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WATER, SANITATION, POLLUTION AND HEALTH IN THE ARCTIC

Hydrologic monitoring tools for freshwater municipal planning in the Arctic: the case of Iqaluit, Nunavut, Canada

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Abstract Freshwater and the services it provides are vital to both natural ecosystems and human needs; however, extreme climates and their influence on freshwater availability can be challenging for municipal planners and engineers to manage these resources effectively. In Arctic Canada, financial and human capital limitations have left a legacy of freshwater systems that underserve current communities and may be inadequate in the near future under a warming climate, growing population, and increasing demand. We address this challenge to community water resource planning by applying several novel water supply forecasting methods to evaluate the Apex River as an alternative freshwater source for Iqaluit, Nunavut (Canada). Surveys of water isotope composition of the Apex River and tributaries indicated that rainfall is the main source of water replenishment. This information was utilized to calibrate a water resource assessment that considered climate forecasting scenarios and their influence on supply, and alternative scenarios for freshwater management to better adapt to a changing climate. We found that under current climate and demand conditions, the freshwater supply of Iqaluit would be in a perpetual state of drawdown by 2024. Analysis of current infrastructure proposals revealed significant deficiencies in the supply extensions proposed whereby the Apex replenishment pipeline would only provide a 2-year extension to current municipal supply. Our heuristic supply forecast methods allowed for several alternative supply strategies to be rapidly evaluated, which will aid the community planning process by specifically quantifying the service life of the city's current and future primary water supply.

Keywords Freshwater modeling · Arctic · Water security · Water resource assessment

Introduction

Clean, affordable, and accessible freshwater is a key resource for all inhabitants of Arctic regions, forming a core component of cultural connections, ecological services, and economic well-being (Gearheard et al. 2010). However, many Arctic communities in Canada depend on a single, small shallow lake reservoir or temporary seasonal replenishment systems. Climate change has the potential to strongly influence northern freshwater ecosystems (Prowse et al. 2006) and their viability for supporting Arctic communities. Therefore, there is a need to evaluate and quantify the influence of changing climate conditions on the sustainability of freshwater supply, especially for communities in remote Arctic regions that have limited access to large reservoirs of freshwater (Instanes et al. 2016).

Temperatures in the Arctic have increased almost twice the global rate of warming during recent decades and are expected to increase an additional 4–7 °C during the next century (Trenberth et al. 2007). Arctic lakes are particularly sensitive as snowmelt, ice cover, evaporation, and thermal stability are easily altered by warming (Medeiros and Quinlan 2011;

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Medeiros et al. 2017). Ice also plays a vital role in limnological and hydrological processes in Arctic regions (Prowse and Brown 2010). Loss and reduced duration of ice cover are expected to lead to greater evaporative stress (Brown and Duguay 2010). As evaporative drawdown intensifies, snowmelt runoff is likely to be of increased importance for replenishing shallow lakes (Bouchard et al. 2013). However, the amount of snow, and thus the amount of snowmelt runoff, is expected to decline for some regions (Derksen and Brown 2012) and is expected to be highly variable elsewhere (Prowse et al. 2011; Krasting et al. 2013). Bouchard et al. (2013) note that reduced snowfall has led to near to complete desiccation of lakes in both central and western Arctic regions of Canada. As such, the availability, quality, and security of freshwater in Canada's Arctic regions have become a pressing issue and of increasing concern among Arctic communities (Prowse et al. 2015; Bakaic and Medeiros 2017; Medeiros et al. 2017).

Iqaluit, the capital of the Canadian Arctic territory of Nunavut, is dependent on a local dammed reservoir, Lake Geraldine, to support over 7500 residents. The capacity of Lake Geraldine is estimated to supply up to 8300 people at the current usage rate (City of Iqaluit 2010); however, the city is undergoing rapid growth that has city managers examining alternative freshwater sources. In 2010, the municipal government identified measures to protect the Niaqunguk River watershed (also known as the Apex River) as a supplemental source of freshwater (City of Iqaluit 2010). Obradovic and Sklash (1986) examined the Apex River watershed and found that subsurface flow from snowmelt runoff was an important contributor, as well as contributions of subsurface flow fed by supra-permafrost groundwater. However, it is uncertain how evaporation influences the water balance in this watershed, yet is imperative for long-term resource planning. Furthermore, the study by Obradovic and Sklash (1986) was conducted over 30 years ago and the regional climate has changed considerably since then (Medeiros et al. 2012; Bakaic and Medeiros 2017).

Forecasting the influence of a changing climate on the contributions from precipitation to northern watersheds is essential to design and manage a municipal water supply. Hydrologic simulations can be carried out by translating precipitation forecasts into runoff forecasts (Staudenmaier 1996), or through integrated watershed simulation models (Bekele and Knapp 2010; Deb et al. 2015); however, these models depend on multiple assumptions made on the relative contribution of snowmelt versus rainfall and their influence on water budgets for any particular year. As Arctic landscapes are much more sensitive to alterations in the seasonal cycle of precipitation and may heavily rely on late-lying snowmelt as the primary mechanism for flow (Obradovic and Sklash 1986; Woo and Young 2006), the relative contributions of snowmelt versus rainfall are essential for accurately predicting the sustainability of Arctic water supply under a changing climate.

Although freshwater managers have identified the Apex River as a potential source for freshwater replenishment of the supply for Iqaluit, Nunavut, there is currently no mechanism to assess the viability of this source to provide a sustainable supply under increased demand and a changing climate. To address this knowledge gap, we employ the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) informed by water isotope tracers to (1) identify, characterize, and model mechanisms for freshwater replenishment; (2) examine multiple climate forecasting scenarios and their influence on supply; and (3) examine alternative scenarios for freshwater management to better adapt to a changing climate. By examining historic climate and river flow, we generate a hydrologic model of the Apex River to predict flow through 2035 and generate forecasts of the sustainability of the freshwater supply for Iqaluit under supplemental replenishment scenarios. We utilize this as a demonstration and evaluation of how these methods can better inform freshwater planning to quantify the needs of municipal freshwater supply in a warming future.

Methods

Study area

Iqaluit is located on the southern part of Baffin Island (Fig. 1) and has experienced a 40% increase in population (~7543 in 2015) since the creation of the territory in 1999 (Nunavut Bureau of Statistics 2016). The Apex River watershed is situated on a fluvial plain and is surrounded by undulating rocky hills (Samuelson 1998; Poland et al. 2001). The watershed consists of many lakes of varying size and depth, as well as the Apex River, which discharges into Koojesse inlet about 3 km from Iqaluit. The landscape has vegetation typical of tundra environments including tundra plants, mosses, herbs, and shrubs (Obradovic and Sklash 1986).

Climate and demand forecasts

A water resource assessment was conducted that integrated meteorological data and municipal water consumption with heuristic climate projections to produce a 20-year quantitative analysis on the sustainability of the municipal water supply of Iqaluit (Fig. 1). The timeframe of this assessment was chosen as a municipal planning horizon to which water managers and decision makers could readily quantify the effect of infrastructure proposals on the sustainability of the

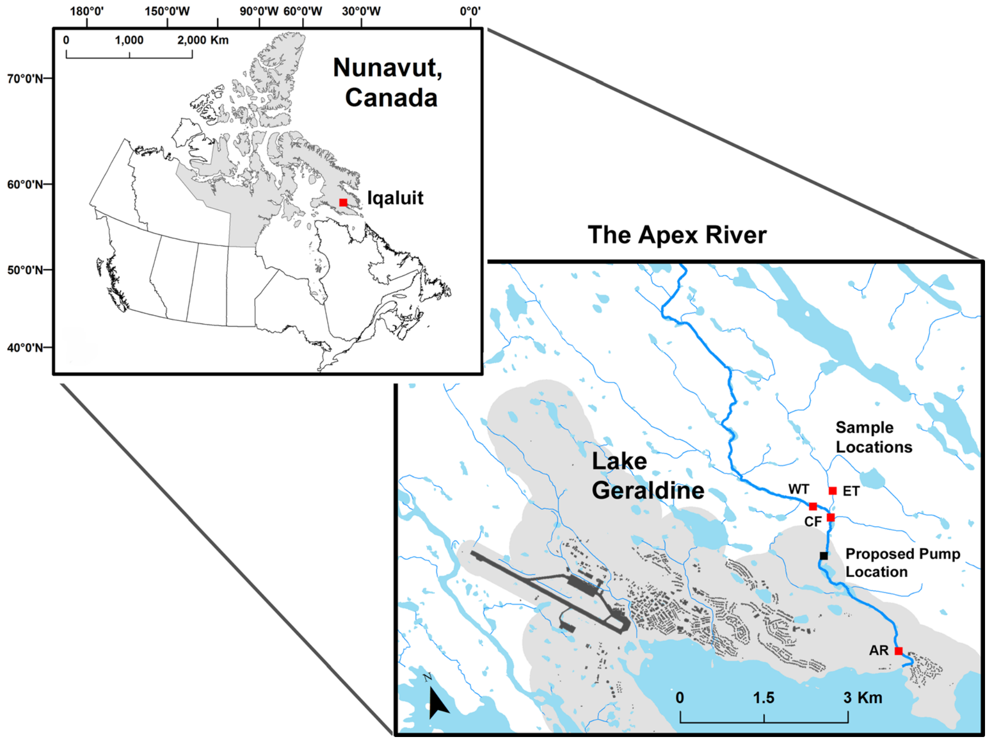

Fig. 1 The Apex River, Nunavut. Location to supplement the freshwater supply of Lake Geraldine (*black square*) and sampling sites for water isotope analysis are indicated (*red squares*). *WT* western tributary, *ET* eastern tributary, *CF* confluence zone, *AR* Apex River mouth

municipal water supply under plausible climate and demand conditions based on current meteorological trends and plausible climate scenarios. Three climate parameters were forecasted: air temperature, snowfall, and rainfall. Three scenarios of climate were considered: low, normal, and high (Table 1). Each scenario represented either the normalized trend (normal) calculated from local meteorological data or a plausible condition outlined in the Representative Concentration Pathway (RCP) 75th percentile trajectory for Nunavut (Environment and Climate Change Canada 2016a). Meteorological data was collected from Environment and Climate Change Canada (2016b). From this dataset, a 30-year climate normal (1981–2011) for average annual air temperature and the average number of days of snowfall and rainfall were calculated (see Bakaic and Medeiros 2017). The average air temperature for Iqaluit has significantly increased ($r^2 = 0.2$, $p < 0.01$) at 0.7 °C per decade since 1981 (Fig. 2). From this, we generated forecasts of climate using 0.7 °C per decade as the 'normal' condition and 0.4 and 1.1 °C per decade as the 'low' and 'high' condition, respectively. Total snowfall and rainfall projections for Iqaluit were compared to rates of change forecast from the RCP 75th percentile trajectory for a high emission scenario for Nunavut (Environment and Climate Change Canada 2016a). Municipal consumption was included as a demand factor and represented a composite of population and daily per capita consumption. The observed average consumption was reported as 352 litres per capita per day (LCD), which reflected the total withdrawal for residential, institutional, and industrial uses (Bakaic and Medeiros 2017). The 'high' and 'low' consumption scenarios were based on a 15% increase in consumption and a 15% reduction in observed consumption, respectively. Together, these four parameters with their three levels of forecast present 81 unique scenarios to simulate the volume of accessible water for municipal consumption in both the Apex River and Lake Geraldine, thereby informing water managers on the influence of various climate, demand, or infrastructure conditions may have on future municipal water supply.

Table 1 Climate and demand settings for the water resource assessment of the Apex River, Nunavut. Plausible future conditions projected for the lower boundary of trends using a linear interpolation of meteorological data ('low'), the observed trends using meteorological data ('normal'), and the IPCC Global Climate Model for Canada's 75th percentile Representative Concentration Pathway (RCP) under a high emission scenario ('high'). Table adapted from Bakaic and Medeiros (2017)

Parameter		Low Boundary	Normal Observed	High RCP 8.5
Air temp	(°C/dec)	0.40	0.70	1.10
Snowfall	(%/dec)	1.80	0	9.35
Rainfall	(%/dec)	−6.90	0	5.60
Demand	(LCD)	299	352	401
Growth	(%/year)	2.04	2.87	3.38

LCD litres per capita per day, *%/dec* percent change per decade

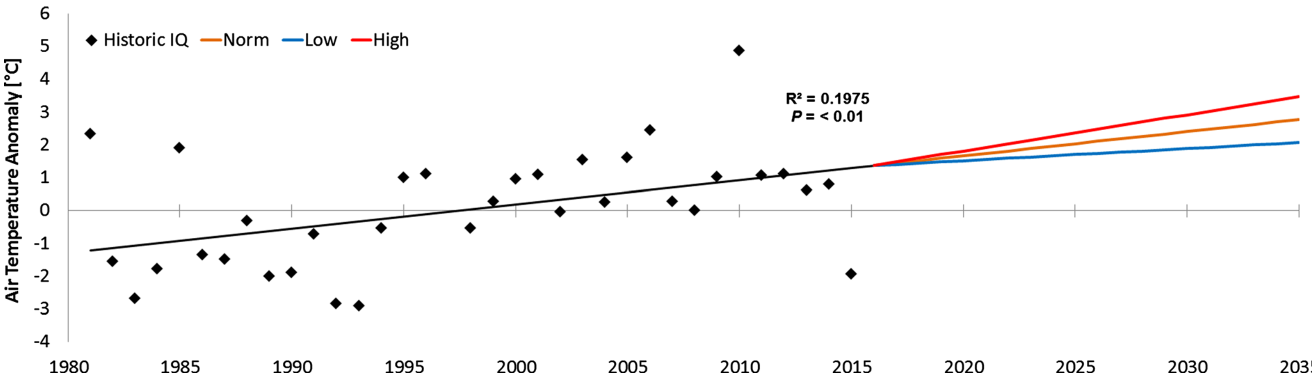

Fig. 2 Air temperature record from Iqaluit, Nunavut 1981–2015 with projected climate scenarios as described in Table 1. The significance of the trend is indicated by a Mann-Kendall analysis ($p < 0.01$)

Hydrometric data: Apex River

Discharge data from 1973 to 1986, and discharge and stage data from 2007 to 2014, were available from a hydrometric station near the mouth of the Apex River supplied by the Water Survey of Canada (2016). Proposals for alternative replenishment of Lake Geraldine from the Apex River are upstream of the hydrometric station, and their historical discharge values were approximated by the ratio of contributing watershed areas. A pumping season starting on July 1 and ending on September 30 would be appropriate for this location (exp Services Inc. 2014). This timing avoids erratic discharges from snow freshet in June, as well as the sporadic conditions surrounding freeze-up in October. Using this period of 92 days from July 1 to September 30, a 'summer' period of historic data was delineated from annual values.

Water isotope sampling and analysis

In order to understand the relative contribution of snowmelt versus rainfall on Apex River flow, water isotope sampling was conducted in 2014. Surface water was sampled six times between May and late August 2014 from four locations along the Apex River and major tributaries (Fig. 1). Water was collected in 30-ml high-density polyethylene sample bottles that were triple rinsed with the sample water, and filled completely without headspace. In addition, rainfall samples were collected from rain events on June 5, July 6, July 21, and August 12, 2014. Snow samples were also collected on May 11, June 25, and June 29, 2014, and were stored in sealed zip lock bags. Once completely melted, snow samples were transferred into sample bottles.

Water samples were transported to the University of Waterloo Environmental Isotope Laboratory and analyzed to determine the oxygen and hydrogen isotope compositions using laser absorption technology. All isotope compositions values are expressed as δ values that represent deviation in parts per mil (‰) from Vienna Standard Mean Ocean Water (VSMOW) with an analytical uncertainty of ±0.2‰ for $\delta^{18}O$ and ±0.8‰ for $\delta^{2}H$.

Hydrological simulation

Hydrologic simulation of the Apex River Watershed was conducted using Hydrologic Engineering Center's Hydrological Modeling Software (HEC-HMS). This allowed for the representation of physical and empirical models of watershed hydrology to be compiled and simulations of river flows to be computed. The drainage areas included in this study were similar to those used by exp Services Inc. (2014) with estimations of surface storage properties extrapolated from Chiasson-Poirier et al. (2015). The settings and inputs for hydrologic simulation (see Supplemental Table S1) were based on standard parameters (Xu and Singh 2004) as well as knowledge of relative contributions of source water from isotope analysis of the Apex River in 2014. Overland flow parameters employed a Clark Hydrograph model, which applied a synthetic unit hydrograph method to precipitation as it traveled from the watershed into Apex River (Sharffenberg 2015). This method conditioned precipitation with a time-area curve that allowed for model calibration of the storage and attenuation of river runoff. The amplitude and duration of river flow peaks in response to precipitation events was adjusted to best match historic data (Sharffenberg 2015).

The methods for collecting and integrating HEC-HMS model parameters were adopted from the Iqaluit hydrology model employed in the initial investigation of the Lake Geraldine watershed by Bakaic and Medeiros (2017). These parameters were used as the foundation for analysis of the Apex River as the watersheds are adjacent and hydrologic conditions can be considered equivalent. The impact of evapotranspiration on watershed hydrology was incorporated into the HEC-HMS model using formulas for potential evapotranspiration derived for this application by Bakaic and

Medeiros (2017) based on the forecasted daily air temperatures for the watershed and modified by a crop coefficient and surface/canopy storage estimation (see Supplementary).

Using hydrometric station records with bias-corrected precipitation records, and assuming the primary mechanism of water replenishment of the Apex River during the simulation period (1 July to 30 September) is rainfall based on the water isotope results (see "Isotopic characterization of replenishment to the Apex River"), our hydrological model was calibrated to seasonal flow volumes during non-peak flow times. We utilized a Muskingum model to simulate river flow dynamics, where calibration of the amplitude of river flow in response to runoff was applied. Muskingum 'K' and 'X' coefficients calibrated the travel time and storage of flow (Sharffenberg 2015). The Temperature Index snowmelt model used by Bakaic and Medeiros (2017) was extended to the Apex River watershed using the same model parameters. Error between historic flow and simulated flow was minimized for individual years of the historic record until parameters for the Clark Hydrograph and Muskingum models converged. This process calculated a historic average seasonal flow error of −7.6% (Fig. 3). With this, the long-term effects of climate forecasts were projected to 2035 and applied to the predicted summer river flows. The year 2035 was chosen for analysis as it represents the maximum deviances between high and low climate scenarios and therefore displays the highest and lowest summer discharge rates. This allowed for an examination of the largest plausible deviance in flow of the Apex River and that effect on possible use of the river as a recharge mechanism for the principle water supply.

Seasonal replenishment forecasts

Daily simulations of air temperature, precipitation, snowmelt, and evapotranspiration within the Apex River watershed were conducted to generate forecasts of discharge from 2016 to 2035. With 27 unique combinations of air temperature, total snowfall, and total rainfall forecasts (see Table 1), the resultant projections of 20-year flow patterns represented a range of plausible future conditions. River discharge forecasts provided reference on feasible extraction rates for the seasonal replenishment pipeline and their associated impacts. Three seasonal replenishment scenarios were created and integrated into the model previously generated for Lake Geraldine with the municipal demand estimated at 401 LCD (see Bakaic and Medeiros 2017). Scenario 1 assumed that water extracted from the Apex River would not exceed a 10% threshold of the total river flow as recommended by the Department of Fisheries and Oceans Canada (2013) to minimize environmental impacts. Scenario 2 utilized estimates of the volume required by a seasonal replenishment program to sustain Lake Geraldine that would be necessary to sustain freshwater supply if a 50% low snowfall and rainfall event occurred in any year from 2021 to 2035. Scenario 3 assumed a replenishment rate that would be required to fully recharge Lake Geraldine if a 100-percentile year of low snowfall and rainfall occurred. For all three scenarios, a pumping season of July 1 to September 30 (92 days) was chosen for analysis, where pumping begins in the year 2021 and continued each year (July-September) until the end of 2035. Allowance was provided for the significant time required for mobilization and execution of infrastructure projects in remote and Arctic communities. A 5-year lead time was simulated for the proposed Apex River scenarios. We also simulated the influence of replenishment if it immediately began in the summer 2017. With this new input, the model was repeated with 27 unique climate scenarios simulated for each of the three replenishment scenarios.

Results

Isotopic characterization of replenishment to the Apex River

Oxygen and hydrogen isotope compositions of water naturally vary as water passes through the hydrologic cycle. Global precipitation isotope compositions typically fall along the Global Meteoric Water Line (GMWL: $\delta^2H = 8 * \delta^{18}O + 10$;

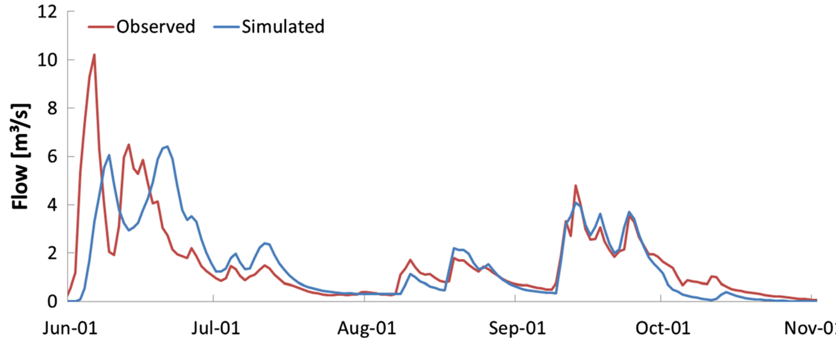

Fig. 3 Example of HEC-HMS simulation comparison between 2012 and 2013 Apex River hydrometric station data and the simulated river flow rate

Craig 1961), whereas waters that have undergone evaporation form linear trajectories below the GMWL and possess corresponding deuterium-excess (d-excess = $\delta^2H - 8 * \delta^{18}O$; e.g., Turner et al. 2014) values <10. Isotope compositions of collected rain and snow samples in the Apex River region plot relatively close to the GMWL indicating that this is a reasonable baseline approximation for 2014 precipitation (Fig. 4a). As expected for regions that experience seasonal climates (Edwards et al. 2004), the snow samples were more isotopically depleted than rainfall samples.

The isotope compositions of the Apex River and tributaries sampled plot close to the GMWL and were generally more enriched than mean annual isotope composition of precipitation (δ_P) except for the earliest samples collected on June 2. This indicates that the main source of water to the Apex River was rainfall for most of the 2014 ice-free season and beginning as early as June 30th (Fig. 4a, b). Based on calculation of d-excess, deviation to low signatures on August 11th at the AR sampling location signifies the first detectable influence of evaporation (Fig. 4c). The other river and tributary sampling locations also display low d-excess values due to evaporation for subsequent water collected on August 18th and 25th. Notably, the d-excess for the sampling location nearest to the proposed pump location ('CF'; Fig. 1) did not show evidence of evaporation until August 18th, which subsequently lessened by August 25th.

Apex River flow

The daily maximum and minimum flow rates of the Apex River from available gauge data indicated typical low flow conditions through the summer season, with values as low as 0.1–0.2 m^3/s in mid-July through the end of September (Fig. 5). A 7-day running average of discharge was computed and annual summer minimums were selected for each year. A probability of exceedance (PoE) curve was fit to the proposed extraction location of the Apex River to indicate the recurrence intervals for extreme low flow periods (Fig. 6). Since 1973, the Apex River has experienced minimum 7-day average flow rates of at least 0.1 m^3/s (97% PoE). Flow rates of 80% PoE provide insight into expected summer low flow rates with a reasonable level of confidence as these flow rates would be exceeded in 80% of summers. Thus, the rate of 0.213 m^3/s (80% PoE) was selected as the minimum summer instantaneous flow rate to be used in selecting extraction rates (Fig. 6).

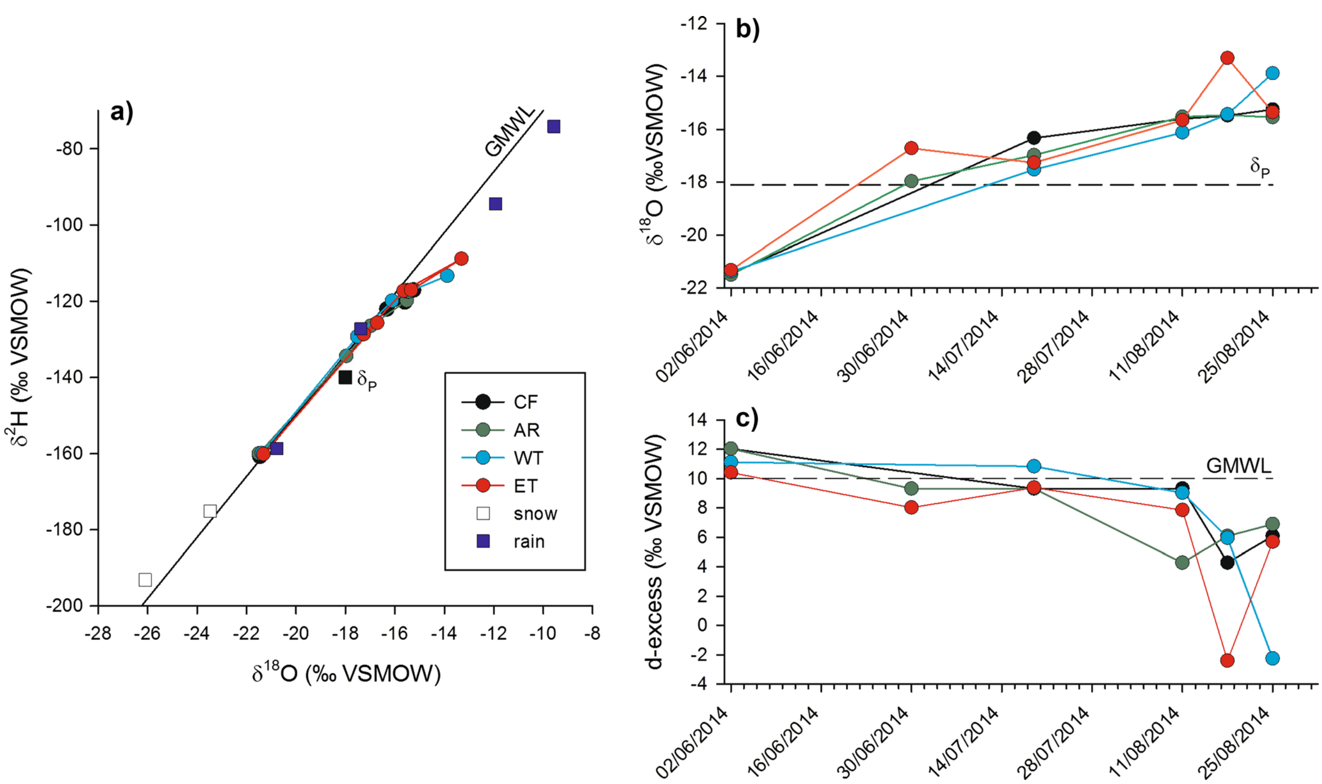

Fig. 4 Results of water isotope analyses. **a** Isotope compositions of the four Apex River and tributary sampling sites as well as precipitation isotope compositions. Note that a third snow sample collected on May 11 has an isotope value ($\delta^{18}O = -29.29$, $\delta^2H = -221.75$) outside the ranges shown but along the Global Meteoric Water Line (GMWL; Craig 1961). The mean annual isotope composition of precipitation ($\delta_P = -18.10‰, -140.00‰$) was obtained from www.waterisotopes.org. **b** Oxygen isotope composition of the four Apex River and tributary sampling sites versus time. **c** Deuterium-excess of the four Apex River and tributary sampling sites versus time

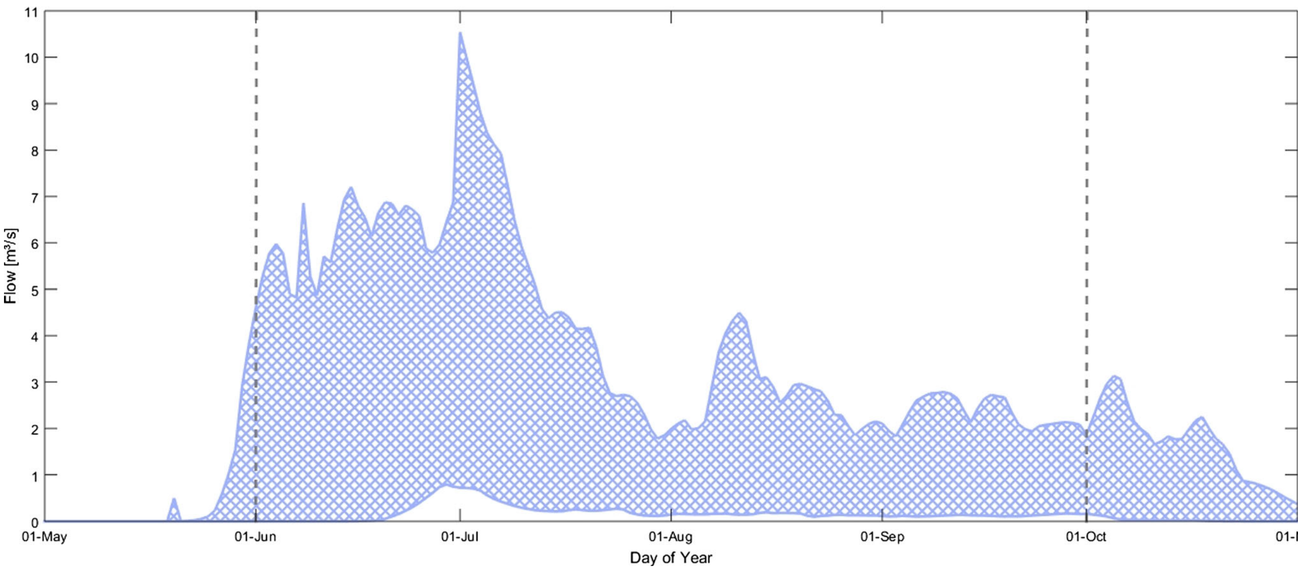

Fig. 5 Range of Apex River flows experienced at pump location throughout the 1973–2015 record. A *shaded area* between daily minimum and maximum flows is shown. *Dashed lines* indicated approximate days when average daily air temperature crosses 0 °C

Apex River forecasts

The long-term effects of climate projected to 2035 indicated that under all forecasted climate conditions, summer river flows would reach a minimum of 0.21 m^3/s (see Supplemental). This value concurred with the 80% PoE flow rate observed through analysis of historic data and represents river baseflow conditions during July and August. Both the analysis of historic flow rates and the forecast of flow rates informed the proposal of Apex River extraction rates to be assessed for summer replenishment scenarios. The proposed seasonal replenishment took into account the historic minimum flow rates along with the possible range of river flow rates based on projected future conditions.

Scenario 1

Environmental management guidelines established by the Department of Fisheries and Oceans Canada (2013) stated that limiting extraction to only 10% of the instantaneous river discharge will result in a low probability of detectable ecosystem impacts. With this limit applied to the forecasted river flows and historic discharge probabilities (Fig. 6), a constant threshold of withdraw was selected to not exceed 10% of the minimum summer flow. Although the naturally fluctuating river discharge would allow for higher withdraw rates during spring freshet and fall rainfall, the conceptual design of the replenishment pump would only allow for constant flow rate operation. Therefore, a pump rate was chosen so as to not exceed the 10% minimum river flow threshold at any time in the replenishment season. Summer flows were forecasted to be at minimum 0.21 m^3/s mimicking the rate of 0.213 m^3/s at 80% PoE from historic data. Based on the historic data analysis, this rate would reach a maximum of 10% of the instantaneous minimum summer flows in 80% of the summers. At this extraction rate, the pumping season would result in 166,925 m^3 of water transferred to Lake Geraldine. Compared to the minimum historical summer volume, this replenishment volume would extract a maximum of 4.3%.

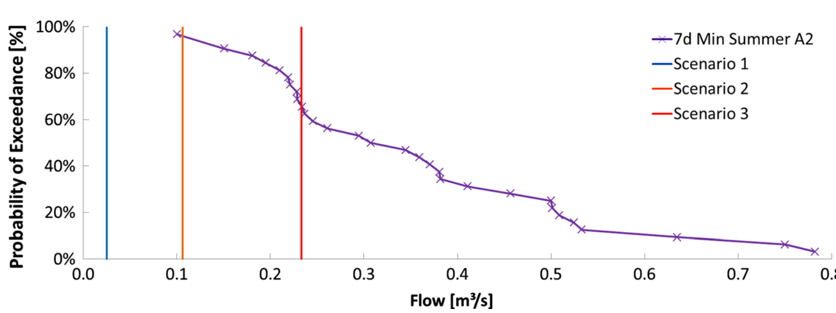

Fig. 6 Probability of exceedance curves presented for the Apex River proposed pumping location. The '7-day Min Summer' curve depicts the annual summer minimums of the 7-day averages of flow rates during July-September throughout the historical record. The proposed flow rates for the three extraction scenarios are shown: scenario 1, 0.025 m^3/s; scenario 2, 0.106 m^3/s; and scenario 3, 0.233 m^3/s

Scenario 2

Under annual conditions where a 50 percentile dry year occurs, 845,000 m^3 of water would be required to replenish Lake Geraldine (Golder Associates 2013). Using this volume as a metric for a continuous replenishment schedule, a pump rate of 0.106 m^3/s over 92 days would be required. Compared to the predicted and historic minimum summer flow rates, scenario 2 represents 50% of the instantaneous flow and therefore well over the Department of Fisheries and Oceans Canada (2013) guidelines for environmental protection. Compared to historic 7-day summer minimums, scenario 2 would exceed the available discharge of the river in 3% of the years. The volume of water transferred in scenario 2 would represent at most 21.8% of the volume past the extraction point on the river. The Department of Fisheries and Oceans Canada (2013) guidelines also suggest that cumulative flow alterations of >30% of the mean annual discharge have a heightened risk of environmental impact. In the specific case of the Apex River, comparison can be made to the mean summer discharge value at 80% PoE (Fig. 6). In this case, the extraction rate of scenario 2 is only 16% of the mean summer discharge.

Scenario 3

The proposed replenishment volume for scenario 3 matched the value that would be required to fully recharge Lake Geraldine if Iqaluit experienced the driest year from their historic record. This would require 1,853,000 m^3 of replenishment over 92 days with a pump rate of 0.233 m^3/s. This pump rate would equal 111% of the minimum flow forecasted and exceed the 7-day summer minimums in 33% of years forecast as the historic probability of exceedance is 66% (Fig. 6). Effectively, at this pump rate, there would be a 1 in 3 chance each summer that the Apex River would be entirely depleted downstream of the pump location. The extraction rate of scenario 3 is well above the Department of Fisheries and Oceans Canada (2013) guideline for heightened risk of environmental impacts and would represent as much as 48% of the river's summer volume based on historic flow. As a point of reference, the total storage volume of Lake Geraldine is 1,956,000 m^3. At such a high volume, scenario 3 represents exceeding the upper boundary of possible replenishment.

Lake Geraldine seasonal replenishment forecasts

We examined a long-term forecast for Iqaluit's water supply with the addition of the seasonal replenishment scenarios proposed for extraction from the Apex River. The 20-year supply forecasts illustrated the range of accessible volume versus time in each replenishment scenario (Fig. 7). Modeled results identified the influence that seasonal replenishment had on extending the Lake Geraldine supply compared to the baseline forecasts without replenishment (baseline). Without seasonal replenishment, the baseline forecast predicted end-of-winter shortages occurring as early as 2026 assuming a consumption of 401 LCD (Bakaic and Medeiros 2017). With the replenishment conditions proposed in scenarios 1 and 2, end-of-winter shortages occurred in 2028 and past 2035, respectively (Fig. 7). With replenishment conditions proposed in scenario 3, end-of-winter shortages would not occur within the 20-year planning horizon.

Flow-controlled seasonal replenishment

Using a 10% extraction threshold for removal of water from the Apex River to avoid potential ecosystem degradation, dynamic cutoffs can be calculated, where the pump extraction rates proposed in scenarios 2 and 3 are only running when extraction is less than 10% of instantaneous flow for any given day. This threshold can be applied to our forecasts for Apex River flow in 2035 to get an estimate of the number of days in the 92-day pumping season where extraction is below the 10% threshold. The pumping scenarios can then be compared to the

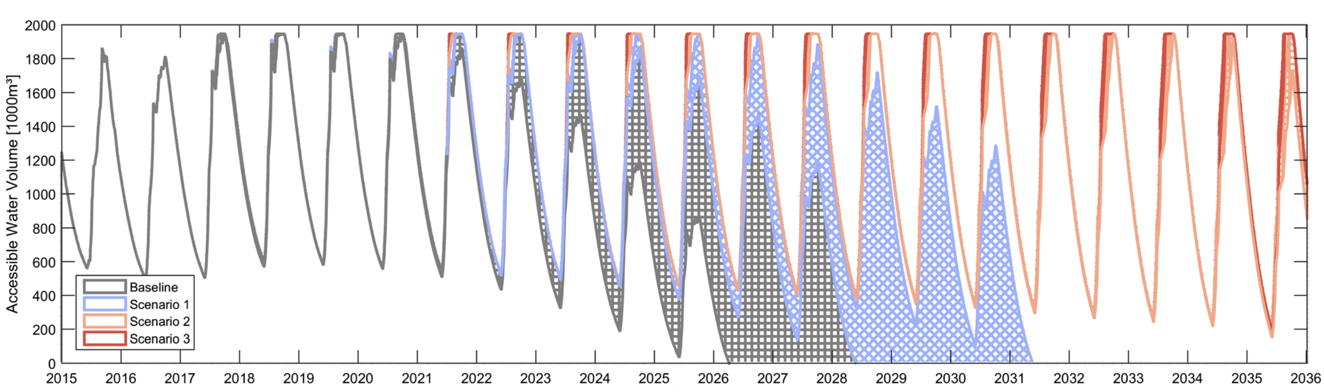

Fig. 7 Results of the long-term forecast of Lake Geraldine water supply over 20 years. These results incorporated the seasonal replenishment program proposed (scenarios 1, 2, and 3) using the forecasts for Apex River usable discharge. Seasonal replenishment commenced in 2021. The baseline forecast assumed a consumption of 401 LCD without replenishment (Bakaic and Medeiros 2017)

upper boundary of predicted river flow to acquire a best-case scenario of allowable pumping days during the summer. Under flow-controlled conditions, scenario 2 and 3 would see their pumping seasons reduced in order to not extract more than 10% of the daily instantaneous river discharge (Table 2). Even under best-case climate scenarios (higher than normal rainfall and snowfall), scenario 2 would only be able to transfer water for <52% the pumping season. Scenario 3, due to its high extraction rate, would only be able to operate for <6.5% of the pumping season.

The impact that a flow-controlled season of replenishment would have on the supply of Lake Geraldine can be assessed through interpolation of the results shown in Fig. 7. If 10% withdrawal rates are maintained, scenario 2 would assume flow-controlled conditions of between 15 and 52% of the transferred volume. Scenario 3 would only be able to achieve a pumping rate of 0.233 m^3/s for 6 days under the best-case climate conditions (highest predicted precipitation). With these flow limitations, scenario 3 would only transfer 120,000 m^3 of water. All three scenarios would extend the supply of Lake Geraldine less than 2 years.

Alternative infrastructure scenarios

Constructing an overwinter reservoir to supplement municipal supply is an alternative that has been proposed and employed in other Nunavut communities (Williams Engineering Canada Inc. 2014). These reservoirs range in volume with the largest in Nunavut currently 103,000 m^3 and ~5.5 m deep (Hall Beach, NU). The primary purpose of these reservoirs is to provide water storage for consumption in addition to the seasonal river flow or lake source used by the municipality. In the proposed scenarios for Iqaluit, an overwinter reservoir would be filled during the summer with excess water from Lake Geraldine and used as a reserve supply over the winter. Using the forecasts of supply for Lake Geraldine and analyzing the recharge versus consumption forecasts, estimates of annual recharge deficit can be made using *worst-case scenarios* (see Supplemental). Under these conditions, annual deficits range from 200,000 to 1,200,000 m^3 in 2035. These deficit values indicate the relative size of an overwinter reservoir that would have an impact on the Iqaluit municipal supply. To investigate the impact of an overwinter reservoir in Iqaluit, three reservoir sizes were chosen and included in the Lake Geraldine simulations (Table 3). Reservoir 1 was chosen to mimic the size of the Hall Beach reservoir at 105,408 m^3 and act as a conservative design, which has already been constructed in the region. Reservoir 2 would mimic the volume of water transferred in scenario 1 of seasonal replenishment from the Apex River. Reservoir 3 would provide insight into a relatively large reservoir at 527,040 m^3, demonstrating the upper end of a feasible water reservoir in the city.

In each scenario, the water from the reservoir is transferred into the municipal water system from October 1 to December 1 (Appendix S3). By increasing the municipal supply right before winter freeze-up, the overwinter reservoir increases the end-of-winter volume by reducing the period during the winter where no recharge is input into Lake Geraldine. This process has the effect of reducing the amplitude of the summer and winter peaks and thereby raising the average of annually accessible volume. The input to the water system in these scenarios can be delivered to the reservoir in multiple ways; delivered by a replenishment pipeline, stored during freshet overflow from Lake Geraldine, or delivered via the melting of snow captured by snow fences (Table 3). Capturing snow to augment municipal supply has been demonstrated by Stuefer and Kane (2013) in the Prudhoe Bay region of Alaska. The impact of each reservoir on the service life of Lake Geraldine was simulated (Appendix S3). Reservoir 1 was found to experience end-of-winter shortages as early as 2027 with severely low volumes in 2026. This scenario offered little improvement over the baseline conditions. Reservoir 2 experienced end-of-winter shortages in 2029, a result similar to the impact seen with the seasonal replenishment program of scenario 2. Reservoir 3 was found to experience end-of-winter shortages as early as 2034, which demonstrated the practical limit of life extension a feasible reservoir could offer.

Discussion

Here, we used a novel hydrologic model informed by water isotope tracers to project the future water supply for the City of Iqaluit using the Apex River and other sources of freshwater to supplement the Lake Geraldine reservoir. Incorporating a number of different scenarios, results show that even the most aggressive engineering and management strategies would only enhance the lifespan of the water supply by 10–15 years.

Table 2 Summary of seasonal replenishment characteristics of the three proposed pumping scenarios when the 10% Department of Fisheries and Oceans Canada (2013) flow control guidelines are applied

	Pump rate (m^3/s)	Extraction potential (m^3)	Days at <10% instantaneous	Flow-controlled volume at <10% (m^3)
Scenario 1	0.021	166,925	92	166,925
Scenario 2	0.106	845,000	14–48	128,217–439,603
Scenario 3	0.233	1,853,000	0–6	0–120,787

Table 3 Summary of overwinter reservoirs incorporated into the LTF Lake Geraldine water supply forecasts. The range of predicted water shortage incorporates all plausible climate forecasts (see Supplemental)

	Pump rate (m^3/s)	Reservoir volume (m^3)	Length of snow fence (m)	Predicted water shortage
Reservoir 1	0.020	105,408	392	2027–2031
Reservoir 2	0.040	210,816	784	2029–2033
Reservoir 3	0.100	527,040	1959	2034–2037

Below, we comment on key aspects of the modeling, address the assumptions and implications, and recommend a future direction.

Rainfall-sourced river discharge

With the Apex River identified as a supplemental freshwater source for Iqaluit, there is a need to understand the hydrologic processes that contribute to the baseflow of the river in any particular year. The isotope results indicated that the Apex River was predominantly influenced by rain during the 2014 ice-free season, in a year with average rainfall (122.2 mm) based on the 1981–2015 climate record. Even with high snowfall during the preceding winter (750.9 mm) that substantially exceeded the 30-year normal condition (289.2 mm; Environment and Climate Change Canada 2016a), isotope data indicates that snowmelt contributions were limited to peak flow during the freshet period (early June). This is in direct contrast to the results of Obradovic and Sklash (1986), who found that snowmelt and groundwater contributions were a primary contribution to Apex River discharge throughout the summer months of 1983, which had lower overall snowfall than in 2013–2014 (Fig. 8). The shift in seasonality between 1983 and 2014 is principally due to the significant increase in temperature (Fig. 2), where a shift in the meltwater season has left the Apex River without late-lying snowmelt contributions that historically contributed to baseflow. Likewise, while net rainfall was higher in 1983 (132.1 mm), the evaporation potential was only 29.4% due to the cooler overall temperatures throughout the summer than in 2014 (where the evaporation potential was 43.8%). This suggests that the Apex River is particularly vulnerable to reduced summer rainfall, which would reduce the amount of available water for seasonal replenishment of the freshwater supply for Iqaluit.

Supply forecasts and seasonal replenishment in Iqaluit

The efficacy of a seasonal replenishment program for Lake Geraldine using the Apex River assumes that a sufficient source of water can be extracted to replenish the water supply. We therefore evaluated the influence of this proposed

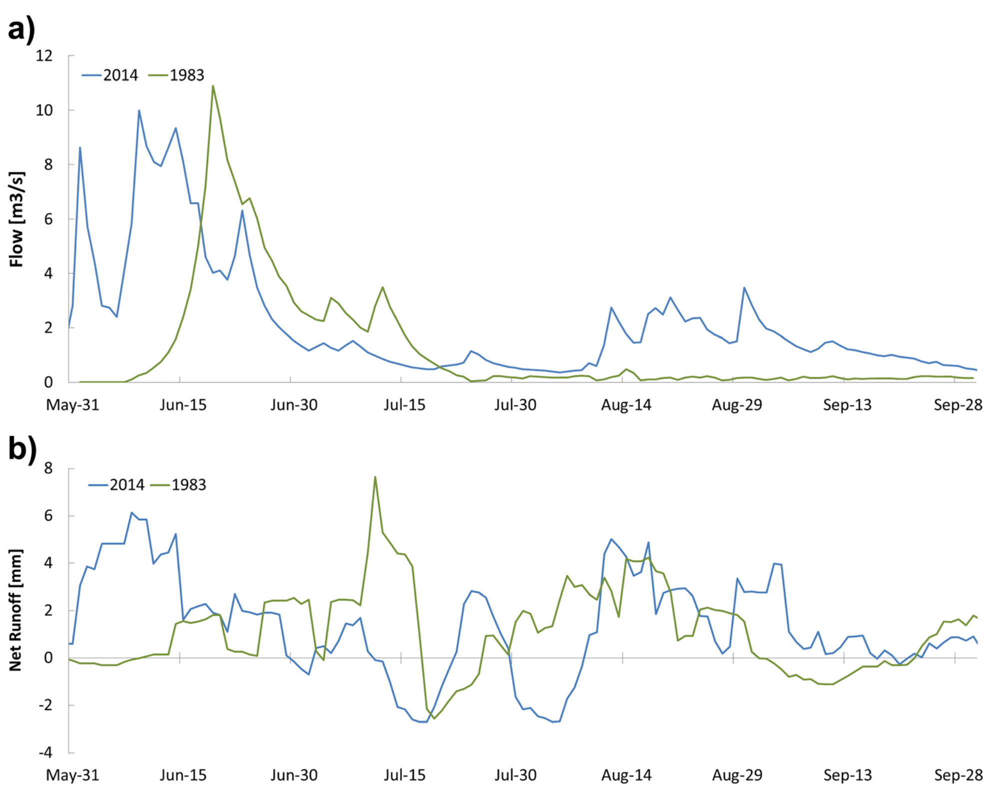

Fig. 8 Comparison of the hydrological conditions present during 2014 and 1983 depicted by **a** the summer river flows of the Apex River and **b** the net precipitation (rainfall − evaporation)

replenishment program by contrasting supply forecasts with and without replenishment.

A review of the end-of-winter accessible volumes indicate that Lake Geraldine will be near desiccation (~200,000 m^3 remaining) in 2025 without seasonal replenishment (baseline vulnerability). If consumption and population growth increase beyond forecasted rates, end-of winter shortages will occur sooner. This vulnerability will also worsen under extreme climate events, such as a 33-year low in snowfall. With the addition of the seasonal replenishment program beginning in 2021, the risk of end-of-winter shortages could be delayed to 2028. Thus, replenishment using a 10% threshold for extraction from the Apex River offered only a 2-year extension to the viability of the freshwater supply, suggesting that the 5-year lead time and financial costs would not be worth the investment (Fig. 7). The maximum length of time that the viability of Lake Geraldine could be extended is 15 years (Scenario 3); however, this would result in extracting 45–100% of the flow of the Apex River. Indeed, the only option to adequately supplement Lake Geraldine from the Apex River would result in the complete desiccation of the Apex River during low flow periods 33% of the time (Fig. 6). This highly undesirable outcome would generate obvious significant ecosystem impact as well as notable impacts on the recreational and social value of the Apex River. Thus, a seasonal replenishment program is not a long-term solution for the freshwater supply of Iqaluit.

A replenishment program that transfers water into Lake Geraldine during the late winter or early spring would have more of an impact on extending the lifespan of the water supply as replenishment would occur when lake levels are at their lowest. Such a replenishment pipeline would require specific design considerations to prevent freezing along with a permanent intake installation allowing for extraction below the layer of lake/river ice. There would be considerable increases in expenses related to an all-winter pipeline compared to a seasonal installation; however, the limited and short-term impact that seasonal replenishment has on the Lake Geraldine supply suggests that an investment into a long-term solution is required. One such solution would be a 15% reduction in municipal consumption compared to the current average. This tactic was evaluated by Bakaic and Medeiros (2017) during their initial evaluation of the Iqaluit municipal supply and served as the only proposed solution which extended supply past 2035 under all climate conditions without significant environmental impact on aquatic or terrestrial ecosystems.

Planning and management for Arctic freshwater resources

The deployment of water resource assessments for the development of municipal planning has been accepted as a prerequisite for water resource planning in other regions (Xu and Singh 2004; Alessa et al. 2008). However, there are uncertainties and lack of data inherent to Arctic regions, which require assumptions to be made regarding mechanisms of recharge. Likewise, environmental change may be rapidly altering hydrologic pathways (Hinzman et al. 2005; Wrona et al. 2016). For example, while freshwater systems may have heavily relied on late-lying snowmelt as the primary mechanism for recharge in the past (Obradovic and Sklash 1986), reductions in snowmelt or increases in rainfall may alter summer water balances (Bouchard et al. 2013; Wrona et al. 2016). This will require inclusion of local knowledge of current hydrology to inform climate and demand forecasting and to provide a heuristic protocol better suited to the Arctic regions where knowledge gaps and uncertainty persist. Through the application of these adapted methods, we have evaluated the Apex River in terms of its suitability as an alternative water supply for Iqaluit. This example serves as a demonstration of the simplicity and effectiveness of our methodology in generating knowledge required for effective municipal water management, which can be applied broadly to other northern communities.

Arctic communities face multiple water quality and quantity challenges in a warming future (Instanes et al. 2016; Wrona et al. 2016; Medeiros et al. 2017), which exemplifies the need for quantitative forecasts. Our results indicate that perspective supplemental water resources are insufficient to meet the near-future freshwater demand for Iqaluit, the growing capital city of the territory with ~8000 residents. Even under very conservative estimates that assume the current rate of consumption, we have quantified extreme vulnerability to the municipal water supply for any currently proposed solutions, highlighting the need for informed organizational management of water security within the territory (Grigg 2016; Medeiros et al. 2017). Alessa et al. (2008) highlighted a systemic lack of an appropriate index for assessing water resource vulnerability and resiliency in Arctic regions and provided a qualitative mechanism to assess the vulnerability of current water resources as well as the impact of proposed solutions on increasing resiliency. The expansion or modification of the Alessa et al. (2008) Arctic Water Resource Vulnerability Index to include quantitative measures of climate and demand over a circumpolar scale could provide information paramount for informing water management strategies.

Conclusions

Decision makers in Arctic regions are faced with numerous challenges when attempting to consider the effects of environmental change on municipal freshwater infrastructure and supply. In order to predict and plan for the sustainability of water supply needs in a warming future, managers require easily accessible information to quantify the current and future needs. Iqaluit is an example of a growing city faced with well-documented water vulnerabilities and a need of an updated water management strategy (Medeiros et al. 2017). The Apex River had been identified as a viable supplemental source to be used in a seasonal replenishment program. Through the application of climate forecasting and hydrologic modeling, 20-year forecasts were generated for total river discharge of the Apex River. Water isotope compositions of surface waters collected in 2014 for the Apex River revealed that the dominant input source water was rainfall. These parameters were used to calibrate and test modeled predictions for the sustainability of Iqaluit's freshwater supply. The proposed replenishment program of diverting water from the Apex River to supplement the municipal water supply for Iqaluit was found to feasibly extend the water supply by only 2 years under a 10% extraction threshold as recommended by the Department of Fisheries and Oceans Canada (2013). We also investigated other seasonal replenishment and supplement proposals (snow fencing, reservoir expansion), which only yielded short-term extensions. This highlights the importance of directly addressing end-of-winter water shortages with overwinter replenishment or with consistent consumption reductions. Our heuristic methods offered a means for municipal planners to be better informed about how climate will influence their decision-making and freshwater strategies in a warming future.

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References

Alessa L, Kliskey A, Lammers R, Arp C, White D, Hinzman L, Busey R (2008) The arctic water resource vulnerability index: an integrated assessment tool for community resilience and vulnerability with respect to freshwater. Environ Manag 42:523–541

Bakaic M, Medeiros AS (2017) Vulnerability of northern water supply lakes to changing climate and demand. Arctic Science 3:1–16

Bekele EG, Knapp (2010) Watershed modeling to assessing impacts of potential climate change on water supply availability. Water Resour Manag 24:3299–3320

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

Brown LC, Duguay CR (2010) The response and role of ice cover in lake-climate interactions. Prog Phys Geogr 34:671–704

Chiasson-Poirier G, Franssen J, Tremblay T, Lafreniere M, Lamoureux S (2015) Identification and characterization of physical controls on subsurface flows during baseflow recession in a small Arctic river. ArcticNet Annual General Meeting, 2015. doi: 10.13140/RG.2.1.3048.9689

City of Iqaluit (2010) City of Iqaluit General Plan Including the Changes Proposed under the 5 year Review Process. City of Iqaluit. Iqaluit, Nunavut

Craig H (1961) Isotopic variations in meteoric waters. Science 133:1702–1703

Deb D, Butcher J, Srinivasan R (2015) Projected hydrologic changes under mid-21st century climatic conditions in a sub-arctic watershed. Water Resour Manag 29:1467–1487

Department of Fisheries and Oceans Canada (2013) Framework for assessing the ecological flow requirements to support fisheries in Canada. Department of Fisheries and Oceans Canada, Ottawa

Derksen C, Brown R (2012) Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. Geophys Res Lett 39:L19504

Edwards TWD, Wolfe BB, Gibson JJ, Hammarlund D (2004) Use of water isotope tracers in high-latitude hydrology and paleohydrology. In: Pienitz R, Douglas M, Smol JP (eds) Long-term environmental change in Arctic and Antarctic lakes, developments in paleoenvironmental research, volume 7. Springer, Dordrecht, pp 187–207

Environment and Climate Change Canada (2016a) Climate data and scenarios for Canada: Synthesis of recent observation and modelling results. Available from http://ec.gc.ca/sc-cs/default.asp?lang=En&n=80E99404-1 [11 Oct 2016]

Environment and Climate Change Canada (2016b) Historical data. Available from: http://climate.weather.gc.ca/historical_data/search_historic_data_e.html [21 Feb 2016]

exp Services Inc. (2014) City of Iqaluit supplementary water supply study. exp Services Inc., Moncton

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 Chang 100:267–294

Golder Associates Ltd. (2013) Lake Geraldine water balance assessment. Golder Associates Ltd., Mississauga

Grigg NS (2016) Water security, disasters, and risk assessment. In integrated water resource management. Palgrave Macmillan, London, pp 375–393

Hinzman LD, Bettez ND, Bolton WR, Chapin FS, Dyurgerov MB, Fastie CL et al (2005) Evidence and implications of recent climate change in northern Alaska and other arctic regions. Clim Chang 72:251–298

Instanes A, Kokorev V, Janowicz R, Bruland O, Sand K, Prowse T (2016) Changes to freshwater systems affecting Arctic infrastructure and natural resources. Journal of Geophysical Research: Biogeosciences 121:1887–1893

Krasting JP, Broccoli AJ, Dixon KW, Lanzante JR (2013) Future changes in northern hemisphere snowfall. J Clim 26:7813–7828. doi:10.1175/jcli-d-12-00832.1

Medeiros AS, Quinlan R (2011) The distribution of the Chironomidae along multiple environmental gradients in lakes and ponds of the eastern Canadian Arctic. Can J Fish Aquat Sci 68:1511–1527

Medeiros AS, Friel CE, Finkelstein SA, Quinlan R (2012) A high resolution multi-proxy record of pronounced recent environmental change at Baker Lake, Nunavut. J Paleolimnol 47:661–676

Medeiros AS, Wood P, Wesche SD, Bakaic M, Peters JF (2017) Water security for Northern Peoples: review of threats to Arctic freshwater systems in Nunavut, Canada. Reg Environ Chang 17:635–647

Nunavut Bureau of Statistics (2016) Population estimates. Nunavut Bureau of Statistics, Canada http://www.stats.gov.nu.ca/en/Population%20estimate.aspx [Accessed May 9, 2016]

Obradovic M, Sklash M (1986) An isotopic and geochemical study of snowmelt runoff in a small Arctic watershed. Hydrol Process 1:15–30

Poland JS, Mitchell S, Rutter A (2001) Remediation of former military bases in the Canadian Arctic. Cold Reg Sci Technol 32:93–105

Prowse TD, Brown K (2010) Hydro-ecological effects of changing Arctic river and lake ice covers: a review. Hydrol Res 41:454–461

Prowse TD, Wrona FJ, Reist JD, Gibson JJ, Hobbie JE, Lévesque LM, Vincent WF (2006) Climate change effects on hydroecology of Arctic freshwater ecosystems. AMBIO: A Journal of the Human Environment 35:347–358

Prowse T, Alfredsen K, Beltaos S, Bonsal BR, Bowden WB, Duguay CR, Korhola A, McNamara J, Vincent WF, Vuglinsky V, Anthony KMW (2011) Effects of changes in arctic lake and river ice. Ambio 40:63–74

Prowse T, Bring A, Mård J, Carmack E, Holland M, Instanes A et al (2015) Arctic freshwater synthesis: summary of key emerging issues. Journal of Geophysical Research: Biogeosciences 120:1887–1893

Samuelson G (1998) Water and waste management issues in the Canadian arctic: Iqaluit, Baffin Island. Canadian Water Resource Journal 4:327–338

Sharffenberg W (2015) Hydrologic modeling system HEC-HMS user's manual. U.S. Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center, Report CPD-74A, Davis

Staudenmaier MJ (1996) A description of the Meso Eta model. NWS Western Region Technical Attachment No. 96-06, NWS Western Region, Salt Lake City, Utah, USA

Stuefer SL, Kane DL (2013) Using snow fences to augment fresh water supplies in shallow arctic lakes. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 13.06, September 2013, Fairbanks 32 pp

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Turner KW, Edwards TWD, Wolfe BB (2014) Characterising runoff generation processes in a lake-rich thermokarst landscape (Old Crow Flats, Yukon, Canada) using $\delta^{18}O$, $\delta^{2}H$, and d-excess measurements. Permafr Periglac Process 25:53–59

Water Survey of Canada (2016) Real-time hydrometric data graph for Lake Geraldine (10UH013). Wateroffice https://wateroffice.ec.gc.ca/report/report_e.html?mode=Graph&type=realTime&stn=10UH013 [Accessed Feb 21, 2016]

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

Woo MK, Young KL (2006) High Arctic wetlands: their occurrence, hydrological characteristics and sustainability. J Hydrol 320:432–450

Wrona FJ, Johansson M, Culp JM, Jenkins A, Mård J, Myers-Smith IH et al (2016) Transitions in Arctic ecosystems: ecological implications of a changing hydrological regime. Journal of Geophysical Research: Biogeosciences 121:650–674

Xu C-Y, Singh VP (2004) Review on regional water resources assessment models under stationary and changing climate. Water Resour Manag 18:591–612