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Chemical and microbial characteristics of municipal drinking water supply systems in the Canadian Arctic

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Abstract Drinking water in the vast Arctic Canadian territory of Nunavut is sourced from surface water lakes or rivers and transferred to man-made or natural reservoirs. The raw water is at a minimum treated by chlorination and distributed to customers either by trucks delivering to a water storage tank inside buildings or through a piped distribution system. The objective of this study was to characterize the chemical and microbial drinking water quality from source to tap in three hamlets (Coral Harbour, Pond Inlet and Pangnirtung—each has a population of <2000) on trucked service, and in Iqaluit (population ~6700), which uses a combination of trucked and piped water conveyance. Generally, the source and drinking water was of satisfactory microbial quality, containing *Escherichia coli* levels of <1 MPN/100 mL with a few exceptions, and selected pathogenic bacteria and parasites were below detection limits using quantitative polymerase chain reaction (qPCR) methods. Tap water in households receiving trucked water contained less than the recommended 0.2 mg/L of free chlorine, while piped drinking water in Iqaluit complied with Health Canada guidelines for residual chlorine (i.e. >0.2 mg/L free chlorine). Some buildings in the four communities contained manganese (Mn), copper (Cu), iron (Fe) and/or lead (Pb) concentrations above Health Canada guideline values for the aesthetic (Mn, Cu and Fe) and health (Pb) objectives. Corrosion of components of the drinking water distribution system (household storage tanks, premise plumbing) could be contributing to Pb, Cu and Fe levels, as the source water in three of the four communities had low alkalinity. The results point to the need for robust disinfection, which may include secondary disinfection or point-of-use disinfection, to prevent microbial risks in drinking water tanks in buildings and ultimately at the tap.

Keywords Drinking water · Chlorination · Arctic communities · Surface water · *Escherichia coli* · Microbial pathogens · Metals · Lead

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Introduction

The typical model of potable water delivery and safety assurance in Arctic Canadian communities is fundamentally different than in communities south of 60° latitude. Within the 25 remote communities of Nunavut, a vast arctic territory of northern Canada (approximately 2.1 million km^2), water is extracted from lakes, rivers or glacial streams and either treated immediately, or conveyed by pipes or trucks to reservoirs within the hamlets where it is subsequently chlorinated as a minimum. The water is then trucked or, less commonly, piped to individual households and buildings (Johnson 2008). Homes and buildings on trucked services receive water deliveries into water holding tanks located inside the buildings.

In Nunavut, the raw water is typically extracted directly from source lakes and rivers and transferred to an intake pumphouse/truckfill station or an engineered reservoir, from which the water is pumped to the truckfill station (Williams

Engineering Canada Inc. 2014). In many hamlets, the raw water is disinfected by chlorination using in-line injection pumps operating simultaneously with the filling of the water trucks at the truckfill stations (Daley et al. 2014). A multi-barrier approach to ensure water safety is used in Iqaluit, where the water treatment plant (WTP) system consists of slow sand filtration and UV disinfection in addition to chlorination. The Government of Nunavut (GN) is currently moving towards implementing multiple barriers in the drinking water treatment in all communities. This implementation in the Canadian Arctic's small, fly-in communities is, however, facing several challenges including availability of technical expertise, difficult year-round access and prohibitive shipping and construction costs (Kot et al. 2015; Johnson 2007). Other challenges include permafrost and distances to service companies (e.g. accredited analytical laboratories).

Drinking water distribution pipes are expensive to operate in the Arctic as it is necessary to keep the water heated and moving at all times to avoid freezing and subsequent failure of the aboveground distribution infrastructure. Within Nunavut, there are currently only three communities where drinking water is supplied by completely (Resolute) or partially (Rankin Inlet and Iqaluit) piped distribution systems. In Iqaluit (pop. ~6700, Statistics Canada 2012), the majority of neighbourhoods are served by a piped system (ca. 62%), while the remaining areas are serviced by water trucks (Trow Consulting Engineers Ltd. 2002).

Trucked systems, although requiring significantly less infrastructure than piped distribution, have their own set of drawbacks. Trucks must be regularly maintained and staffed with trained operators, and community roads must be cleared of snow to enable trucks to access reservoirs and buildings. Compared to on-demand water delivery via piped systems, trucked distribution to homes and buildings yields a defined amount of available drinking water determined by the capacity of the water tanks and frequency of delivery.

There are several points along the delivery train where water may become contaminated with microbes (bacteria, viruses, protozoa) or chemicals (heavy metals, organics, disinfection by-products). The surface water resources, which are used for extraction of drinking water in the area, are vulnerable to contamination from anthropogenic or wild-life activities (Davies and Mazumder 2003) and may be sensitive to climate change as alterations to seasonal precipitation and temperature patterns may affect run-off events, available freshwater resources and microbial ecology (Harper et al. 2011a; Martin et al. 2007; Medeiros et al. 2017). The delivery train, the management and maintenance of municipal (truck, pumps, pipes), as well as in-home infrastructure (plumbing and water tanks), play a large role in the potential for water contamination (Ashbolt 2015; Ercumen et al. 2014). In particular, the risk of microbial and chemical contamination may be greater due to stagnant water in tanks receiving an intermittent supply (World Health Organization 2011). Corrosion of drinking water distribution system components, such as pipes and household plumbing fixtures, and the subsequent release of heavy metals including lead, copper and zinc is an issue that has been widely studied in non-Arctic municipalities in Europe and North America (Zietz et al. 2010). In particular, drinking water has been shown to be a potentially significant source of lead exposure (Remmer 2010). Heavy metal release is influenced by a number of factors including, but not limited to, water quality (alkalinity, pH, etc.), stagnation times, temperature and disinfectant residuals (Wang et al. 2014). Biofilm formation and detachment in water conveyance and storage systems has also been documented to adversely affect water quality in conventional piped distribution systems, and can potentially facilitate the survival and proliferation of opportunistic pathogens such as *Pseudomonas aeruginosa* (Liu et al. 2013; Falkinham et al. 2015). To date, metal corrosion potential has not been investigated within remote, arctic communities which are serviced by trucked distribution systems.

The collection and representativeness of health data appertaining to water-related illness and disease in Canada's northern regions is limited (Metcalfe et al. 2011; Harper et al. 2011b, 2015a). Based on self-reported health outcomes, Harper et al. (2011a, 2015b) have suggested that rates of gastrointestinal illness in northern communities are comparatively higher than the Canadian national average and may be associated with water resources. To date, evidence linking higher incidence of gastrointestinal illness or other adverse health effects to specific drinking water-related exposures remains uncertain (Martin et al. 2007; Messier et al. 2012; Fillion et al. 2014; Goldfarb et al. 2013; Harper et al. 2011a; Hastings et al. 2014; McKeown et al. 1999; Pardhan-Ali et al. 2012a, b, 2013).

The objective of this work was to assess the municipal drinking water quality and identify potential sources of contamination from the original source (e.g. lake, river, glacier) to the tap (the point of human use) in Coral Harbour, Pangnirtung, Pond Inlet and Iqaluit, representing four different locations, water treatment systems and community sizes in Nunavut, Canada. It should be noted that this was exploratory and proactive research aiming to assess the drinking water quality and water delivery methods (piped versus trucked) rather than to respond to known water quality issues (reactive research).

Materials and methods

Source and drinking water samples were obtained from four communities in different geographical locations of Nunavut, Canada (Fig. 1, Table 1).

The population size of the studied communities varied from 834 in Coral Harbour to 6699 in Iqaluit (Table 1). Each

Fig. 1 Location of study sites in the territory of Nunavut, Canada

hamlet was visited once: Coral Harbour (March, 2013), Pond Inlet (July, 2013) and Pangnirtung (August, 2013). The town of Iqaluit, which has a mixed distribution system, was visited twice (June and September, 2014) to study temporal differences.

With the exception of Coral Harbour (due to winter conditions), samples were obtained from the freshwater source (i.e. rivers, water reservoirs and/or engineered lakes), from which the community extracts drinking water prior to the treatment. Treated drinking water samples were obtained from the freshly treated water (water treatment plants), and along the distribution system, which included samples from delivery trucks, domestic water tanks (Coral Harbour) and taps in public/commercial buildings and homes. In Iqaluit, tap water samples were obtained from all types of buildings supplied by the piped distribution system or trucks.

The sampling plan was designed to obtain representative water samples in each community for a mixture of private and public housing buildings of different ages, as well as public buildings such as libraries and community halls. As Coral Harbour was the pilot site, treated water samples were obtained both from building water tanks and from cold water taps in the kitchen (area of food and beverage preparation) to determine if there were differences in the water quality. As there were no discernable differences (data not shown), it was decided only to sample the cold water tap fixtures in the remaining communities. Such tap water samples were assumed to be the most representative of the human oral exposure to

potential waterborne contaminants originating from the source water, distribution system or cold-water premise plumbing; contaminants specific to hot water distribution, such as the opportunistic pathogen *Legionella pneumophila*, were not assessed in this exploratory study. Table 1 contains detailed information about the community location, size, drinking water treatment, distribution system, sampling dates and number of samples that were obtained from each community for this study.

At the time of sampling, household inhabitants and public building managers were interviewed to provide context for the chemical and microbial results. They were asked about their views on the drinking water supply, perceptions of health risk, habits of water usage, the age of their home or building and the condition of the water tank and premise plumbing. Local research assistants were hired in each community to assist with the interviews and provide language translation between Inuktitut and English when needed.

Sample collection and water quality analysis

A 1-L sample was retrieved in a sterilized Nalgene high-density polyethylene (HDPE) container (Fisher Scientific, Nepean, ON, Canada) from each sample location for general water quality analysis and for treated water sample measurement of the residual free chlorine concentration. This sampling approach was used in Pond Inlet, Pangnirtung and Iqaluit; Coral Harbour, which served as a pilot study site, was sampled using a different method, described in the next section. The tap was run for approximately 1–2 min before collection of the water sample, to simulate a typical ingestion scenario (Deshommes et al. 2016). General physicochemical water quality indicators which included temperature, pH and specific conductivity (SpC) were measured with a multi-parameter water quality sonde (600R, YSI Environmental Incorporated, San Diego, CA, USA). Free chlorine was measured by the DPD free chlorine method (Hach Method 2001; 0.02–2.0 mg/L) using a portable photometer (Pocket Colorimeter II; Hach Company). These analyses were carried out in a field laboratory within 2 h of being sampled.

Metals and alkalinity analysis

Coral Harbour served as the pilot study for the sampling program, and in this community, the tier 1 sampling protocol suggested by Health Canada (2009a) was used to investigate heavy metals indicative of corrosion issues, particularly Pb, in the drinking water. In Coral Harbour, first-flush water samples (500 mL) were obtained by the primary occupants or user in the buildings after an overnight stagnation period. Further samples (4 L) were retrieved from the tap later in the day when additional samples were retrieved for microbiological parameters. On these occasions, the taps were run for 1–2 min prior to collecting a bulk water sample. The sampling strategy was revised for the remaining communities due to logistical challenges with obtaining the first flush samples. For Pond Inlet, Pangnirtung and Iqaluit, samples for metals were collected at the same time as the other water quality parameters (i.e. after a 1-min flushing period). A 100-mL subset of each sample was preserved (pH < 2) with nitric acid and transported to the Clean Water Laboratory (CWL) located at Dalhousie University, Halifax, Nova Scotia, Canada. An additional 200-mL subset was kept at 4 °C and transported to the CWL for alkalinity analysis.

Total metals contained in the drinking water samples were measured through inductively coupled plasma mass spectrometry (ICP/MS) following Standard Methods 3125 (APHA 1998) on an XSeries2 ICPMS (Thermo Scientific, Mississauga, ON, Canada) following the manufacturer's instructions. Prior to analysis, the samples were heat digested with nitric acid according to Standard Method 3030D (APHA 1998). Alkalinity was measured following Standard Method 2320 (APHA 1998), using the low alkalinity procedure (4d). Filtered water (0.22 μm; Millipore) was used as a blank control sample in all analysis. Appropriate standards were used according to the respective standard methods.

Table 1 Drinking water quality in Nunavut: characteristics of each study site and sampling program

Study site	Location	Population (2011 census[a])	Source water	Treatment	Distribution	Sampling dates	Total sample numbers
Coral Harbour	64° 08′ N; 83° 09′ W	834	Post River, reservoir	Direct chlorination in trucks	Trucked	March 12–14, 2013	16
Iqaluit	63° 44′ N; 68° 31′ W	6699	Lake Geraldine, reservoir	Sand filter, UV and chlorination	Mixed truck and piped	June 23–27, repeated September 21–24, 2014	69
Pangnirtung	66° 08′ N; 65° 41′ W	1425	Duval River, reservoir	Chlorination at pumping station	Trucked	July 24–28, 2013	21
Pond Inlet	72° 41′ N; 77° 57′ W	1549	Salmon River, surface, reservoir	Chlorination at pumping station	Trucked	July 19–22, 2013	31

[a] Statistics Canada (2012)

Table 2 Primers used in TaqMan assays for detection of bacterial and protozoan pathogens

Pathogen and primer names	Sequence 5′ to 3′	Annealing temperature (°C)	Reference
Campylobacter jejuni			
hipO-F	TGCT AGTGAGGTTG CAAAAGAATT	60	LaGier et al. (2004)
hipO-R	TCAT TTCGCAAAAA AATCCAAA		
hipO-p	FAM-ACGATGAT TAAATTCACAAT TTTTTTCGCCAA A-TAMRA		
Cryptosporidium parvum			
JVAG-F	ACTTTTTGTTTGTT TTACGCCG	55	Jothikumar et al. (2008)
JVAG-R	AATG TGGTAGTTGC GGTTGAA		
JVAG2–p	FAM-ATTTATCT CTTCGTAGCGGC G-BHQ1[b]		
Escherichia coli eae-positive[a]			
EaeF	GTAAGTTACACTAT AAAAGC ACCGTCG	59	Ibekwe et al. (2002)
EaeR	TCTG TGTGGATGGT AATAAATTTTTG		
EaeP	FAM-AAATGGAC ATAGCATCAGCA TAATAGGCTTGC T-BHQ1		
Giardia lamblia			
Gl18s-F	GACG GCTCAGGACA ACGGTT	60	Verweij et al. (2004)
Gl18s-R	TTGC CAGCGGTGTC CG		
Gl18s-p	FAM-CCCGCGGC GGTCCCTGCTAG -TAMRA		
Helicobacter pylori			
HP-FOR	TTAT CGGTAAAGAC ACCAGAAA	54	He et al. (2002)
HP-REV	ATCA CAGCGCATGT CTTC		
Listeria monocytogenes			
HlyQF	CATG GCACCACCAG CATCT	56	Rodriguez-Lazaro et al. (2004)
HlyQR	ATCCGCGTGTTTCT TTTCGA		
HlyQP	FAM-CGCCTGCA AGTCCTAAGAC-GCCA-TAMRA		
Salmonella enterica			
InvAF	AACG TGTTTCCGTG CGTAAT	56	Cheng et al. 2008
InvAR	TCCATCAAATTAGC GGAGGC		
InvAP	FAM-TGGAAGCG CTCGCATTGTGG -BHQ1		

FAM fluorescein, *BHQ1* black hole quencher

[a] The Ibekwe et al. (2002) method, which targets the *eae* gene (intimin), detects enterohemorrhagic and enteropathogenic *E. coli* (e.g. O157:H7, O145:H28, O55:H7 and O111:H7; see Huang et al. 2017 for details)

Microbiological analysis

For microbiological analysis, 8 L of water was collected in two 4 L sterilized plastic containers (Fisher Scientific, Nepean, Ontario, Canada). A 200-mL subsample was removed for faecal indicator bacteria analysis and preserved with 0.2 mL of 3% (*w*/*v*) sodium thiosulphate to inactivate residual chlorine. The subsamples were transported at 4 °C to the Northern Water Quality Laboratory (NWQL) located at the Nunavut Research Institute in Iqaluit, Nunavut, where they were analysed within 24 h of being sampled.

The remaining portions of each sample were used for molecular detection of selected waterborne pathogens. Waterborne microbial cells were concentrated onto a nitrocellulose membrane filter with a pore size of 0.45 μm (Whatman Laboratory Division, Maidstone, UK); specific volumes depended on the turbidity and solids content of the water, but a minimum of 1 L was concentrated in the field. These filters were transported (4 °C) to NWQL and subjected to DNA extraction within 24–48 h.

Enumeration of total coliforms and *Escherichia coli*

Faecal indicator bacteria consisting of total coliforms and *E. coli* were enumerated in 100 mL sample volumes using the Standard Method 9223 (APHA 1998), which is based on the addition of the Colilert defined substrate (IDEXX Laboratories, Inc., Westbrook, ME, USA) to the sample followed by transfer to QuantiTray/2000 (IDEXX Laboratories, Inc.) incubation trays following the manufacturer's protocols. Each water sample was analysed in duplicate.

Table 3 Source water quality of the study sites

Community	Source (no. of samples)	Temp. (°C)	pH	SpC (μS/cm)	Total coliforms (MPN/100 mL)	*E. coli* (MPN/100 mL)	Pathogens
Iqaluit	Lake Geraldine/water reservoir (7)	5.7 ± 2.2	7.0 ± 0.3	33 ± 7	5	<1[a]	BDL
Pangnirtung	Water reservoir (2)	12.1 ± 0.3	7.2 ± 0.1	15 ± 2	<1	<1	BDL
	Duval River (3)	14.9 ± 0.6	7.1 ± 0.2	8.9 ± 4	2	<1	BDL
Pond Inlet	Water reservoir (6)	12.7 ± 0.1	7.4 ± 0.1	73 ± 0.5	1	<1[a]	BDL
	Salmon River (4)	12.3 ± 0.3	7.3 ± 0.1	22 ± 0.7	266	<1	BDL

SpC specific conductivity, *BDL* below the detection limit of the qPCR assays for pathogenic agents

[a] One sample tested positive for 1 MPN/100 mL

Pathogen marker tests

The presence of waterborne bacterial and parasitic pathogens was analysed using quantitative polymerase chain reaction (qPCR) procedures. First, DNA was extracted from the microbes on the drinking water filters using the PowerWater (Coral Harbour) or PowerSoil (the other communities) DNA Isolation kits (MoBio Laboratories Inc., Carlsbad, CA, USA) following the manufacturer's instruction. Where PowerSoil kits were used, the filters were placed in a 15-mL centrifuge tube (Fisher Scientific) with 10 mL of 0.85% saline. Cells were released from the filters by vortexing sample tubes for 3 min and then harvested by centrifugation at 3200×*g* for 10 min after removal of the filters. The resuspended pellet (250 μL) was used for DNA extraction. Extracted genomic DNA was stored at −20 °C and transported to CWL in Halifax (NS) for further analysis.

The presence of the pathogens was detected through qPCR protocols that were based on previously published primer sequences targeting the following zoonotic waterborne pathogens: *Listeria monocytogenes*, *eae* positive pathogenic *E. coli*, *Helicobacter pylori*, *Campylobacter jejuni*, *Salmonella enterica*, *Giardia lamblia* and *Cryptosporidium parvum* (Table 2). The selection of pathogens was based on information in Goldfarb et al. (2013) and the prevalence of *H. pylori* infections reported by local health authorities in Coral Harbour and other Nunavut communities (McKeown et al. 1999; Goodman et al. 2008). Other zoonotic pathogens relevant to Arctic carnivores (e.g. *Trichinella*, *Echinococcus*) or opportunistic pathogens of hot water distribution (e.g. *Legionella pneumophila*, *Mycobacterium avium*) were not included yet may be important for community health in Nunavut.

All qPCR analyses were performed on a CFX96 Touch system (Bio-Rad Laboratories Inc., Hercules, USA). Each qPCR reaction (25 μL) contained 7.7 μL of DNase-free water (Fisher Scientific), 12.5 μL of TaqMan master mix (SsoAdvanced Universal Probes Supermix 2×, BioRad), 0.3 μL each of the forward and reverse primers (10 μM), 0.2 μL of TaqMan hydrolysis probes (10 μM) and 4 μL of

Table 4 Quality of treated water sampled from delivery trucks and taps

Community	Site	Service (no. of trucks or building samples)	Temperature (°C)	pH	SpC (μS/cm)	Alkalinity (mg $CaCO_3$/L)
Coral Harbour	Truck	(6)	2.2 ± 1.0[a]	7.6 ± 0.2	181 ± 16	–
	Tap[b]	Trucked (28)	17.1 ± 3.8	7.6 ± 0.2	167 ± 29A	76 ± 2.2A
Iqaluit	Truck	(6)	9.1 ± 2.1	6.8 ± 0.2	51 ± 10	–
	Tap	Trucked (21)	20.8 ± 3.4	7.0 ± 0.4	41 ± 10B	14 ± 1.8B
		Piped (36)	12.8 ± 2.0	6.7 ± 0.2	42 ± 11B	14 ± 2.1B
Pangnirtung	Truck	(3)	15.6 ± 2.6	7.5 ± 0.5	15 ± 0.4	–
	Tap	Trucked (12)	21.2 ± 3.5	7.1 ± 0.2	15 ± 0.6C	6.3 ± 3.2C
Pond Inlet	Truck	(4)	12.2 ± 0.7	7.4 ± 0.1	78 ± 1	–
	Tap	Trucked (18)	21.8 ± 3.3	7.3 ± 0.2	82 ± 14D	21 ± 1.1D

Different capital letters following tap water conductivity or alkalinity values indicate significant differences ($p < 0.05$) among samples

SpC specific conductivity

[a] Temperatures in water samples obtained from trucks and taps in buildings serviced by trucks (and in Iqaluit, a piped distribution system) were significantly different ($p < 0.05$) from each other within each of the communities

[b] Samples from building water tanks and taps were combined as samples from within the building were not significantly ($p > 0.05$, data not shown) different from each other

Table 5 Presence of faecal indicator bacteria and pathogens in truck and tap water samples

Community	Service	Total coliforms (positives/total samples)	*E. coli* (positives/total samples)	Pathogens (present/absent)
Coral Harbour	Truck	1/6[a]	1/6[a]	BDL
	Tap (trucked)	1/28[b]	1/28[b]	BDL
Iqaluit	Trucks	0/6	0/6	BDL
	Taps (trucked)	3/21	0/21	BDL
	Taps (piped)	2/36	0/36	BDL
Pangnirtung	Trucks	0/3	0/3	BDL
	Taps (trucked)	0/12	0/12	BDL
Pond Inlet	Trucks	0/3	0/3	BDL
	Taps (trucked)	1/18[c]	1/18[c]	BDL

BDL below the detection limit

[a] One of the truck samples tested positive for total coliforms and *E. coli*

[b] One of two tap samples from the same building was positive for total coliforms and *E. coli*

[c] One of two tap samples from the same building tested positive for total coliform and *E. coli* following the water tank running dry

sample DNA. For the *Helicobacter* assay, 12.5 μL of SybrGreen master mix (SsoAdvanced Universal SybrGreen 2×, BioRad) was used in place of the TaqMan master mix, and no hydrolysis probes were added. Positive controls contained DNA extracted from *Salmonella* Typhimurium (American Type Culture Collection, ATCC 14028), *E. coli* O157:H7 (strain EC 961019, kindly provided by H. Schraft, Lakehead University, Thunder Bay, ON, Canada), *Ca. jejuni* (kindly provided by L. Waddington, Canada Food Inspection Agency, Dartmouth, NS, Canada), *L. monocytogenes* 568 (serogroup IIa), *H. pylori* (ATCC 43504), *G. lamblia* (Waterborne Inc., G/C Positive Control, PC101; New Orleans, LA, USA) and *Cr. parvum* (Waterborne Inc., PC101). Blank DNA extraction controls, no template controls and positive DNA controls were included in the qPCR runs. qPCR efficiencies and limit of detection (LOD) were obtained from standard curves of 10-fold dilutions of DNA extract produced from cultures with known concentrations of cells or (oo)cysts per milliliter for all pathogens, resulting in qPCR efficiencies ranging

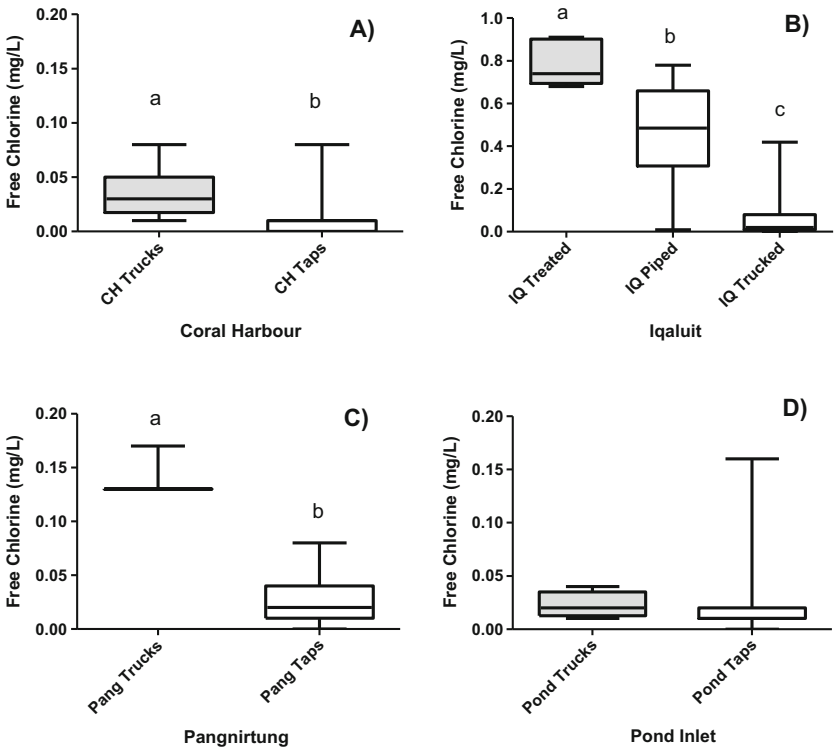

Fig. 2 Box plots showing residual free chlorine concentrations (mg/L) in the treated water from delivery trucks and water taps in **a** Coral Harbour, **b** Iqaluit, **c** Pangnirtung and **d** Pond Inlet. In each plot, the labelling of boxes with *different letters* indicates significant ($p < 0.05$) differences among samples. The median (50th percentile) free chlorine content is shown as the central line in the box plot, while the lower and upper hinges represent the 25th and 75th percentiles, respectively, and the whiskers the 10th and 90th percentiles

Table 6 Number and percentage of buildings with exceedances for the metal concentrations in tap water within the four Nunavut communities

Metal	Health Canada Health Objectives[a] Concentration (μg/mL)	Community			
		Coral Harbour (9)[b]	Iqaluit (30)	Pangnirtung (14)	Pond Inlet (17)
Pb	MAC ≤ 0.01	–	4 (7%)	6 (50%)	4 (7%)
Cu	AO ≤ 1.0	–	9 (16%)	2 (17%)	3 (18%)
Fe	AO ≤ 0.3	2 (13%)	1 (2%)	–	3 (18%)
Mn	AO ≤ 0.05	–	–	–	2 (12%)
Zn	AO ≤ 5	–	–	1 (8%)	–

[a] Health Canada (2017)—*MAC* maximum acceptable concentrations, *AO* aesthetic objectives

[b] Number of buildings that were sampled within each community

from 82 to 108% and R^2 values from 0.986 to 0.998. Two technical replicates were run for all standards, samples, negative controls and non-template controls, and the difference of the threshold cycle (Ct) value between the replicates was less than 0.5. Results were reported as the presence/absence of the selected waterborne pathogen in 1 L. The LODs were 150 copies/L for bacterial pathogens and 1500 copies/L for *Giardia* and *Cryptosporidium*.

Statistical analyses

The characteristics of the water samples were compared among and within communities using *t* tests and analysis of variance (ANOVA, unbalanced to accommodate different data sets) where relevant (GraphPad Prism version 5, San Diego, CA, USA). Results were considered significant at the 5% level ($p < 0.05$).

Results and discussion

General water characteristics and microbial quality

The pH values of the source water in the three communities were comparable, ranging from an average of 7.0 in Iqaluit to 7.4 in Pond Inlet (Table 3). Due to the winter conditions, source water samples could not be obtained from Coral Harbour.

In contrast, the specific conductivity was slightly different between sites, with values of 15, 33 and 73 μS/cm in the water reservoirs of Pangnirtung, Iqaluit and Pond Inlet, respectively (Table 3). The specific conductivity in the Pond Inlet water reservoir, which is normally filled with surface and subsurface runoff from the contributing watershed, was markedly higher than in the adjacent river (22 μS/cm) that is used to refill the reservoir when necessary. The river in Pangnirtung was used

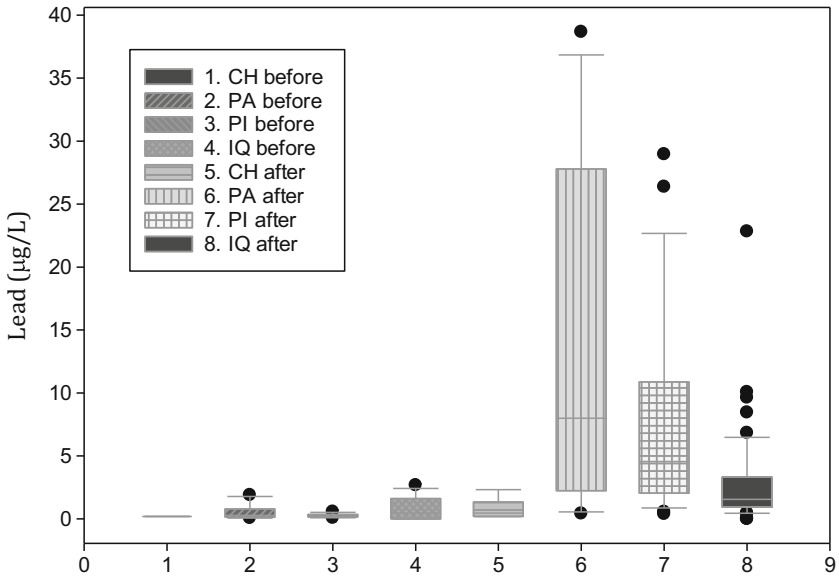

Fig. 3 Lead (Pb) concentrations in drinking water before (source water, water treatment plant and truck samples) and after (tap samples) passage through the premise plumbing distribution system in the communities of Coral Harbour (*CH*), Pangnirtung (*PA*), Pond Inlet (*PI*) and Iqaluit (*IQ*), Nunavut, Canada. Health Canada's maximum acceptable concentration for lead is 10 μg/L. The median (50th percentile) lead concentration is shown as the central line in the box plot, while the lower and upper hinges represent the 25th and 75th percentiles, respectively, and the whiskers the 10th and 90th percentiles. Outliers are represented as *dark circles*

to refill the water reservoir which likely resulted in similar specific conductivity at both sampling sites in Pangnirtung.

Coliform bacteria were detected within the raw water of the rivers and engineered water lake/reservoirs of Iqaluit and Pond Inlet, as well as in the reservoir in Pangnirtung (Table 3). Levels of *E. coli* were mostly below the detection limit (1 MPN/100 mL), except for positive results in one out of seven or six samples in the water reservoirs of Iqaluit and Pond Inlet, respectively.

The quality of the tap water varied among communities (Table 4). Within each of the communities, truck water temperatures were consistently significantly ($p < 0.05$) lower than the tap water temperatures. This may be due to the common placement of water tanks next to furnaces, an assumption supported by significantly ($p < 0.05$) higher tap water temperature in Iqaluit buildings served by trucks than in buildings served by piped connections. Specific conductivity and alkalinity of the tap water also varied significantly ($p < 0.05$) among all four communities, reflecting different contents of charged ions and buffering capacity or water hardness. With the exception of Coral Harbour (76 mg $CaCO_3$/L), the alkalinity of the drinking water was very low (≤20 mg $CaCO_3$/L). Low alkalinity may be problematic in these communities as corrosion of lead, copper and iron pipes increases under low alkalinity conditions (Health Canada 2009a; Boulay and Edwards 2001).

In general, the faecal indicator bacteria (total coliform and *E. coli*) levels were low or below detection limit from the treated drinking water samples (Table 5). *E. coli* was detected in one water sample from a truck and from a building tap in Coral Harbour. In Pond Inlet, the only *E. coli* detection was associated with a water tank that had run dry and then been refilled. As with the source water, none of the pathogens were detected in any of the treated water samples. Although this result does not exclude source waters as potential reservoirs for some common pathogens prevalent in Arctic communities, it is consistent with the investigations of Hastings et al. (2014) and Pardhan-Ali et al. (2013) of possible risk factors and exposures in the region. It should be noted, however, that in some cases, the methods of concentration and quantification yielded detection limits that were higher than the infective dose for humans; thus, true pathogen risk cannot be asserted in this study. For example, giardiasis can occur with exposure to as few as 10 *Giardia* cysts (Furness et al. 2000). Particularly for protozoan pathogens, employing more advanced techniques of high-volume cartridge filtration, immunomagnetic separation and/or flow cytometry may improve quantification levels approaching infective doses (Hsu et al. 2005; Keserue et al. 2011; Wohlsen et al. 2004).

The average concentrations of free chlorine in freshly treated drinking water samples ranged from very low values of 0.03 mg/L in Coral Harbour and Pond Inlet to the intermediary level of 0.14 mg/L in Pangnirtung and 0.87 mg/L in Iqaluit (Fig. 2). This demonstrated that the free chlorine content in the drinking water in all communities, with the exception of Iqaluit, fell below Canadian recommendations for free chlorine residuals (0.2–1.0 mg/L) in drinking water to provide the water with protection in the distribution system (Health Canada 2009b). Factors that may be contributing to levels below recommendations in trucked systems are lack of training for operators, operator variability, lack of on-site chlorine test instruments and difficulties in controlling dosage.

In Iqaluit, tap water from buildings on a trucked service contained significantly ($p < 0.05$) less free chlorine residuals than tap water obtained from buildings serviced by the piped system (Fig. 2b). In the latter case, the drinking water complied with the Health Canada guideline with an average free chlorine concentration of 0.51 mg/L. In Pangnirtung, free chlorine was also observed to decrease significantly ($p < 0.05$, Fig. 2c) from 0.14 mg/L in the freshly treated water to 0.02 mg/L in the tap water samples.

This lack of residual chlorine in the tap water samples from buildings on trucked services could have been caused by a number of different factors related to the reactivity of chlorine such as depletion from biofilms in the tanks, lack of routine cleaning and disinfection, high water temperatures and residence time in the storage receptacles (Rossman et al. 1994; Niquette et al. 2011).

According to residents who participated in the study, domestic water tanks in the four communities were refilled every 1–3 days. Daley et al. (2014) have also reported, however, that delays in refill service to houses on truck systems, which resulted in water tanks running dry, may occur up to several times per month. These interruptions may occur because of weather, mechanical failure or increased water demand within the home. Large disruptions in water distribution systems as well as more routine problems like water outages, inadequate secondary disinfection and loss of chlorine residual have been shown to increase the risk of waterborne illness (Craun and Calderon 2001; Ercumen et al. 2014). Consequently, biofilm formation and microbial regrowth within trucked systems may warrant further examination given the high frequency of disruptions. Maintenance of residual chlorine in the distribution trucks can be improved with operator training on dosage and contact time requirements for disinfection. In cases where low residual chlorine is problematic due to low water use, it may be prudent to install UV disinfection on a household level.

Heavy metals and corrosion issues

In Coral Harbour, where alkalinity levels and pH levels were highest, concentrations of heavy metals in tap water samples were below Health Canada guidelines, with the exception of two houses that had elevated Fe concentrations (Table 6). This was also the only community where first flush samples were collected, which would represent a worst case scenario. This

contrasted with Pond Inlet, Pangnirtung and Iqaluit where concentrations of heavy metals exceeded Health Canada guidelines in tap water samples collected from several buildings (Table 6). Lead concentrations, in particular, exceeded the Health Canada maximum acceptable concentration (MAC) in 7–50% of the buildings sampled in these three communities. Other metals that exceeded Health Canada Aesthetic Objectives (AO) at least once included Cu in all three communities, Fe in Iqaluit and Pond Inlet and Mn in Pond Inlet.

Concentrations of these metals in source waters and truck samples were all less than the Health Canada guidelines. Using Pb as an example, Fig. 3 shows the low levels of Pb in the water from the source, water treatment plants and trucks before its passage through the water tanks and premise plumbing after which higher Pb levels, including several exceedances, were observed in the tap water. Therefore, it is likely that the Pb and perhaps also the other metals in the tap water originated from corrosion of household storage tanks and premise plumbing.

Low alkalinity levels (e.g. ≤20 mg $CaCO_3$/L) in these three communities would make water distribution components susceptible to this process (Health Canada 2009a). It should also be noted that the building tap water samples collected in these three communities were not specifically collected after a stagnation period, and it is possible that concentrations of these metals may be higher if a stagnation period was captured (Health Canada 2009a). Fillion et al. (2014) reported that blood lead levels in adults and children in Nunavut were higher than in other parts of the country, and also suggested that tap water, in addition to other environmental sources, could be a contributing factor. It is recommended that further sampling, utilizing Health Canada or other sampling protocols (Deshommes et al. 2016) for corrosion assessment, be conducted in Nunavut communities with low source water alkalinity (e.g. ≤20 mg $CaCO_3$/L), to assess lead exposure through drinking water. Once the true risk of heavy metal exposure due to corrosion is determined, strategies to mitigate corrosion can be prepared, which may include alterations to water treatment, such as increasing alkalinity or adding corrosion inhibitors, or replacing water distribution infrastructure with non-corrosive materials such as polyvinyl chloride (PVC) piping (Health Canada 2009a).

Conclusions

Source waters in the four study communities were observed to be of relatively good quality. Selected pathogens were not detected in any of the samples, and levels of faecal indicator organisms were low. However, additional sampling during high-risk time periods (i.e. snowmelt) or follow-up investigation using more sensitive concentration and quantification methods is warranted to fully characterize source water vulnerability for microbial hazards. Free chlorine levels in water samples collected in residences and public buildings serviced by trucked water delivery were below Health Canada guidelines, representing a vulnerability in the drinking water management system in small arctic communities. Microbial regrowth in water tank biofilms is a potential concern due to the lack of secondary disinfection; this would particularly be an issue for tanks that are not cleaned on a regular basis. Lead and several other metals were detected at concentrations that exceeded Health Canada guidelines in tap water samples in three of the four communities (Pond Inlet, Pangnirtung and Iqaluit). Future research should focus on (i) establishing best practices for maintaining secondary disinfection within trucked water distribution systems, (ii) identifying if corrosion associated with water distribution system components (trucks, household storage tanks, premise plumbing) is contributing to elevate metal concentrations and (iii) establishment of storage tank cleaning and residual disinfection maintenance programs in communities which receive trucked water.

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