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

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41 **Title: Chemical and Microbial Characteristics of Municipal Drinking Water**

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72 **Supply Systems in the Canadian Arctic**

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4 20 **Abstract.**
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7 21 Drinking water in the vast Arctic Canadian territory of Nunavut is sourced from
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9 22 surface water lakes or rivers and transferred to man-made or natural reservoirs.
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11 23 The raw water is at a minimum treated by chlorination and distributed to customers
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14 24 either by trucks delivering to a water storage tank inside buildings or through a
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16 25 piped distribution system. The objective of this study was to characterize the
17
18 26 chemical and microbial drinking water quality from source to tap in three hamlets
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20 27 (Coral Harbour, Pond Inlet and Pangnirtung – each have a population of <2,000) on
21
22
23 28 trucked service, and in Iqaluit (population ~ 6,700), which uses a combination of
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26 29 trucked and piped water conveyance. Generally, the source and drinking water was
27
28 30 of satisfactory microbial quality, containing *Escherichia coli* levels of <1 MPN/100
29
30 31 mL with a few exceptions, and selected pathogenic bacteria and parasites were
31
32 32 below detection limits using quantitative polymerase chain reaction (qPCR)
33
34 33 methods. Tap water in households receiving trucked water contained less than the
35
36 34 recommended 0.2 mg/L of free chlorine, while piped drinking water in Iqaluit
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38 35 complied with Health Canada guidelines for residual chlorine (i.e., >0.2 mg/L free
39
40 36 chlorine). Some buildings in the four communities contained manganese (Mn),
41
42 37 copper (Cu), iron (Fe) and/or lead (Pb) concentrations above Health Canada
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44 38 guideline values for the aesthetic (Mn, Cu and Fe) and health (Pb) objectives.
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46 39 Corrosion of components of the drinking water distribution system (household
47
48 40 storage tanks, premise plumbing) could be contributing to Pb, Cu, and Fe levels, as
49
50 41 the source water in three of the four communities had low alkalinity. The results
51
52 42 point to the need for robust disinfection, which may include secondary disinfection
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43 or point-of-use disinfection, to prevent microbial risks in drinking water tanks in
44 buildings and ultimately at the tap.
45
46 Keywords: Drinking water, chlorination, arctic communities, surface water,
47 *Escherichia coli*, microbial pathogens, metals, lead

48 **Introduction**

49 The typical model of potable water delivery and safety assurance in Arctic
50 Canadian communities is fundamentally different than in communities south of 60
51 degrees latitude. Within the 25 remote communities of Nunavut, a vast arctic
52 territory of northern Canada (approximately 2.1 million km²), water is extracted
53 from lakes, rivers or glacial streams and either treated immediately, or conveyed by
54 pipes or trucks to reservoirs within the hamlets where it is subsequently
55 chlorinated as a minimum. The water is then trucked or, less commonly, piped to
56 individual households and buildings (Johnson, 2008). Homes and buildings on
57 trucked services receive water deliveries into water holding tanks located inside the
58 buildings.

59 In Nunavut, the raw water is typically extracted directly from source lakes
60 and rivers and transferred to an intake pumphouse/truckfill station or an
61 engineered reservoir, from which the water is pumped to the truckfill station
62 (Williams Engineering Canada Inc. 2014). In many hamlets, the raw water is
63 disinfected by chlorination using in-line injection pumps operating simultaneously
64 with the filling of the water trucks at the truckfill stations (Daley et al. 2014). A
65 multi-barrier approach to ensure water safety is used in Iqaluit, where the water
66 treatment plant (WTP) system consists of slow sand filtration and UV-disinfection in
67 addition to chlorination. The Government of Nunavut (GN) is currently moving
68 toward implementing multiple barriers in the drinking water treatment in all
69 communities. This implementation in the Canadian Arctic's small, fly-in
70 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 above ground 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. ~6,700, 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 & Mazumder 2003) and may be

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4 94 sensitive to climate change as alterations to seasonal precipitation and temperature
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7 95 patterns may affect run-off events, available fresh water resources, and microbial
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10 96 ecology (Harper et al. 2011a; Martin et al. 2007; Medeiros et al. 2017). The delivery
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12 97 train, the management and maintenance of municipal (truck, pumps, pipes), as well
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14 98 as in-home infrastructure (plumbing and water tanks), play a large role in the
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17 99 potential for water contamination (Ashbolt 2015; Ercumen et al. 2014). In
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19 100 particular, the risk of microbial and chemical contamination may be greater due to
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22 101 stagnant water in tanks receiving an intermittent supply (World Health
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24 102 Organization 2011). Corrosion of drinking water distribution system components,
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26
27 103 such as pipes and household plumbing fixtures, and the subsequent release of heavy
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29 104 metals including lead, copper, and zinc is an issue that has been widely studied in
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32 105 non-Arctic municipalities in Europe and North America (Zietz et al. 2010). In
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34 106 particular, drinking water has been shown to be a potentially significant source of
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37 107 lead exposure (Renner 2010). Heavy metal release is influenced by a number of
38
39 108 factors including, but not limited to, water quality (alkalinity, pH, etc.), stagnation
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42 109 times, temperature, and disinfectant residuals (Wang et al. 2014). Biofilm formation
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44 110 and detachment in water conveyance and storage systems has also been
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47 111 documented to adversely affect water quality in conventional piped distributions
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49 112 systems, and can potentially facilitate the survival and proliferation of opportunistic
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52 113 pathogens such as *Pseudomonas aeruginosa* (Liu et al. 2013; Falkinham et al. 2015).
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54 114 To date, metal corrosion potential has not been investigated within remote, arctic
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57 115 communities which are serviced by trucked distribution systems.
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The collection and representativeness of health data appertaining to water-related illness and disease in Canada's northern regions is limited (Metcalf et al. 2011; Harper et al. 2015a; Harper et al. 2011b). 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; 2012b; 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 (Figure 1, Table 1).

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

The population size of the studied communities varied from 834 in Coral Harbour to 6,699 in Iqaluit (Table 1). Each 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.

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	6,699	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	1,425	Duval River, Reservoir	Chlorination at pumping station	Trucked	July 24-28, 2013	21
Pond Inlet	72°41'N; 77°57'W	1,549	Salmon River, Surface, Reservoir	Chlorination at pumping station	Trucked	July 19-22, 2013	31

^a –Statistics Canada, 2012.

With the exception of Coral Harbour (due to winter conditions), samples were obtained from the fresh water source (i.e., rivers, water reservoirs, and/or engineered lakes), from which the community extract 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

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4 165 Harbour was the pilot site, treated water samples were obtained both from building
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6 166 water tanks and from cold water taps in the kitchen (area of food and beverage
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8 167 preparation) to determine if there were differences in the water quality. As there
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10 168 were no discernable differences (data not shown), it was decided only to sample the
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12 169 cold water tap fixtures in the remaining communities. Such tap water samples were
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14 170 assumed to be the most representative of the human oral exposure to potential
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16 171 waterborne contaminants originating from the source water, distribution system, or
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18 172 cold-water premise plumbing; contaminants specific to hot water distribution, such
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20 173 as the opportunistic pathogen *Legionella pneumophila*, were not assessed in this
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22 174 exploratory study. Table 1 contains detailed information about the community
23
24 175 location, size, drinking water treatment, distribution system, sampling dates and
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26 176 number of samples that were obtained from each community for this study.
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34 177 At the time of sampling, household inhabitants and public building managers
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36 178 were interviewed to provide context for the chemical and microbial results. They
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38 179 were asked about their views on the drinking water supply, perceptions of health
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40 180 risk, habits of water usage, the age of their home or building, and the condition of
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42 181 the water tank and premise plumbing. Local research assistants were hired in each
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44 182 community to assist with the interviews and provide language translation between
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46 183 Inuktitut and English when needed.
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54 185 ***Sample Collection and Water Quality Analysis***

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57 186 A 1 L sample was retrieved in a sterilized Nalgene High Density Polyethylene
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59 187 (HDPE) container (Fisher Scientific, Nepean, ON, Canada) from each sample location
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for general water quality analysis, and for treated water samples 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 minutes 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 two hours 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 minutes prior to collecting a bulk water sample. The sampling strategy was revised for the remaining communities due to logistical

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4 211 challenges with obtaining the first flush samples. For Pond Inlet, Pangnirtung and
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6 212 Iqaluit, samples for metals were collected at the same time as the other water
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9 213 quality parameters (i.e., after a 1 minute flushing period). A 100 mL subset of each
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11 214 sample was preserved (pH <2) with nitric acid and transported to the Clean Water
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14 215 Laboratory (CWL) located at Dalhousie University, Halifax, Nova Scotia, Canada. An
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16 216 additional 200 mL subset was kept at 4°C and transported to the CWL for alkalinity
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19 217 analysis.

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22 218 Total metals contained in the drinking water samples were measured through
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24 219 inductively coupled plasma mass spectrometry (ICP/MS) following Standard
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26 220 Methods 3125 (APHA, 1998) on an XSeries2 ICPMS (Thermo Scientific, Mississauga,
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29 221 Ontario, Canada) following manufacturer's instructions. Prior to analysis, the
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31 222 samples were heat digested with nitric acid according to Standard Method 3030D
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34 223 (APHA, 1998). Alkalinity was measured following Standard Method 2320 (APHA,
35
36 224 1998), using the low alkalinity procedure (4d). Filtered water (0.22 µm; Millipore)
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39 225 was used as a blank control sample in all analysis. Appropriate standards were used
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41
42 226 according to the respective standard methods.

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45 46 228 ***Microbiological Analysis***

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49 229 For microbiological analysis, 8 L of water was collected in two 4 L sterilized
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51 230 plastic containers (Fisher Scientific, Nepean, Ontario, Canada). A 200 mL subsample
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54 231 was removed for fecal indicator bacteria analysis, and preserved with 0.2 mL of 3%
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56 232 (w/v) sodium thiosulphate to inactivate residual chlorine. The subsamples were
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59 233 transported at 4°C to the Northern Water Quality Laboratory (NWQL) located at the
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234 Nunavut Research Institute in Iqaluit, Nunavut, where they were analyzed within 24
235 hours of being sampled.

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

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244 ***Enumeration of Total Coliforms and Escherichia coli***

245 Fecal indicator bacteria consisting of total coliforms and *E. coli* were
246 enumerated in 100 mL sample volumes using the Standard Method 9223 (APHA,
247 1998), which is based on the addition of the Colilert defined substrate (IDEXX
248 Laboratories, Inc., Westbrook, ME, USA) to the sample followed by transfer to
249 QuantiTray/2000 (IDEXX Laboratories, Inc.) incubation trays following
250 manufacturer's protocols. Each water sample was analyzed in duplicate.

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252 ***Pathogen Marker Tests***

253 The presence of waterborne bacterial and parasitic pathogens was analyzed
254 using quantitative polymerase chain reaction (qPCR) procedures. First, DNA was
255 extracted from the microbes on the drinking water filters using the PowerWater
256 (Coral Harbour), or PowerSoil (the other communities) DNA Isolation kits (MoBio

257 Laboratories Inc., Carlsbad, CA, USA) following manufacturer's instruction. Where
258 PowerSoil kits were used, the filters were placed in a 15 mL centrifuge tube (Fisher
259 Scientific) with 10 mL of 0.85% saline. Cells were released from the filters by
260 vortexing sample tubes for three minutes and then harvested by centrifugation at
261 3200 x *g* for 10 minutes after removal of the filters. The resuspended pellet (250 µL)
262 was used for DNA extraction. Extracted genomic DNA was stored at -20°C and
263 transported to CWL in Halifax (NS) for further analysis.

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

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
<i>Campylobacter jejuni</i>			
hipO-F	TGCTAGTGAGGTTGCAAAAGAATT	60	LaGier et al., 2004
hipO-R	TCATTTTCGCAAAAAAATCCAAA		
hipO-p	FAM-ACGATGATTAAATTCACAATTTTTTTTCGCCAAA-TAMRA ^a		
<i>Cryptosporidium parvum</i>			
JVAG - F	ACTTTTTGTTTGTGTTTACGCCG	55	Jothikumar et al. 2008
JVAG- R	AATGTGGTAGTTGCGGTTGAA		
JVAG2 - p	FAM-ATTTATCTCTTCGTAGCGGCG-BHQ1 ^b		
<i>Escherichia coli eae</i> -positive ^c			
EaeF	GTAAGTTACACTATAAAAGCACCGTCG	59	Ibekwe et al., 2002
EaeR	TCTGTGTGGATGGTAATAAATTTTGT		
EaeP	FAM-AAATGGACATAGCATCAGCATAATAGGCTTGCT-BHQ1		
<i>Giardia lamblia</i>			
GI18s-F	GACGGCTCAGGACAACGGTT	60	Verweij et al., 2004
GI18s-R	TTGCCAGCGGTGTCCG		
GI18s-p	FAM-CCCGCGGCGGTCCCTGCTAG-TAMRA		
<i>Helicobacter pylori</i>			
HP-FOR	TTATCGGTAAAGACACCAGAAA	54	He et al., 2002
HP-REV	ATCACAGCGCATGTCTTC		
<i>Listeria monocytogenes</i>			
HlyQF	CATGGCACCACCAGCATCT	56	Rodriguez-Lazaro et al., 2004
HlyQR	ATCCGCGTGTCTTTCTTTTCGA		
HlyQP	FAM ^a -CGCCTGCAAGTCCTAAGACGCCA-TAMRA		
<i>Salmonella enterica</i>			
InvAF	AACGTGTTTCCGTGCGTAAT	56	Cheng et al., 2008
InvAR	TCCATCAAATTAGCGGAGGC		
InvAP	FAM-TGGAAGCGCTCGCATTTGTGG-BHQ1		

^a –FAM – fluorescein

^b –BHQ1 – Black hole quencher

^c –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).

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

292 Universal Probes Supermix 2x, BioRad), 0.3 µL each of the forward and reverse
 293 primers (10 µM), 0.2 µL of TaqMan hydrolysis probes (10 µM), and 4 µL of sample
 294 DNA. For the *Helicobacter* assay, 12.5 µL of SybrGreen master mix (SsoAdvanced
 295 Universal SybrGreen 2x, BioRad) was used in place of the TaqMan master mix, and
 296 no hydrolysis probes were added. Positive controls contained DNA extracted from
 297 *Salmonella* Typhimurium (American Type Culture Collection, ATCC 14028), *E. coli*
 298 O157:H7 (strain EC 961019, kindly provided by H. Schraft, Lakehead University,
 299 Thunder Bay, ON, Canada), *Campylobacter jejuni* (kindly provided by L. Waddington,
 300 Canada Food Inspection Agency, Dartmouth, NS, Canada), *L. monocytogenes* 568
 301 (serogroup IIa), *Helicobacter pylori* (ATCC 43504), *Giardia lamblia* (Waterborne
 302 Inc., G/C Positive Control, PC101; New Orleans, LA, USA) and *Cryptosporidium*
 303 *parvum* (Waterborne Inc., PC101). Blank DNA extraction controls, no template
 304 controls, and positive DNA controls were included in the qPCR runs. qPCR
 305 efficiencies and limit of detection (LOD) was obtained from standard curves of 10
 306 fold-dilutions of DNA extract produced from cultures with known concentrations of
 307 cells or (oo)cysts/mL for all pathogens, resulting in qPCR efficiencies ranging from
 308 82% to 108%, and R² values from 0.986 to 0.998. Two technical replicates were run
 309 for all standards, samples, negative controls, non-template controls and the
 310 difference of the threshold cycle (Ct) value between the replicates was less than 0.5.
 311 Results were reported as the presence/absence of the selected waterborne
 312 pathogen in 1 L. The LODs were 150 copies/L for bacterial pathogens and 1500
 313 copies/L for *Giardia* and *Cryptosporidium*.

315 ***Statistical Analyses***

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

321 **Results and Discussion**

322 ***General Water Characteristics and Microbial Quality***

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

327 In contrast, the specific conductivity was slightly different between sites,
328 with values of 15, 33 and 73 $\mu\text{S}/\text{cm}$ in the water reservoirs of Pangnirtung, Iqaluit
329 and Pond Inlet, respectively (Table 3). The specific conductivity in the Pond Inlet
330 water reservoir, which is normally filled with surface and subsurface runoff from
331 the contributing watershed, was markedly higher than in the adjacent river (22
332 $\mu\text{S}/\text{cm}$) that is used to refill the reservoir when necessary. The river in Pangnirtung
333 was used to refill the water reservoir which likely resulted in the similar specific
334 conductivity at both of the sampling sites in Pangnirtung.

Table 3. Source water quality of the study sites.

Community	Source (#Samples)	Temp. (°C)	pH	SpC ^a (µS/cm)	Total coli-forms (MPN /100 mL)	<i>E. coli</i> (MPN /100 mL)	Pathogens
Iqaluit	Lake Geraldine/Water reservoir (7)	5.7±2.2	7.0±0.3	33±7	5	<1 ^b	BDL ^c
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 ^b	BDL
	Salmon River (4)	12.3±0.3	7.3±0.1	22±0.7	300	<1	BDL

^a – Specific conductivity

^b – One sample tested positive for 1 MPN/100 mL

^c – Below the detection limit of the qPCR assays for pathogenic agents

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.

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

Community	Site	Service (# truck or building samples)	Temperature (°C)	pH	SpC ^c (μ S/cm)	Alkalinity (mg CaCO ₃ /L)
Coral Harbour	Truck	(6)	2.2 ± 1.0 ^b	7.6±0.2	181±16	-
	Tap ^a	Trucked (28)	17.1 ± 3.8	7.6±0.2	167±29 ^{Ad}	76±2.2 ^A
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±10 ^B	14±1.8 ^B
		Piped (36)	12.8 ± 2.0	6.7±0.2	42±11 ^B	14±2.1 ^B
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±0.6 ^C	6.3±3.2 ^C
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±14 ^D	21±1.1 ^D

^a - 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.

^b - 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.

^c - Specific conductivity

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

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 2011).

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

Community	Service	Total coliforms (Positives/total samples)	<i>E. coli</i> (Positives/total samples)	Pathogens (Present/absent)
Coral Harbour	Truck	1/6 ^a	1/6 ^a	BDL ^d
	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

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

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4 384 ^b –One of two tap samples from the same building was positive for total coliforms
5 385 and *E. coli*
6 386 ^c –One of two tap samples from the same building tested positive for total coliform
7 387 and *E. coli* following the water tank running dry.
8 388 ^d –Below the detection limit
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13 390 In general, the fecal indicator bacteria (total coliform and *E. coli*) levels were
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15 391 low or below detection limit from the treated drinking water samples (Table 5). *E.*
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17 392 *coli* was detected in one water sample from a truck and from a building tap in Coral
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19 393 Harbour. In Pond Inlet, the only *E. coli* detection was associated with a water tank
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21 394 that had run dry and then been refilled. As with the source water, none of the
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23 395 pathogens were detected in any of the treated water samples. Although this result
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25 396 does not exclude source waters as potential reservoirs for some common pathogens
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27 397 prevalent in Arctic communities, it is consistent with Hastings et al. (2014) and
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29 398 Pardhan-Ali et al. (2013) investigations of possible risk factors and exposures in the
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31 399 region. It should be noted, however, that in some cases the methods of
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33 400 concentration and quantification yielded detection limits that were higher than the
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35 401 infective dose for humans; thus, true pathogen risk cannot be asserted in this study.
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37 402 For example, giardiasis can occur with exposure of as few as 10 *Giardia* cysts
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39 403 (Furness et al. 2000). Particularly for protozoan pathogens, employing more
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41 404 advanced techniques of high-volume cartridge filtration, immunomagnetic
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43 405 separation, and/or flow cytometry may improve quantification levels approaching
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45 406 infective doses (Hsu et al. 2005; Keserue et al. 2011; Wohlsen et al. 2004).
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Figure 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.

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 (Figure 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 (Figure 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 the free chlorine was also observed to decrease significantly ($p<0.05$, Figure 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

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4 443 water demand within the home. Large disruptions in water distribution systems, as
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7 444 well as more routine problems like water outages, inadequate secondary
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9 445 disinfection, and loss of chlorine residual have been shown to increase risk of
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11 446 waterborne illness (Craun and Calderon 2001; Ercumen et al. 2014). Consequently,
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13 447 biofilm formation and microbial regrowth within trucked systems may warrant
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15 448 further examination given the high frequency of disruptions. Maintenance of
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17 449 residual chlorine in the distribution trucks can be improved with operator training
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19 450 on dosage and contact time requirements for disinfection. In cases where low
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21 451 residual chlorine is problematic due to low water use, it may be prudent to install
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23 452 UV disinfection on a household level.
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32 454 ***Heavy Metals and Corrosion Issues***

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34 455 In Coral Harbour, where alkalinity levels and pH levels were highest, concentrations
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36 456 of heavy metals in tap water samples were below Health Canada guidelines, with the
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38 457 exception of two houses that had elevated Fe concentrations (Table 6). This was
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40 458 also the only community where first flush samples were collected, which would
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42 459 represent a worst case scenario. This contrasted with Pond Inlet, Pangnirtung, and
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44 460 Iqaluit where concentrations of heavy metals exceeded Health Canada guidelines in
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46 461 tap water samples collected from several buildings (Table 6). Lead concentrations,
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48 462 in particular, exceeded the Health Canada Maximum Acceptable Concentration
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50 463 (MAC) in 7 – 50% of the buildings sampled in these three communities. Other
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52 464 metals that exceeded Health Canada Aesthetic Objectives (AO) at least once included
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54 465 Cu in all three communities, Fe in Iqaluit and Pond Inlet, and Mn in Pond Inlet.
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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 (2006) – MAC: maximum acceptable concentrations and AO: aesthetic objectives

^b –Number of buildings that were sampled within each community

Concentrations of these metals in source waters and truck samples were all less than the Health Canada guidelines. Using Pb as an example, Figure 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.

Figure 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.

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

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4 496 blood lead levels in adults and children in Nunavut were higher than in other parts
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7 497 of the country, and also suggested that tap water, in addition to other environmental
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9 498 sources, could be a contributing factor. It is recommended that further sampling,
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11 499 utilizing Health Canada or other sampling protocols (Deshommes et al. 2016) for
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14 500 corrosion assessment, be conducted in Nunavut communities with low source water
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16 501 alkalinity (e.g., ≤ 20 mg CaCO_3/L), to assess lead exposure through drinking water.
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18 502 Once the true risk of heavy metal exposure due to corrosion is determined,
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21 503 strategies to mitigate corrosion can be prepared, which may include alterations to
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23 504 water treatment, such as increasing alkalinity or adding corrosion inhibitors, or
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25 505 replacing water distribution infrastructure with non-corrosive materials such as
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27 506 polyvinyl chloride (PVC) piping (Health Canada 2009a).
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33 34 508 ***Conclusions***

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37 509 Source waters in the four study communities were observed to be of relatively good
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39 510 quality. Selected pathogens were not detected in any samples, and levels of fecal
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41 511 indicator organisms were low. However, additional sampling during high risk time
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43 512 periods (i.e., snowmelt) or follow-up investigation using more sensitive
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45 513 concentration and quantification methods is warranted to fully characterize source
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47 514 water vulnerability for microbial hazards. Free chlorine levels in water samples
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49 515 collected in residences and public buildings serviced by trucked water delivery were
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51 516 below Health Canada guidelines, representing a vulnerability in the drinking water
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53 517 management system in small arctic communities. Microbial regrowth in water tank
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55 518 biofilms is a potential concern due to the lack of secondary disinfection; this would
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4 519 particularly be an issue for tanks that are not cleaned on a regular basis. Lead and
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7 520 several other metals were detected at concentrations that exceeded Health Canada
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9 521 guidelines in tap water samples in three of the four communities (Pond Inlet,
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11 522 Pangnirtung, and Iqaluit). Future research should focus on (i) establishing best
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17 524 systems, (ii) identifying if corrosion associated with water distribution system
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19 525 components (trucks, household storage tanks, premise plumbing) is contributing to
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22 526 elevate metal concentrations, and (iii) establishment of storage tank cleaning and
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24 527 residual disinfection maintenance programs in communities which receive trucked
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