and W_{use} is the water used for residential purposes. Water-use scenarios for both trucked and piped distribution systems were modeled in all communities. Percolation to groundwater was assumed to be negligible due to permafrost.

Underestimation of precipitation due to snow undercatch and water losses due to sublimation were not included in the water balance calculations. Both can range between 10% and 50% of annual precipitation (Liston and Sturm, 2004). Characterization of these processes requires detailed meteorological data, which are not available across all communities. As this study was intended as a screening-level assessment, these components were assumed to be of approximately equal magnitude and not included in the water balance.

Watershed Delineation

Study site watersheds were delineated with ESRI ArcGIS ArcMap version 10.3.1 using data obtained from Natural Resources Canada (GC, 2020a). The Geospatial Data Extraction tool was used to download digital elevation models (DEMs) and hydrography. To minimize distortion, all data were projected in the local UTM zone (e.g., NAD 1983 UTM Zone 15N).

The Arc Hydro (Maidment, 2002) tool was used to preprocess DEMs and the Point Delineation feature was used to delineate each watershed. Flowing watercourses were delineated at the extraction point, while lakes were delineated at the lake outlet, such that the entire contributing area of the lake was included. Because of the nature of the topography and the quality of DEMs available, some watersheds could not be delineated using Arc Hydro (Grise Fiord, Sanikiluaq, and Baker Lake) and therefore were delineated manually using topographic maps.

Water Usage

Annual historical water use values were calculated using the most recent population figures according to census data. These water use values were held constant throughout the historical water balance calculations to provide a conservative estimate of water availability. The projected water usage from 2014 to 2035 was determined based on population projections available from the Government of Nunavut (2014). The population growth rate from 2014 to 2035 was used to project the populations to 2070. The annual projected water usage for each community was determined using standard design equations shown in Equations 2 and 3 for northern communities from Heinke et al. (1991). The residential water use (RWU) was assumed to be 90 L per person per day for trucked water distribution systems, and 225 L per person per day for piped water distribution systems (Smith and Emde, 1999), which are engineering design standards used in northern Canada. These design standards were used instead of reported water usage rates to compare vulnerabilities across the 24 communities assuming comparable water infrastructure functionality. It should be noted that actual water usage in certain communities can deviate from these assumed values, as reported by Bakaic and Medeiros (2016) and Bakaic et al. (2018).

For a population (Pop.) size of 0 to 2000 people, the total water use per capita was estimated using Equation 2:

$$RWU \times \left[1.0 + (0.00023 \times Pop.)\right] \qquad \text{[Eq. 2]}$$

For a population size of 2000 to 10 000 people, the total water use per capita was estimated using Equation 3:

$$RWU \times \left[-1.0 + (0.323 \times InPop.)\right] \qquad \text{[Eq. 3]}$$

Climate Data

Historical climate data were downloaded from the Environment and Climate Change Canada website (GC, 2020b). The statistical software package R was used to generate annual precipitation amounts based on daily historical climate records at each station. When more than 30 consecutive days of data were missing from any given year, the year was removed from the dataset. The monthly mean, minimum, and maximum temperature for each month were calculated for each site with R statistical software. The nearest climate station to each study site was used.

Assessments of future climate scenarios were performed using precipitation and temperature datasets generated from GCM output. Numerous GCMs available to generate projections of future climate conditions are described in detail in IPCC (2013). The publicly available GCM datasets were sourced from the Pacific Climate Impacts Consortium (PCIC) based at the University of Victoria (PCIC, 2016). The PCIC provides statistically downscaled climate datasets for Canada.

To provide a range of possible future climate projections, four GCMs were selected based on the 12 models available through the PCIC portal. The number of GCMs was reduced from 12 to four by selecting those with the lowest observed bias for precipitation and temperature for northern regions (see Sheffield et al., 2013). The four GCMs selected were CCSM4-r2, CNRM-CM5-r1, CSIRO-Mk3-6-0-r1, and MRI-CGCM3-r1. The Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ) method was used for statistical downscaling of the GCMs to the study sites.

Three representative concentration pathways (RCPs) (2.6, 4.5, and 8.5) were compared in the generation of future climate projections for one site (Coral Harbour). These RCPs represent three different scenarios for future climate change based on carbon concentrations and radiative forcing in the atmosphere. For subsequent sites, an RCP of 4.5 was selected to simplify data analysis since few differences in water yield were observed between the RCP scenarios. The RCP 4.5 emission scenario was also deemed to be the most likely scenario based on fossil fuel production forecasts (Ward et al., 2011).

Selection of Study Periods

Three study periods were selected for the water balance analysis: 1950 – 2015 (historical), 2016 – 40, and 2041 – 70. Hindcast GCM datasets (i.e., 1950 – 2015) were compared to historical climate data to assess the validity of the future climate projections. These study periods were selected to (1) provide verification of past known climatic conditions at the sites (i.e., past 65 years), (2) generate projections of near-term water availability for infrastructure planning decisions (i.e., 25-year planning horizon), and (3) assess far-term projections of water availability (i.e., 25 – 50-year planning horizon).

Evapotranspiration

Evapotranspiration was estimated for all the study sites using the Priestley and Taylor (1972) method according to Xu and Singh (2002) and Allen et al. (1998). Radiation was estimated from temperature data from historical datasets and climate model projections. The Priestley-Taylor method incorporates an alpha coefficient (α), which represents physical evaporation processes as a lumped term. Commonly, α is assumed to be 1.26, which is a valid assumption when land conditions are wet or humid (Xu and Singh, 2002). In a review of ET in Arctic tundra environments, Eugster et al. (2000) reported that α ranged widely from 0.23 to 1.51 for tundra and boreal ecosystems. Intersystem variability of ET is attributed to various factors including vegetation cover, regional and microclimates, permafrost and soil moisture content (Liljedahl et al., 2011). Roulet and Woo (1986) emphasized that α should be treated exclusively as an empirical factor. Due to these complexities in Arctic environments, we calibrated α using streamflow data from several watersheds gauged by the Water Survey of Canada (WSC). The procedure involved optimization of α so that ET calculated from the Priestley-Taylor expression matched the actual evapotranspiration (AET, mm/year) estimates calculated from water balances represented by Equation 4:

$$AET = \frac{(P - Q)}{Area} * 1x10^3 \qquad \text{[Eq. 4]}$$

where P is volume of annual precipitation over the water year from 1 October to 30 September (m^3/year), Q is the cumulative volume of water discharged and measured at the hydrometric station over the water year (m^3/year), and area is the drainage area (m^2) gauged by the hydrometric station.

We performed the AET calibration routine on four Nunavut watersheds (Freshwater Creek near Cambridge Bay, Diana River near Rankin Inlet, Kirchoffer River near Coral Harbour, and the Apex River near Iqaluit) gauged by Environment and Climate Change Canada (GC, 2020c). Only years with sufficient climate and hydrometric data were used for the alpha calibration process. The calibrated α were averaged, which resulted in a value of 0.22 used throughout the water balance calculations.

Characterization of Water Shortage Risk

Since this was intended as a screening-level assessment of natural supply, a use-to-resource type index was used to characterize the relative risk of municipal water shortages. This simple metric, calculated as the percentage of water yield used for municipal demands, allows for cross-site comparison:

$$Water\ Use\ Percentage = \frac{(W_{use})}{(P - ET)} * 100 \qquad \text{[Eq. 5]}$$

A value of 40% or greater was characterized as high risk, values between 20% and 40% were characterized as medium risk, values of 10% to 20% were characterized as moderate risk, and values less than 10%, as low risk. These thresholds are often used in water stress indices (e.g., Raskin et al., 1997; Vörösmarty et al., 2005; OECD, 2009). Although these cut-offs were not specifically designed or validated for northern regions (GC, 2017), the vulnerability level thresholds were considered reasonable for evaluating relative vulnerabilities across the study communities. If a community is using greater than 40% of the total annual available water supply, before accounting for any other water storage infrastructure challenges, this should be considered a high vulnerability scenario.

Statistical Analysis

For each study period and climate scenario, the median water availability, 50-year return period minimum precipitation and maximum ET were determined. EasyFit 5.6 Professional statistical software was used to fit the annual time series to chosen probability distributions. The 50-year return period minimum precipitation was calculated by fitting each dataset to a lognormal probability density function. The 50-year return period maximum ET was calculated by fitting each dataset to a general extreme value probability density function.

A Mann-Kendall statistical test was performed on the historical precipitation and estimated evapotranspiration data as well as each of the hindcast climate datasets. The null hypothesis, which was no trend, was tested at the 95% confidence level for precipitation and evapotranspiration for all communities with complete historical datasets. This test was performed to verify whether the time series trends were statistically significant. The results of this test were then compared to the hindcast climate projections from the PCIC datasets to verify consistency in climate trends. The Mann-Kendall tests were performed with MATLAB R2015b and Microsoft Excel 2013 software packages according to the method described in Gocic and Trajkovic (2013). To be used in the statistical assessment, several criteria were applied to the datasets: a minimum length of 30 years; no more than three consecutive years of data missing, for a maximum of two occurrences; and a dataset which spans until at least the year 2000.

RESULTS AND DISCUSSION

Climate Projection Verification

Overall, the water availability estimates (P−ET) from GCM hindcasts compared well with the water availability calculated from the observed historical climate data. In Coral Harbour, for example, the percent differences between the GCM hindcast and historical median water availability were 2% for both CCSM4 and CNRM-CM5, 6% for CSIRO, and 9% for MRI. This result indicated that the selected models were appropriate to use in calculations for future projections of water availability.

The Mann Kendall statistical test generally indicated neutral trends in precipitation and increasing trends in evapotranspiration. Only three out of 14 communities showed a significant increase in historical precipitation: Coral Harbour, Naujaat, and Resolute (Fig. 2). Kimmirut was the only community to show a significant decrease in precipitation. Based on the PCIC hindcast datasets, 4 out of 24 communities had statistically increasing precipitation: Arctic Bay, Grise Fiord, Kugaaruk, and Resolute.

A total of 16 out of 20 communities had increasing trends in historical evapotranspiration (Fig. 3). The statistics performed on the PCIC hindcasts generally agreed, with significant increases in evapotranspiration detected in 22 out of 24 communities.

Water Use Percentages

The median water use percentage was calculated for each study period, water distribution method, and community. A vulnerability level was then computed for each GCM scenario and the highest percentage for each of the three study periods was identified (Table 2).

Based on the median values, 17% of communities will have high vulnerability to water scarcity before 2070, while 8% are at medium risk, 8% are at moderate risk, and 67% are low risk. Of the factors examined in this analysis, the dominant contributing factor to the vulnerability level was

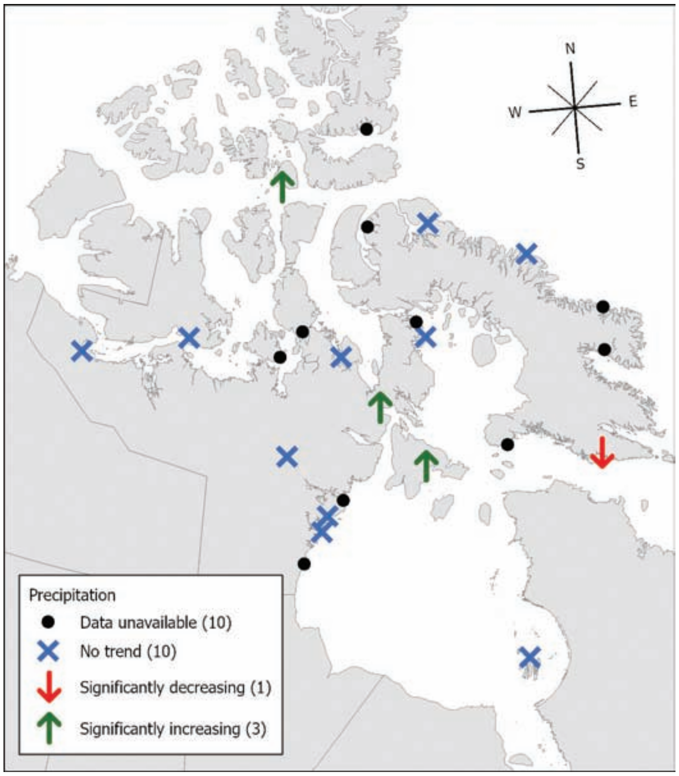

FIG. 2. Statistical trends in historical precipitation datasets from Environment Canada.

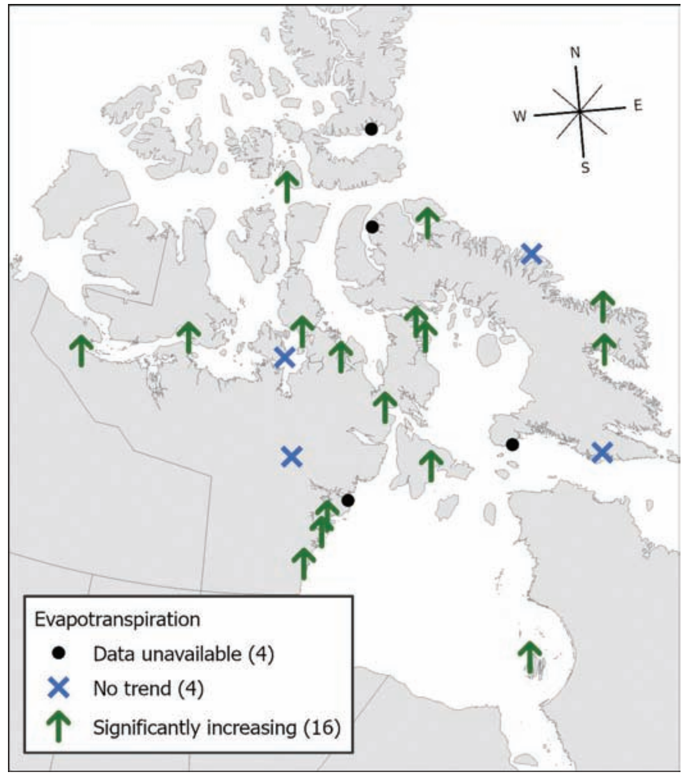

FIG. 3. Statistical trends in evapotranspiration based on historical data.

TABLE 2. Water shortage threat levels based on median water availability estimates. Bold text = high vulnerability (> 40% water usage), red text = medium vulnerability (20–40% water usage), blue text = moderate vulnerability (10–20% water usage), and regular text = low vulnerability (<10% water usage).

Community	Water use %					
	Historical		2016–40		2041–70	
	Trucked	Piped	Trucked	Piped	Trucked	Piped
Arctic Bay[1]	< 1	< 1	< 1	< 1	< 1	< 1
Arviat	< 1	< 1	< 1	< 1	< 1	1.1
Baker Lake	< 1	< 1	< 1	< 1	< 1	< 1
Cambridge Bay	36	**90**	30	**74**	39	**98**
Cape Dorset	30	**75**	**45**	**112**	**67**	**168**
Chesterfield Inlet	< 1	< 1	< 1	1.2	< 1	1.9
Clyde River	**40**	**101**	**61**	**151**	**89**	**223**
Coral Harbour	< 1	< 1	< 1	< 1	< 1	< 1
Gjoa Haven	5.5	14	9.5	18	13	29
Grise Fiord	13	33	16	**41**	17	**42**
Hall Beach	1.4	3.4	3.6	8.9	7.1	18
Igloolik	27	**67**	**67**	**167**	**108**	**271**
Kimmirut	< 1	1.5	< 1	1.8	1.4	2.1
Kugaaruk	< 1	< 1	< 1	< 1	< 1	< 1
Kugluktuk	< 1	< 1	< 1	< 1	< 1	< 1
Naujaat	< 1	1.7	1.6	3.9	5.2	11
Pangnirtung	< 1	< 1	< 1	1.5	< 1	1.8
Pond Inlet	1.6	4.1	3	7.4	4.3	11
Qikiqtarjuaq	< 1	1.1	< 1	1.2	< 1	1.5
Rankin Inlet Char	< 1	1.9	1.6	3.9	2.7	6.6
Nipissar	19	**48**	**40**	**99**	**67**	**166**
Resolute	2.3	5.8	1.8	4.6	2	4.9
Sanikiluaq	< 1	< 1	< 1	1.7	1.6	3
Taloyoak	10	25	18	46	28	**69**
Whale Cove	2.8	7.1	4.9	12	7.9	20

TABLE 3. Water shortage threat levels based on 50-year return period minimums. Bold text = high vulnerability (> 40% water usage), red text = medium vulnerability (20 – 40% water usage), blue text = moderate vulnerability (10 – 20% water usage), and regular text = low vulnerability (<10% water usage).

Community	Water use %					
	Historical		2016 – 40		2041 – 70	
	Trucked	Piped	Trucked	Piped	Trucked	Piped
Arctic Bay[1]	**100**	**100**	< 1	1.7	< 1	1.3
Arviat	< 1	< 1	< 1	1.0	< 1	1.9
Baker Lake	< 1	< 1	< 1	< 1	< 1	< 1
Cambridge Bay	**110**	**276**	**91**	**228**	**95**	**236**
Cape Dorset	**51**	**128**	**73**	**183**	**114**	**284**
Chesterfield Inlet	1.2	2.9	1.2	3.0	1.6	4.1
Clyde River	**250**	**626**	**123**	**308**	**170**	**424**
Coral Harbour	< 1	< 1	< 1	< 1	< 1	1
Gjoa Haven	17	**43**	28	**54**	30	**66**
Grise Fiord	39	**97**	32	**80**	30	**76**
Hall Beach	3.8	9.5	7.1	18	12	31
Igloolik	**52**	**130**	**134**	**334**	**191**	**478**
Kimmirut	1.2	2.9	1.1	2.7	2.1	3.0
Kugaaruk	< 1	< 1	< 1	< 1	< 1	< 1
Kugluktuk	< 1	< 1	< 1	< 1	< 1	< 1
Naujaat	1.2	3.1	2.7	6.7	7.5	16
Pangnirtung	< 1	1.9	1.3	3.2	1.4	3.5
Pond Inlet	7.0	17	5.2	13	10	25
Qikiqtarjuaq	< 1	2.3	1.1	2.7	1.1	2.9
Rankin Inlet Char	1.4	3.6	3.3	8.2	5.1	13
Nipissar	36	**91**	**82**	**205**	**127**	**318**
Resolute	13.1	33	3.7	9.3	3.5	8.7
Sanikiluaq	< 1	1.3	1.1	2.7	2.3	4.4
Taloyoak	**51**	**128**	**48**	**121**	**61**	**152**
Whale Cove	5.4	14	10	25	15	38

[1] Arctic Bay was classed as high vulnerability of water shortage based on one extreme year of low precipitation in combination with high ET. Future climate projections did not produce these extreme low precipitation values.

the size of the watershed, which ranged in area from less than 27 ha to 24 million ha. Source water vulnerability corresponds largely with watershed area and increased as the watershed area decreased. The four communities with high vulnerability years had source watersheds ranging in size from 57 to 269 ha. Conversely, Baker Lake utilized less than 1% of the water available and withdrew from the largest watershed of 24 million ha.

Water use percentages were also calculated using estimates of 50-year return period minimum precipitation and maximum evapotranspiration. Again, the vulnerability level was identified based on the most conservative predictions from the four GCM scenarios for each study period (Table 3). As expected, the results obtained from the 50-year return period analysis displayed an increase in vulnerability levels compared to the median water use percentage results. Approximately 25% of the study sites were projected to experience high vulnerability by 2070. The percentage of study sites displaying medium and moderate levels were 8% and 12%, respectively. Finally, 55% of the communities were determined to have a low vulnerability level to 2070. The results for Arctic Bay were interesting, as the historical analysis generated a water use percentage of 100% (high vulnerability), while the two future time periods generated values of less than 1% (low vulnerability). The historical climate records were examined to identify the reason for this variability, and it was attributed to a single year with very low recorded precipitation (1965; 52.1 mm). Future climate projections did not produce any annual precipitation estimates this low.

Figures 4, 5, and 6 illustrate the geographic trends in vulnerability levels associated with water availability across the territory for historical conditions, for 2016 – 40, and for 2041 – 70, respectively for the 50-year probability estimates. Generally, the geographic distribution of communities that have high vulnerability do not show clear spatial trends, although these communities tend to be in the mid to high Arctic. As previously discussed, the most influential factor appears to be the size of the source watershed—sites drawing from sources in watersheds with a smaller surface area appeared to be more frequently subjected to concerning water use percentages. In general, water use percentages were observed to increase with time (Tables 3 and 4), but these trends were not consistent across all communities.

Results from this study indicate that several communities in Nunavut are currently using greater than 40% of the available water on an annual basis from their source watersheds, and that these water use percentages will generally increase in the future. This is the first time that water budgets have been computed and compared across Nunavut. The results have illustrated that even with improved water access/storage infrastructure, several communities will also need to look for new source

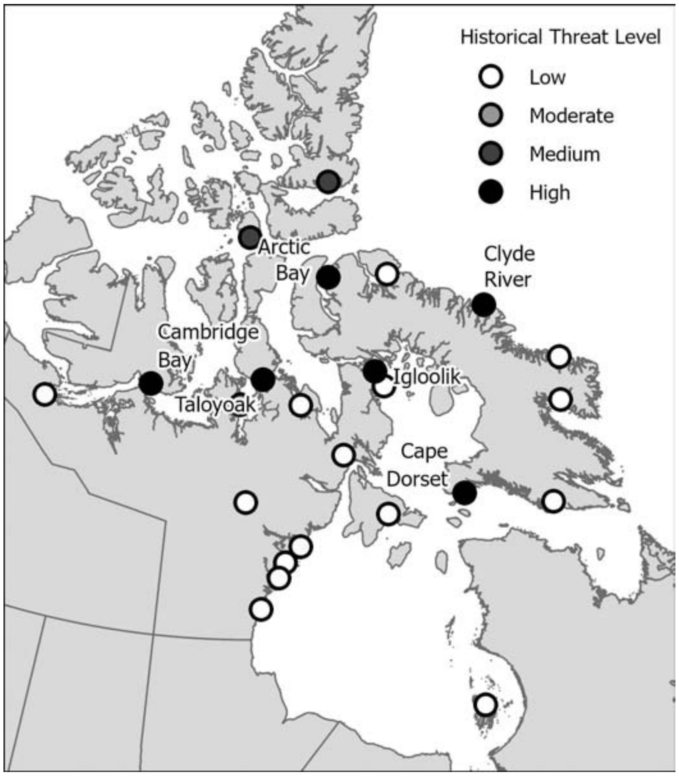

FIG. 4. Historical water shortage threat map based on 50-year probability estimates.

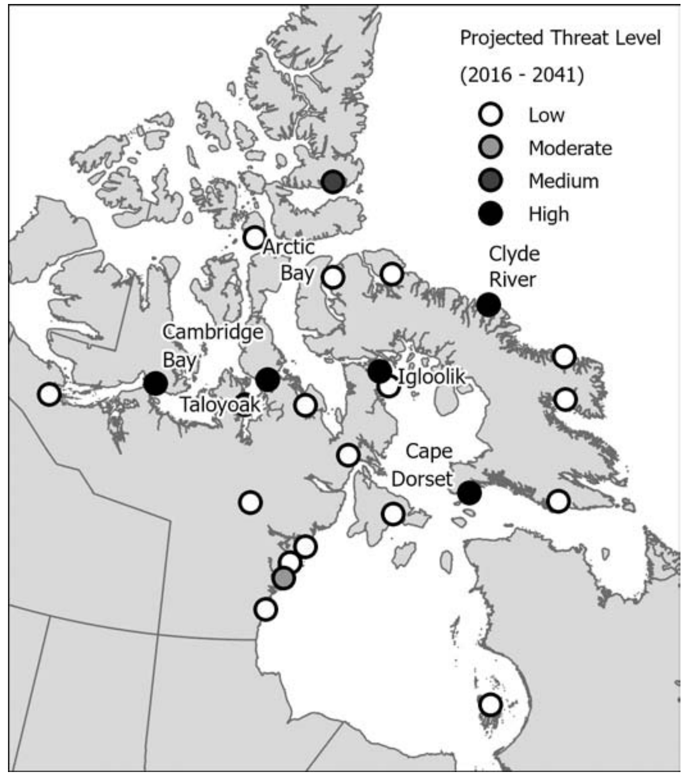

FIG. 5. Projected water shortage threat map for 2016–40 based on 50-year probability estimates.

watershed systems to supply their needs. We reiterate that this assessment only focused on the ability of the source watershed to supply adequate water volumes on an annual basis and did not include an analysis of the storage infrastructure, seasonality in water availability, or deviations in water usage from standard planning and design assumptions. There may be communities where the capacity or integrity of the storage system, either a reservoir or lake, may cause potential water supply vulnerability, especially during the winter months (Medeiros et al., 2017).

The type of water infrastructure used in the community for water distribution (i.e., trucked vs. piped) also affects the level of vulnerability in some communities, as trucked water distribution systems have lower water demands. Increased demand from piped distribution infrastructure should be taken into consideration when making decisions regarding infrastructure changes to ensure that existing source watersheds can supply the increased demand. The results from this study generally reinforce findings from previous studies that source water supply quantities may not be sufficient in some northern communities (Goldhar et al., 2014; Bakaic and Medeiros, 2016; Bakaic et al., 2018).

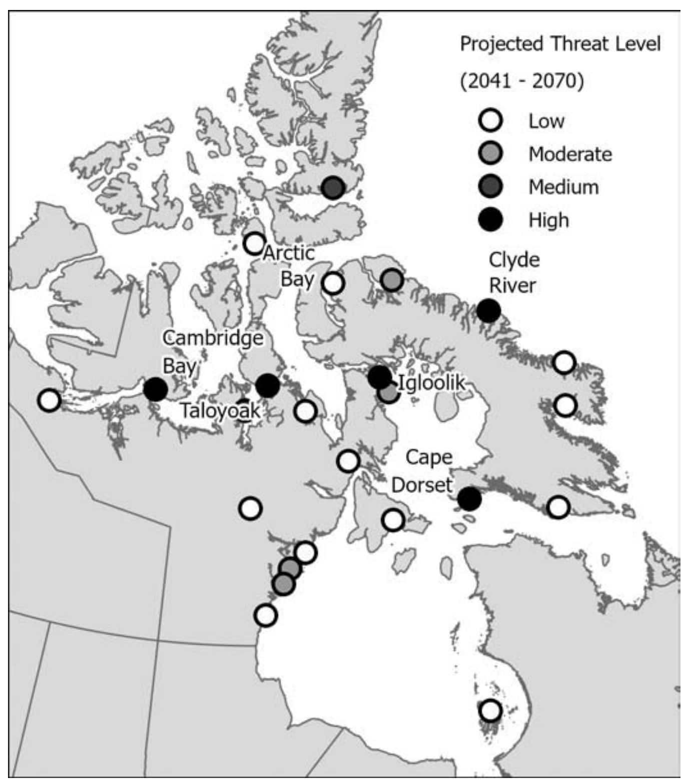

FIG. 6. Projected water shortage threat map for 2041–70 based on 50-year probability estimates.

CONCLUSIONS

This study has generated the first inventory of source watersheds used for community water supplies in Nunavut. The findings indicate that several Nunavut communities currently have source watersheds that are insufficient for supplying their current or future water demands. The vulnerability to water shortage was assessed based on median water balance estimates, as well as 50-year return period minimum water availability estimates. The 50-year return period estimates provide a more realistic and conservative assessment of which communities may be at risk. Using historical climate records, when the 50-year low precipitation and high ET scenarios were considered and assuming no changes in the water delivery system, we classified seven communities as high vulnerability (i.e., using more than 40% of annual water availability). When future conditions were considered, six communities were classed as having high vulnerability to water shortages. In general, water use percentages were projected to increase in the future, although only minor changes were observed in vulnerability levels when comparing historical and future scenarios. Four communities changed from low to moderate vulnerability levels for the worst-case (i.e., 50-year probabilities) future scenarios.

We recommend that efforts be focused on identifying either new or backup water supply watersheds for communities with high, medium, and moderate vulnerability classifications. This study has provided a screening-level methodology for ranking source water vulnerability in multiple communities to identify potential water scarcity problems with consideration of changing climate and demographics. This type of planning tool will be useful for managers of territorial drinking water infrastructure and may be transferrable to other northern Canadian and international jurisdictions.

This study only looked at one component of water supply systems in Nunavut, the source watersheds, and further work should be conducted to evaluate other factors (e.g., storage and distribution infrastructure) that could also contribute to water security risks. We also recommend that additional hydrometric monitoring be undertaken in source watersheds to better understand hydrologic variability in these systems and to allow for further validation of water balance models.

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REFERENCES

Alessa, L., Kliskey, A., Lammers, R., Arp, C., White, D., Hinzman, L., and Busey, R. 2008. The Arctic water resource vulnerability index: An integrated assessment tool for community resilience and vulnerability with respect to freshwater. Environmental Management, 42(3): 523.
https://doi.org/10.1007/s00267-008-9152-0

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy: Food and Agriculture Organization of the United Nations.
http://www.fao.org/3/X0490E/X0490E00.htm

Bakaic, M., and Medeiros, A.S. 2016. Vulnerability of northern water supply lakes to changing climate and demand. Arctic Science 3(1):1–16.
https://doi.org/10.1139/as-2016-0029

Bakaic, M., Medeiros, A.S., Peters, J.F., and Wolfe, B.B. 2018. Hydrologic monitoring tools for freshwater municipal planning in the Arctic: The case of Iqaluit, Nunavut, Canada. Environmental Science and Pollution Research 25(33):32913–32925.
https://doi.org/10.1007/s11356-017-9343-4

Bakker, K. 2012. Water security: Research challenges and opportunities. Science 337(6097):914–915.
https://doi.org/10.1126/science.1226337

Cisneros, J.B.E., Oki, T., Arnell, N.W., Benita, G., Cogley, J.G., Döll, P., Jiang, T., and Mwakalila, S.S. 2014. Freshwater resources. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., et al., eds. Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. 229–269.

Cook, C., and Bakker, K. 2012. Water security: Debating an emerging paradigm. Global Environmental Change 22(1):94–102.
https://doi.org/10.1016/j.gloenvcha.2011.10.011

Daley, K., Castleden, H., Jamieson, R., Furgal, C., and Ell, L. 2014. Municipal water quantities and health in Nunavut households: An exploratory case study in Coral Harbour, Nunavut, Canada. International Journal of Circumpolar Health 73(1): 23843.
https://doi.org/10.3402/ijch.v73.23843

Daley, K., Truelstrup Hansen, L., Jamieson, R.C., Hayward, J.L., Piorkowski, G.S., Krkosek, W., Gagnon, G.A., et al. 2017. Chemical and microbial characteristics of municipal drinking water supply systems in the Canadian Arctic. Environmental Science and Pollution Research 25:32926–32937.
https://doi.org/10.1007/s11356-017-9423-5

Dudarev, A.A., Dushkina, E.V., Sladkova, Y.N., Alloyarov, P.R., Chupakhin, V.S., Dorofeyev, V.M., et al. 2013. Food and water security issues in Russia II: Water security in general population of Russian Arctic, Siberia and Far East, 2000–2011. International Journal of Circumpolar Health 72(1): 22646.
https://doi.org/10.3402/ijch.v72i0.22646

Dunn, G., and Bakker, K. 2011. Fresh water-related indicators in Canada: An inventory and analysis. Canadian Water Resources Journal 36(2):135–148.
https://doi.org/10.4296/cwrj3602815

Engstrom, R.N., Hope, A.S., Stow, D.A., Vourlitis, G.L., and Oechel, W.C. 2002. Priestley-Taylor alpha coefficient: Variability and relationship to NDVI in Arctic tundra landscapes. JAWRA Journal of the American Water Resources Association 38(6):1647–1659.
https://doi.org/10.1111/j.1752-1688.2002.tb04371.x

Environment Canada. 2011. Data sources and methods for the water availability indicator. Ottawa, Ontario: Government of Canada.
http://www.publications.gc.ca/collections/collection_2012/ec/En4-144-30-2011-eng.pdf

Eugster, W., Rouse, W.R., Pielke, R.A., Sr., McFadden, J.P., Baldocchi, D.D., Kittel, T.G.F., Chapin, F.S., III, et al. 2000. Land-atmosphere energy exchange in Arctic tundra and boreal forest: Available data and feedbacks to climate. Global Change Biology 6(S1):84 – 115.
https://doi.org/10.1046/j.1365-2486.2000.06015.x

Evengard, B., Berner, J., Brubaker, M., Mulvad, G., and Revich, B. 2011. Climate change and water security with a focus on the Arctic. Global Health Action 4(1): 8449.
https://doi.org/10.3402/gha.v4i0.8449

GC (Government of Canada). 2017. Water availability, indicator initiative. Water quantity. Ottawa, Ontario: Environment Canada, GC.
https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity.html

———. 2020a. Geospatial data extraction. GeoGratis. Ottawa, Ontario: Natural Resources Canada, GC.
https://www.nrcan.gc.ca/topographic-information/10785

———. 2016b. Historical climate data. Ottawa, Ontario: Environment Canada, GC.
http://www.climate.weather.gc.ca

———. 2020c. Historical hydrometric data search. Water level and flow. Ottawa, Ontario: Environment and Natural Resources.
https://wateroffice.ec.gc.ca/index_e.html

GN (Government of Nunavut). 2012. Nunavut census population by region and community, 1981 to 2011 censuses. Iqaluit: Nunavut Bureau of Statistics.
http://www.stats.gov.nu.ca/en/Census.aspx

———. 2014. Nunavut population projections by region and community, 2014 to 2035. Iqaluit: Nunavut Bureau of Statistics.
http://www.stats.gov.nu.ca/en/Population%20projections.aspx

Gocic, M., and Trajkovic, S. 2013. Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. Global and Planetary Change 100:172 – 182.
https://doi.org/10.1016/j.gloplacha.2012.10.014

Goldfarb, D.M., Dixon, B., Moldovan, I., Barrowman, N., Mattison, K., Zentner, C., Baikie, M., Bidawid, S., Chan, F., and Slinger, R. 2013. Nanolitre real-time PCR detection of bacterial, parasitic, and viral agents from patients with diarrhoea in Nunavut, Canada. International Journal of Circumpolar Health 72(1): 19903.
https://doi.org/10.3402/ijch.v72i0.19903

Goldhar, C., Bell, T., and Wolf, J. 2014. Vulnerability to freshwater changes in the Inuit settlement region of Nunatsiavut, Labrador: A case study from Rigolet. Arctic 67(1):71 – 83.
https://doi.org/10.14430/arctic4365

Heinke, G.W., Smith, D.W., and Finch, G.R. 1991. Guidelines for the planning and design of wastewater lagoon systems in cold climates. Canadian Journal of Civil Engineering 18:556 – 567.
https://doi.org/10.1139/l91-068

Hinzman, L.D., Bettez, N.D., Bolton, W.R., Chapin, F.S., Dyurgerov, M.B., Fastie, C.L., Griffith, B., et al. 2005. Evidence and implications of recent climate change in northern Alaska and other Arctic regions. Climatic Change 72:251 – 298.
https://doi.org/10.1007/s10584-005-5352-2

Instanes, A., Kokorev, V., Janowicz, R., Bruland, O., Sand, K., and Prowse, T. 2016. Changes to freshwater systems affecting Arctic infrastructure and natural resources. Journal of Geophysical Research: Biogeosciences 121(3):567 – 585.
https://doi.org/10.1002/2015JG003125

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. Cambridge, United Kingdom and New York: Cambridge University Press.
https://www.ipcc.ch/report/ar5/wg1/

Johnson, K. 2007. The social context of wastewater management in remote communities. Proceedings of the Annual Conference of the Western Canada Water and Waste Association, 23 – 26 October 2007, Edmonton, Alberta.
https://issuu.com/cryofront/

———. 2008. A brief history of the past 60 years of northern water and waste. Proceedings of the Annual Conference of Western Canada Water and Waste Association, 23 – 26 September 2008, Regina, Saskatchewan.
https://issuu.com/cryofront/

———. 2017. Nunavut's water: An abundant resource in short supply. Cyrofront – News, views and muse from the Arctic. Western Canada Water 69(3):61 – 63.
https://cdn.ymaws.com/www.wcwwa.ca/resource/resmgr/magazine/wcw_fall2017.pdf

Larsen, J.N., Anisimov, O.A., Constable, A., Hollowed, A.B., Maynard, N., Prestrud, P., Prowse, T.D., and Stone, J.M.R. 2014. Polar regions. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., et al., eds. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. 1567 – 1612.

Liljedahl, A.K., Hinzman, L.D., Harazono, Y., Zona, D., Tweedie, C.E., Hollister, R.D., Engstrom, R., and Oechel, W.C. 2011. Nonlinear controls on evapotranspiration in Arctic coastal wetlands. Biogeosciences 8(11):3375 – 3389.
https://doi.org/10.5194/bg-8-3375-2011

Liston, G.E., and Sturm, M. 2004. The role of winter sublimation in the Arctic moisture budget. Nordic Hydrology (Hydrology Research) 35(4-5):325 – 334.
https://doi.org/10.2166/nh.2004.0024

Loring, P.A., Gerlach, S.C., and Huntington, H.P. 2013. The new environmental security: Linking food, water, and energy for integrative and diagnostic social-ecological research. Journal of Agriculture, Food Systems, and Community Development 3(4):55 – 61.
https://doi.org/10.5304/jafscd.2013.034.005

Maidment, D.R., ed. 2002. Arc Hydro: GIS for water resources. Redlands, California: ESRI Inc.

Medeiros, A.S., Wood, P., Wesche, S.D., Bakaic, M., and Peters, J.F. 2017. Water security for northern peoples: Review of threats to Arctic freshwater systems in Nunavut, Canada. Regional Environmental Change 17(3):635 – 647. https://doi.org/10.1007/s10113-016-1084-2

Mendez, J., Hinzman, L.D., and Kane, D.L. 1998. Evapotranspiration from a wetland complex on the Arctic coastal plain of Alaska. Hydrology Research 29(4-5):303 – 330. https://doi.org/10.2166/nh.1998.0020

OECD (Organisation for Economic Co-operation and Development). 2009. Managing water for all, an OECD perspective on pricing and financing. Paris, France: OECD. https://www.oecd.org/env/resources/managingwaterforallanoecdperspectiveonpricingandfinancing.htm

PCIC (Pacific Climate Impacts Consortium). 2016. Statistically downscaled climate scenarios: Data portal. Victoria, British Columbia: PCIC. https://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios

Plummer, R., de Loë, R., and Armitage, D. 2012. A systematic review of water vulnerability assessment tools. Water Resources Management 26(15):4327 – 4346. https://doi.org/10.1007/s11269-012-0147-5

Priestley, C.H.B., and Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100(2):81 – 92. https://doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2

Raskin, P., Gleick, P., Kirshen, P., Pontius, G., and Strzepek, K. 1997. Comprehensive assessment of the freshwater resources of the world: Water futures: Assessment of long-range patterns and problems. Report prepared for the Commission for Sustainable Development, 5th session. Stockholm, Sweden: Stockholm Environmental Institute. https://mediamanager.sei.org/documents/Publications/SEI-Report-WaterFutures-AssessmentOfLongRangePatternsAndProblems-1997.pdf

Roulet, N.T., and Woo, M.-K. 1986. Wetland and lake evaporation in the low Arctic. Arctic and Alpine Research 18(2):195 – 200. https://doi.org/10.2307/1551129

Sheffield, J., Barrett, A.P., Colle, B., Nelun Fernando, D., Fu, R., Geil, K.L., Hu, Q., et al. 2013. North American climate in CMIP5 experiments. Part I: Evaluation of historical simulations of continental and regional climatology. Journal of Climate 26(23):9209 – 9245. https://doi.org/10.1175/JCLI-D-12-00592.1

Smith, D.W., and Emde, K.M.E. 1999. Effectiveness of wastewater lagoons in cold regions. In: Margesin, R., and Schinner, F., eds. Biotechnological applications of cold-adapted organisms. Berlin and Heidelberg: Springer. 235 – 256. https://doi.org/10.1007/978-3-642-58607-1_16

Statistics Canada. 2017. Nunavut [Federal electoral district], Nunavut and Nunavut [Territory] table. Census Profile. 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa, Ontario: Statistics Canada. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E

Vörösmarty, C.J., Douglas, E.M., Green, P.A., and Revenga, C. 2005. Geospatial indicators of emerging water stress: An application to Africa. Ambio: A Journal of the Human Environment 34(3):230 – 236. https://doi.org/10.1579/0044-7447-34.3.230

Ward, J.D., Werner, A.D., Nel, W.P., and Beecham, S. 2011. The influence of constrained fossil fuel emissions scenarios on climate and water resource projections. Hydrology and Earth Systems Sciences 15(6):1879 – 1893. https://doi.org/10.5194/hess-15-1879-2011

Williams, P., Kliskey, A., McCarthy, M., Lammers, R., Alessa, L., and Abatzoglou, J. 2019. Using the Arctic water resources vulnerability index in assessing and responding to environmental change in Alaskan communities. Climate Risk Management 23:19 – 31. https://doi.org/10.1016/j.crm.2018.09.001

Xu, C.-Y., and Singh, V.P. 2002. Cross comparison of empirical equations for calculating potential evapotranspiration with data from Switzerland. Water Resources Management 16(3):197 – 219. https://doi.org/10.1023/A:1020282515975