Weather, environmental conditions, and waterborne

*Giardia* and *Cryptosporidium* in Iqaluit, Nunavut

Stephanie Masina, Jamal Shirley, Jean Allen, Jan M. Sargeant, Rebecca A. Guy, Peter M. Wallis, J. Scott Weese, Ashlee Cunsolo, Anna Bunce and Sherilee L. Harper

**ABSTRACT**

Indigenous communities in the Arctic often face unique drinking water quality challenges related to inadequate infrastructure and environmental contamination; however, limited research exists on waterborne parasites in these communities. This study examined *Giardia* and *Cryptosporidium* in untreated surface water used for drinking in Iqaluit, Canada. Water samples (*n* = 55) were collected weekly from June to September 2016 and tested for the presence of *Giardia* and *Cryptosporidium* using microscopy and polymerase chain reaction (PCR). Exact logistic regressions were used to examine associations between parasite presence and environmental exposure variables. Using microscopy, 20.0% of samples tested positive for *Giardia* (*n* = 11) and 1.8% of samples tested positive for *Cryptosporidium* (*n* = 1). Low water temperatures (1.1 to 6.7 °C) and low air temperatures (−0.1 to 4.5 °C) were significantly associated with an increased odds of parasite presence (*p* = 0.047, *p* = 0.041, respectively). These results suggest that surface water contamination with *Giardia* and *Cryptosporidium* may be lower in Iqaluit than in other Canadian regions; however, further research should examine the molecular characterization of waterborne parasites to evaluate the potential human health implications in Northern Canada.

**Key words** | Arctic, Canada, Inuit health, parasites, waterborne disease, water quality

*Stephanie Masina* (corresponding author)
*Jan M. Sargeant*
*Anna Bunce*
*Sherilee L. Harper*

Department of Population Medicine, University of Guelph, 50 Stone Road East, Guelph, Ontario, Canada N1G 2W1

E-mail: s.masina23@gmail.com

*Jamal Shirley*
*Jean Allen*

Nunavut Research Institute, P.O. Box 1720, Iqaluit, Nunavut, Canada X0A 0H0

*Jean Allen*

Indigenous and Northern Affairs Canada, P.O. Box 2200, Iqaluit, Nunavut, Canada X0A 0H0

*Jan M. Sargeant*

Centre for Public Health and Zoonoses, University of Guelph, 50 Stone Road East, Guelph, Ontario, Canada N1G 2W1

*Rebecca A. Guy*

National Microbiology Laboratory, Public Health Agency of Canada, 110 Stone Road West, Guelph, Ontario, Canada N1G 3W4

*Peter M. Wallis*

Hyperion Research Ltd, 1008 Allowance Avenue SE, Medicine Hat, Alberta, Canada T1A 3G8

*J. Scott Weese*

Department of Pathobiology, University of Guelph, 50 Stone Road East, Guelph, Ontario, Canada N1G 2W1

*Ashlee Cunsolo*

Labrador Institute, Memorial University, 219 Hamilton River Road, Happy Valley-Goose Bay, Labrador, Canada A0P 1E0

*Sherilee L. Harper*

School of Public Health, University of Alberta, 3-300 Edmonton Clinic Health Academy, 11405 - 87 Ave, Edmonton, Alberta, Canada T6G 1C9

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INTRODUCTION

In the Arctic, many Indigenous communities experience inequitable challenges in accessing safe drinking water (Marino et al. 2009; Harper et al. 2011; Goldhar et al. 2014; Daley et al. 2015; Bradford et al. 2016). Both water quantity and quality in these remote communities are often challenged by inadequate infrastructure, limited resources, environmental contamination, and climate change (Martin et al. 2007; Harper et al. 2011, 2015b; Daley et al. 2015), which can result in frequent drinking water advisories and disruptions to drinking water services (Goldhar et al. 2015; Daley et al. 2014). Northern residents are concerned about these drinking water challenges (Garner et al. 2010; Wright et al. 2018); for instance, a survey found that 35.9% of all Inuit adults in Canada felt their drinking water was contaminated at certain times of the year, and 15.0% felt their drinking water at home was not safe for consumption (Garner et al. 2010). Empirical evidence from Inuit communities in Canada supports these concerns, with research documenting high levels of Escherichia coli and total coliforms in untreated surface water that is commonly used for drinking (Harper et al. 2011), stored household water containers (Martin et al. 2007; Wright et al. 2017), as well as truck and tap water samples (Daley et al. 2017).

These water challenges have important implications for human health. For instance, one of the highest rates of self-reported acute gastrointestinal illness in the global literature was reported in Northern Canada, with drinking water associated with higher odds of acute gastrointestinal illness (Harper et al. 2015a). Additional research found that Giardia was one of the most common pathogens causing gastrointestinal illness in the Northwest Territories (Pardhan-Ali et al. 2012), with risk factors including the consumption of untreated water (Pardhan-Ali et al. 2013). In Nunavut, Cryptosporidium was the most commonly identified pathogen among diarrheic patients (Goldfarb et al. 2013).

Originating from human or animal feces, Giardia and Cryptosporidium are enteric parasites that are common causes of waterborne diseases in Canada (i.e., giardiasis and cryptosporidiosis) (Schuster et al. 2005). Theoretically, one Giardia cyst or Cryptosporidium oocyst can cause infection when ingested by humans (Health Canada 2012); however, research suggests that the minimum infectious dose is 9–10 (oo)cysts, which is a relatively low infectious dose compared to many waterborne pathogens (Smith et al. 2006). Thus, it is important to understand and monitor the frequency, concentration, and distribution of these parasites in drinking water sources to protect human health in northern communities. This is particularly important considering the differences in sources of contamination between northern and southern communities. For instance, northern wildlife reservoirs may account for differences in waterborne pathogens compared to warmer, more southern communities (Jenkins et al. 2013).

Despite the high rates of parasitic infection in humans in Northern Canada (Pardhan-Ali et al. 2012; Goldfarb et al. 2015), most drinking water research in this region has focused on indicator bacteria, such as Escherichia coli and coliforms (Martin et al. 2007; Harper et al. 2011; Daley et al. 2017; Wright et al. 2017). However, E. coli and coliforms may not be accurate indicators of all types of fecal contamination in water due to differences in pathogen sources, transport characteristics, and survival in the environment (Wu et al. 2011). For instance, studies found poor correlations between indicator bacteria and waterborne parasites because, compared to parasites, indicator bacteria are often not as stable in the environment; therefore, the absence of indicator bacteria may not indicate the absence of parasites (Edberg et al. 2000; Health Canada 2012).

The goal of this study was to investigate the presence of Giardia and Cryptosporidium in untreated surface water that is used by some community members for drinking in Iqaluit, Nunavut, Canada. Specific objectives were to: (i) estimate the prevalence and concentrations of Giardia cysts and Cryptosporidium oocysts in local rivers over time; (ii) examine associations between indicator bacteria and parasites in these surface waters; and (iii) identify potential associations of parasites in surface water with meteorological conditions (e.g., air temperature, precipitation) and water quality parameters (e.g., water temperature, turbidity).
METHODS

Study location

Nunavut is Canada’s newest and largest territory, with approximately 36,000 residents living in 26 communities (Statistics Canada 2017b). Iqaluit (64°N, 69°W) is north of the tree-line, and is the capital city of Nunavut (Figure 1), with a population of 7,740 residents, 83.8% of whom identify as Inuit (Statistics Canada 2017a). A mixed economy of wage-based employment and subsistence activities exists in Iqaluit, where many residents participate in subsistence hunting, trapping, foraging, and gathering of water as part of daily life (Harder & Wenzel 2012; Daley et al. 2015). Treated piped or trucked water is available to most residents in Iqaluit, but, similar to other Inuit communities (Martin et al. 2007; Harper et al. 2011; Daley et al. 2015; Wright et al. 2017, 2018), some prefer to collect untreated surface water in personal storage containers to use for drinking. Collecting, consuming, and sharing drinking water from traditional sources remain integral cultural practices for many Inuit in Canada that contribute to physical, social, and spiritual well-being; many Inuit still identify traditional raw water sources as their preferred drinking water sources (Martin et al. 2007; Goldhar et al. 2013). These water sources are often perceived to be superior in quality to chlorinated tap water as they are believed to be better tasting and more nourishing (Marino et al. 2009; Goldhar et al. 2013).

Research approach

This study was guided by an EcoHealth approach, implementing systems thinking, transdisciplinary, community-based, and knowledge-to-action research methods (Charron 2012). The research question, study design, data collection, interpretation, and knowledge mobilization were conducted by a collaborative team of Indigenous and non-Indigenous researchers, regional specialists, community members, and government stakeholders. The collaborative and community-based nature of this work was identified as an important aspect of conducting environmental health research in the Circumpolar North, specifically with Indigenous communities (Jones et al. 2018). In particular, this study was co-led by the Nunavut Research Institute (NRI; http://www.nri.nu.ca/) in Iqaluit. The NRI runs a community-based microbial monitoring program in Iqaluit, testing...
river water for *E. coli* and coliforms (NRI 2015). In this study, we worked with the NRI to investigate the presence of *Giardia* and *Cryptosporidium* within their existing water monitoring program in three local rivers (Figure 1).

**Data collection and analysis**

**Water data**

Government, non-government, and NRI partners selected Sylvia Grinnell and Apex Rivers as study locations because they have been used for decades by community members as culturally important sources for untreated drinking water. Carney Creek, a waterbody that flows through an industrialized part of the city, was selected as a study site to examine the quality of surface water within Iqaluit that is not used for drinking. Local personnel were hired and trained by NRI and University of Guelph researchers to collect water samples and perform initial laboratory analyses. Based on the schedule and laboratory capacity at the NRI, water samples (*n* = 55) were collected twice per week from 29 June 2016 to 28 September 2016 at Sylvia Grinnell River (63.76496°N, 68.58106°W), Apex River (63.73192°N, 68.44973°W), and Carney Creek (63.74903°N, 68.53251°W) (Figure 1). Water samples from each site were collected and tested for (a) selected parasites and (b) indicator bacteria.

(a) **Parasites**: Water samples were collected in 5, 10, and 20 L collapsible low-density polyethylene carboys (Cole-Parmer®, Vernon Hills, IL, USA) by holding the carboys approximately 10 cm below the surface of the water. Samples were transported immediately to the NRI laboratory and processed within 1 hour of sample collection. Water samples were processed at the NRI for *Giardia* and *Cryptosporidium* isolation using the IDEXX Filta-Max® system (IDEXX Laboratories Inc. 2002), following the United States Environmental Protection Agency (EPA) Method 1623 (EPA 2005). Specifically, 5–10 L of sample water was used to flush the Filta-Max® system without the filter, and an average of 92.3 L (median = 109.3 L; range = 6.8–121.3 L) of sample water was then filtered through a 1.0 μm Filta-Max® filter cartridge (IDEXX Laboratories Inc., Westbrook, ME, USA) at a flow rate of 1–5 L/min. Water volumes were measured by collecting filtered sample water in a graduated container. Lower water volumes and flow rates were obtained with some highly turbid samples, but only one filter was used for each sample. After removal of the filter, the Filta-Max® system was flushed with 10 L of tap water and the carboys were washed with laboratory detergent and rinsed with tap water, according to Method 1623 (EPA 2005). The filters were refrigerated (4 °C) until shipment to Hyperion Research Ltd in Medicine Hat, Alberta (http://www.hyperionlab.ca), a laboratory accredited by the Canadian Association for Laboratory Accreditation for the detection of *Giardia* and *Cryptosporidium* in water. Every effort was made to get the samples to the laboratory within the 96-hour window specified by Method 1623 (EPA 2005), but this was not always possible because of airline schedules and weather delays, which was consistent with other research from Northern Canada (Wallis et al. 1996). One study found that sample holding times of up to 2 weeks had no significant effect on the identification of *Giardia* and *Cryptosporidium* parasites from surface water samples (Robertson & Gjerde 2000), so with appropriate packaging and refrigeration of samples, a 2-week holding time was deemed suitable for this study. All samples were shipped by air in Styrofoam™ coolers with ice packs and arrived at the laboratory well below the temperature limit (<20 °C). To evaluate the effect of delays in sample processing, a trip control was prepared by spiking duplicate filters with 224 *Giardia* cysts (obtained from Mongolian gerbil feces infected with *G. lamblia* WB trophozoites) and 148 *Cryptosporidium* oocysts (obtained from C57BL6/6N mice infected with *C. parvum* AZ-1) at Hyperion Research Ltd on 29 September 2016. One filter was stored at 5 °C for 5 days and then processed, while the second filter was shipped to Iqaluit and received back 33 days later and processed on 31 October 2016.

Compared to bacteria, parasites are more difficult to identify in water because they cannot be readily cultured in defined media as can many pathogenic bacteria, and they are found at lower concentrations in the environment (Straub & Chandler 2003). As such, to increase the sensitivity of our testing and avoid false negatives, we examined samples using microscopy and molecular methods. *Giardia* cysts and *Cryptosporidium* oocysts from both the control samples and study samples were isolated from water according to Method 1623: (i) elution of (oo)cysts from filters, (ii) concentration of sample material, and (iii) immunomagnetic separation (EPA 2005). Samples were then examined by
immunofluorescence (Waterborne™ Inc., New Orleans, LA, USA) and microscopy for enumeration of (oo)cysts, with a detection limit of 1.0 (oo)cysts/volume filtered (average 90 L) (EPA 2005). (Oo)cyst recoveries (%) from filters during sample processing were determined through parallel evaluation of filters inoculated with known parasite concentrations, using the same sources and concentrations of parasites as the trip control samples. For genotyping, sample material was scraped from microscope slides and slide surfaces were swabbed to recover sample material, as described by Ruecker et al. (2005). Samples were subjected to five cycles of freeze–thaw (liquid nitrogen/65 °C) to break down (oo)cyst cell walls, followed by digestion with proteinase K (Thermo Fisher Scientific®, Waltham, MA, USA) and detergents (ATL lysis buffer, Thermo Fisher Scientific®; sodium dodecyl sulphate, Honeywell Riedel-de Haën™, Germany). DNA was isolated by capture on spin columns (Qiagen® Hilden, Germany) and eluted with 10 mM Tris buffer. For DNA amplification, nested polymerase chain reaction (PCR) assays were used to target the triose phosphate isomerase and glutamate dehydrogenase genes for Giardia (Sulaiman et al. 2003; Read et al. 2004) and the 18S rRNA gene for Cryptosporidium (Xiao et al. 1999; Ruecker et al. 2005), with positive and negative controls included. Agarose gel electrophoresis (1.5%) was used to analyze PCR products. All DNA extractions and PCR assays were conducted by Hyperion Research Ltd.

(b) Indicator bacteria: Two 100-mL water samples from each site were tested at the NRI for the quantification of indicator bacteria (most probable number (MPN) per 100 mL of water), using the EPA-approved Colilert® system (IDEXX Laboratories Inc., Westbrook, ME, USA) (IDEXX Laboratories Inc. 2005).

Environmental and meteorological data

Water quality parameters were measured and recorded; a field probe (Orion 3 Star, Thermo Fisher Scientific©) was used to measure the water temperature (°C) and electrical conductivity (μS/cm) of the surface water on each sampling day, while a laboratory probe (Orion Star A215, Thermo Fisher Scientific©) measured pH, and a turbidity meter (2100Q Turbidimeter, Hach®, Loveland, CO, USA) measured turbidity (nephelometric turbidity unit; NTU) of each sample in the laboratory. For Sylvia Grinnell and Apex Rivers, water level (m) data were collected from Environment Canada for each sampling day and the 3 days prior to sampling (Environment Canada 2016).

Meteorological data in Iqaluit were collected from Environment Canada for each sampling day and the 3 days prior to sampling, including daily mean, minimum, and maximum air temperature (°C), as well as daily total precipitation (mm) (Government of Canada 2017).

Statistical analyses

All statistical analyses were conducted using Stata 13.1 (College Station, TX, USA). The significance level of statistical tests was α < 0.05.

Parasite prevalence and concentrations: Descriptive statistics were used to determine the prevalence and mean concentrations of Giardia and Cryptosporidium from Sylvia Grinnell River (n = 24), Apex River (n = 26), and Carney Creek (n = 5).

Indicator bacteria and parasites: Indicator bacteria concentrations from each site were summarized using descriptive statistics. The prevalence of positive E. coli samples (%) as well as the concentrations of E. coli and total coliforms (MPN/100 mL water) detected in each sample were summarized for Sylvia Grinnell River (n = 24), Apex River (n = 26), and Carney Creek (n = 5). Linear regression was used to examine the unconditional association between E. coli and total coliform concentrations, and logistic regressions were used to examine unconditional associations between the presence/absence of parasites (i.e., Giardia and/or Cryptosporidium) and the concentration of each indicator bacteria (i.e., E. coli and total coliforms).

Environmental conditions and parasites: Descriptive statistics were used to summarize water quality parameters and meteorological conditions. Exact logistic regressions were used to examine associations between the presence/absence of parasites (i.e., Giardia and/or Cryptosporidium) and environmental exposure variables that were selected a priori (Table 1). Five water quality parameters and meteorological variables were chosen (three variables including 3-day lag periods) based on a previous meta-
analysis (Young et al. 2015), resulting in 14 environmental exposure variables that were tested (Table 1). Specifically, we examined the unconditional association of parasite presence/absence with air temperature and cumulative precipitation (each with 3-day lag periods). We also examined the association of parasite presence/absence with water temperature, turbidity, and water level (with a 3-day lag period), while controlling for the sampling location as a fixed effect. Observations from Carney Creek were excluded from regression analyses due to a limited number of observations from all sample sites. We also examined the association of parasite presence/absence with air temperature and cumulative precipitation (each with 3-day lag periods). We also examined the association of parasite presence/absence with water temperature, turbidity, and water level (with a 3-day lag period), while controlling for the sampling location as a fixed effect. Observations from Carney Creek were excluded from regression analyses due to a limited number of observations from all sample sites.

**RESULTS**

**Parasite prevalence and concentrations**

Using microscopy, 20.0% ($n = 11/55$) of samples tested positive for *Giardia* and 1.8% ($n = 1/55$) of samples tested positive for *Cryptosporidium* from all sample locations (Table 2). However, at drinking water collection sites (i.e., Sylvia Grinnell and Apex Rivers), 22.0% ($n = 11/50$) of samples tested positive for *Giardia* and 2.0% ($n = 1/50$) of samples tested positive for *Cryptosporidium*. There was a higher number of positive samples found at Sylvia Grinnell River ($n = 7$) and Apex River ($n = 5$) compared to Carney Creek ($n = 0$). Among positive results, the average concentration of *Giardia* was 1.57 cysts/100 L at Sylvia Grinnell River ($n = 7$) and 0.88 cysts/100 L at Apex River ($n = 4$), while the average concentration of *Cryptosporidium* was 0.90 oocysts/100 L at Apex River ($n = 1$) (Figure 2). Using microscopy, parasites were detected in water samples throughout the summer, but a higher number of positive samples was detected in the late summer and early fall (Figure 2). Using PCR, *Giardia* and *Cryptosporidium* were not detected in the water samples ($n = 55$); therefore, it was not possible to determine the species or genotypes of parasites that were present.

Evaluation of control samples (i.e., of known concentrations) revealed that (oo)cyst recoveries ranged from 40.0% to 92.0% for *Giardia* cysts and 25.9% to 53.0% for *Cryptosporidium* oocysts in the laboratory during the study period. The trip control samples ($n = 2$) resulted in recoveries of 71.0% for *Giardia* cysts and 47.0% for *Cryptosporidium* oocysts after 5 days of storage in the lab.
and recoveries of 55.0% for *Giardia* cysts and 28.0% for *Cryptosporidium* oocysts after 33 days in transit.

**Indicator bacteria**

A statistically significant, positive association was confirmed between *E. coli* and total coliforms (Coef. = 0.77; *p* < 0.001; 95% CI = 0.70–0.84). Thus, for each one unit increase in total coliforms per 100 mL of water, *E. coli* increased by 0.77 units per 100 mL of water. While 30.9% (*n* = 17/55) of samples tested positive for *E. coli* (Table 2), only four of these positive samples were found at parasite-positive sites (Figure 2). No statistically significant associations were found between *E. coli* and the presence of parasites (*p* = 0.383; 95% CI = 0.28–1.63), or between total coliforms and the presence of parasites (*p* = 0.222; 95% CI = 0.97–1.00).

**Environmental conditions**

On sample collection days, the mean water temperature and turbidity were 8.2 °C and 7.0 NTU, respectively (Table 3). The mean air temperature and precipitation on the day of water collection were 6.7 °C and 4.5 mm, respectively, and the daily water level generally decreased over time from June to September 2016 (Figure 3).

At Sylvia Grinnell and Apex Rivers, low water temperature (≤35th percentile; 1.1 to 6.7 °C) at the time of sampling...
was significantly associated with an increased odds of parasite presence, while controlling for sampling location (Table 4); specifically, lower water temperatures increased the odds of parasite presence by four times, compared to higher water temperatures. Low mean air temperature (≤35th percentile; −0.1 to 4.5 °C) 3 days prior to sampling was also significantly associated with the increased odds of parasite presence (Table 4); specifically, low mean air temperature increased the odds of parasite presence by four times, compared to high air temperature. Cumulative precipitation, water level, and turbidity were not associated with the presence/absence of parasites.

**DISCUSSION**

In Iqaluit, *Giardia* (20.0%) and *Cryptosporidium* (1.8%) prevalence in untreated surface water appeared to be lower than in surface water from the Yukon Territory (32% *Giardia*, 14% *Cryptosporidium*; Roach et al. 1993), British Columbia (86% *Giardia*, 63% *Cryptosporidium*; Prystajecky et al. 2014), Ontario (36% *Giardia*, 15% *Cryptosporidium*; Edge et al. 2013), as well as Alberta and several US states (81% *Giardia*, 87% *Cryptosporidium*; LeChevallier et al. 1991). Although it is difficult to compare our results to studies using different sampling methodologies, our results indicate that the risk of surface water contamination by *Giardia* and *Cryptosporidium* in Iqaluit may be lower than in other regions of North America, including northern or subarctic communities that are south of the tree-line. These findings could be explained by watershed characteristics, environmental conditions, and sources of contamination (LeChevallier et al. 1991). Surface waters in Iqaluit may be at a low risk of *Giardia* and *Cryptosporidium* contamination due to a lack of agricultural runoff, or differences in wildlife populations and human population densities between Northern and Southern Canada (Wilkes et al. 2011; Ruecker et al. 2012; Jenkins et al. 2013; Statistics Canada 2017c). For instance, *Giardia* has been identified in livestock and companion animals, but its impact on northern wildlife populations and species is unknown (Jenkins et al. 2013).

Although the prevalence of *Giardia* and *Cryptosporidium* in Iqaluit’s surface waters appeared to be lower than in other regions of Canada, differences between the use and treatment of raw drinking water sources between Northern and Southern Canadian communities should be considered (Martin et al. 2007; Harper et al. 2011; Daley et al. 2011).

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**Table 3** | Water quality parameters from each sample location in Iqaluit, Nunavut from June to September 2016

<table>
<thead>
<tr>
<th></th>
<th>Sylvia Grinnell River (n = 24)</th>
<th>Apex River (n = 26)</th>
<th>Carney Creek (n = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water temperature (°C)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>8.0</td>
<td>7.9</td>
<td>10.5</td>
</tr>
<tr>
<td>Median</td>
<td>8.2</td>
<td>7.8</td>
<td>9.6</td>
</tr>
<tr>
<td>Range</td>
<td>2.3–13.7</td>
<td>1.1–15.1</td>
<td>5.6–16.3</td>
</tr>
<tr>
<td><strong>Conductivity (μS/cm)</strong></td>
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<td></td>
</tr>
<tr>
<td>Mean</td>
<td>40.3</td>
<td>55.5</td>
<td>177.3</td>
</tr>
<tr>
<td>Median</td>
<td>41.8</td>
<td>59.7</td>
<td>193.6</td>
</tr>
<tr>
<td>Range</td>
<td>25.7–49.9</td>
<td>26.9–76.2</td>
<td>123.4–218.1</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>7.2</td>
<td>7.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Median</td>
<td>7.2</td>
<td>7.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Range</td>
<td>6.9–7.7</td>
<td>6.9–7.6</td>
<td>7.7–8.2</td>
</tr>
<tr>
<td><strong>Turbidity (NTU)</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Mean</td>
<td>0.5</td>
<td>3.4</td>
<td>56.1</td>
</tr>
<tr>
<td>Median</td>
<td>0.4</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Range</td>
<td>0.2–3.2</td>
<td>0.1–31.2</td>
<td>0.9–274.7</td>
</tr>
</tbody>
</table>
Raw surface water is typically treated before consumption in Southern Canada; however, for community members in Iqaluit who drink untreated surface water, the health implications from this study are unclear. Since all water samples tested negative for *Giardia* and *Cryptosporidium* using PCR, genetic characterization was not possible, which is relevant because of differing human health risks from different species and types of these parasites (Ryan et al. 2014; Heyworth 2016). An inability to determine if the parasites found in Iqaluit were *Giardia duodenalis* (assemblages A or B) or *Cryptosporidium* species that cause disease in humans (e.g., *C. parvum* and *C. hominis*) hampers determination of the clinical relevance of these results. Since the parasites found by microscopy were low in concentration and mostly in poor condition, with many (oo)cysts not containing cytoplasm, there was insufficient DNA to be amplified by PCR for detection (Figure A1, available with the online version of this paper).

To our knowledge, no published research exists on the genetic characterization of *Giardia* and *Cryptosporidium* from surface water in Northern Canada. However, studies in this region have found zoonotic genotypes of *Giardia duodenalis* (assemblages A and B) in humans (Iqbal et al. 2015), dogs (Salb et al. 2008), as well as terrestrial (Kutz et al. 2008) and marine wildlife (Dixon et al. 2008; Levesque et al. 2010). Although the sources of contamination in these
studies are unclear (e.g., sources could include water, food, or person-to-person contact), our results suggest that water could be contaminated by, or be a source of *Giardia* infection for humans, dogs, and wildlife. Fewer studies exist on *Cryptosporidium* species, which may also be transmitted indirectly through contaminated water in this region (Jenkins et al. 2013). For instance, some research in Northern Canada found zoonotic *Cryptosporidium* species may also be transmitted indirectly through contaminated water in this region (Jenkins et al. 2013). For instance, some research in Northern Canada found zoonotic *Cryptosporidium parvum* among diarrheic patients in Nunavut (Iqbal et al. 2015) and *Cryptosporidium hominis* in human stool samples in Nunavik (Thivierge et al. 2016). Considering the limited research on the species and genotypes of these parasites in water in the north, as well as their potential public health impact (Jenkins et al. 2013), future research is warranted to investigate the genetic diversity and source attribution of *Giardia* and *Cryptosporidium* in Northern Canada to further understand transmission sources and pathways.

No significant associations were found between indicator bacteria and parasites, which is consistent with research in other locations (Harwood et al. 2005). For instance, a literature review from 40 years of published research found that indicator organisms (including *E. coli* and coliforms) were not significantly associated with pathogen presence (including *Giardia* and *Cryptosporidium*) in water (Wu et al. 2011). Although the sample size in this study was relatively small (*n* = 55), our study results suggest that *E. coli* and total coliforms may not be accurate indicators for *Giardia* and *Cryptosporidium* in Iqaluit’s surface waters. Despite their limitations, indicator bacteria can be a useful tool to assess water quality and are currently the primary standard by which government authorities in Nunavut assess the quality of drinking water; therefore, it is still a useful tool to continue monitoring these parameters in untreated, traditional drinking water sources in Iqaluit.

Water and air temperatures were negatively associated with parasite presence, which is consistent with research suggesting that *Giardia* and *Cryptosporidium* survival is higher in some low water temperature ranges (i.e., 0–10 °C) compared to many other waterborne pathogens (DeRegnier et al. 1989). These results are also consistent with research from Northern Canada documenting higher rates of gastrointestinal illness in the late summer and fall, when air temperatures ranged from approximately −5 to 12 °C (Harper et al. 2011). Similarly, studies from Ontario found higher rates of giardiasis (Greig et al. 2001) and *Cryptosporidiosis* (Majowicz et al. 2001) in the late summer and fall months. Therefore, it is possible that human exposure to *Giardia* and *Cryptosporidium* through untreated surface waters may increase in the cooler fall months, when the atmospheric and water temperatures are lower than in the summer months. Other factors may also contribute to the contamination of raw drinking water in the late summer and fall months, such as the migration of geese and other wildlife from the north.

Although the sample size in this study was relatively low, the association between parasite presence and temperature found in this study and in previous research (DeRegnier et al. 1989) may have important implications in the context of climate change. Temperatures have increased in the Arctic and are projected to rise more rapidly in this region compared to the global mean (IPCC 2014). In Iqaluit, median annual temperatures are expected to rise 1.3–2.4 °C over the next 20 years, with the greatest seasonal increase expected in the winter (Lewis & Miller 2010). Given that parasite presence was associated with air temperatures of −0.1 to 4.5 °C and water temperatures of 1.1 to 6.7 °C in Iqaluit, climate change could have implications for parasite occurrence in northern surface waters if spring ice break-up occurs earlier and fall ice freeze-up occurs.

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**Table 4** Significant univariable exact logistic regression models for environmental exposure variables in association with the presence/absence of *Giardia* and/or *Cryptosporidium* parasites at Sylvia Grinnell and Apex Rivers in Iqaluit, Nunavut from June to September 2016

<table>
<thead>
<tr>
<th>Variable</th>
<th>OR</th>
<th>p</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water temperature (at collection)*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature (&gt;35th percentile; Ref. to 6.8 to 15.1 °C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low temperature (≤35th percentile; 1.1 to 6.7 °C)</td>
<td>4.07</td>
<td>0.047</td>
<td>0.89–22.11</td>
</tr>
<tr>
<td>Mean air temperature (3 days prior to sampling)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature (&gt;35th percentile; Ref. to 4.7 to 12.5 °C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low temperature (≤35th percentile; −0.1 to 4.5 °C)</td>
<td>4.43</td>
<td>0.041</td>
<td>0.93–25.13</td>
</tr>
</tbody>
</table>

*Models controlling for sampling location as a fixed effect. OR, odds ratio (i.e., the odds that parasites were found given the particular exposure, compared to the odds that parasites were found in the absence of that exposure); CI, confidence interval.
later due to increasing winter temperatures. These warmer winter temperatures may result in extended spring and fall months, as well as periods of low water temperatures (i.e., around 1.1 to 6.7 °C), which may increase the risk of water contamination with *Giardia* and *Cryptosporidium* in Iqaluit. Further research examining parasite associations with seasonality and long-term weather trends is needed to further develop and test these hypotheses.

Extreme meteorological events (i.e., high-level water level and high-level cumulative precipitation) were not associated with parasite presence in Iqaluit. These results are not consistent with other research documenting associations between heavy precipitation and increased risk of water contamination and waterborne infections in Southern Canada (Charron *et al.* 2004; Parkinson & Butler 2005; Thomas *et al.* 2006). Our findings could be explained by differences in wildlife populations and human population densities between Northern and Southern Canada (Jenkins *et al.* 2013). Considering there may be fewer sources of these parasites in Iqaluit, heavy precipitation and runoff may not increase the risk of surface water contamination to the same magnitude as in southern locations. Future studies should continue to monitor the impacts of extreme meteorological events on parasite presence in Iqaluit's surface waters, particularly as the local population continues to increase (Statistics Canada 2017a), and residents continue to use the study sites as sources of raw, untreated drinking water.

Several limitations were identified in this study. First, this study was limited by a relatively small sample size (*n* = 55), which may have impacted our confidence intervals as well as statistical power to detect significant associations between parasites and environmental conditions. Limited sample sizes are common in studies examining parasites in water (Wu *et al.* 2011; Young *et al.* 2013), which may be due to the complex procedures involved (Health Canada 2012). Second, the EPA Method 1623 often results in a wide range of (oo) cyst recovery due to significant losses of sample material during the processing of water samples, which can restrict the accuracy of the results (Smith & Nichols 2010; Health Canada 2012). Recoveries in this study varied from 25.9 to 92.0%, which may have caused an underrepresentation (i.e., misclassification bias) of the prevalence and/or concentrations of parasites in Iqaluit's surface waters; however, recoveries were acceptable according to the EPA criteria of 24–100% (EPA 2005). Furthermore, the EPA suggests that water samples should be processed and analyzed within 96 hours of sample collection (EPA 2005). Similar to other studies in remote communities (Wallis *et al.* 1996), our samples were processed an average of 10 days after collection due to challenges with airline schedules and weather delays. The trip control showed that (oo)cyst recovery was reduced by approximately 18.0% after 33 days of transit. Therefore, the reduction in (oo)cyst recovery over longer transit times may have further underrepresented parasite presence in Iqaluit. Indeed, the effect of extended holding times was less than the residual standard deviation normally found with Filta-Max filters using lab ongoing precision and recovery data (EPA 2005). Finally, the number of environmental exposure variables tested in this study (*n* = 14) may have led us to detect significant associations by chance (i.e., type I error). However, these water quality and meteorological variables are typically tested in research examining *Giardia* and *Cryptosporidium* in water (Wilkes *et al.* 2011; Young *et al.* 2015), so it was important to consider these variables in our statistical analyses.

**CONCLUSION**

This study estimated the prevalence and concentrations of *Giardia* and *Cryptosporidium*, as well as environmental temperatures associated with these parasites in untreated surface water used for drinking in Iqaluit, Nunavut. The prevalence of *Giardia* and *Cryptosporidium* appeared lower than in other regions of Canada. Considering that local untreated surface waters remain a highly valued drinking water resource for many Inuit residents of Iqaluit, the current study results may have important value in informing efforts to identify, monitor, and mitigate waterborne pathogen exposure risks to community members. This study contributes to the limited research on waterborne parasites in this region, and ultimately, provides a more thorough understanding of water quality in Northern Canada.

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